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Theoretical Approaches to the Mesh Selectivity of the Trawl Nets*

By

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Contents

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Introduction

There are many research reports on the mesh selectivity of trawl nets. One of the major objectives of these researches is to provide basic data relating to the rational level of exploitation of the demersal fish stocks. To achieve this, the gear regulations including mesh regulation have been imposed world-widely as the most practical method of conservation. The earliest paper of mesh selectivity, which was published in England, dates back to the late 19th century. Since that time a great deal of studies on this subject has been made in Europe. Further studies were held in aveyance in time of war. However, extensive research works were reopened in Europe and the U.S.A. shortly after the World War II, in order to impose new mesh regulation internationally for conservation purposes. A decrease in production of important fish species, such as cod, *Gadus morhua* and haddock, *Merlanogrammus aeglefinus*, on the fishing grounds in the North Atlantic promoted the international mesh selectivity research in the early 1950's. As referred to the recent researches in Europe, not only the bottom trawls but also the midwater trawls are employed to determine a desired mesh size and to discuss the mesh selectivity characteristics for many species. Thus, a number of extensive literatures have been accumulated by the member countries of International Commission for the North west Atlantic Fisheries (ICNAF) or International Commission for the Exploration of the Sea (ICES) and the experimental results have been applied to conservation measures.

On the other hand, only few examples of mesh experiments are shown in Japan, except for the research conducted in the East China and Yellow Seas during the period from 1951 to 1960. After that time, a very small amount of work was temporarily undertaken by means of the cover-net method by government-operated research vessels. For this single reason, the mesh selectivity data is conspicuously lacking at present in Japan. In addition, it seems that no research project is being organized in the near future covering this area of research. Taking the above real condition into account, it is necessary to estimate theoretically the mesh selectivity characteristics of trawl nets without recourse to the field experiments from the view-point of making up for insufficient data. In this regard, the author began to study a theoretical approach to the mesh selectivity of trawl nets on the basis of a probability model. Some facts confirmed experimentally so far are introduced in this thoretical approach so as to get better conclusions. After comparing the theoretical results obtained with the experimental results, the author found out that only little differences exist between the two. With this, the initial purpose of this study was achieved successfully and the results mentioned below could be applicable to the mesh regulation for the Japanese trawl fishereies. Although the mesh regulation is no more than only one method of control of a fishery, this has been accepted as the most efficient and practical measure of conservation.

At present time, the Japanese trawl fisheries are facing with the serious international constraints since many foreign countries have proclaimed the 200-mile fishery exclusive zone. Namely, the catch quota for the Japanese trawlers within this zone is still decreasing and will be in no way increased beyond the existing level in the future. Furthermore, the present size of codend's meshes enforced in the productive grounds in the world will be strict and must be increase to larger size, to allow the escape of immature fish which are uneconomical to land. Such a trend of world influence has given impulse to re-exploite and utilize the fish stocks at their maximum in the territorial grounds and contiguous waters around Japan. Standing on a different viewpoint, this is a rare oppotunity to review the mesh selectivity of trawl nets for forecasting the future of the Japanese trawl fisheries both here and abroad.

In this study, the author examined the theoretical results in respect to mainly the distant water trawlers which use comparatively large mesh. However, whether or not the results here are applicable to the small meshed coastal trawlers could not be presented. This is due primarily to the lack of the mesh selectivity data for the small-scale gears. By referring to the formation of the theory used in this study, it could be recognized that the approach might be favourable for the estimation of mesh selectivity for such small-scale trawl nets. Also, the results would be useful as a part of the conservation measures to fill up a gap time till the mesh experiments are executed in detail.

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1. Background for this study and probability model for analyzing the mesh selectivity of trawl nets.

1.1. Brief history on the Japanese trawl fisheries with reference to management.

The dawn of the modernization in the fishing circles is dated way back in the late 19th century or the first decade in the present century.[1,2] In those days, a number of local fishermen along the coast depended upon a fishery with simple technology, in which the small-scale fishing gears and sailing boats propelled by oars were entirely employed. It might be considered, however, that at that time they could supply home demands for the marine products by such a low productive means. After that time, the growing demands arisen from the increase of human population had exceeded the supply because the catches were limited on the narrow fishing grounds within a distance of several miles from the shore line. This accelerated the excessive competition among the coastal fishermen, consequently, drained the fishing grounds of their resources. As a result of over-competition, operation in inshore areas became uneconomical. One of the major counterplans to overcome this serious condition was to expand the fishing grounds from the inshore waters towards to the off-shore.

Some paper have shown that the off-shore grounds were already verified to be promising ones by the foreign steamships fishing out around Japan in order to catch marine mammals such as whales, sea otters, fur seal and so on. On the other hand, the most important national policy of the time was an enrichment and strengthening of the economy mainly by the consolidation of key industries under full support of the government. Joining this nation-wide modernization, the conversion from the inshore fisheries to the off-shore fisheries took place by the introduction of progressive fishing techniques from overseas. It is even said that the introduction of these techniques was through the efforts of a few private initiators, rather than the support of the government of the time. This modernization movement gave birth to fisheries legislations1); the incentive high sea fisheries law proclaimed in 1897 and later, in 1901, fisheries law. It goes without saying that the former law was aimed at finding a way out of the depression of coastal fisheries, and the latter was a basic law of controlling marine fisheries wholly and inland fisheries as well. In 1906, the former was revised and served as a keystone of success in the Japanese distant trawl fishery. Shortly after, a newly-invented otter trawling method, an English invention, was introduced into Japan. This method came already into use in European countries as the most effective fishing technique after 1892. Because of its high fsihing efficiency, otter trawling was the focus of the world's attention.

Although the advent of such a new fishing method brought about spectacular catch increase, a maiden attempt to industrialize otter trawling in Japan, however, was in vain owing to incomplete refregerating plant on fishing vessels and limited market. It took three years after introduction for the otter trawl fishery to attain some amounts of success. Thereafter, step-by-step modifications of trawl nets and equipment of fishing vessels were made by trial and error method, and then the size of net gradually increased through the initial stage of development. It is a well-known example that the Vigneron Dahle gear invented in 1925 was a typical improved model over the ordinary otter trawl assembly in that stage of development. In the course of empirical development, catch efficiency became naturally higher and higher. In addition to the experimental works, the theoretical study concerning the hydrodynamic properties of parts of nets, riggings and other individual components of gears has brough about a marked improvement in gear designing The sustained effort in the improvement of not only the gear materials but also equipment of fishing vessels hasten the pace for the otter trawl fishery to occupy a higher position both internally and internationally2,3,4) Besides the above distant trawl fishery, there was another trawl fishery which belongs to a medium category in accordance with the size of vessels in use.

Medium scale trawl fishery spread out throughout Japan in about 1909. The fishery statistics showed that during half a century or more, this fishery ranked high among all the fisheries and also ranked undoubtly with the otter trawl fishery. As a matter of course, the otter trawl and medium trawl fisheries are at present highly mechanized but show quite a different stage in the history of their respective expansions. The expansion of otter trawling had a different history with that of the medium scale trawling. The former had developed into more typical fishery by introducing and learning foreign fishing techniques as pointed above, whereas, the latter has established itself firmly in Japan on the basis of the vessel-and-gear improvements undertaken by precursors among the local fishermen.[5,6] This fact must be worthy of special mention.

In 1917, the advent of powered craft equipped with an internal combustion engine in place of hot bulb engine as well as mechanized net hauler made rapid progress for the medium scale trawl fishery.[2,5] Later, in 1921, this fishery legally formulated with a full definition and in 1924, this was divided into the two sub-groups under the new licence system. These two, "*the Ito-sokobiki fishery and the Isei-sokobiki fishery*", had been named to clearly specify their repective authorized waters.[5,7] A very clearly defined line of demarcation, Long. 130°E, had been drawn in order to separate the authorized waters for each fishery, whose brief review and legal definition are as follows :

The Ito-sokobiki fishery. This can be classified by actual trawling forms of a single boat, two-boat tarwling. The single trawling form is classified into another two different types ; the ordinary trawl and the Danish seine. The two-boat trawl became known as bull trawls or pair-trawls. The authorized waters included the entire Japan Sea, the Okhotsk Sea and the Northwest Pacific Ocean of the Japan archipelago chain east of 130°E longitude beyond several nautical miles from the shore line. The coastal shallow waters were authorized to only the inshore fishermen in the interests of not only for their protection but also for the avoidance of complication between the other fisheries. The size of fishing boat in use was 15 gross tons or more, while that of inshore trawlers was less than 15 gross tons. For a long time, this fishery and inshore fishery had competed each other with regard to annual catch.

The Isei-sokobiki fisheries. This was one of the most important distant trawl fishery during the prewar years and the early postwar period. Fishing vessel holding a licence could engage in fishing in the East China and Yellow Seas which were bounded on the West by 130°E longitude, on the North by 25°N latitude. A number of two-boat trawlers and some medium otter trawlers were authorized to fish in these waters. With the two-boat trawlers, their size should be above 50 gross tons or more, whereas, the stealmade vessel having a capacity of more than 200 gross tons was required for otter trawlers. In these fishing grounds, the otter trawl and two-boat trawl had a steady growth on a hot competition against each other.

As stated above, it is apparent that the foundation of high-sea fishery was set up in the better combination of the governmental incentive policy and private citizens' efforts with the improvement of fishing techniques. Although the otter trawl fishery fell off badly for a long while after the World War I, the advent of powered trawlers with diesel engine and sharp freezing plant in 1930, provided again great stimului to the expansion towards oversea fishery, and also moved towards a conception that the larger the size of trawler becomes the more the catch increases. In those days, the Japanese trawlers fished out already to the waters of the Northwest coast off Australia as well as the South China Sea. In addition to this, there were some center bases of the Japanese trawlers' operation in the South America and Mexico.[8] However, on outbreaking of the military coup, so-called 2.26 incident, in 1936, it entailed such a national policy that the munitions industries took precedence of all others, so it followed justly that the considerably developed oversea fisheries sank down to a lower level and then impotency. Such a declining tendency in the past continued untill the World War II came to an end in 1945. Here, the serious damage in the fishing circles recieved is examined.

According to the records of annual marine products during the 20-year period, 1926-1945, the total catches in 1926 reached about 3.07 million tons. Since then, the annual catches had increased at an average of about 2.5 percent a year during the ten year period after 1926. Thus, the highest catch record, 4.33 million tons in the prewar period was achieved in 1936. After that time, the annual catches dropped year by year, finally resulted in the lowest record in landing with 1.82 million tons in 1945, the year of the war ended. This figure was equivalent to barely 20 percent on the annual catches in 1975[9]. The Japanese faced with unprecended food shortage after the war surrender and the way of supplying necessary amount of food was really the biggest social problem to be solved as early as possible. It was natural that the increase of food production was regarded as of most important policy. In this regard, the promoting countermeasures for the fishery of all kinds, especially for the high-sea fishery which was seriously damged during the war, had been taken and played relatively important part in the food supplies. On this account, the fisheries reconstruction plan was studied before anything else, in which the old fisheries legislation was drastically revised just after the war. On the other hand, it might be said that Japan had a highly skilled fisheries techniques at that time. There was, however, little opportunity to make use them in the fishing activity due to the shortage of materials for marine equipment production. Practically, the reformation depended upon whether or not the persons concened in the fishery could get various necessary meterials for carrying on their activities. This was one of the main reasons why it took some five or six years till the annual catch attained its prewar level. The shortage of shipping was fatal to the reconstruction of fishery in particular. Therefore, a master plan, the fishing vessel-building programme, was formulated and immediately put into execution under the approval of the occupation force's headquarter[2].

When referring to this programme, the supplementary exercise of trawlers tonnage acquired the greatest importance, followed by whaler, tuna and skipjack boat. Both the number of fishing vessels by their types and total tonnages approved were as follows :

	No. of vessels.	Total tonnages.
Medium trawlers	323,	24,081,
Otter trawlers	32,	9,510,
Whalers Tuna and skipjack boats Others	61,	13,940.

It may be fairly said from the above fact that the trawl fishery played a leading role in the reconstruction period. The marine production showed a steady growth during the occupation period after the above vessels took in actual fishing. The catch record, 4.82 million tons for the year 1952, beat the previous peak record, 4.33 million tons made in 1936. In the year 1952, Japan has concluded the treaty of peace with many nations, at the same time the demarcation lines, all of which were ordered by the late General MACARTHUR and the obstruction in the way of expansion for the oversea fishery activity were removed. This provided a new starting point for the oversea fishery at the postwar. In the initial stage of the oversea trawling in that time, the old-fashioned side-trawlers were entirely employed but on and after 1960, the stern trawlers with the latest processing plant up to 5,000 gross tons entered service in the oversea fishing grounds, such as the Bering Sea and the Atlantic Ocean.[8] According to the licence system on the new fisheries legislation, the existing trawl fisheries are brought under six categories by the size of vessel, trawling method and the waters authorized. These are :

- Trawl fisheries.
  - Trawl fisheries designated by the Minister.
    - (1) Mothership type trawl fishery.
    - (2) Far-sea otter trawl fisheries.
      - (i) The North Pacific and the Bering Sea.
      - (ii) The South Pacific, Indian Oceans and the Atlantic Ocean.
      - (iii) The North Pacific and the Bering Sea based trawl fishery.
      - (iv) Oversea shrimp trawl fishery.
    - (3) Trawl fishery in the East China and Yellow Seas.
    - (4) Medium scale trawl fishery around Japan including the Okhotsk Sea.
  - Trawl fisheries licenced by the local governments.
    - (5) Small-scale trawl fisheries.
      - (i) Trawl fishery of the first kind.
      - (ii) Trawl fishery of the second kind.
      - (iii) Trawl fishery of the third kind.
      - (iv) Trawl fishery by harness of wind or tide.
      - (v) Others.

Previously stated "*the Ito-sokobiki fishery*" was reclassified in the above category, (4), in accordance with a partial revision of the fisheries law in 1963. Simultaneously, the fishing ground for "*the Isei-sokobiki fishery*" belonging to the category (3) was extended from the East China and Yellow Seas to the Northern waters of the South China Sea, north off 10°N latitude and west off 121°E longitude. The changes of annual catch in the various trawl fisheries by their classifications are shown in Fig. 1. Here, the annual change of catches every five years after the World War II is presented. The total catch by every trawlers has amounted to some 30 to 50 percent of the whole marine products in Japan. As it is obvious from Fig. 1, the mothership type and far-sea otter trawl fisheries showed a rapid growth ratio in the North Pacific Ocean and the Bering Sea.[9]

However, the ratio is shown downward for recent several years due to the enactment of the Fishery Conservation and Management Acts abroad. Accordingly, the domestic fisheries which are not affected by any foreign fisheries controls, especially in the small-scale trawl fisheries, have become very important in recent years. Although the annual catch by small-scale trawlers is relatively small compared to the large-scale ones, its growth is steady. Also, we can hardly afford to overlook the small-scale trawl fishery, which has played a important socio-economical role in each regional society.

With the catch in the Northern waters, the decreasing tendency will continue for sometime because the almost fertile grounds are under the foreign controls. Namely, on opening the second session, the International Conference of the Law of the Sea, held in Caracas, Venezuela, Japan was placed at disadvantage in being strictly restricted to trawling within the foreign conservation zones. After that, 200-mile fishery conservation zones were issued by the many nations. In addition to this, there are many devloping countries pursuing a fishery exploitation plan. Such countries have put a permission system to foreign fishing vessels operating in their waters. Usually, the fishing activities, whatever the gear may be, are admitted only under the article of great restrictions on the fishing gear, fishing season, species to be caught, catch quota and so forth.

The mesh regulation is widely known as an effective method of gear restrictions for the purpose of proper fisheries management.[10~13] In international fishing grounds, no trawlers can operate without the application of a certain gear restriction. All the trawlers must conform with the rules prescribed by the countries where fishing operations are to be conducted. Taking such a current situation relating to the fishery into account, fishery scientists in

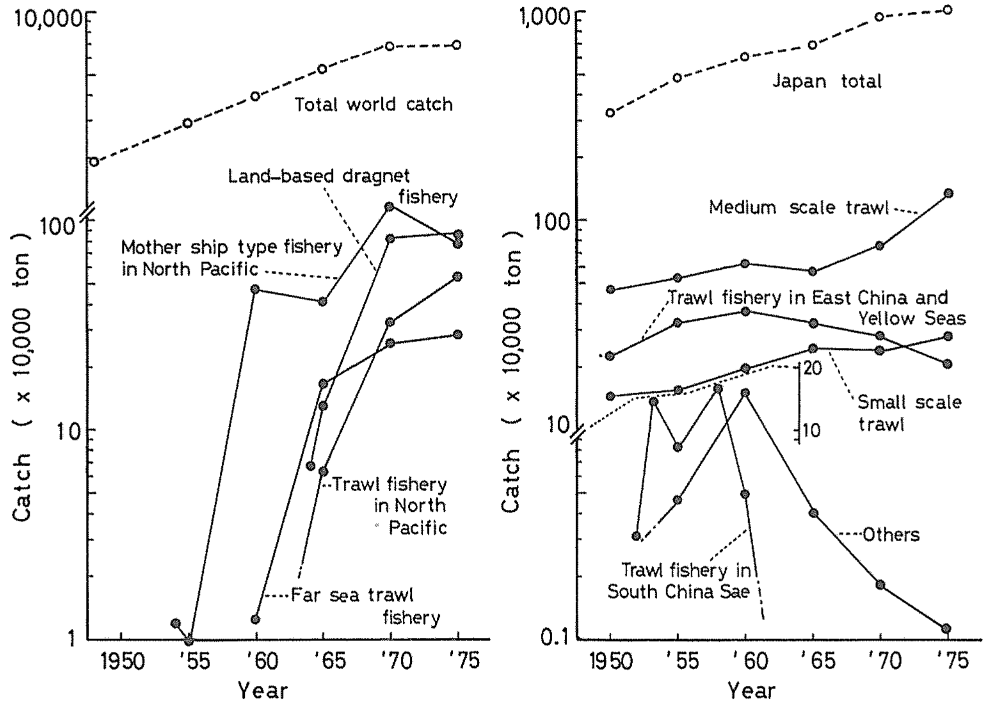

Fig. 1. The catch record shown by the type of Japanese trawler.

Japan should takè part in a possitive attitude toward research investigations leading to proper management of fishery resources in foreign waters. Moreover, in order to place the future of the Japanese oversea trawl fisheries beyond the fear of collapse, the persons concerned must make it clear that they maintain their fishing activity on the basic principle of regulating the fishing intensity at a rational level.

1.2. Past mesh selectivity data and their application to the management of trawl fisheries.

There are many reports on the mesh selectivity experiments which were contributed effectively toward the determination of a desire size of mesh in codend. The enforcement of mesh regulation is one necessary means to maintain the fish stocks at a rational level, in the light of highly advanced state of trawling techniques at present. In the Northern European nations and the U.S.A, the research on the mesh selectivity has a history of about 90 years, since Fulton[14] presented the first report on this subject. This was made for the purpose of providing an adequate standard of mesh regulation for the trawl nets. However, in Japan, it was not until the year 1936 that the mesh selection experiments were made.[15,16] The researches by the European nations are being conducted continuously on the commercial trawler-and-gear principle in the Atlantic fishing grounds as well as the North Sea with international cooperation[17~21]. On the other hand, there is a few reports in Japan and government-operated research vessels and specially designed gears were mainly used.[22,23]

When referring to the experimental results published so far, there are many factors influencing mesh selectivity, such as the dimensions and over-all rigs of gears, the type of netting meterials, the size and composition of catch and the behavioural pattern of fish species in the condend. Considering the rapid changes in the netting materials and the steady progress in trawling techniques, it would be advisable to continue further study on the mesh selectivity both experimentally and theoretically. For better conservation purpose, an alteration of the present mesh size may probably be increased. In such a case, a new set of criteria for the mesh size regulation should be decided after many considerations, namely : the latest experimental and theoretical results on the mesh selectivity for many species with various mesh sizes, fishing intensity and the existing level of fish population. Of all the facts verified experimentally, some of them will serve as useful references for the theoretical approach to mesh selectivity, so here the author will show only the important items among the experimental results.

According to PARRISH,[24] the processes of selection in fishing can be divided into the following three categories ; (i) availability, (ii) vulunerability and (iii) inherent gear selectivity. The last mentioned is the concern of this study and some explanations will be added accordingly.

Generally, for whatever gear, nets by their design, construction and mode of operation, have inherent properties. Inherent gear selectivity, the selection of fish by the gear itself, is commonly defined as mesh selection. The experimental results reported so far expressed the fish escape through meshes of trawls according to a relation between the fish body sizes and the mesh sizes of nets. This means that the mesh size is the primary variable in the mesh selection. Also, relatively large differences in length of fish caught with a given mesh size arise from the nature of inherent gear selection. The real mesh regulation is no other than the practical application of this nature and its better application becomes the main subject for the furture of trawl fisheries.[14,25] Among the various net gears, trawl nets were the first type of gear used for the mesh selectivity experiments. The reason why the trawl nets were used may be stated as follows ;

(I) The European countries faced with the continuous drain of demesal fish resources on their fishing grounds ;

(ii) it was necessary to re-examine the effects of old mesh regulation, which was decided after empirical knowledge gathered from fishermen in some selected fishing regions.

As for the control of trawl fisheries in the Northeastern Atlantic grounds at that time, it would seem perhaps most fitting to say that the determination of the new set of criteria of mesh size regulation and its imposition were urgently needed.[5] The main reason of resources reduction in those grounds would be that a great number of trawlers of different nationalities operated intensively at the same time there for a long period. Under this circumference, the first mesh selectivity experiment was conducted.[14]

Mesh regulation alone and also other known methods of control of a fishery were entirely necessary to keep the demersal fish resources at a certain desired level. The mesh regulation which is well known among the fishermen as one of the conservation measures is applicable to all. As to the other measures, there are ; (i) closed seasons and areas, (ii) imposition of catch quota and (iii) a certain minimum size limit by fish species. They are also accepted as the most effective and practical methods of control. The mesh regulation means the use of the minimum mesh size limit and is effective in curtailing the destruction of the undersized fish, which are important for stock replenishment. As a matter of fact, the small and immature fish are rejecting at sea as uneconomical even though the fishermen had a large catch of them. It must be, accordingly, kept in mind that we can improve the mesh selectivity by developing ways to perimit the escape of many small fish. Some studies that attempted to design net with improved escapement characteristics have resulted in new trawl nets as a saving gear and gears with special device to sort out small fish.[11,14,25,26] However, none of these gears might have been used in practical fishing because of gears' handling difficulties.

The restriction of the fishing effort, which is in effect equivalent to the "vessel-day" limitation, is another effective method of conservation. The effort restriction in common language is the quota system, showing the total allowable level of foreign fishing within the fishery conservation zones. A drastic and sudden decrease in the catch quota for the Japanese trawlers in those zones would put them into confusion. In view of the trend of the world opinion, the quota will be on downward trend in accordance with the allocations by nation set forth by the foreign Governments. The Japanese trawlers can operate in those waters in conformity with the existing international fishery regulations. Following these international regulations, careful consideration should be given to the gear-and-effort restrictions in the domestic grounds around Japan, too. In other words, the trawl fisheries have developed so much that their operations must be restricted.

The following are points to be taken into consideration in connection with the problems encountered in applying mesh regulation.

(i) There are different mesh regulations in the international fishing grounds. At present, the mesh sizes of codend issued internationally differs somewhat according to the main species to be caught by fishing grounds and trawling methods, i.e. either bottom trawl or midwater trawl. The current mesh sizes in the Northeast coast of the U.S.A are more than 40 mm for the midwater trawl nets and 90 mm for the bottom trawl nets. When the mesh-reglation is set forth, its criterion was drawn by the conclusions from not only the mesh experiments but also the analysis of fish resources. To give an example of the legal minimum mesh size enacted in Japan for the East China and Yellow Seas grounds, no trawlers may use any trawl nets having, in any part of the net, meshes of less than 54.5 mm (inside stretch measure) pursuant to the fisheries law revised in 1963.[27,28] However, in recent years many fishermen have used a little larger mesh, 66 mm for the lenghtening piece laced in front of the codend at their voluntary agreement. This is because of the decrease of annual catch in those grounds.

(ii) it is necessary to determine a suitable mesh size after consideration of the factors affecting mesh selectivity as indicated above, and the other factors such as duration of tow and towing speed, etc.

(iii) Only the mesh size which is effective to protect some major species has been generally accepted as a criterion of better mesh size regulation. It is evident that this size may not always provide the necessary protection to other species. This means the mesh regulations to control catches become quite difficult in the complex trawl fishery where many species are taken simultaneously.

Considering the above, it should be noted, firstly, to secure the proper fishing intensity for a given population of an important species and secondly, to get the additional information about the growth and mortality of fish. as well as morphological characteristics. In connection with the past years' mesh size regulations, the author will state how the experimental results of mesh selectivity were reflected in the current legal sizes for codends.

BEST[14] pointed out that a size of about two inches was enacted as a legal minimum in some 600 years before, in 1376, in Great Britain. After that time, the minimum size was increased to two and half inches in 1558. And this size was enacted as a standard mesh size until the closing years of the last century. In the year 1888, the British Parliament enacted a new fishery regulation for her domestic fisheries.[29] This regulation is suggestive of the prototype of the existing international fisheries regulations. According to that British regulation, fishing grounds were divided into eight sub-waters and this includes ;

(i) fishing gear and method were subject to restriction by sub-waters;
(ii) the same might be said of the closed season and fishing time allowed by gear type.

There was the same sort of regulation in France, Belgium, Denmark and so forth at that time, but all of these regulation were not based on the international criterion. Therefore, one could hardly hope to control the over-fishing for the resources throughout the North Sea under such regulations. This played an initiation to conclude an international fishery treaty among the nations concerned for the purpose of controlling their fishing activities. Thus, many fishery treaties, agreements or conventions were signed between Great Britain and France, or between the U.S.A and Canada. Each nation instructed administratively for trawl fisheries as a separate case. This resulted in remarkable flourish in the trawl fishery in the Northern Europe, especailly in England.[6] The following is an example of how the trawlers increased in number and then drained the fishery resources. In England at that time, the sail trawlers which were entirely used, numbered as high as 955 units but this figure soon raised to more than 3,000. Since the powerful steam trawlers came into general use in the early 1880's, many trawling firms were established, on adopting such trawlers. It could be said that the powered trawlers had a ten-fold fishing efficiency, compared to the sailing one. On this account, the fishing grounds were expanded ranging from the southern part of the Arctic Ocean to off the coast of the Northwest Africa. In spite of this exapnision, it might be said that the excess fishing effort made in these grounds drain their resources, in particular, the North Sea and its adjacent waters. The priority need of a joint investigation about fishery and oceanography, paving the way to settlement of fishery problems, arose from among the Northern European nations. Soon after FULTON published his report on the mesh selection of trawl net, the time was ripe for establishing an international organizaton.[14] In 1902, the ICES, thus , was established in Copenhagen.[30] The ICES has scientific staff covering from the 14 member countries. The initial objectives of the ICES were to encourage and coordinate the scientific research among the member countries. However, from the necessity of advancing the wide regional research, the ICES dissolved for the better in 1968 and its member countries increased to the 17 countries. It is generally agreed that the ICES, a successful organization, made the most impressive contribution to marine science during the last three quarters of this century. There is an extensive literature in the field of fishery-oceanography in the ICES's publications which have been accumulated by specialists of wide fields.

Here are some of the outstanding contributions from these publications, particularly with respect to the mesh selectivity of fishing gears and related items ;

(i) making clear the mesh selectivity of gill net for herring, *Clupea harengus*, and deciding an optimum mesh size to keep herring population at a certain desired level ;
(ii) collecting useful data to enforce the uniform mesh regulation in the North Sea trawl fishery for every trawlers ;
(iii) developing a kind of saving gear with sharp mesh selectivity so as to allow undersized fish to escape.

In the manner now described, the Northern European nations made various fisheries and biological researches with close cooperations in order to utilize the living resources at maximum sustainable yield in the limited fishing gorunds. As a result, the best possible conservation measures were taken against over-fishing according to a stage in the evolution of many fisheries. On the contrary, there was few control measure for trawl fishery in Japan. The following is a summary of fishery regulation in the early days.

In the age before and after the enactment of old fisheries law in 1901, the fishery control had been entrusted to the local fishermen under their voluntary agreement through the Agriculture and Commerce Ministry Ordinance, No.7 of 1885. This control, however, was ineffective in actual fisheries. The main reason might be that although the fishermen exerted to themseves to protect the fish population and to keep order in their respective fishery activities,[7] the decreasing tendency of annual catch besides the increasing demands made them disordered. Under such conditions, the regulation itself was impracticable because it took away the livelihood of the fishermen. The expansion of fishing grounds was only the way to solve the difficulty in those days. Later, the fishery regulation enacted separately by the local governments was revised in a nation-wide uniform legislation through the evolutional process of fishing techniques such as the trawling. But there were no provisions regarding mesh regulation, with only one notable exception of the mesh regulation under the Ministry Ordinance, No.8 (Fishery legislation for the Seto-Inland water trawl fishery) of 1909 for the small-scale trawlers.[7] It is said that this was really the first gear restriction in Japan but never the regular one.

The first mesh experiment in Japan got a start in 1936[16] but discontinued during the period before and after the World War II. A long series of mesh experiments by using trawl nets was reopended by AOYAMA and his working group, in the East China and Yellow Seas, in the early 1950's.[27,29,31~34] The experiments were completed in 1963 after accomplishing desire results. By introducing such experimental results, the Japanese government set forth at first a regular mesh regulation for the trawlers in those grounds. Thereafter, a few mesh experiments were carried out using the government-operated research ships on and off. According to the papers reported by AOYAMA, the trace of the development in the mesh selectivity study could be devided into the following three stages[31];

(i) the age setting the mesh experiments in several European nations;
(ii) the age of the mesh selectivity curves estimated through those experiments ;
(iii) the age of application of the experimental results for the fishery management.

Northern European nations and the U.S.A. entered the age (iii) in 1930's, while Japan and the other nations entered the same age (iii) after the 1950's. Namely, Japan had a start of less than 20 years as compared with the European nations and the U.S.A. The reason for this delay might be as follows ;

(i) the World War II created a great blank in the fishery reasearch programme ;
(ii) in the earlier stage of developments, especially in the distant water trawling, Japan was the first to succeed in the fishery modernization among the Asian nations, consequently, the productive continental fishing grounds off broad coasts along those nations were greatly developed. In such a way, the Japanese trawlers had their unrivalled sphere for along time ;
(iii) as the fishing grounds were expanded, new resources could be discovered easily. There was, therefore, no pressing need of the imposition of strict conservation measures and the gear restriction for those trawlers.

Such a fishery development was not permanent, since a fishing ground under continuous exploitation will reach its maximum sustainable yield. It is natural that the better the newly developed grounds were in terms of resources potential, the more the fishing activities increase, and as a result, the grounds are over exploited. With the decrease of annual catches by the Japanese trawlers operating in the East China and Yellow Seas, some scientists pointed out clearly "This is a good example of waste-grounds due to the insufficient fishery regulations". When citing the recent records of catch in those waters, the annual catch (= 370 thousand tons) by the Japanese trawlers had a peak in 1961 and decreased every year since. The record dropped to less than 200 thousand tons in 1976, though both trawlers and gears employed were greatly improved in their size as well as in their gear efficiency. The constantly decreasing outlook is black, indeed, so strong control, reducing the number of licenced trawlers, was taken for the last ten years in order to maintain a proper level of fishing effort. However, there is no clear indication of population recovery, which would be impossible without a strict control of fishing.[35] On the one hand, a makeshift measure was being undertaken ; that is, the legal mesh size, 54.5 mm was extended voluntarily to 66 mm in the lengthening piece laced in front of the codend. A question of importance is to reduce the present level of fishing effort in order to pave the way for a steady progress for these fisheries ; next to this is imposing new mesh regulation. At the same time further intensive fishery research should be done continuously, including the mesh selectivity experiments with various trawl nets of larger meshes.

Viewing the trawl fisheries in the Atlantic grounds as a whole, a larger number of mesh experiments were carried out. At present, merely the demersal fish and pelagic species and some kinds of crustecea are chosen for the subject of experiments.[17,19,21] Moreover, better experimental results were accumulated for many years because the commerical trawler and gear (not the specially designed gear for research purpose[36]) were employed.[37~40] Generally, this type of experiment is inefficient, labourious, tedious, expensive and probably unsuccessful. Such limitations accompanied with the type of experiments conducted would be another major reason why the mesh selectivity study is backward in Japan just after the World War II.

If a theoretical study on the mesh selectivity is developed highly and the results obatined through this study can be applied to desire control of trawl fishery, then this sort of study has a significant meaning. The main object of this study is two-fold ;

(i) to present basic data for the rational control of the Japanese trawl fishery, especially for the mesh regulation ;

(ii) to supplement the lack of experimental data about the mesh selectivity.

In proceeding this study, it is better to look for some essential items required to establish a theory in the experimental results reported so far. Likewise, it is necessary to take some factors influencing mesh selectivity into account. From the above point of view, the author will examine only the specially important items here because it is difficult to theorize all of the factors. The factors considered will be described item by item later to help the establishment of theory.

1.2.1. Principal methods of determining the selection ogives and their respective peculiarities. The methods which were used in investigating the mesh selectivity can be divided into two large groups ; the direct observations and the comparative fishing experiments. Each of these methods has merits and demerits, which should be taken into consideration in this study. The former, the direct observations, were made by using underwater cameras and television, and skin divers. These are suited for clarifying the mechanism or process of mesh selection, particularly in the behaviour pattern of fish in the codend during fishing operation. Although useful experimental results by means of direct observation were reported, this is generally unsuitable for collecting the data enough to estimate the mesh selectivity curves. The latter, three different procedures, were used almost exclusively for collecting the necessary mesh selectivity data ; (i) the cover-net method, (ii) the alternate haul method and (iii) the trouser-trawl method. In the strict sense, (ii) is different from the following two, viz. :

(ii)-(i) Alternate haul with different

codends by a single vessel.

(ii)-(ii) Parallel hauls by a pair of vessels using different codends exchanged between each haul.

Among the three, (i) and (ii) were widely used in mesh selection experiments by many workers since the World War II, but there are a few reports on method (iii)[17]. Whatever the method, it is desirable to use a certain commercial gear and not a specially designed gear[36].

The merits and demerits of each method are mainly summarized as follows :

The cover-net method. This is the simplest method not only for determining the selection curves but also for estimating the effects of the selectivity of such factors as the mesh size and composition of the catch, duration of tow, speed of towing, netting materials and so on. However, this method has one of the most significant demerits that is called "making effect". This is an effect of the cover-net made of smaller netting on the release of smaller categories of fish because the cover interferes with escapement when pressed against the main net. Use of proper design and attachment of the cover-net is a better way of minimizing the masking effect[32,41]. The cover should be sufficient slack to allow it to rise up free of codend. To minimize possible masking effect, it is not necessary to use the meshes of cover smaller than necessary. On the other hand, this method has such a merit that the experimental results are independent of the catching efficiency of the gear.

The alternate haul method. This method has no masking effect but has the disadvantage that the between-haul sampling variation becomes large.[18,42~45] The experimental results obtained by this method are not independent of the catching efficiency of the gear, so the results often differed from those by the cover-net method. The catch-difference between the two nets gives rise to one problem, that the selection curves rise above the 100 percent selection point. Namely, cases not frequently occuring in which the length groups, in the catch by the larger mesh exceeds those by the smaller mesh. The adjustment of 100 percent selection point can be made by a method to remove the effect of inequalities in total number of fish entered into the two nets. The alternate haul method is particularly suitable for use on commercial vessels operating under normal fishing condition. This is one of the greatest advantages. The results obtained by this method will give a practical estimate of profit or loss to a fisherman due to the change in mesh size.

The trouser-trawl method. This is known as a modification of the alternate haul method.[17,45] As the trouser is divided longitudinally with different mesh sizes each half, the catch-difference comes out in the number of fish entering into the two legs. Therefore, the mesh selectivity data can be easily obtained. On adopting this method in the experiments, a little care should be paid, that is to say, the expansion and configuration of the two legs are different each other during the operation. These are caused by the difference in the force which the legs recieve. The bias in catch between the two legs must be eliminated by changing them over between hauls. In recent years, the advantage of this method was understood renewedly, so some workers made good use of it but there are a few results published so far. Many workers recommended to use the method (i) jointly with the method (ii) in order to make clear or lessen the experimental errors due to those methods, though the method (iii) is available.

The variations in the methods lead to some experimental errors but such errors can be corrected to some extent by comparing the respective results obtained.

However, theoretically, this is difficult and no enough data is available for evaluation. Accordingly, the author tries to estimate the mesh selection curves giving the values of selection parameters as a foundation underlying any mesh regulations in disregard to these errors. An additional remarks would be made with reference to the direct observation. This is a promising technique not only to estimate the errors in experimenting but also to get more detail underwater information such as the behaviour pattern and shoaling behaviour by species against moving nets. Therefore, the direct observation was encouraged with a view of collecting such an underwater information. The fish behaviour is also one of the most important factors affecting the mesh selectivity.

1.2.2. Some factors affecting the mesh selectivity. There are many factors affecting mesh selectivity, some of which were made clear through a number of mesh selectivity studies. The important factors are shown below.

Netting materials. The most important is the netting materials from which the codend is made, and the physical properties of the netting yarns such as elongation, flexibility, methods of fabricating netting, i.e. single or double twine, and braided yarn or cabled one, soft or hard twisted twine, etc. To examine the effect of netting materials on the mesh selectivity, an index, the selection factor (Sf) was used[46~49] The Sf is defined as the raio of the 50 percent selection length to the size of mesh, both measures in the same unit, i.e.

$$\mathrm{Sf} = \frac{50\% \text{ selection length}}{\text{internal mesh size}}$$

For a particular design of codend and a given species, the larger the value of Sf becomes, the escape of fish increases. When referring to the published results, the mesh selectivity for the net made of synthetic fiber is usually sharper than that of natural fiber. As the trawl nets made of synthetics were predominantly used since the early 1960's, investigations were made with a view of checking the quality of the values Sf between those nets and the nets made of natural fibers[41,44,46,50~52] The results of those investigations show that the relation expressing the mesh size and the value of Sf is approximately given by a straight line for many species within the existing mesh sizes ranging from 50 mm to 120 mm. However, exceptions occur for several particular species, in which a curvilinear relationship is observed between the two. In this case, as a matter of convenience, the curvilinear realtion can be approximated with two straight lines having different gradients by dividing it into the two at the point near its largest curvature. By means of comparing the degree of the gradient, the effect of the netting materials on the mesh selectivity can be estimated roughly. In recent years, further investigations were carried out for examining the effect on the physical properties on the mesh selectivity. For example, the ICES/ICNAF Joint Working Group on selectivity revealed the values Sf for various codends made of polyamid continuous filament, polyethylene monofilament, polypropylene monofilament and continuous filament[20]. Those codends also were made of hard twisted yarn, soft twisted yarn, untreated yarn to produce a high elongation and treated yarn to produce a low elongation, etc. In spite of the fact that such a special effort is made to find out the relation between the physical properties and the mesh selectivity, a little is known about this relation at present.

Towing speed. A few data are available to estimate the effect of towing speed on the escapement.[24,53] However, there is a general conclusion reached by some workers that the mesh selectivity becomes worse as the towing speed increases. According to the report presented by LUCAS *et al*,[54] there is the weight of available evidence that indicates the noticeable difference in the mesh selectivity between the trawl net and the seine net. They also pointed out in the reports that those difference would arise from the inequality in the towing speed between these two types of gear. Namely, larger individuals of fish escaped from the meshes of seine net as compared with the trawl net. Almost the same experimental results[51] were shown by CLARK,[55] in which he pointed out that the vessel-to-vessel difference in the mesh selectivity might be caused by the inequality of vessels' towing speeds. On the other hand, there are some experimental results contrary to the above that the towing speed did not extert upon the mesh selectivity[56]. BOEREMA[47] conlcuded that there was no marked difference between the 50 percent selection length and the towing speed, after investigating the trawl nets' selectivity. AOYAMA[32] obtained similar results in his experiments. As is stated above, there are just contradicting results on this point, though the towing speed can be considered as one of the substantive factors affecting the mesh selectivity.

Duration of tow. There are considerable amount of experimental results so far made on the effect of the duration of tow on the mesh selectivity[24,53] The results opposite to each other were shown however. One of them revealed by CLARK[13] indicated that the escapement increased with the duration of tow. His experimental results were obtained by varying the duration of tow from 20 min. to 80 min. for the trawl net. The conclusion he arrived at was that the oppotunity to escape diminished as the number of fish which were crowded into the codend increased. On the other hand, according to the result presented by PARRISH[56] there was no significant difference in the mesh selectivity curves between the one and half hour trawling and the three hour trawling. Since the duration of tow and the size of catch have obviously close connection with each other, it would be better to deal with the multiplying effect of these two factors on the escapement as a single factor.

Catch size. Consistent conclusion was presented on the relation between the size of catch and the mesh selectivity[21,55,57]. Most of the experimental results showed that the size of catch was a significant variable in the codend selection, i.e. lower escapement is associated with the larger catch for a certain length of tow. Furthermore, this was proved by the fact that the values of Sf became smaller as the size of catch increased. BOHL[21] also reported much the same results as the above, on the basis of his recent mesh experiment.

It was well demonstrated that the characteristics of mesh selection varied with the above-mentioned factors. And all of these factors are associated with the conditions of fishing and experiment. It is, therefore, very difficult to express those factors by mathematics. In this study, no attempt was made to consider quantitatively the effects of those factors on the mechanism of escape. However, it is possible to make adequate correction for these effects by means of comparing and contrasting the data of past experiments and the theoretical results as described later.

1.2.3. Importance of underwater observations.

In accordance with the rapid progress in the branch of the technique for collecting the underwater information, the following valuable data have been accumulated, principally as a result of direct observations by frog-men using camera and by the underwater television[42,53,54,58,59] ; (i) the behaviour of gear, the expansion and configuration of condend in action, (ii) the working shape of the meshes in the codends, (iii) the behaviour of fish species in codends during the process of escapement, i.e. whether the fish swim more as a shoal or in any direction relative to the netting, and (iv) the related physical properties of trawls. Through these observations, it became clear such a incidental fact that meshes of codend in action had less flexibility. This fact was accepted as established, in the size of meshes ranging less than about 90mm. At the same time the accumulation of the systematic underwater information gave the selectivity studies another aspect.[50,60,61] In other words, the mesh selectivity was investigated from all appraoches, one of which was based on the geometrical relation of both fish and mesh shapes to make clear the characteristics of escapement in more detail. This was because the fish ability to escape depended greatly upon the differences in the fish and mesh shapes as well as the flexibility of meshes in the codends.

In view of the apparent effect of the relative magnitude of fish shape to mesh shape on selectivity, attention might specially be made on the relation between either the girth or the ratio of the body depth to breadth and the inner-circumference of mesh or its actual shape. New attempts to use such relations provided a classic example of the improved method of investigation. Since then, the measurements of the important and possible dimensions for fish species, such as the above dimensions and the cross-sectional shape of fish if desired, were encouraged. The detail underwater information, together with the introduction of the new attempts based on the plane geometrical dimensions, provided a benifical effect upon the analysis of the factors causing variations or errors in the mesh selection. As described above, the underwater information supplied important clues to guide the theoretical study on the mesh selectivity. Also, it is not too much to say that more definitive answers to some problems about selectivity were derived from the plane or solid geometrical approach. Referring to the above, the author will use the direct observational evidences as much as possible in this study, because it is based on a probability model constructed from the relation between the mesh shape and the cross-sectional shape of fish.

1.2.4. Necessity for developing saving gear. In the mesh selection research, what is most important is to make use the experimental results for the rational fishery management or conservation purposes. Apart from all the existing prohivitive countermeasures, attempt to develop and design trawl nets with improved escapement characteristics will also play an important role for the trawl fishery in the future[3]. So far, gear technologists tried to develop special gear of some kinds, socalled "Saving gear or Saving trawl", performing an effective function in curtailing the destruction of undersized fish. When referring to the past trial saving gears, it seems that all-out effort was made to design a net with wide open-meshes to allow as much undersized fish as possible to escape in live condition. Although such trial gears were put to the test for practical application on and off, up to present there is no particular saving gear with excellent selectivity[14,53,62] The difficulty faced in those trials is due to the physical properties existing in the trawl net itself, i.e. tension in net makes its meshes close. A brief review of principal saving gears is presented here.

Merchand[26,63] made a basic research for a saving trawl, in which he pointed out that this type of research was begun at first around 1930 in England, Norway and the U.S.A. In these countries, the study of saving trawl might have been directed toward either the partial improvement of traditional trawl nets or fitting up some attachment with these nets. However, there are a very few studies on the saving gear in Japan and these were begun comparatively late. The recent example of substantial achievement are as follows ; (i) a selective harvesting gear and (ii) a shrimp trawl. The former was developed and tested by ELLIS *et al* [64] in 1975, and this offers the latest example of success in the course of developing a new saving trawl. This trawl, a promising one, has a special attachment so as to sort out only the main objects being fished from particular fish species and crustecea such as halibut, *Hippogossus h. stenolepis,* and king crab, *Paralithodes camtschatica,* which must be protected against trawling under the present legislation of the U.S.A The latter also may be a kind of saving trawl, which was invented by JURKOVICH[65]. This has a trash chute so as to sort out only the shrimp from the fish and bottom debris. This type of shrimp sorting trawl is widely used in commercial practice in the coast along the Mexican Gulf, but the former is not widely used yet because there still remains some gear technological problems to be solved.

A path has thus far been opened in the study of saving gear. At present, this study is still at a step-by-step modification stage for practical use. It needs, therefore, further examination and long-term experiment before the saving gear will recieve sufficient recognition as being a better method of protecting undersized fish. In executing a developing project of saving gears, further attention should be paid to such problems in gear designing as (i) how to match well the inherent physical properties and construction characteristics of the saving gear against the chance to escape for the undersized fish, (ii) how to remove gear-handling difficulties on board if some extra attachments are fitted with, and (iii) how to keep the gear at a certain desire trawling condition in a continuous sequence of setting out, towing and hauling back the gear. It may be hardly avoidable to use special attachments or extra webbing with larger mesh in order to give the gear more effecient mesh selectivity, bacause the selectivity in the present type of codend is very limited in its efficiency. In this regard, the author tried to make a pilot saving gear with an intention to improve the efficiency of selectivity by way of extending the plane area of extra webbing as much as possible[62,66] This resulted in a such an innovation as "Saving trawl with bottom curtain", in which a belt-shaped webbing is attached so that undersized fish may escape easily from the meshes of this webbing before entering into codend. Likewise, a preliminary experiment was carried out using this pilot saving gear but this will not be disccussed here. The author's attempt is, so to speak, a gear technological application of the theoretical study on mesh selectivity[67~69] to the development of a new saving gear in a wide sence. The theoretical results in the following sections will also give useful suggestion in advancing the study of saving gear.

1.2.5. The purpose of the theoretical study. In this section the author adds supplementary explanations about the technical terms of mesh selection curves, then followed by the primary purpose of this study.

Fig. 2. shows the relationship between length of fish and the percentage retained for a given size of mesh. From this, it is possible to determine the percentage of fish at each cm length that are retained from the mesh. Here, the results typical of the kind obtained from experiments with trawls is a sigmoid curve known as a **selection ogive or selection curve.** The

slope of the curves basically differs according to the type of gear employed, the size of mesh and the species to be caught. With the selection curve for trawls, the region (a_0-b_0) is defind as the selection range, and the lengths at a_0 and b_0 are called the lower selection length and the upper selection length, respectively. The fish within the selection range are caught by a certain size of mesh according to their sizes of length. In mesh selectivity study, a particular length known as the 50 percent length is often used. This is the length at which the 50 percent of fish are retained. In regard to this length, the other lengths are similarly used; *ergo*, 25 and 75 percent selection lengths. The interquartile range between 25 and 75 percent selection lengths is defined as a selection span, which is used as an index of the sharpness of selection. As is obvious from Fig. 2, beyond the length b_0, no escapes occur, while every fish have a chance to escape if the fish are below the length b_0. As a necessary consequence, how to derive mesh selectivity curves theoretically is in itself the problem to be solved in the further analysis.

With the selection curve for the gill net, its shape remarkably differs from that for the trawl. This is because of the difference in catching mechanism of both gears. Namely, in the meshing mechanism of gill nets, only the fish within the length range corresponding to $(a-d)$, as shown in Fig. 2, are subject to be caught. Smaller fish can pass through the meshes of gill nets, while larger one easily aviod the net by dodging it or staying ahead of it. In fact, gill net selectivity depends upon the lengths corresponding with girths of different parts of the body of fish. Therefore, gill nets have a selection curve at each end of the length range. The selection at the lower length range presented by $(a-b)$ corresponds with the girths near the posterior membrane of gill cover. And the selection at the upper length range presented by $(c-d)$ corresponds with the girths near the maximum body depth. The slope of the selection curve becomes a little skew in the upper selection range, due to the increase of catch by entangling. Such being the case, it is said that trawls have a single selection curve and gill nets have selection curves at both ends of the length range[24] The studies on the gill net selectivity were highly developed both experimentally and theoretically. The study led by HOLT[70] enhanced the level of research in the theoretical field. Since then, a lot of findings were reported by ISHIDA[71], NASHIMOTO[45], and REGIER[72]. Consequently,

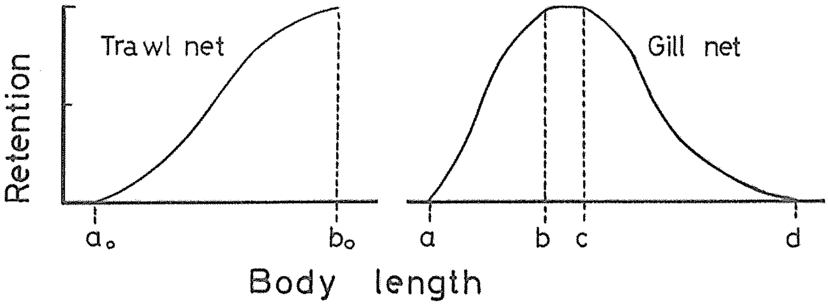

Fig. 2. Schematic representation of the mesh selectivity curves by the type of gear.
(a_0-b_0)----Selection range.
$(a-b)$------Selection corresponding at the gill cover
$(c-d)$------Selection corresponding at the body girth.

it seems that there are few problems remaining unsolved at present. These problems will be, however, solved through further research works sooner and later.

As for the theoretical studies on the trawl net selectivity[24,67-69,74], there are a few reports, in spite of the fact that the selectivity was clarified experimentally. A theoretical investigation of a mean to systematize such complicated mesh selectivity of trawl nets also is important because Japan lags far behined other countries in the field experiments. The theoretical methods of determining the trawl nets' selectivity could be divided into the two groups from the methodological view-point. One is a probability method, in which BUCHANAN-WOLLASTON[73] and JONES[24] analyzed the selectivity by using many biological data, but this method may not be a conclusive one yet. Another one is a joint method ; a geometrical and probability method which was presented by the author[67] and SATOW[74]. This method is mainly based on the relation between the mesh shape and the cross-sectional shape of fish as a clue. However, the selection curves estimated from the author's method deviated somewhat from the experimental selection curves. Accordingly, there is a room for improvement of the former theoretical approach to the mesh selectivity of trawl nets. In this study the author will discuss the mesh selectivity of trawl nets by introducing an improved method.

On the other hand, when considering the present situation of highly developed Japanese trawl fisheries as well as the lack of the mesh selectivity data, it is primarily important to prepare the possible data relating to mesh regulation for trawl nets. In addition to this, collecting the latest collaborative data is essential to protect the undersized and uneconomical fish, and to make the best use of the limited fish population. From the facts described above, the author tries to present useful data for the management of trawl fishery in Japan. At the same time, the present study will serve an additional purpose of filling up a definitive gap till a series of mesh experiment shall be done.

1.3. Probability model for analyzing the mesh selectivity.

If once selection curves are obtained, it is favourable for the estimation of various parameters of selectivity characteristics. Since it is very difficult to express mesh selection curves over their whole selection range by mathematical equations, they were estimated by the mesh experiments. However, it may be possible to derive approximate theoretical selection curves by adopting an available probability model. Under this idea, the author adopted the following model. That is to say, this model is made by a combination of the relation between the fish-and-mesh shape, and the moving action of fish against mesh surface when fish approach and try to pass through the meshes. Here, only the main points of the model are shown below, all of which are prerequisite to derive the theoretical selection curves and may be summarized.

(i) All the fish have an equal chance to escape from the meshes of codend when they approach and try to pass through the mesh, regardless of mesh location in codend. In the further analysis, the author assumes that escapes from specially fixed meshes never occur to any fish. This leads to a hypothesis that there is no any difference in the mesh selectivity mesh by mesh, in view of the fact that the actual shape of codend presents a kind of long-tapered bag with almost the same size of meshes.

(ii) When a fish approaches and tries to pass through a mesh, the probability that the point of the center axis of fish body along its length passes through is always the same at any point of the mesh surface. Namely, the author assumes that a fish does not necessary always make its body axis coincide with the center of mesh. In connection with the probability, the author must offer an additional remark ; no special consideration was paid out with regard to the task relating to the meshes under condition which fish is gilled. In other words, the author did not consider the reverse effect of the mesh selectivity on the meshing phenomena, such as the gilling of fish by the mesh.

(iii) Some observation results on the swimming behaviour of fish showed that they do not posses so much judging-ability in such a limited space as in a codend. That is, they may not change their swimming postures so as to coincide their body depths with the longer diagonal line of the mesh. Therefore, the author assumes that every fish always keep at a constant swimming posture continuously when passing through the mesh. Next assumption is the mutual relation between the swimming posture and the mesh surface. Here, for the convenience' sake, let a mesh and a cross-sectional shape of fish body be replaced by a lozenge and an ellipse, respectively. A passing-angle between the major axis of ellipse and the longer diagonal line of lozenge varies as the case may be when the fish pass through the meshes. Considering the above, here the author assumes that the various passing angles occur at completely the same probability for any fish and mesh. It is evident that the difference in the magnitude of passing angle is one of the influential factors affecting escapement. Whether or not fish succeed in escaping depends partly upon the afore-said difference, even if the fish of the same size pass through the same meshes. Accordingly, a new dimensionless quantity defined by the value (ψ/π), is introduced in order to express the difficulty of escapement in the further analysis, hence (ψ) is a passing angle.

(iv) Every fish entered into a codend can approach any mesh from all directions wherever the meshes are. Since the meshes being observed by fish extend over all directions, thereupon, the following assumption can be deduced. Fish approach the meshes from all directions but there is no difference in the number of fish by direction.

According to this probability model, it may be sufficient to estimate the selection curves theoretically by choosing an arbitrary mesh in the codend. With an intention to make rough estimate of the general tendency of mesh selectivity, at the outset, the author shall deal with a theoretical approach to the selectivity by means of a simple probability model, i.e. the two dimensional model based on the above items, **(i)**, **(ii)** and **(iii)**. Furthermore, additional theoretical approach shall be discussed by applying the three dimensional model based on the four items, i.e. from **(i)** to **(iv)**, for the purpose of filling a lacuna in the simple model. Finally, the author shall give it his general consideration, focusing on the plausibility of the theoretical selection curves, by comparing his theroretical results and the experimental results of other researchers.

2. Theoretical approach to the mesh selectivity based on the two dimensional model.

In this section, the problem of how to estimate theoretically the mesh selection curves are discussed and also the author will mention that the results obtained are practical and useful in the establishment of the control measures such as a mesh regulation. The theoretical method stated below has such an enormous advantage that the selection curves can be estimated from a few data about the bodily measurements of fish, without recourse to the field experiments. The measurements required for estimation are only the body depth and breadth at the proximity of the greatest girth of fish. Owing to the lack of experimental results on mesh selectivity at present, it would be necessary to supplement the insufficient data by such a theoretical method. At the same time, the solution obtained through this study must be very close to the experimental results. In order to arrive at a logical theoretical approach, a full understanding of the actual mesh selectivity is necessary. In this respect, some important results published so far were used as reference for the two dimensional model.

2.1. A method of estimating theoretical selection ogives.

As a first approximation, a "passability" that a fish tries to pass through a mesh was prescribed by the relative magnitude of the cross-sectional shape of the fish to the shape of mesh in codend. In order to express this ability in a theoretical function, it is necessary to introduce some assumptions in respect with the mesh shape, the cross-sectional shape and the behaviour pattern when the fish passes through the mesh. The following assumptions were made in working out the theory of mesh selection process. Reference standards of these assumptions are based on the notes presented in the summary report of the Joint Scientific Meeting of the ICNAF, ICES[13]. According to this report, particularly important factors to consider are fish size, fish shape, fish behaviour, mesh size, mesh shape and mesh location. The author makes probable assumptions with respect to these items, in the light of many experimental facts.

2.1.1. Assumptions for working out the theory. Before describing the two dimensional model, the author will discuss these assumptions, which can be conveniently brought under the three main categories; mesh, fish and fish behaviour. In the following paragraphs, the assumptions are presented item by item.

(i) Assumption about mesh shape. Generally, the working shape of mesh in a codend changes slightly according to towing speed, mesh location and bulk of fish entered in the codend. The codend is, indeed, the most important part for the escapement of fish. Therefore, it might be sufficient to discuss within the meshes of codend except for the other components of net such as square and wings, in case of considering the mesh selectivity[24]. From the fact that the codend is made of meshes of the same size throughout its whole length, it may be concluded that all the meshes take the shape of a diamond[48,54] However, a slight distortion in mesh shape will arise from variations in the forces acting on different parts of the codend as it has the external appearance of a long-tapered webbing bag in motion. As for the actual shape of meshes, some measurements of mesh angle were investigated by visual observation and by using underwater cameras or T.V. sets. Because the meshes are of the diamond-like shapes, a smaller angle of the diamond was measured in order to present mesh shape correctly as a measure. Referring to the measurements of mesh angle in codends, it could be considered the smaller angle to be almost 60° at normal towing speed[42,48,69,75,76]. For example, CLARK[48,58] reported on the basis of his underwater television studies that the smaller angle of 62° was obtained at the towing speed of two and half to three knots. On making the assumption about the mesh shape, to what extent the meshes in codend under tow are flexible and are distorted by the flow of water should be taken into consideration. As for these physical properties, it can be concluded from the papers presented by LUCAS[54] and CLARK[48] that the meshes are in fairly rigid and stiff conditions due to the drag effect in so far as the trawl is in motion at normal towing speed. Furthermore, it seems reasonable to conclude in fact that there are certainly the distorted meshes by their respective locations. There is, however, little distortion if any, for netting with the least flexibility. If the meshes are easily distorted, its derivative problem can be solved to some extent by treating the mesh angle as a variable in the theory. The above collaborative data lead to the first assumption on the mesh and its shape necessary for theory-advancing. Namely,

(a) The actual shapes of meshes in codend are considered to take the same of a diamond throughout the whole length of codend.

(b) Mesh distortion is taken to be a change in the distance between opposite knots. Here, it is assumed that there is no change in the shape of the legs and are taken to be straight.

In the further analysis, the following dimensions of a mesh are used ; the smaller mesh angle, (2θ), and the length of leg between the center of two knots, $(T/4)$. In this case, if the diameter of netting twine is so small as to be negligible, comparing with the length of one leg, the knot-to-knot length is equal to $(T/4)$., consequently the inner circumference of a mesh becomes (T).

(ii) Assumption about the fish shape. Although the body length was widely used in the mesh selectivity studies as a measure of expressing the size of fish body, apart from this, the girth and the ratio of body depth to breadth were used to investigate the selection characteristics much clearly. It can be said that such measures at right angles to the mesh surface are the most important dimensions to represent the size of fish[77]. Accordingly, some workers revealed the effects of the morphological characteristics of fish species on the inherent gear selectivity, by using the relation between the maximum girth or the cross-sectional shape of fish body at that point and the inner circumference of mesh. In practice, it is more or less tedious to measure the corss-sectional shape correctly. For this reason a possible measure, such as the maximum girth or the girth at the posterior edge of gill cover, were measured instead of the cross-sectional shape.

However, it should be noted that the girth itself has a weakpoint ; even the different species in equivalent girths have entirely different cross-section. And the cross-sectional shape varies with the measuring positions, the sex and the spawning condition by sex,13.53) too. To make up for such weakpoint and to save time needed for measuring girth or cross-sectional shape instead, an approximation method was adopted, that is, the cross-sectional shape of a fish has an elliptical form at the region of its maximum girth. KANADA78.79), and NASHIMOTO45) took this approximation method and they estimated the optimum hang-in percentage of a net gear in their respective studies. Also, the author reported that the approximation method would be favourable for the study of mesh selection, as a result of measurements of cross-sectional shapes for 11 species69) By using this approximation method, no measurement of girth is required.

Let $(2a)$ and $(2b)$ be the long and short axes of the ellipse, respectively, and the eccentricity, (ε) of ellipse can be obtained from the following equation ;

$$\varepsilon = \sqrt{a^2-b^2}/a, \quad \text{where,} \quad 0 \leqq \varepsilon < 1\,.$$

The circumference of ellipse which corresponds to the girth is determined by the complete elliptic integral of the second kind, here, only the final results are shown below :

$$G = 4a\int_0^{\frac{\pi}{2}} \sqrt{1-\varepsilon^2\sin^2\mu}\,d\mu$$

$$G = 2\pi a\Big[1-\Big(\frac{1}{2}\Big)^2\varepsilon^2-\Big(\frac{1\cdot 3}{2\cdot 4}\Big)^2\frac{\varepsilon^4}{3}-\cdots\cdots -\Big\{\frac{1\cdot 3\cdots\cdots(2n-1)}{2\cdot 4\cdots\cdots\cdots 2n}\Big\}^2\frac{\varepsilon^{2n}}{(2n-1)}-\cdots\Big] \quad (1)$$

$$\equiv 2\pi a\Phi \quad (1)'$$

Thus, the approximate girth can be estimated from the measurements of body depth and breadth which correspond to the long and short axes of ellipse, respectively. If the value of ε is so small as 0.9, the approximation equation, $G = 2\pi a\Big(1-\dfrac{1}{4}\varepsilon^2\Big)$, can be used for estimation of the girth instead of Eq. 1. In case where the value of ε takes above 0.9, it is necessary to determine to what higher terms in Eq. 1 can be omitted for estimating the reliable girth. The degree of ε is equivalent to that of thiness or flatness of the cross-sectional shape of fish. The shape becomes gradually thinner as the value ε increases, just like as flat-fish. Also, in case of $\varepsilon = 0$, the cross-section is a circular shape. Therefore, the degree of the ε value supplies a clue to distinguish the fish species roughly in one view. The difference in the cross-sectional shape being one of the important factors affecting the mesh selectivity, the causal relation between them was investigated in detail. On the other hand, to simplify the theoretical approach, it is of an advantage to use the approximation method. Considering the above advantage, the author makes the following assumption with respect to the fish shape :

(a) The cross-sectional shape at the region of the greatest girth can be approximated by an ellipse. And the eccentricity of ellipse is used as an index of the degree of thiness or flatness of fish body.

(b) Among the same species, the fish of various sizes have similar cross-sectional shapes at any position of body. For example, the ratio of the body depth to body breadth at the greatest girth is equal to that of head depth to head breadth at the gill cover of fish.

(iii) Assumption about fish behaviour. In this study the term "fish behaviour" is constructed in a very narrow sense referring to that behaviour when the fish enter into the codend. So far as this study is based on a geometrical relation between the mesh shape and the cross-sectional shape of fish as a clue, it is of primary importance to define further the behaviour pattern or swimming pattern of the individual fish among the fish school in the codend when they try to escape from the meshes. That is to say, the fish behaviour used here is a kind of escaping action from the commencement of approach of a fish to a mesh until the completion of escape or halting to escape in front of the mesh. However, it might be not practical to put a uniform definition to various swimming patterns for many fish of different kinds. A uniform definition may be permitted to be used in this study at least so long as this is used under very rigid meanings as stated above. Although it is certain that the fish behaviour in a wide sense were investigated considerably,[58,59,75,76], little experimental evidence is available on such a limited meaning, especially in the behaviour pattern in the midist of passing through the mesh within the very limited interval of time. Moreover, this evidence seems to be insufficient unto the need of the present purpose. On this account, the author made probable analogical assumption about the fish behaviour after referring to previous observations[78,80,81] by other researchers, all of which were obtained through the experimental studies in both field and laboratory. However, further explanation is necessary for the general tendency of the fish behaviour in the codend.

In general, it was considered that a school of fish interacts individually on their own behaviour[82], consequently, they are hardly dispersed after forming a school but they are divided sometimes into several subgroups under certain environmental stimulus. Such a general tendency may be applicable to some extent to fish school entered in a codned[81], too. To the author's knowledge, no investigations have been made on how the environmental stimulus exert influence on the behaviour of a particular individual among the school. At the present level of knowledge on the variations in shoaling behaviour of fish in the codend, it is said that the fish move one after the other.

The fish maintain continuously the axis of their body depths at an upright position anywhere and anytime, just before approaching the meshes of codend[54,58,59,76], And also, they seldom change this swimming posture so that they may take their ease while escaping from the mesh. In other words, there is no apparent reason for believing that the fish change the axis of body depth to let coincide with the longer diagonal line of the diamond-like mesh, immediately before a part of fish body comes in contact with one of the meshes' legs. Some direct observation about the behaviour patterns or spatial distributions of fish[78,83] suggested the approaching angle of fish against the netting. One of them showed that some species are more or less of such a tendency as if they would make themself aline their heads with the obstacles like the webbing at right angles when they met the webbing or in other similar manner. It is practically impossible for the fish to maintain its swimming position in the codend considering the strong water flow and obstruction from in comming fishes for the entire duration of the tow. More cares should be taken in applying the assumption about fish behaviour to this study. That is, the fish cannot display a good judging ability whether they can pass through the given mesh or not. The ability depends mainly upon the correlation among the magnitude of underwater visibility, the eye-sight of fish and whose perception against obstacles. To put it concretely, the trawl nets usually are towed in the deep layer or at twighlight so that the eye-sight of fish made ineffective. Therefore, it might be quite all right to say that the fish are under a condition where they cannot distinguish exactly the shape of meshes in the above-said dark environment. From the collaborative data described above, it is advisable to set up an assumption generally applicable to the fish species as much as possible in the moving net. In the further analysis, the author neglects the special case where the fish get out of the mesh from their caudal fin at first. Namely, the analysis will be made under a tacit assumption that the fish usually pass through the mesh from their heads. The assumptions to be answered are the following :

(a) When the fish approach the meshes to pass through, the axis of their body depths, the lateral lines, are kept in a vertical position to the mesh surface.

(b) When passing through the meshes, they keep their bodies at the same swimming posture during from beginning to end. Namely, they never change their bodies about the axis of their lengths when passing through the mesh.

The mesh selectivity under the assumption that the fish do escape from the meshes at arbitrary approaching angles and directions against the mesh surface will be discussed later.

2.1.2. Relation between mesh shape and fish shape. The substantial property of mesh which sorts the fish out according to body length was often liken to an old proverb "a square peg in a round hole or a round peg in a square hole". In other words, whether or not a fish can pass through a mesh can be prescribed by the relation between the mesh shape and the cross-sectional shape of fish body. For estimating a family of theoretical ogives, it is necessary to make clear the mutual relation between them first of all. This relation can be obtained by the geometrical method on the basis of the above-said two dimensional model and the assumptions.

Assuming that here is a diamond-like mesh having an inner cirumference (T) with wider angle (2θ) and that an elliptical cross-section of fish having the major axis ($2a$) where the eccentricity (ε) approaches this mesh, the following three cases should be taken into account. Namely, whether or not the fish can pass through the mesh depends entirely upon the combination of the four variables, ($T/4$, 2θ, $2a$, ε), as well as from what point on the diamond plane the center of ellipse passes through. The three cases are :

(a) If the major axis, ($2a$), is equal to the distance between the two opposite sides of the mesh, or is smaller than this distance, every fish has a chance to escape. This case is given by the following inequality,

$$2a \leq \frac{T}{4}\sin 2\theta, \quad \frac{2a}{T/4} \leq \sin 2\theta. \qquad (45^\circ \leq \theta < 90^\circ). \tag{2}$$

(b) The ellipse is larger than the maximum inscribed ellipse in the diamond, under the condition which the direction of the major axis of ellipse is the same to that of the longer diagonal line of the diamond. If the ellipse is above this size, no escapes occur.

$$2a > \frac{T}{4}\frac{\sin 2\theta}{\sqrt{1-\varepsilon^2 \sin\theta}}\,,$$

$$\frac{2a}{T/4} > \frac{\sin 2\theta}{\sqrt{1-\varepsilon^2 \sin^2\theta}}\,. \tag{3}$$

(c) When the major axis ($2a$) lies between Ineq, (2) and (3), only some fish can pass through the mesh. This case must be separately treated according to the size of ellipse in the following two, referring to the assumptions stated previously. Namely, since the fish have the same chance to approach the mesh even though the major axis ($2a$) coincides with either the longer diagonal line or the shorter one, the two different cases should be discussed. These are :

(c)—(i) The major axis lies in the same side with the shorter diagonal line of the diamond-like mesh, and is larger than Ineq. (2).

$$\sin 2\theta < \frac{2a}{T/4} < \frac{\sin 2\theta}{\sqrt{1-\varepsilon^2\cos^2\theta}}. \quad (4)$$

(c)—(ii) The major axis lies in the same side with the longer diagonal line of the diamond-like mesh, and is smaller than Ineq, (3).

$$\frac{\sin 2\theta}{\sqrt{1-\varepsilon^2\cos^2\theta}} < \frac{2a}{T/4} < \frac{\sin 2\theta}{\sqrt{1-\varepsilon^2\sin^2\theta}}. \quad (4)'$$

It should be considered that here, the ellipse within Ineq, (4), has a chance to approach the mesh from the same side with the longer diagonal line. Fig. 3. shows the relation between the diamond-like mesh and the ellipse, together with the respective corresponding equations for the three cases. From Fig. 3, the maximum limit of body depth can easily be arrived at. This is given by,

$$2a = \frac{T}{4}\frac{\sin 2\theta}{\sqrt{1-\varepsilon^2\sin^2\theta}}. \quad (5)$$

This value, ($2a$) represents the largest fish that could be caught. Therefore, there is only a few probability of being retained in such a case where the centers of both diamond and ellipse completely coincide with each other, as shown in Fig. 3—**(C)**.

Next, let suppose that the fish look for a way of escape among the various shapes of mesh before their eyes, then the probability of escape depends upon ; firstly the four variables($T/4$, 2θ, $2a$, ε), secondly, an included angle between the major axis of

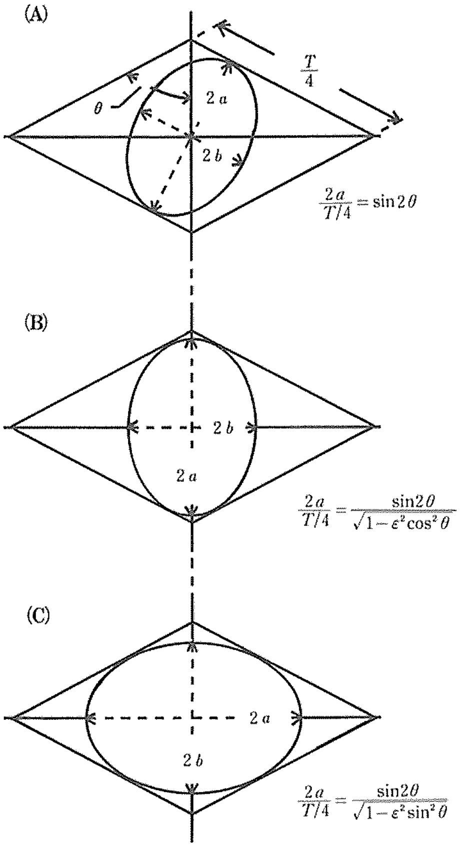

Fig. 3. Positional relationship between diamond-shaped rigid mesh and ellipse comes in touch with mesh-legs, on the assumption that the cross-sectional shape of fish body at the greatest girth is approximated by an elliptical form.
Notes : 1/2 mesh size ; $T/4$,
Mesh angle ; 2θ
Body depth; $2a$,
Body breadth ; $2b$,
Eccentricity of ellipse ; ε
The relative magnitude of a fish to a mesh of codend ; $2a/(T/4)$,
Lower selection limit ; (A),
Upper selection limit, in the cases of the major axis of ellipse lied in the same side with the shorter and longer diagonal lines of lozenge ; (B) and (C).

ellipse and the longer diagonal line of the diamond, and finally in what point the ellipse's center passes through away from the center of diamond. The ratio $\left(\frac{2a}{T/4}\right)$ of the body depth to the length of one leg of mesh stands for the relative magnitude of the cross-sectional shape of the fish to the mesh shape, hereafter, this is merely called "relative magnitude" in brevity. The way of how to derive the relative magnitude is shown in Appendix —(I)—(A) at the end of this paper. Paying a little attention to the relative magnitude, which is expressed by a function of θ and ε, it can be easily said that the mesh selectivity can be analyzed by mesh angle and mesh size.

2.1.3. Theoretically represented selection range. Net gears belonging to trawls or Danish seines have a single selection curve representing the range of retention for the gear from zero to 100 percent. And all the published reports showed that the selection curves rise smoothly through the selection range at zero percent point and continuously to rise up to 100 percent selection point therefrom. The body depth corresponding to those points are requred for drawing the theoretical selection curves first of all. According to the most general definition of the terms on mesh selectivity, zero percent selection point means that the length of fish at which zero percent is retained by a particular gear and 100 percent escape. Other points are similary used, i.e. 50 percent and 100 percent selection lengths. In the further analysis, the abbreviated expressions, the lower and upper selection points are used for the zero and 100 percent selection lengths, respectively, for convenience.

As for the theoretical lower and upper selection points, the most probable ones should be chosen and it is necessary to express them in terms of the body depth or relative magnitude in place of the body length. From the practical point of view, use of the body depth may be unfavourable and impracticable because the body length is used as the commonest measure of fish body. However, it is unavoidable to use such a new measure as the body depth for both upper and lower points because the relative magnitude is a theoretical foundation in this study. If once these points are equivocally chosen, it is difficult to derive better theoretical selection curves so as to be in fairly good approximation to the experimental selection curves. Special attention should be, therefore, paid to choose them.

With the theoretical upper point, as is obviously from Fig. 3, the relative magnitude given by Eq. (5) will supply a certain clue to choose it as properly as possible. By underlying assumptions, as a first approximation, it may safely be assumed that Eq. (5) is available for the upper point bacause the fish being larger than this relative magnitude have no chance to escape. On the contraty, if the mesh can be regraded as being perfectly flexible whilst the gear is in action, the upper point should be chosen so that the inner circumference of a mesh may be equal to the maximum girth of a fish body, i.e. $2a = G/\pi\Phi$ from Eq. (1)′. In practice, the published selectivity data showed that the relative magnitude being the full equivalent of the value of $2a = G/\pi\Phi$ is unavailable to the upper points. One other point that has to be explained is the fact that the flexibility of meshes throughout the codend under two is not so as large as expected. No matter how those meshes are slightly flexible in contrast to the underlying assumptions, the individuals with the girth exceeding the inner circumference seldom get through the mesh. Consequently, most of them are to be caught. It was shown in the data of girth measurements that very rare cases arose as yet in which the fish with the girth being equal to the inner circumference were able to escape unless either partial mesh-breaking in codend was brought about or the fish body was particularly elastic[24]. From the above considerations, Eq. (5) can be adopted as a proper theoretical upper point. In connection with this, an additional remark is necessary as reference here ; the relative magnitude corresponding to Fig. (3)—**(B)** is a maximal when the fish approaches the mesh from the direction of the shorter diagonal line and is not the upper point.

With the theoretical lower point, it is difficult to estimate it properly in comparison with the estimation of the upper point. In the strict sense of the theory, this point should be defined in such a limit value that the body depth is reduced to zero. The value zero is, however, unavailable for this point because of the necessity of a positive finite value of body depth. The fish of certain ages are not only a direct object of fishing but also the main subject to discuss. Therefore, it is absolutely necessary to adopt a certain positive finite value above zero to the lower point. This in turn proves that every fishing gears always are made with a view to catching fish which already attained to certain size of their body depths. Also, when considering the actual configuration of trawl nets, the codend acts just like as a funnel to let the sea water flow in the midist of towing. Even if the meshes are deformed by applying the towing force, every meshes hold a certain diamond shape and the area bounded by the four legs of a mesh hardly becomes nill. On the other hand, there are numerous cases that the lower point was not clearly determined experimentally. In those cases, a rough estimation of the lower point could

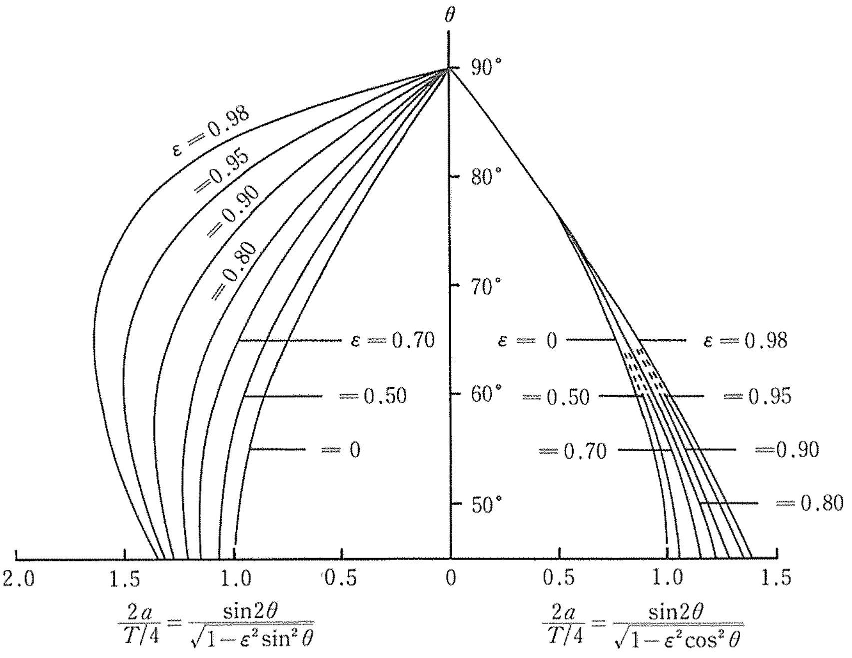

Fig. 4. Values of relative magnitude $\left(\frac{2a}{T/4}\right)$ in the lower and upper selection limits by the mesh angle (θ) and eccentricity (ε)

be gotten by means of extending the selection curves downward along their forms. The lower point estimated in this way shows considerable amount of scatter in many cases and varies with the size of mesh used and fish species. This indicates how difficult to choose this point theoretically and properly. On account of difficulty in choosing a well-founded lower point, the relative magnitude expressed by the following equation is tentatively applied to the lower point for convenience' sake. Some derivative problems and errors due to this application will be discussed later.

$$\frac{2a}{T/4} = \sin 2\theta \tag{6}$$

Then, since by definitions, both upper and lower points, the whole selection range discussed can be obtained as follows ;

$$\sin 2\theta \leq \frac{2a}{T/4} \leq \frac{\sin 2\theta}{\sqrt{1-\varepsilon^2 \sin^2\theta}}$$

Fig. (4) shows the changes in the values of the relative magnitudes corresponding to Fig. (3)—(**B**) and —(**C**) for the combination of mesh angle (θ) and eccentricity (ε).

2.1.4. Representation of the selection ratio. Usually, in reference to the selection of certain sizes of particular species, this ratio means the percentage or the ratio representing the fish either retained by the gear or escaping from it at each size interval. In order to estimate theoretically a family of selection curves, it is necessary to express the selection ratio in a form of theoretical function through the whole selection range derived so far. As it might well be explained, the selection ratio varies primarily according to the mutual relation of the mesh size to the fish size. Besides this, it should not be overlooked that the selection ratio is influenced significantly by some factors, such as specific behaviour of fish in codend, and changes in the towing conditions of gear. However, the clear reasons for the effects of the above factors on the mesh selection were not satisfactorily explained as yet because of very few information about the various sense organs of the fish and their perception against the moving nets, their reactions as well. This sort of effect perhaps depends upon the contingency led by the perception of fish.

According to BUCHANAN-WOLLASTON[84], the contingency depending on the fish behaviour in slection process was defined as a term" chance selection". That is to say, it seems reasonable to conclude, in fact, that whether the fish make escape or not could be considered as the problem of probability depending upon their behaviour as an additional way of thinking. Further arguments with regard to the fish behaviour will only lead to confusion, so this matter will not be dwelt any longer. Thereupon, as one way to overcome this difficulty somehow, the author tried to consider the items relating to the fish behaviours all at once. Saying it in detail, the probability of an ellipse being retained by a diamond-like mesh is used as an index of the selection ratio.

As a first approximation, it may be quite all right to consider this probability as an index of the selection ratio, hence, retention ratio. Let this probability be replaced by (P). Its theoretical procedure is shown below. Here, consider the case where an ellipse passes through a mesh in one geometrical plane and it may be easily understood that the probability must be proportional to an areal ratio. In other words, whether or not a fish can pass through a mesh is prescribed by what positions in the mesh surface the center of ellipse passes through. Taking this note, the author adopts the areal ratio of the area surrounded by the path, that is described by the ellipse's center around the center of diamond, to the area of mesh itself as this probability. The outline of obtaining the areal ratio is as follows :

Let (ψ) be a certain inclination angle between the major axis of ellipse and the longer diagonal line of diamond. Hereupon, it is sufficient to discuss within the limits of the previously stated selection range. If the ellipse is rotated around the center of diamond so as not to change the angle (ψ), then the path of ellipse's center makes a parallelogram after fully circulation around the center of diamond, as shown in App. fig. 3. Let the area of parallelogram be replaced temporally by $S(\psi)$, which varies, of cource, according to the degree of relative magnitude. Subsequently, when the inclination angle changes infinitestimally ($\Delta\psi$), the area surrounded by the path of ellipse's center must be a little larger than that obatined before the angle changes.

Let $S(\psi)\Delta\psi$ be this area, whereas the area of diamond can be expressed by $(T/4)^2 \cdot \sin 2\theta$. Therefore, the required areal ratio is generally given in the form of the following integral by introducing a standardizing constant.

$$P = \frac{\int_0^{\pi} S(\psi)d\psi}{\pi\left(\frac{T}{4}\right)^2 \sin 2\theta} = \frac{2\int_0^{\frac{\pi}{2}} S(\psi)\,d\psi}{\frac{\pi}{2}\left(\frac{T}{4}\right)^2 \sin 2\theta} \qquad (7)$$

The detail description of the areal ratio is attached as Appendix–(I)–(B).

It is, however, undesirable to adopt instantly this areal ratio as a better index of the selection ratio, disregarding the difficulty of escapement from the mesh. There are several problems along with this difficulty which should be closely examined. Careful attention should specially be paid to the fact that the difficulty depends upon the distance between the center of ellipse and that of the diamond. The closer the center of ellipse gets to the center of diamond, the lower the difficulty of escapement becomes and *vice versa.* For instance, there is apparently significant difference in the difficulty of escapement between the following two cases, i.e. one is the case which the centers of both ellipse and diamond coincide with perfectly, another is the case which the center of ellipse lies eccentrically away from the center of diamond. In spite of the fact that there is marked difference in the difficulty between them, the areal ratio obtainable from Eq. (7) is entirely equal in its value for the above two cases. This is a main reason why the areal ratio cannot instantly be applied to the index of the selection ratio as good. One more attention should also be paid to theorizing

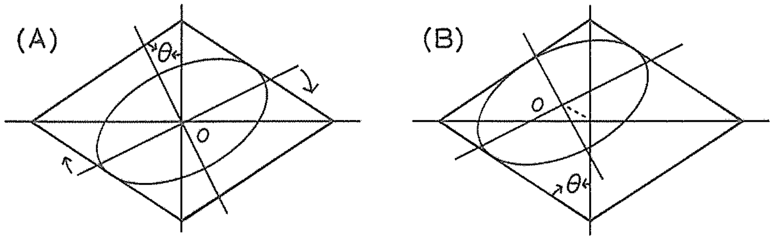

Fig. 5. Comparison of a degree of movable angle while the center of ellipse is fixed at a certain point in the mesh.

Notes : (A)--- Ellipse is able to turn in the direction of arrow.
(B)--- Ellipse cannot turn due to contacting the mesh legs at three points.

such a difficulty beforehand. With an intention to do so, the author attempts to express this difficulty, keeping his mind upon it varying proportionally with the distance between both centers.

Fig. 5 illustrates a typical example of the difference of the difficulty due to the positional variations of both centers, provided that there is no difference in the inclination angle in Fig. (5), **(A)**—and—**(B)**. As may be seen from Fig. (5), it is possible for the ellipse to rotate in the direction of arrow when it passes through the diamond so as to coincide their centers with perfectly. On the other hand, the ellipse shown in Fig. (5)–**(B)** cannot rotate in any direction in the diamond because the sides of diamond come in contact with the three points on the circumference of ellipse. If the center of ellipse lies between the above **(A)** and **(B)**, the movable angle for the ellipse increases proportionally to the distance between both centers. Paying attention to such variations of positional relations, a certain possible moving angle can be used as an index of that difficulty or the ease of retention instead. With regard this angle, it must be noted that the possible moving angle varies with the entering direction of ellipse toward the diamond. This variation is due to the relative magnitude, and the included angle between the major axis of ellipse and either the longer diagonal line or the shorter one of the diamond. Fig. 6 makes it easy to explain the difficulty on account of the changes by the entering angle.

In using this difficulty as the index, an incidental consideration must be given well to the entering conditions. that is, the ellipse can approach itself toward the diamond so as to let its mojor axis fix either the longer diagonal line or the shorter one of the diamond. The possible limit of the moving angle changes with these conditions. This limits can be expressed by the following equations ;

In the case of the ellipse approaching the mesh along its longer diagonal line,

$$\psi_i = \theta - \sin^{-1}\left[\frac{1}{\varepsilon}\sqrt{1-\left\{\frac{\sin 2\theta}{\left(\frac{2a}{T/4}\right)}\right\}^2}\,\right]. \qquad (8)$$

In the case of the ellipse approaching the mesh along its shorter diagonal line,

$$\psi_j = \left(\frac{\pi}{2}-\theta\right) - \cos^{-1}\left[\frac{1}{\varepsilon}\sqrt{1-\left\{\frac{\sin 2\theta}{\left(\frac{2a}{T/4}\right)}\right\}^2}\,\right]. \qquad (9)$$

The method of deducing Eqs. (8) and (9) are shown in Appendix—(I)—**(C)**.

From the practical standpoint, it can be considered that whether the fish have the same relative magnitude in making those

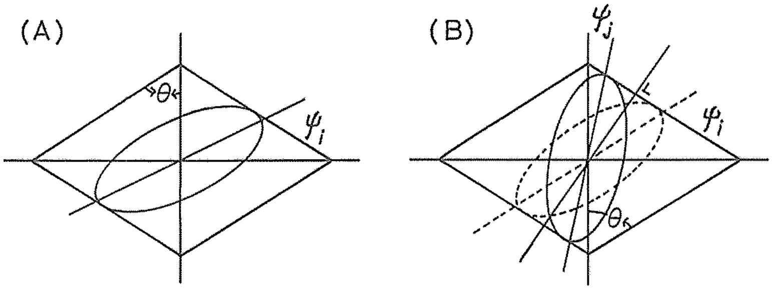

Fig. 6. Movable angles (ψ_i, ψ_j) of the major axis of ellipse against the longer and shorter diagonal lines of mesh.
These angles vary with the relative magnitude.

escape or not can be prescribed by the multiplicative effects of the probability of being retained and the difficulty of escapement. Therefore, as a first approximation, the author makes an attempt to use the theoretical selection ratio that is symbolized by the product of the value of areal ratio and the moving angle. This procedure would be accepted upon such a real fishing condition that every fish entered into the codend have a chance to escape from all directions for the various shapes of meshes, keeping their body depth at upright position. The difficulty represented by a dimensionless quantity which is obtained by dividing the moving angle (ψ) by $\pi/2$ is used in the further analysis.

Further examination is necessary with respect to applying the above product to the index of the selection ratio. Namely, Eqs. (8) and (9) give the maximum movable angle for the ellipse under condition which the relative magnitude is held constant. These Eqs do not mean a freely movable angle. The freely movable angle is produced by slipping-off distance of the center of ellipse from the center of diamond. The freely movable angle and the possible moving angle must be equal only in the case where the two centers coincide precisely with. This forms one of the exceptions but in many cases the freely movable angle becomes smaller than the possible moving angle. Because there is an equivocal face in terms of the above-said two angles, it is better to examine the correlation among the two angles, the difficulty and the probability of ellipse being retained. The following is a result of investigation on this matter.

Let (β) be a certain freely movable angle and this is shown in Fig. 7, together with the maximum moving angle (ψ_i or ψ_j) which can be also obtained from Eq. (8) or (9). In this figure, when the center of ellipse gets through the point (O), the movable angle less than (ψ_i) is produced. If an irregular relation is found out between the probability and the angle (β), the above-said product of the areal ratio and the moving angle is not necessarily a better index of the selection ratio. Meanwhile, should no special irregularity arise between them, that product will be considered to be one of the available evidence to show the better index. No irregularity would be ideal, but slight irregularity will appear for various combinations of ellipses and diamonds.

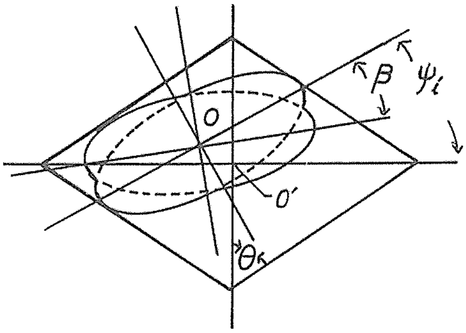

Fig. 7. Freely movable angle (β) of ellipse while its center is fixed at an arbitrary point (O) near the center of mesh (O').

In order to examine the presence of irregularity, the following example will be given ; an ellipse passes through the diamond-like mesh under condition which its center is located at an arbitrary point (O), apart from the center of diamond (O'). Here, assume that there are two congruent ellipses whose centers coincided with in the diamond. Then, turn these two ellipses in the opposite direction around their centers so that the three contact points are just made on the sides of diamond with the circumference of ellipses. By this turning, a special petal-like shape is made as shown in Fig. 7. Hereafter, this special shape is called "a combined ellipse" for brevity.

This example offers the ideal one which shows clearly the difference between the maximum movable angle and the freely movable angle. The included angle between the two major axes of combined ellipse is not larger than the freely movable angle. As is seen from Fig. 7, the further the position of the center (O) goes away from the point (O'), the smaller the freely movable angle becomes.

An investigation on how much the irregularity exsists can be made by almost the same procedure as that described for Eq. (7). Namely, the existence of the irregularity can be checked on the basis of the relation between the angle (β) and the probability of being retained for various combined ellipses. When referring to the equations shown in Appendix—(I)—(A), (B) and (C), the probability of the combined ellipse being retained can be formularized as follows, here, only the most general case is given,

In the case of $\theta < \beta$,

$$Pd = \frac{1}{\pi}\int_0^{\pi}\left(\frac{2a}{\sin 2\theta}\right)^2 QR\,d\psi\,. \tag{10}$$

where, Pd is the probability of being retained and

$$Q = \frac{T}{4} - \frac{2a\sqrt{1-\varepsilon^2\sin^2(\theta-\psi)}}{\sin 2\theta}$$

$$R = \frac{T}{4} - \frac{2a\sqrt{1-\varepsilon^2\sin^2(\theta+\psi-\beta)}}{\sin 2\theta}$$

As a result of investigating the relation between the probability (Pd) and the angle (β), curvilinear relations were found out between them. After rearranging the results by the relative magnitude $\left(\frac{2a}{T/4}\right)$, ($\theta$) and ($\varepsilon$), those relations are shown in Fig. 8, for nine combinations of (θ) and (ε). As is apparent from Fig. 8, all the curves are almost homologous under certain combinations of (θ) and (ε), regardless of the changes in the value of relative magnitude. However, this homologous relations are slightly distorted in some cases but there are little differences. Also, in case of a cetain fixed value of ε, even if the value θ changes, there are considerable strong homologous relations among the curves.

From the fact that there is no remarkable irregularity, at least it can be said that the previously stated product is one of the better index of the selection ratio. Thus the selection ratio can be computed on the lines indicated. If the selection ratio is represented by (Sr), then the following equation can be obtained by definitions,

$$Sr = k_1\,\psi\,S\,, \tag{11}$$

and by definition Eq. (11) can be rewritten as follows :

$$Sr = k_2\frac{\psi}{\pi}P\,, \tag{11$'$}$$

hence k_1 and k_2 are constants and $S = P\left(\frac{T}{4}\right)^2\sin 2\theta$, P and ψ are the areal ratio and the maximum movable angle, respectively.

The right side of Eq. (11)′ stands for the volume of a particular pillar whose area of its base is nothing else than the area surrounded by the path of the center of ellipse. And the height of the pillar corresponds to the possible moving angle. Use of the above volume is a kind of convenience method of eliminating the effect of the difference of that difficulty on the mesh selectivity, so the total cubic volume of the pillar is applied as a measure of the selection ratio. Also, from the other view point of making that difficulty uniformly, applying such a volume is much better than the area of base of the pillar alone, though it is certain that the area itself consists of some different difficulty-zones.

To reiterate the items relating to the selection ratio, they are as follows :

(i) As a measure of the selecton ratio, Eq. (11)′ is applied.

(ii) The selection ratio can be expressed by the function of the relative magnitude because Eqs. (7), (8) and (9) are also the function of the relative magnitude.

(iii) Favourably, the upper and lower selection points can be expressed by the relative magnitude, too.

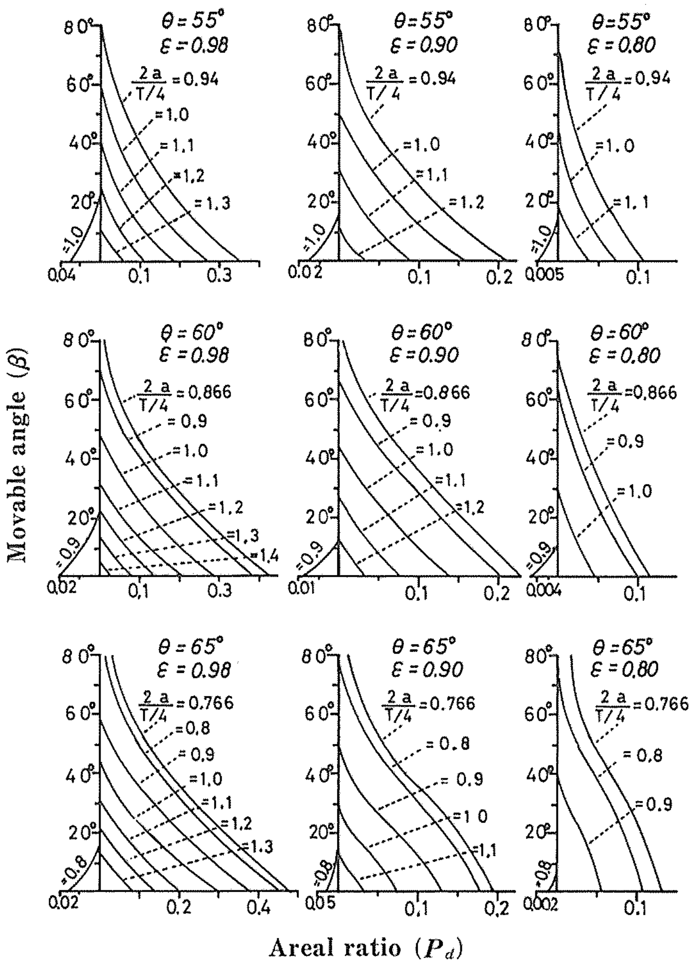

Fig. 8. Relation between the freely movable angle (β) of the ellipse and areal ratio (P_d) within the selection range. The (P_d) values can be calculated from the Eq. (11)'. The curves on the right and left of ordinate show the changes of (P_d) values in the longer and shorter diagonal lines of the mesh, respectively.

2.2. Theoretical ogives.

Under the idea which is described above, the values of parameters necessary for a quantitative determination of the theoretical selection curves can be derived. The selection ratio can be calculated from Eq. (11)′ for arbitrary relative magnitudes covering the whole selection range. The resultant values obtained from Eq. (11)′ were changed as percent units for each corresponding selection range because the values are all absolute less than one.

2.2.1. Ogives rearranged by mesh angle and fish shape. According to the above discussion, a family of the theoretical selection curves can be expressed in the coordinate system with the selection percentage as Y-axis and the relative magnitude as X-axis. On computing the selection ratio, the following two cases

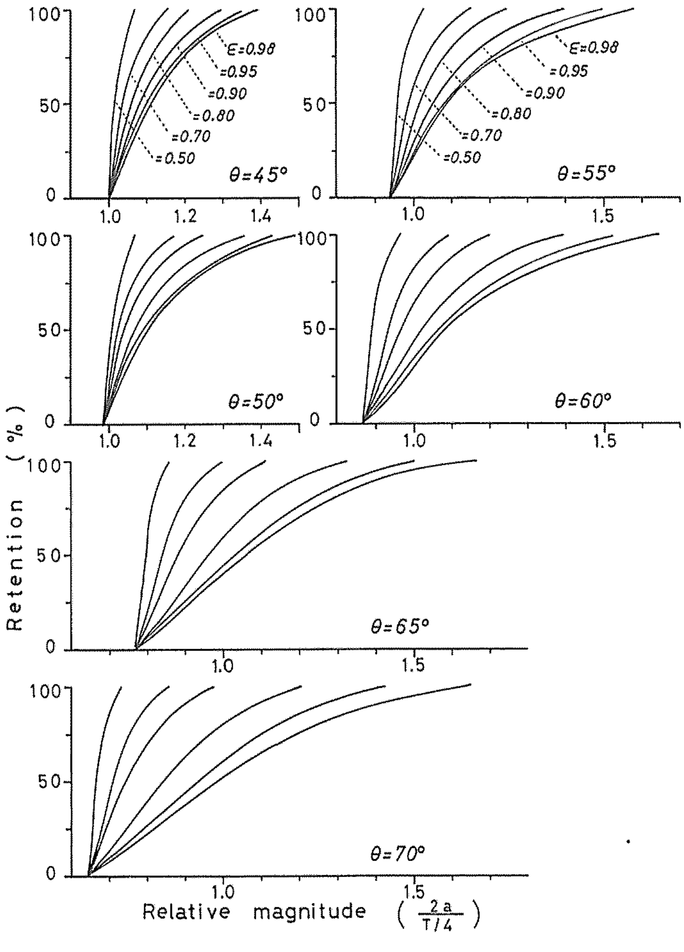

Fig. 9. Theoretical mesh selectivity curves derived considering whether fishes can pass through the mesh or not is prescribed by the relative magnitude $\left(\frac{2a}{T/4}\right)$.

must be considered on account of the underlying assumption that the mesh is fairly rigid and diamond shaped.

Case one : where the fish are within the range of relative magnitude being applied in Eq. (4), and they approach themselves to the meshes with an intention to escape, each fish will be made to keep its body depth along either the longer diagonal line or the shorter one of the mesh. Moreover, each fish has an equal chance of approaching the mesh, irrespective the direction of the diagonal lines. If the fish approach to the meshes along the longer diagonal line, the chance to escape always becomes greater than for the shorter diagonal line.

Case two : when comparing the selection ranges represented by Eqs. (4) and (4)′, it is obvious that there is significant difference in the chance to escape between the two. As for the fish corresponding to the range of relative magnitude expressed by Eq. (4)′, they have no chance to escape in the case where they approach the meshes so as to keep their body depths along the shorter diagonal line. However, they have some chances to escape from the meshes when approaching those meshes so as to keep their body depths along the longer diagonal line. Such a chance to escape depends upon ;

(i) The degree of the relative magnitude ;
(ii) The relative positions of the centers of both mesh and diamond ;
(iii) The inclination angle between the axis of body depth and either the longer diagonal line or the shorter one.

Accordingly, there is no longer any problem in computing the selection ratio for the fish having the relative magnitude above the range given by Eq. (4). On the contrary the fish within the range given by Eq. (4)′ comes into question on computing the selection ratio. For this case, the following method was chosen to compute the selection ratio. Namely, in light of the prerequisite defined so far, the selection ratio should be computed by distinguishing the longer diagonal line from the shorter one. Because the smaller fish have much chance to escape, the selection ratio for those fish must be expressed as a sum of each value obtained individually from Eq. (11)′ under the above distinction. As a result of computation, it was known that the selection ratio for the shorter diagonal line was so slight as to be almost negligible. The theoretical selection curves obtained are arranged by the combination of (θ) and (ε), and are shown in Fig. 9.

2.2.2. Changing tendency of theoretical ogives. As may be seen from Fig. 9 at a glance, it may be concluded that the theoretical selection curves change with the values of (θ) and (ε). The general characteristics of those curves may be summarized as follows ;

(i) When θ is constant, the slope of curves becomes sharp as the value of ε increases. This means that the sharpness of selection depends mainly upon the value of ε, and the closer the value ε approaches zero. i.e. the circular cross-section, the sharper the selection becomes.
(ii) The selection range has a tendency to be widen as both θ and ε values increase. This tendency is remarkable in case where ε is greater than 0.9.
(iii) The slope of those curves is gentle in the region above 50 percent point as a whole but becomes steeper and steeper in the region beyond this point.
(iv) The upper selection point moves from the less relative magnitude to the higher relative magnitude as the values θ and ε increase, while the

lower selection point moves from the higher relative magnitude to the lesser one only in the case where the value θ increases.

And the lower selection point does not change with the value of ε when θ is constant. The value of relative magnitude at the lower selection point is definitely closer to 1.0 as the value θ approaches 45°. On the other hand, the relative magnitude at the upper selection point does not exceed a certain limited value, which changes with the value of θ and ε. This limit can be estimated by referring to Fig. 4.

2.3. Selection characteristics of the theoretical ogives.

The mesh selection characteristics revealed so far through the experimental studies were made full use not only in the mesh regulation enforcement but also in the establishment of rational management of trawl fisheries. According to many published results, specially important selection characteristics are probably the sharpness of selection and 50 percent selection point (or length). Of these two, 50 percent selection point is essential to decide a better criterion of the size of meshes in codends for the mesh regulation purpose. Next to this point, the quartile points such as 25 and 75 percent selection points also are important to check whether the mesh size decided only by 50 percent point is good or not as expected. In this section the author deals with the sharpness of selection and 50 percent selection point in order to offer a reference standard for further mesh regulation. The following indicates the relation between the selection characteristics and some selection variables.

2.3.1. Sharpness of selection. For a certain species, if the average half escape from given meshes with the same size and the other half retain, this is the very case corresponding to "knife-edge selection" or "absolute selection". Consequently, the mesh selectivity curve for this case is given by a straight line at right angles with X-axis. These are, however, few cases in a thousand or more. In many cases, the sharpness of selection can be evaluated to some extent on the basis of the degree of slope of selection curves because of their various slopes. When using the slope instead of the selection range , it is easy to evaluate the sharpness of selection. In this regard, the author might draw a logical conclusion from the following examples.

If the fish having the circular cross-section in diameter ($2a$) tries to escape from a square mesh whose length of leg is ($T/4$), the absolute selection arises under the condition where the centers of cross-section and mesh coincide. This is because all the fish can pass through the mesh in case of $2a < T/4$, while all fish retain in case of $2a > T/4$. Another situation, if the shape of mesh changes into a certain diamond, all the fish can escape from the mesh when $2a < (T/4)\cdot\sin 2\theta$ but retained when $2a > (T/4)\cdot\sin 2\theta$. From the above examples, it would seem to be a theoretical conclusion that the sharpness of selection might depend mainly upon the cross-sectional shape of fish body. It is, however, certain from Fig. 9. that the changes in mesh angle have some effects upon the sharpness of selection, though this effect is by far less than that of cross-section.

In using the selection range as an index of the sharpness of selection, it becomes a serious problem on how both upper and lower selection points can be estimated correctly. In the past experimental researches, cases not frequently occuring where the clear lower selection points were not estimated on account of the difficulty of obtaining enough samples to estimate those points during experimental fishing. For this reason, many workers presented the sharpness of selection by using another index such as the interquartile range expressed by the range between 25 and 75 percent selection points. This is commonly called "selection span". The selection span ($S.Sp$) has such a good point that the sharpness of selection can be estimated even if one of the upper point and the lower point be not known clearly. By using ($S.Sp$), the sharpness of selection is discussed and expressed by the differences of the value of relative magnitude at both 25 and 75 percent points.

Fig. 10 shows the relation between ($S.Sp$) and the values of (θ) and (ε). Each curve in Fig. 10 may be considered to be a simple proportional relation but there are large difference in their slopes. When identifying tentatively each curve as a straight line in order to estimate roughly the interrelation between ($S.Sp$) and (θ) or (ε), the following tendency became clear. Namely, the straight lines vary with the changes in the values of (θ) and (ε). The interrealtion between ($S.Sp$) and (θ) is positive when the value of (ε) exceeds 0.8 and the coefficient of these lines becomes gradually smaller with the decrease of the (ε) value. Whereas, the interrelation turns negative in case of $\varepsilon < 0.8$ and the line for $\varepsilon = 0.5$ approaches the abscissa asymptotically. From the above examination, the following logical conclusion may thus be inferred.

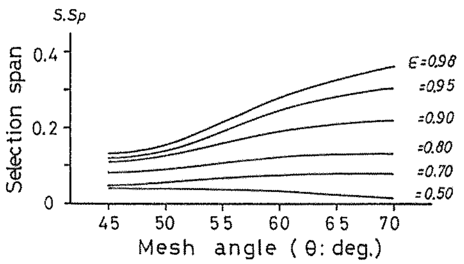

Fig. 10. Relation between the value of selection span (S, S_p) and the mesh angle (θ).

According to the morphological measurements of various species presented by the author[69], the common spindle-shaped fish have about 0.8 in (ε) values. As for those species, it is difficult to increase the sharpness of selection even though the trawl nets are improved so as to make their meshes open in codend for the purpose of sorting selectively only the optimum size of fish. However, if the fish to be caught are those like flat-fish whose value of (ε) is usually above 0.95, such an attempt of gear-improvement is one of the effective manners to increase the sharpness of selection. Meanwhile, from the view point of maintaining the fishery production in an adequate level, another close examination is necessary about the relation between ($S.Sp$) and the lower selection point. This examination is important to enforce the mesh regulation. To illustrate the matter, examples are shown below :

From Fig. 10, the value of ($S.Sp$) is about 0.6 in case of $\theta = 60°$ and this value decreases by approximately one-half, about 0.3, when $\theta = 45°$. Accordingly, if the trawl nets were improved so that the mesh angle may be changed from 60° to 45°, the value of ($S.Sp$) is reduced. In this case, the lower selection point moves from the value of relative magnitude $\left(\frac{2a}{T/4}\right) = 0.866$ for $\theta = 60°$ to that of $\left(\frac{2a}{T/4}\right) = 1.00$ for $\theta = 45°$. Therefore, to keep the sharpness of selection sharper by changing the mesh angle moves, in effect, the lower selection point from the lower to the higher. This results in a reduction of fishery production because much of the adequate size of fish to be caught can pass through. In view of the discussion, it is recommended that further study be made on the improvement of gear designing. For progressive gear development, Fig. 10 gives useful suggestions in promoting the gear improvements in such an attempt as that described above as well as in developing a kind of saving gear.

2.3.2. Fifty percent selection point. The term, 50 percent selection point, is the length of fish at which 50 percent are retained by a trawl nets. Hereafter, this point is abbreviated by 50% R.P. This point was regarded as of major importance in the field of fish population dynamics. For example, in trawl fisheries the optimum catch was estimated on the assumption that the absolute selection occured just at 50% R.P. And also, the existing mesh regulations were enforced under such population analysis in the productive fishing grounds all over the world. However, in enforcing the mesh regulations, it is very difficult to decide a certain criterion of mesh size in the trawl fisheries because many species are taken simultaneously. In addition to this, the difficulty lies in the fact that there is a little amount of scatter in 50% R.P among the same species for a given mesh. In this case, the choice of the best 50% R.P. becomes a serious matter. Because of this, the mesh regulation enforced so far was conlcuded from the following general considerations ; (i) the amount of fishing effort, (ii) total allowable catch by species and (iii) 50% R.P. of some major species which are taken in great quantities and are of high commercial importance. There are still considerably many species not investigated

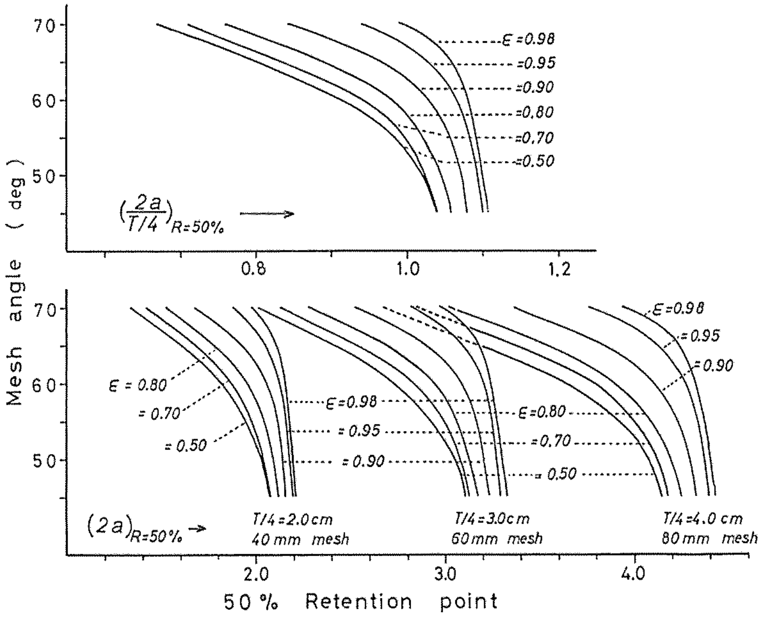

Fig. 11. Relation between 50% retention point and mesh angle.
Upper --- 50% point expressed by the relative magnitude.
Lower --- 50% point expressed by the body depth.

yet on 50% R.P. Among them are species of low commercial value at present but may be utilized for food in the near future. In this sense, it is desirable to investigate 50% R.P. for as many species as can be, so the author extends his examination between 50% R.P. and the other variables, ($T/4$, θ, ε) in much the same manner as described in the sharpness of selection. The results obtained are shown in Fig. 11, in which the relative magnitude corresponding to 50% R.P. is represented by $\left(\frac{2a}{T/4}\right)_{R=50\%}$. Likewise, as a way of illustrating how the changes of mesh size exert on 50% R.P, a new measure $(2a)_{R=50\%}$ is introduced. This measure means the body depth corresponding to 50% R.P. and can be calculated by replacing nearly the existing mesh sizes, 40mm, 60mm and 80mm by the denominator of the above relative magnitude, as shown in the lower part of Fig. 11. The factor influencing 50% R.P. can be summarized as follows ;

In general, the value of $\left(\frac{2a}{T/4}\right)_{R=50\%}$ has a tendency to become larger with the increase of value (ε) when (θ) is constant. This tendency becomes more pronounced as the value (θ) increases. No doubt the mesh size is one of the most influencial factors over 50% R.P.

2.4. Examination of the plausibility of the theoretical ogives.

It goes without saying that first it is importance to check whether the theoretical ogives obtained are practical or not. Accordingly, the plausibility of the thoretical ogives will be checked by comparing the results here with the experimental selection ogives by other researchers.

2.4.1. Materials and method. All mesh selectivity data required for the examination are cited from the papers presented by AOYAMA[32]. The comparison was made between the theoretical results and the experimental results under the following directions. In comparing, what is most important is to choose as many species as possible. In other words, it is necessary to choose various shapes of cross-section. Paying more attention to this point, the author chose the different species, all of which have distinctive features not only in their morphological characteristics but also in their swimming behaviours. Next, it is necessary to deduce the relation between the body depth and the body length. If this relation cannot arrived at, it is impossible to make direct comparison of the theoretical selection curves with the experimental ones because the body depth is entirely used as a measure of fish body in this study. Accordingly, the length-depth relationships and the value of (ε) by species were calculated by using the data on the biological measurements. Those data[85] were cited from the report published by Seikai Regional Fisheries Laboratory and partly cited from the paper presented by the author[69]. Table 1 shows the regression equations between the body depth and body length in which all the (ε) values are the average of total examined number of individuals. Combining these regression equations and the mesh sizes presented in AOYAMA's papers, the selection lengths were converted in relative magnitudes. In further analysis, the theoretical relative magnitudes are represented by $\left(\frac{2a}{T/4}\right)_{\mathrm{Th}}$, whereas, the experimental ones by $\left(\frac{2a}{T/4}\right)_{\mathrm{EX}}$. Here, the author compared the above two, respectively, in their sizes at the three main selection points, 25% R.P., 50% R.P. and 75% R.P. In this comparison, the choice of the mesh angle for the experimental

Table 1. The average eccentricity (ε) of the cross-sectional shapes on the assumption that each fish body has an elliptical form and regression equations between body depth (or body breadth) and body length by the species.

Species			Samples examined			
No.	Name*	ε	No.	Ranges of body length (cm)	Regression equations** (cm)	Corr. coef.
1	*Tanakius Kitaharai* (Flat fish, Yanagi-mushigarei)	0.98	15	15.1 - 21.3	B. D. = 0.31T.L.+0.05	0.854
2	*Rhinoplagusia japonica* (Tongue fish, Kuro-ushinoshita)	0.98	6	26.8 - 33.2	B. D. = 0.45T.L.−5.34	0.899
3	*Trichiurus lepturus* (Hair tail, Tachi-uo)	0.95	20	16.5 - 46.2	B. D. = 0.18A.L.+0.03	0.960
4	*Pseudosciaena manchurica* (Yellow croaker, Kin-guchi)	0.89	12	19.5 - 32.3	B. D. = 0.21T.L.+0.50	0.793
5	*Argyrosomus argentatus* (White croaker Shiro-guchi)	0.87	10	15.6 - 19.3	B. D. = 0.24T.L.+0.13	0.700
6	*Argyrosomus nibe* (Black croaker, Kuro-guchi)	0.85	33	16.6 - 39.0	B. D. = 0.29T.L.−1.48	0.990
7	*Suggrundus meerdervoorti* (Flat head, Me-gochi)	0.80	23	12.2 - 40.2	B. B. = 0.15T.L.+0.29	0.962
8	*Saurida tumbil* (Lizardfish, Wani-eso)	0.50	42	19.5 - 49.6	B. B. = 0.15T.L.−0.29	0.950
9	*Uranoscopus japonicus* (Stargazer, Mishima-okoze)	0.50	20	9.5 - 26.0	B. B. = 0.22T.L.−0.13	0.950
10	*Parabembras curtus* (Flat head, Uba-gochi)	0.45	14	16.2 - 22.2	B. B. = 0.17T.L.−0.40	0.930

Notes : * Common names and Japanese names are given in the parentheses.

** The regression equations were determined on the data report of biometrial measurement of fish caught in the East China and Yellow Seas, Vo. III, published by Seikai Regional Fisheries Laboratory in Nov, 1950 and the author's paper. In this Table, T.L., A.L., B.D. and B.B., are abbrevations for Total length, Snout-anus length, Body depth and Body breadth, respectively. In the further analysis, (ε) was used instead of the average value of the eccentricity.

relative magnitude is in itself a problem. That is to say, the value of $\left(\frac{2a}{T/4}\right)_{\mathrm{Th}}$ can be obtained separately by mesh angle, while the value of $\left(\frac{2a}{T/4}\right)_{\mathrm{Ex}}$ can be obtained in utter disregard of the mesh angle. It needs, therefore, a certain standard of mesh angle for the experimental relative magnitudes. This standard must be about right under the actual fishing condition.

The necessary mesh angle was decided as follows. Namely, although some experimental evidences are available on the actual mesh shape during operation, a proper mesh angle would be known by synthesizing these evidences. For example, CLARK[48] showed that an average mesh angle of 62° was obtained in his mesh measurements. Also, according to BEVERTON *et al*[57], the ratio of the longer diagonal line to the shorter one of the diamond-like mesh varied from 4:3 to 2:1 with the most usual ratio being about 3:2 under the normal towing speed was reported. It can be concluded from these ratios that the mesh angles vary from about 64° to 53°, the most usual angle being about 57°. Therefore, it may be quite all right to consider that at the normal towing speed the mesh angle shows a slight variation within the region of $60° \pm 5°$. Because to some extent the differences came out in mesh angle, it is decidedly better to compare the theoretical relative magnitude corresponding to the three mesh angles, 55°, 60° and 65° with the experimental relative magnitude.

Before making comparison, further discussion should be made on the errors in estimation of selectivity curve. In general, experimental selection curves are deformed at the vicinity of both upper and lower selection points, especially at the lower point. The cause of error, more than to any other, must be attributed to the insufficient number of fish caught, and this gives rise to an accidental error in the calculation of selection ratio. There are other errors produced by the differences in experimenting methods. The selection curves obtained by the cover-net method has, for instance, a gentle slope at their rising parts as compared with those parts estimated by the alternate-haul method. It was generally understood that the gentle slope was due to much more catches of smaller category of fish by the masking effect of the cover-net. Such errors make the selection range wider and consequently, a true selection range becomes narrower than an apparent selection range. The error produced by the degree of coefficient of each regression equation in Table 1 should be also taken into account. This kind of error does not exert influence upon only a limited range of fish lengths (or body depths), but has effects evenly upon the whole selection range. When considering the above-said various errors, the sum of errors appear greatly at the part of the selection range extending far from 50% R.P. to both upper and lower points.

The same remark can be applicable to the theoretical ogives because of the underlying assumptions and the use of the approximation equations for both lower and upper points. It should be noted here that the error arisen from the assumptions exerts influence upon the whole selection range, while, at each end of theoretical ogives the errors in making approximation and assumption appear simultaneously. On the basis of the assumption about the mesh, there is no need of discussion about the shrinkage or elongation of netting twine. However, in connection with the elasticity of fish body, further examination is necessary on this matter beforehand. In spite of the fact that the physical properties of netting twine and the elasticity of fish body have much effect on the mesh selectivity[32,44], a little was investigated about those factors, especitally on elasticity. As for the elongation of netting twine, it was recognized that the netting twine had a tendency to be more or less elongated proportional to the number of times of regular use of the gear[32]. Therefore, the elongation of netting twine moves the selection curves from the true positions to the right-hand side along X-axis as a whole. The moved distance depends upon the extent of elasticity. From the reason above, strictly speaking, the value $\left(\frac{2a}{T/4}\right)_{\mathrm{Th}}$ modified by removal of the effects of the elongation and the elasticity should be used for the comparison. Since there is meager data to evaluate them properly, the nominal mesh size is used instead of the internal mesh size which is required for calculating the experimental value $\left(\frac{2a}{T/4}\right)_{\mathrm{Ex}}$, as a simplest method of modifying that effects.

2.4.2. Comparison of the theoretical results and the experimental results. The result of the comparison, which was made by introducing a fitting ratio (Q), is shown in Table 2. As is evident from Table 2, the sign of (Q) varies with the species, mesh size and angle, and the selection point. At the same time there is great amount of scattering in (Q) values. The negative sign stands for the theoretical ogives situating on the left-hand side of the experimental selection curves. The changes of (Q) value are within the following ranges :

Mesh angle	Ranges
55°,	$-0.38 < Q < +0.26$,
60°,	$-0.27 < Q < +0.24$,
65°,	$-0.14 < Q < +0.26$.

Here, when classifying the ten species used in Table 2 into the three subgroups according to their morphometrical characteristics, it becomes clear that the sign of (Q) tends to change with this characteristics. The subgroups are ;

(i) Flat-fish type.
  (the value ε above 0.98)
    Flat-fish (specie No. 1),
    Tongue fish (species No. 2).
(ii) Common fusiform type.
  $(0.8 < \varepsilon < 0.95)$
    Hair tail (species No. 3),
    Yellow croaker (species No. 4),
    White croaker (species No. 5),
    Black croaker (species No. 6).
(iii) Circularity cross-section type.
  (the value ε less than 0.8)
    Flat head (species Nos. 7 and 10),
    Lizardfish (species No. 8),
    Stargazer (species No. 9).

Among the above three groups, in the species described under (i), the positive sign of (Q) appears frequently, while the negative sign appears frequently in the species described under (iii). The positive and negative value of (Q) are seen at random in the species described under (ii). At least in so far as relatively much amount of scatters are seen in the value of (Q), the theoretical ogive must be chosen of such an approximate curve that its characteristics agree well with the experimental selection curve. Likewise, the choice of fairly good theoretical ogive should be made under careful attention to the degree of (Q) value, mesh angle, species and so on. However, from the practical viewpoint, it is tedious to choose the best approximation curve from among the curves in Fig. 9. If there is little scatter in the (Q) values, there is no problem in the selection. For the yellow croaker and the white croaker, their approximation curves can be easily chosen because of less scattering. On account of the existence of much amount of scattering, the choice of better theoretical ogives is in itself a problem.

As a matter of practical convenience, it is better to decide a standard of

Table 2. Comparison of the values of theoretical relative magnitude $\left(\frac{2a}{T/4}\right)_{\mathrm{Th}}$ in three mesh angles (θ) with those of experimental relative magnitude $\left(\frac{2a}{T/4}\right)_{\mathrm{EX}}$ in three main retention points (R.P.).

Species*	ε	$T/4$	R. P.	Relative magnitude				Fitting ratio		
				$\left(\frac{2a}{T/4}\right)\mathrm{Ex}$	$\left(\frac{2a}{T/4}\right)\mathrm{Th}$ (B)			$Q = \frac{(A)-(B)}{(A)}$		
No.		(cm)	(%)	(A)	$\theta = 55°$	$\theta = 60°$	$\theta = 65°$	$\theta = 55°$	$\theta = 60°$	$\theta = 65°$
1	0.98	3.62	25	1.16	1.01	0.98	0.92	0.13	0.16	0.21
			50	1.29	1.09	1.08	1.06	0.16	0.16	0.18
			75	1.65	1.22	1.26	1.24	0.26	0.24	0.25
2	0.98	3.00	25	1.13		Do.		0.11	0.13	0.19
			50	1.28				0.15	0.16	0.17
			75	1.58				0.22	0.20	0.22
3	0.95	2.71	25	1.01	1.00	0.96	0.90	0.01	0.05	0.11
			50	1.17	1.08	1.07	1.03	0.08	0.08	0.13
			75	1.33	1.20	1.21	1.17	0.10	0.09	0.12
	Do.	3.99	25	0.91		Do.		−0.10	−0.05	0.10
			50	0.94				−0.15	−0.14	−0.10
			75	1.12				−0.07	−0.08	−0.04
4	0.89	3.99	25	1.00	0.99	0.94	0.86	0.01	0.06	0.14
			50	1.12	1.06	1.03	0.95	0.05	0.08	0.15
			75	1.26	1.15	1.13	1.06	0.09	0.10	0.16
	Do.	5.78	25	1.04		Do.		0.04	0.10	0.17
			50	1.20				0.12	0.14	0.21
			75	1.32				0.13	0.14	0.20
5	0.87	3.00	25	0.99	0.99	0.94	0.85	0	0.05	0.14
			50	1.11	1.05	1.00	0.93	0.05	0.10	0.16
			75	1.26	1.14	1.10	1.05	0.09	0.13	0.17
6	0.85	3.00	25	0.81	0.98	0.93	0.84	−0.21	−0.15	−0.04
			50	0.95	1.04	0.99	0.92	−0.09	−0.04	0.03
			75	1.08	1.11	1.08	1.01	−0.03	0	0.06
7	0.80	2.71	25	0.81	0.98	0.92	0.83	−0.21	−0.14	−0.02
			50	0.95	1.02	0.98	0.88	−0.07	−0.03	0.07
			75	1.03	1.08	1.04	0.96	−0.05	−0.01	0.07
8	0.50	2.71	25	0.69	0.95	0.88	0.79	−0.38	−0.27	−0.14
			50	0.80	0.96	0.89	0.80	−0.20	−0.11	0
			75	0.93	0.98	0.91	0.81	−0.05	0.02	0.13
	Do.	3.99	25	0.69		Do.		−0.38	−0.27	−0.14
			50	0.79				−0.22	−0.13	−0.01
			75	0.90				−0.09	−0.01	0.10
9	0.50	3.00	25	0.69		Do.		−0.38	−0.27	−0.14
			50	0.81				−0.19	−0.10	0.01
			75	1.01				0.03	0.10	0.20
10	0.45	3.00	25	0.80	0.95	0.87	0.78	−0.19	−0.09	0.03
			50	0.98	0.96	0.88	0.79	0.02	0.10	0.19
			75	1.08	0.97	0.89	0.80	0.10	0.18	0.26

Notes : * As in Table 1.

The experimental value of relative magnitude $\left(\frac{2a}{T/4}\right)_{\mathrm{EX}}$ were calculated numerically from the selection curves referring to AOYAMA's papers, and the regression equations as shown in Table 1, when the denominator substituted the length of half mesh size (2 legs and 2 knots) for $T/4$.

theoretical ogive. For this, a tentative examination is required whether or not the theoretical ogives corresponding to a certain mesh angle in Fig. 9 hold fairly good approximations. The theoretical ogives for $\theta = 60°$ is chosen as a standard, largely from the reasons that the actual mesh angle can be regarded as being 60°, and also the average of the summed up value of (Q) becomes a minimum in case of $\theta = 60°$, as is apparent from Table 2. If slight differences are revealed through this examination, the theoretical ogives for $\theta = 60°$ can be considered to be the standard. And it may be very convenient to offer basic data for mesh regulation as quickly as possible. Here, the author took the two species in Table 2 for the examination and clarified that the theoretical ogives for $\theta = 60°$ were very close to the experimental curves. The yellow croaker whose value of (Q) at 75% R.P. shows $(+)$ 0.1 when the mesh size (hence, equal to half of mesh size, $T/4$) is 3.99 cm. This (Q) value does not exceed the margine of experimental error, 1.5 cm in the length of body. This degree of error can be accepted for practicality. Since such a slight error was taken place whenever and wherever the mesh experiments were carried out, this can be considered as an experimental error. The lozardfish whose value of (Q) at 25% R.P. shows $(-)$ 0.27 in case of $T/4 = 2.71$ cm. According to the same procedure, it could be made clear that the error amounted to some 3.0cm in the body length. This error is somewhat larger than that in the first case. However, the length error, 3 cm, might not be large, as was often the case with the experimental selection curves for the error in their appears in part such as at 25% R.P. In the above examination, since the two species may be or may not be extreme examples, it is better to check how much errors are presented in the body length for the ten species. Table 3. shows the result of examination on the errors in body lengths at 50% R.P. The values presented in the column $(B.L)_{Th}$ in Table 3 correspond to the body lengths which were estimated theoretically from the regression equations in Table 1 and theoretical ogives for = 60°. The result indicates that each value in Table 3 is as small as in the range of the experimental errors. It could be, therefore, concluded from the above examination that the theoretical ogives for $\theta = 60°$ hold to a fairly good approximation for many species within the interquartile selection range.

Table 3. Comparison of the 50% retention length.

Species* No.	$\frac{T}{4}$	50% release length (cm)		Error
		$(BL)_{Ex}$**	$(BL)_{Th}$***	
1	3.62	14.9	12.5	2.4
2	3.00	20.4	19.0	1.4
3	2.71	17.4	16.0	1.4
4	3.99	18.9	17.2	1.7
5	3.00	13.3	12.0	1.3
6	3.00	14.9	15.3	−0.4
7	2.71	15.2	15.7	−0.5
8	2.71	16.4	18.0	−1.6
9	3.00	11.6	12.7	−1.1
10	3.00	19.6	17.9	1.7

Notes : * The species numbers are the same to Table 1.
** Cited from the AOYAMA's report.
*** Estimated from this theory.

2.5. Discussion.

A family of theoretical selectivity curves was estimated by introducing the two dimensional model and the probability method. This was done with a view of making up for the lack of basic data for the mesh regulation for the Japanese trawl fishery. The model was based on the geometrical relation between the mesh shape and fish shape. Among the theoretical ogives obtained separately by various mesh angles, the ogives for $\theta = 60°$ could be considered to be good approximations to the experimental selection curves for many species, at least within the interquartile selection range after checking their validities. However, the approximated ogives seem to deviate somewhat at either end from the experimental selection curves reported so far, especially in the rising part of curves. This deviation probably is due to the underlying assumptions presented here. Also, the deviation is due partly to the fact that the approximation equations were applied to both lower and upper selection points, that is, Eq. (6) for the former and Eq. (5) for the latter. Since these two points are of importance for the establishment of the mesh selectivity theory, the approximation equations are discussed about their validity a little further.

With the upper selection point, it should be considered that the value of upper selection point obtainable from Eq. (5) is small, in comparison with the real value estimated from the experimental curve. The reasons why the theoretical value of upper point is small are twofolds : (i) the assumption that the mesh is rigid and (ii) the disregard of the elongation of netting twine and the elasticity of fish muscle. According to the author's trial calculation, the differences in the body lengths at the upper selection point were two percent in the error of their length's units at the most. Therefore, it could be recognized that no remarkable difference might be found in the body lengths at that point between both experimental and theoretical selection curves. Furthermore, there is not so much difference in the (Q) values of the theoretical ogives for $\theta = 60°$ at 75% R.P. which is closer to the upper selection point. It could be, therefore, concluded that the upper selection point can be approximated by Eq. (5). There is a reason therefore to believe that the above judgement is to some extent valid. Furthermore, some workers cralified that the flexibility of meshes in codend is less when the gear is towed at the normal towing speed. From this, it becomes clear that the meshes hardly change so that their shapes fit the girth of fish body closely. Based on such argument, it could be considered that the main cause of difference in the upper point (in two percent in length) is to be sought in the multiplying effect of the elongation and elasticity. MARGETTS[61] reported similar conclusion on this matter. In actual fishing operation, the afore-said difference or effect will not be in serious problem in studying the mesh selectivity, and also the existing mesh regulations will permit of catching all the fish grown to their lengths equal to the upper selection point.

With the validity of the theoretically defined lower selection point, there is no clear supporting clue to judge whether or not Eq. (6) is a first approximation. According to a judgement based on only the value of relative magnitude at the lower selection point, the value obtained by Eq. (6) will be excessively estimated. In addtion to this, it is difficult to know to what extent the lower selection points are excessively estimated because of the lack of proper experimental values of lower selecton points. As was pointed out previously, it is difficult to decide the most reliable value of lower selection point only from the selection curves revealed experimentally. In many cases, the estimated lower selection points have considerably wide range owing to the experimental errors. Meanwhile, it is also very difficult to decide properly the theoretical lower selection point by the two dimensional model alone. In order to decide much better theoretical lower selection point, it is necessary to introduce further complicated model. However, from the reason that there are relatively small differences in the values of (Q) at 25% R.P. close to the lower selection point, it could be allowed to use Eq. (6) as a first approximation of the theoretical lower selection point.

Among all the theoretical ogives shown in Fig. 9, the ogives for $\theta = 60°$ would be useful in estimating the mesh selectivity characteristics for the existing large scale trawl nets. Also, the other theoretical ogives for various mesh angles and Figs. 10 and 11 would be useful to seek that characteristics and to amend the criterion of the mesh size enforced presently. At the same time, the ogives obtained by different mesh angles would provide an effective data for estimating the mesh selectivity of the nets such as seines and a kind of surrounding net having the same constructional function as the trawl. It is, of course, necessary to collect more detail information about mesh angles of those gears in order to estimate their mesh selectivity correctly. If those gears have less flexibility in their meshes, better mesh selection curves could be made clear from the theoretical ogives presented in Fig. 9. Moreover, the theoretical ogives obtained have such an enormous advantage that the effects of mesh angle and the fish shape on the mesh selectivity may be easily estimated separately. Besides this, another advantage is that it is enough to get only small amount of data of the body depth and breadth with statistical confidence for the estimation of the theoretical ogives.

The author pointed out that there were many factors influencing mesh selectivity. Typical factors are the materials of netting twine, differences in the experimental methods, the experimental errors, towing speed, duration of tow and amount of catch. etc. In order to make clear the effects of those factors theoretically, it is necessary to present them by mathematical formula. If further complicated probability model is constructed with an intention to clarify those effects, several incidental problems to consider will arise along with its construction. Paying more attention to this point, the author tried to construct another mesh selectivity theory in order to improve the two dimensional model. This is presented in the following section.

3. Theoretical approach to the mesh selectivity based on the three dimensional model.

As is obvious from the preceding section, it could be concluded that the thoretical ogives based on the two dimensional model are in approxmate agreement with the experimental mesh selection curves. However, in order to improve the theoretical approach to the mesh selectivity, it may be necessary to adopt a new method where the swimming action of fish will be expressed by space coordinate system. In this section, the author, therefore, tries to analyze the mesh selectivity by using a three dimensional model, in which a fish has a chance to approach a mesh not only from all directions but also with all inclination angles against the mesh surface. For the purpose of examining whether the three dimensional model is good or not, the author carried out a series of experiments by using a number of model fish. The experiments were made under actual and comparable fishing conditions, i.e. those answering the three dimensional model as nearly as possible. Comparing the theoretically obtained result with the experimental result, it was revealed that there was no remarkable difference between them. Accordingly, it may be concluded that the results obtained are applicable to the mesh selectivity of actual trawl in fishing operation and provide some clues for improving the model.

3.1. A method of estimating theoretical ogives.

It is beyond doubt that fish take various swimming actions in the codend. For the purpose of expressing those actions as they are, it is quite agreed that the adoption of the space coordinate system is the best method. In other words, theoretical ogives were deduced by applying a three dimensional model.

3.1.1. Three dimensional model of fish swimming action. Since the results shown in the preceding section indicated that the general tendency became clear in regard to the changes in the theoretical ogives if the four variables. ($T/4$, θ, $2a$ and $2b$) were known. Therefore, the generality of the theoretical ogives obtainable on the three dimensional model could be made clear after an investigation is made of a special example among the various fish shapes. That is to say, it must be possible to some extent to estimate the mesh selectivity characteristics for many species under the analysis for the specially selected fish shape. Thereupon, the author concentrated on the theoretical ogives for $\varepsilon = 0$, a simplest and typical example, in this section.

Now, in order to experss the swimming action by the space coordinate system, it is assumed that a fish has a chance to approach a mesh from all directions and with all inclination angles against the mesh surface. When the fish having the value of $\varepsilon = 0$, i.e. the circular cross-section with radius (a) approaches the diamond mesh with its included angle of 60°. The probability of this fish being retained can be computed from much the same procedure as stated in the two dimensional model. Let the rectangular coordinates be (X) and (Y) in the mesh surface and (Z) extending perpendicular upward. The fish approach the mesh at an arbitrary inclination angle (α) with respect to the (Z)—axis. Fig. 12 shows a graphical illustration for the three dimensional expression of a fish swimming action. Here, if the dimension of mesh is

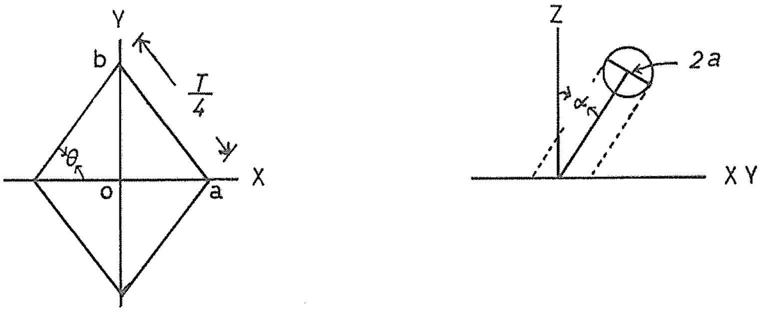

Fig. 12. Dimensions of the diamond-like mesh and schematic representation showing that a fish having a circular cross-sectional body shape (dia : $2a$) passes through the mesh with inclination angle (α).

represented by the same manner as in Fig. 3, then the equation expressing the side (ab) of the diamond-like mesh is given in the folllwing function when the point (O) in Fig. 12 is the origin and also mesh angle equal to 60°.

$$Y = -\sqrt{3}X + \frac{\sqrt{3}}{2}\left(\frac{T}{4}\right) \qquad (12)$$

The method of Euler's angle transformation is applied to the mesh in order to proceed to the three dimensional analysis. In other words, the three dimensional expression of swimming action can be looked as identical to the investigation by using the projection of the mesh shape on a horizontal plane. Under this idea, in the coordinate axes shown in Fig. 12, the coordinate transformations were performed three times. This transformation was made in the following order.

If the Z-axis is turned for a certain angle (ρ), then both axes, X and Y become new coordinate axes, X' and Y' respectively. This angular transformation can be expressed by the following equation :

$$R_\rho(Z) \equiv R_1$$

Hence, the angle (ρ) corresponds to ↗ the approaching direction for the mesh surface by definition.

Secondly, by turning the Y'-axis for a certain angle (ϕ) around its own axis, another new coordinate axis, (Z'), can be obtained. The angle (ϕ) corresponds to the inclination angle. By the same manner or representation of the above transformation, this angular transformation is as follows :

$$R_\phi(Y') \equiv R_2$$

$$R_2 = R_\rho(Z)R_\phi(Y)R_\rho^{-1}(Z)$$

Finally, turn the Z'-axis for an angle $(-\rho)$ and the following experssion can be obtained by the same prodecure.

$$R_{-\rho}(Z') \equiv R_3$$

$$R_3 = R_\phi(Y')R_{-\rho}(Z)R_\phi^{-1}(Y')$$

Combining the above three expressions, the following expression can be derived :

$$\begin{aligned} & R_{-\rho}(Z')R_\phi(Y')R_{-\rho}(Z) \\ &= R_\phi(Y')R_{-\rho}(Z)R_\phi^{-1}(Y')R_\phi(Y')R_\rho(Z) \\ &= R_\phi(Y')R_{-\rho}(Z)R_\rho(Z) \\ &= R_\rho(Z)R_\phi(Y)R_\rho^{-1}(Z) \\ &= R_1R_2R_3 \end{aligned}$$

This can also be expressed in terms of a determinant as follows :

$$R_1R_2R_3 = \begin{pmatrix} \cos\phi\cos^2\rho+\sin^2\rho, & -\cos\phi\sin\rho\cos\rho, \ +\cos\rho\sin\rho, & -\cos\rho\sin\phi, \\ -\cos\phi\sin\rho\cos\rho+\sin\rho\cos\rho, & \cos\phi\sin^2\rho+\cos^2\rho, & \sin\phi\sin\rho, \\ \sin\phi\cos\rho, & -\sin\phi\sin\rho, & \cos\phi, \end{pmatrix}$$

The question to discuss is the mesh surface in a fixed coordinate system which is located on the horizontal plane for $Z=0$ in the model. Therefore, it is quite all right to consider one of Euler's angles $(-\rho)$ to be zero. Here, express the mesh surface that is turned for the angle, ρ and ϕ by the new coordinate axis, (x) and (y), not (X) and (Y). Thus, the equation representing the side of diamond which is projected on the horizontal plane can be derived :

$$y = -\frac{U}{V}x + \frac{\sqrt{3}}{2V}(T/4). \qquad (13)$$

where, $V = \cos\phi + (1-\cos\phi)\cdot\left(\cos^2\rho + \frac{\sqrt{3}}{2}\sin 2\rho\right)$,

and $U = \sqrt{3}\cos\phi + (1-\cos\phi)\cdot\left(\sqrt{3}\sin^2\rho + \frac{1}{2}\sin 2\rho\right)$.

These two, U and V, can be obtained by solving the determinant derived so far.

3.1.2. Representation of the selection ratio.

In order to compute the probability of the circular cross-section being retained for the mesh with its mesh angle of 60°, it is necessary to consider the case where this cross-section passes though the given mesh projected on the horizontal plane, x-y. First it is necessary to decide the passable region which the cross-section is possible to pass through the mesh. Fig. 13 shows this region. In this case, it is sufficient to discuss within limits of the first quardrant of the plane, x-y, because the fish shape is symmetric with respect to all directions. The necessary region can be derived by the following method.

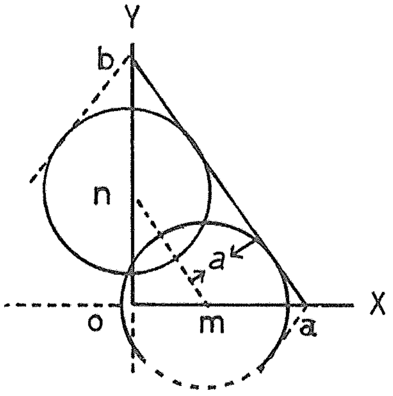

Fig. 13. The passable scope of a circular cross-section in the mesh where the coordinates were performed in Euler's angles (ρ, ϕ) transformations.

Since the side (ab) of the mesh which lies in the horizontal plane is given by Eq. 13, an equation expressing the line (mn) in Fig. 13 can be set up mathematically. Namely, under the given condition that the line (mn) connecting the centers of two circles in Fig. 13 is closer to the origin (o) by distance (a), which is equal to the radius of cross-section, the folllwing equation expressing the line (mn) can be obtained :

$$y=-\frac{U}{V}x+\frac{\sqrt{3}}{2V}(T/4)-\frac{\sqrt{U^2+V^2}}{V}a \qquad (14)$$

Now, the passable region corresponds to the area of $\varDelta$omn can be easily computed. The cross-section with radius (a) can pass through that mesh so long as its center exists within the area, ($\varDelta$omn).

As for the manner of representation of the selection ratio, the ratio of the area of $\varDelta$omn to that of mesh (correctly speaking, a quarter of the area of mesh) can be used as an index of the selection ratio by referring to the preceding section. Such a manner is based on the idea that the selection ratio presented in the two dimensional model is expanded three-dimensionally. From Fig. 13 and Eqs. (13) and (14), the area of $\varDelta$omn which is denoted by (s) given by the following equation.

$$s=\frac{(T/4)^2}{4VU}\left(\sqrt{3}-\frac{2a}{T/4}\sqrt{U^2+V^2}\right)^2$$

A universal equation of the areal ratio, the probability in question, is thus given in the form of the following integral for all combinations of (ρ) and (ϕ).

$$P=\frac{\dfrac{1}{4VU}\displaystyle\int_{U_1}^{U_2}\int_{V_1}^{V_2}\frac{1}{V+\sqrt{3}U-4}sdVdU}{\dfrac{\pi}{2}\displaystyle\int_0^{\frac{\pi}{2}}\frac{xy}{2}\cos\phi\sin\phi\, d\phi}. \qquad (15)$$

$$v_1=1, \qquad v_2=\sqrt{\frac{3}{\left(\frac{2a}{T/4}\right)^2}-3}. \qquad (16)$$

$$u_1=\sqrt{3}, \quad u_2=\sqrt{\frac{3}{\left(\frac{2a}{T/4}\right)^2}-1}. \qquad (17)$$

The way of deriving Eqs. (15), (16) and (17) are shown in Appendix-(II)-(A).

3.2. Theoretical ogives.

A family of theoretical ogives are presented in much the same method as shown in Fig. 9. The selection ratios necessary for each relative magnitude were computed from Eq. (15). There was an open question on computing the selection ratio, however. That is, the selection of a correct lower selection point. As is obvious from Eqs. (16) and (17), it is possible to calculate the selection ratio up to the finite large relative magnitude. This in turn proves to be able to calculate it up to the infinite small value of $(2a)$. Such a calculation is really wasted upon the practical fishery because only the comparatively large fish are subject of trawling. One way of answering this question would be to give a certain degree of body depth $(2a)$ beforehand so that reliable selection ranges with a little different regions may be given.

3.2.1. Approximated lower selection points. Since by definition, theoretical upper selection point can be obtained from Eqs. (16) and (17), it is first necessary to choose the lower selection point reliable. The most practical lower selection point could be determined on evaluating several sets of the concrete values of $(2a)$ prepared in advance. Careful attention should be paid out before deciding those values. Namely, under the given conditions of mesh and circular cross-section, the relative magnitude corresponding to the lower selection point must be less than 0.866. This figure is no more than the maximum relative magnitude, the upper selection point. The necessary lower selection points, saying it differently, to have selection ranges, could be estimated by means of substituting a certain definitive value into the inclination angle (α).

To take a concrete example, if the inclination angle is 60°, then a corresponding value of the lower selection point, about 0.43, can be obtained from the equations derived so far. In this example, the selection range is 0.43−0.866, and it will become clear that the fish has no chance to escape from the given mesh when inclination angle (α) is larger than 30° against the horizontal plane. After checking some experimental lower selection points, it seems that the size of fish may correspond to a suitable lower selection point. However, it is better to use some other values for the lower selection point because this point usually has a considerable amount of scatter. Thereupon, all tenth's decimals between 0.4 and 0.8, inclusive, are applied to the tentative lower selection points in anticipation of some fluctuation at the initial. Those decimals also are kind of estimates for convenience in order to decide the two upper limits (u_2 and v_2) of the integral (15).

3.2.2. Ogives rearranged by mesh angle. The theoretical ogives can be estimated by solving the intergral (15) under the condition which the lower selection points are within the region from 0.4 to 0.8.

With the theoretical ogives for the other mesh angles, the corresponding selection ranges can be obtained according to the same way of thinking as stated for the mesh angle of 60°. Therefore, when treating the mesh angle (θ) as a variable, the theoretical ogives for various mesh angles can be obtained, provided that the selection range varies with the degree of mesh angle. In this section, the author dealt with the theoretical ogives only for $\theta = 45°$, 55°, 60° and 65° considering the actural mesh angles in trawl nets. The specially selected mesh angle, $\theta = 45°$, will be useful for the estimation of selection characteristics for the gears other than trawl nets. The results of computation are shown in Fig. 14, by rearranging them with respect to the degree of mesh angle and the selection range. In Fig. 14, the two groups of theoretical ogives separately drawn for $\theta = 45°$ and $\theta = 60°$ were obtained by calculation but the other two groups were by means of the interpolation and extrapolation.

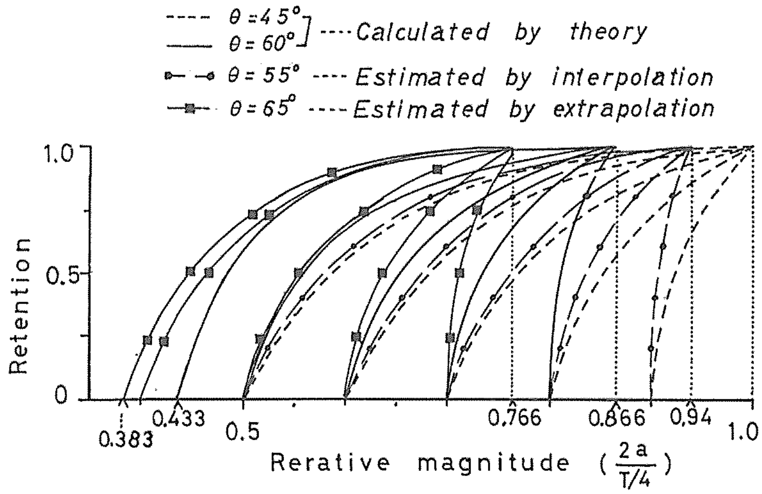

Fig. 14. Theoretical selection curves for small fish by the mesh angle (θ) and degree of relative magnitude $\left(\frac{2a}{T/4}\right)$.

3.2.3. Changing tendency of theoretical ogives. The calculated selection ratios for the four mesh angles could be fitted reasonable well by a family of theoretical ogives separating out from each at the upper selection point. From Fig. 14, it may be concluded that all of the theoretical ogives come under almost the same category of curve. If the upper selection points move parallel along the abscissa and gather themself at a point on this abscissa, it can be easily made clear that the ogives obtained come within the same category. The rising parts of the ogives become extremely sharp, especially in the lower part of less than 25% R.P. Such a sharp characteristics of ogives is striking, in comparison with the lower part of the ogives shown in Fig. 9. The fact that small size of fish was applied to the lower selection point in the three dimensional model supplies a reason for the sharper changing tendency at that point.

3.3. Experimental verification of the theoretical results.

A series of experiments using many model fish was carried out for the purpose of verifying the results obtained theoretically, in the still water tank of the Faculty of Fisheries, Hokkaido University, Hakodate, Japan.

3.3.1. Materials and method. The commercially-available ready made plastic model fish were used in the experiments. The probability of the model fish being retained for the three different sizes of meshes were examined by means of dropping down them perpendicularly on the mesh surface. The total number of model fish dropped were divided into the two groups which were designated "passed" and "retained" classes by visual observations through the observation window of the water tank, and consequently the probability of the model fish being retained can be calculated by mesh size. In the experiments, the three types of model fish having different specific gravities were prepared with an intention to check out whether there was any difference in the effects of sinking speed of model fish on the probability. By such a trial experimental method, it could be estimated to some extent how the actual swimming speed of fish exerts influence on the mesh selectivity. Table 4 shows the principal bodily measurements of model fish used according to type. These data were taken from the average of ten measurements. The sinking speed was measured by taking continuous photographs of the sinking model fish at a speed of five frames per second. As a result of measurement of sinking speed, no significant change in the sinking speed was noticed at the layer of 50 cm deep from the water surface among the same type of model fish. Accordingly, the meshes for the present experiments were fixed at this layer. The shapes and sizes of meshes used are shown in Fig. 15, together with the method of fixing the meshes in the water tank. As is apparent from Fig. 14, all the mshes have a right hexagonal shape but differ in the lengths of their sides. These lengths are identical with the lengths of 45 mm, 54 mm and 60 mm in terms of the rhombic mesh size. The meshes were made of the Nylon 210 *den*/3×4/Z.

There is one major reason why the special mesh shape such as a right hexagon was used. That is, there is a great difference between the cross-sectional shape of fish in the three dimensional model and that used in the experiments. It goes without saying that the theoretical ogives were derived on the relation between the circular cross-section and the diamond-like mesh. Therefore, the changes in probability which would arise from the rotation about the longitudinal axis of fish body along its length need not be considered. On the contrary, the cross-section of model fish can be approximated by an ellipse on referring to the bodily measurements. So far as those model fish are used, it is essential to conduct the experiments by using a special mesh shape so as not to arise the above-mentioned change in probability. A circle mesh shape is the most desirable to eliminate this change but is difficult to make, especially in making them in some continuous row of circular meshes. Next to the circular mesh, a right polygon is one of the best shapes. Nevertheless, it is difficult to make too in interconnecting adjacent polygonal meshes with the same shape one by one. Moreover, in this experiments, it was necessary to prepare some meshes with polygonal shape so as not to give any change in the probability even though the model fish dropped to the mesh surface at a time. After considering the above items, the author adopted the right hexagon as an approximated shape of circle for easy manufacture and carried out the experi-

Table 4. Characteristics of three different types of model fish.

Type of model fish	Body size (cm)	Density	Center of gravity*	Sinking speed (cm/sec)**
I	Total length = 5.11	1.065	0.45	29.9
II	Body depth = 2.42	1.071	0.43	37.5
III	Body breadth = 1.14	1.100	0.41	42.5

Notes ; * The ratio of total length to the distance between the snout and the center of gravity.
** At a layer of 50 cm deep from the surface.

ments by means of dropping many model fish one after another.

Webbings of different mesh sizes woven by hand were stretched tightly on their respective square wire frames along their edges, so all the stripes are formed a plane net (Fig. 15). During the experiments, the center of each webbing always was kept at 50 cm depth from the water surface, which corresponds to the layer of minimum change in the sinking speed. Total number of model fish referred to a single series of experiment was some 300 individuals.

With an intention to correspond the inclination angle (τ) of plane nets against the vertical axis to Euler's angle (ϕ), this inclination angle was changed in the following three steps : 30°, 60° and 90° for each experiment. Naturally, the last

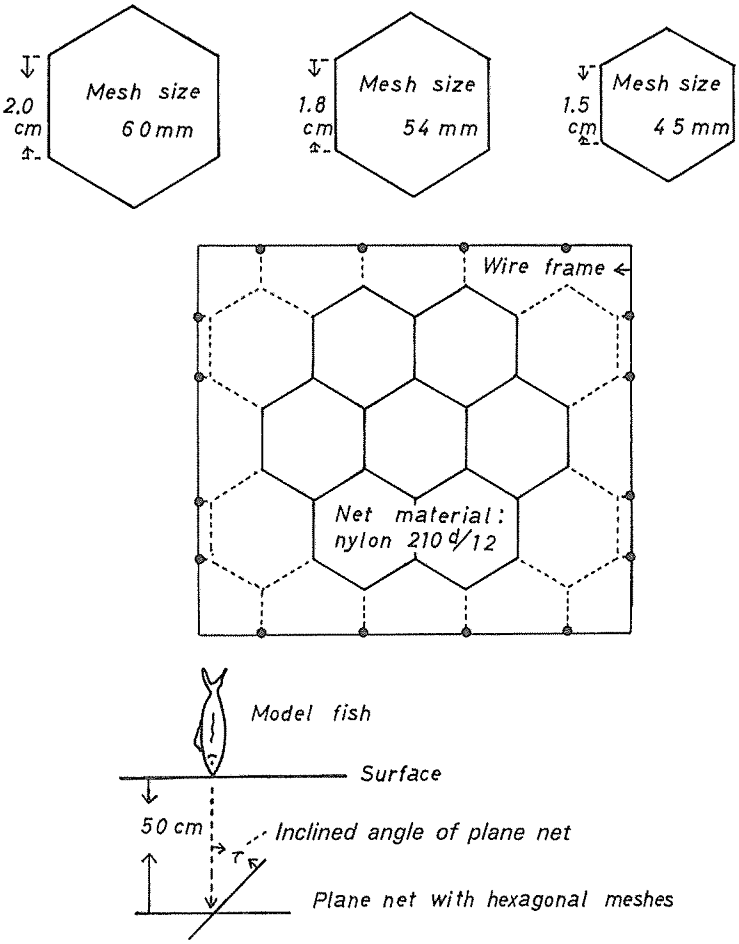

Fig. 15. The size of hexagonal mesh tightly attached to a wire frame and net materials used in this experiments (Upper and middle). And the side view of the nets against a model fish in the experimental tank (Below).

mentioned angle (90°) stands for the horizontal plane parallel to the water surface. Thus, the experiments could be carried out by altering their conditions series by series, which consisted of the nine combinations of mesh size, inclination angle and type of model fish. In each experiment, the model fish were put in the twill grating order with six-mm distance so that they may fall evenly down on the seven meshes of the plane net. At least this distance is required to set the model fish in a row when considering the breadth of model fish. Henceforth, the author used the averaged probability of retention of seven meshes in his examination for the theoretical results.

In order to get necessary data for the examination, the following visual observations were made during the experiments ;

(i) The number of model fish which pass through the mesh without touching the meshes' legs. Let this number be replaced by (N_P) ;

(ii) The number of model fish which pass through the mesh after touching with the meshes' legs. Let this number be replaced by (N_{PT}) ;

(iii) The number of model fish retained after touching with the meshes' legs. Let this number be replaced by (N_{RT}) ;

(iv) The number of model fish retained by two-point contact with the meshes' legs. Let this number be replaced by (N_R) ;

3.3.2. Results. The experimental results obtained are shown in Table 5, item by item, regradless of the type of model fish because there was no remarkable difference in the probability of retention among the three types of model fish. Applying the experimental results to the actual trawl fishery, then the figures given in the line (N_P) in Table 5 are equivalent for the number of fish which have no chance to be caught. Likewise, the figures given in the lines, (N_{PT}) and (N_{RT}) are unknown in the actual trawling. The conclusive reason for this is that it is entirely impossible to distinguish all the fish entered in the codend from those being in contact or not with mesh leg. At present, there is no clue as to whether or not the fish entering the codend come in contact with meshes. On the contrary, the theoretical results presented in the previous section were derived under the condition where all the fish were subject to be caught even in the case of slight touching of the mesh leg. For the above reason, when comparing the theoretical results with the experimental results, it is necessary to

Table 5. Passing through and retaining numbers of the model fish shown in the groups of the mesh size and inclination angle.

Mesh size Inclined angle (deg.) Pass or retain		45 mm			54 mm			60 mm		
		90	60	30	90	60	30	90	60	30
N_P	Pass through the mesh without touching a mesh-leg.	113	62	11	197	150	33	251	209	139
N_{PT}	Pass through the mesh after touching one of the mesh-legs.	725	760	594	693	732	702	644	686	695
N_{RT}	Retain after touching one of the mesh-legs.	0	9	263	0	5	144	0	3	60
N_R	Retain.	62	69	85	10	14	21	2	3	7
N_T	Total.	900	900	953	900	901	900	897	901	901

examine the unknown quantities such as (N_{RT}) and (N_{PT}) a little further. As an aid in examining this matter, the author shall refer to some ratios as follows :

$$(N_{RT}+N_{PT}+N_R)/N_T = 1-(N_P/N_T)$$

Then, $1-(N_P/N_T) \equiv R_P$.

The following empirical equations between the ratio (R_P) and the inclination angle (τ) could be obtained from the experimental data by usual statistical method. Those are,

For 45 mm mesh :

$$R_P = 1.0, \quad (0^\circ \leq \tau \leq 26^\circ)$$

$$R_P = -1.89 \cdot 10^{-3}\tau + 1.05, \quad (26^\circ \leq \tau \leq 90^\circ)$$

For 54 mm mesh :

$$R_P = 1.0, \quad (0^\circ \leq \tau \leq 22^\circ)$$

$$R_P = 1.75 \cdot \tau^{-0.18}, \quad (22^\circ \leq \tau \leq 90^\circ)$$

For the 60 mm mesh :

$$R_P = 1.0, \quad (0^\circ \leq \tau \leq 19^\circ)$$

$$R_P = 1.99 \cdot \tau^{-0.23}, \quad (19^\circ \leq \tau \leq 90^\circ)$$

As those equations afford a basis for closer examinations for the direct comparison of the theoretical results with the experimental data, all of them are illustrated in Fig. 16, in which there are singular points. The singular points which correspond to the specific inclination angles of 19°, 22° and 26° for the respective hexagonal meshes are conveniently called a critical angle, where no model fish can pass through the corresponding meshes. In other words, if the plane nets were inclined to more than these angles, no model fish can pass through each mesh. The critical angle can be estimated geometrically from the relation between the hexagonal mesh and the elliptical cross-section of model fish. As was stated previously, the ratio (R_P) must be the probability of fish being retained in the three dimensional model. And this ratio increased gradually as the mesh size decreased. At the same time, this ratio increases with the increase of inclination

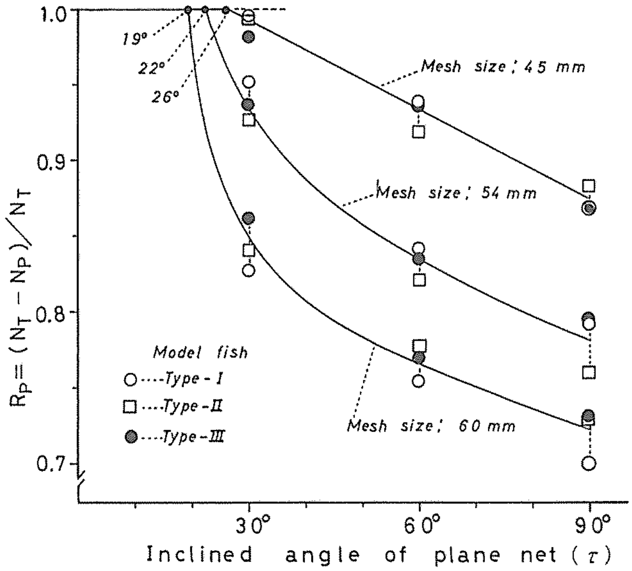

Fig. 16. Relation between the inclination angle of plane net and ratio (R_P) of the value of (N_T-N_P) to that of N_T. N_T and N_P are as in Table 5.

angle (τ). The smallest ratio in its value being about 0.7 appeared when the mesh size is 60 mm and the inclination angle is 90°, i.e. horizontal plane.

Next, the retention ratio should be studied "which is expected in the practical fishery." The author then took up another ratio which was denoted by the following expression :

$$R_1 \equiv (N_{RT}+N_R)/N_T$$

The ratio (R_1) is nothing less than the real retention ratio. According to the same statistical method as in the ratio (R_P), the following empirical equations were deduced :

For the 45 mm mesh :

$R_1 = 1.0, \quad (0^\circ \leq \tau \leq 22^\circ)$

$R_1 = 4.81 \cdot 10^2 \cdot \tau^{-2.02}, \quad (22^\circ \leq \tau \leq 90^\circ)$

For the 54 mm mesh :

$R_1 = 1.0, \quad (0^\circ \leq \tau \leq 20^\circ)$

$R_1 = 1.32 \cdot 10^4 \cdot \tau^{-3.18}, \quad (20^\circ \leq \tau \leq 90^\circ)$

For the 60 mm mesh :

$R_1 = 1.0, \quad (0^\circ \leq \tau \leq 17^\circ).$

$R_1 = 3.08 \cdot 10^4 \cdot \tau^{-3.66}, \quad (17^\circ \leq \tau \leq 90^\circ).$

Fig. 17 shows the relation between the ratio (R_1) and the inclination angle (τ). The ratio approaches zero with the increase of inclination angle. In case of 60 mm mesh size, the ratio approaches zero near the point of the inclination angle showing about 60°, while in case of 45 mm mesh size, the ratio does not become zero even at the inclination angle of 90° but is less than 0.1 when this angle shows 90°.

Lastly, since there is no doubt that the figures shown in the line (N_R) in Table 5 correspond to the most reliable number to be caught, the author examined one more ratio. This ratio was denoted by,

$$R_2 \equiv N_R/N_T$$

When deducing the equation between the ratio (R_2) and the inclination angle (τ), the following equations were obtained by mesh size :

For the 45 mm mesh :

$R_2 = 1.0, \quad (0^\circ \leq \tau \leq 15^\circ)$

$R_2 = 5.31 \cdot 10 \cdot \tau^{-1.52}, \quad (15^\circ \leq \tau \leq 90^\circ)$

For the 54 mm mesh :

$R_2 = 1.0, \quad (15^\circ \leq \tau \leq 90^\circ)$

$R_2 = 1.19 \cdot 10^3 \cdot \tau^{-2.71}, \quad (14^\circ \leq \tau \leq 90^\circ).$

For the 60 mm mesh :

$R_2 = 1.0, \quad (0^\circ \leq \tau \leq 13^\circ).$

$R_2 = 2.82 \cdot 10^3 \tau^{-3.18}, \quad (13^\circ \leq \tau \leq 90^\circ).$

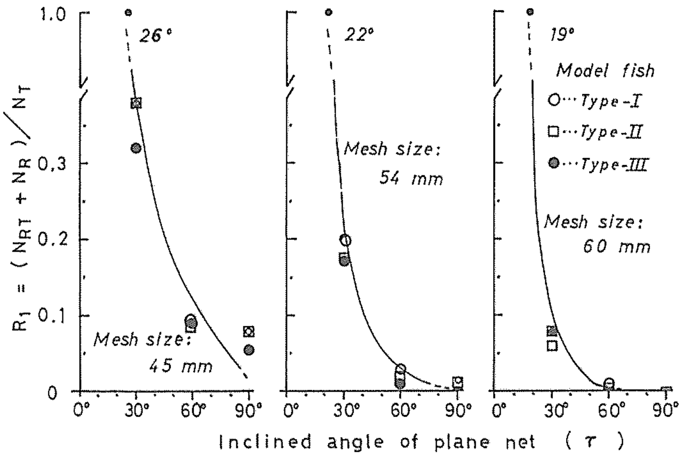

Fig. 17. Relation between the inclination angle of plane net and ratio (R_1) of the value of ($N_{RT}+N_R$) to that of N_T. N_{RT} and N_P are as in Table 5.

These equation are shown graphically in Fig. 18. When contrasting Figs. 17 and 18, little difference is seen between the two ratios, R_1 and R_2, under the same value of inclination angle. This is because of little difference in the fugures presented in Table 5, and a little difference exisits in the ratios among the mesh size. However, in the curves for the mesh size being 45 mm, there is a slight difference in the region of inclination angles from about 40° to 90° between the two ratios, R_1 and R_2.

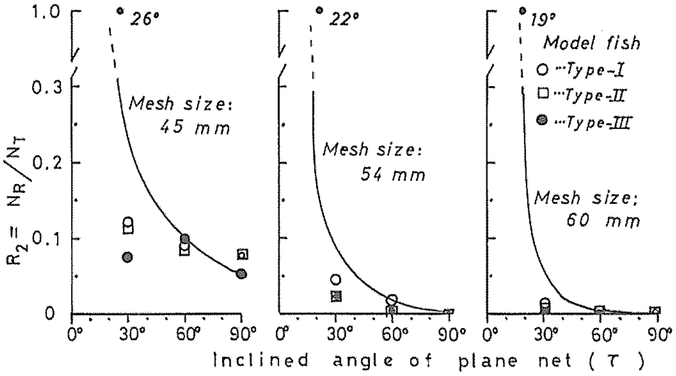

Fig. 18. Relation between the inclination angle of plane net and ratio (R_2) of the value of N_R to that of N_T. N_R and N_T are as in Table 5.

3.3.3. Comparison of the thoretical results and the experimental results. In the present experiments, the author applied the inclination angle of a plane net to one of Euler's angles used in three dimensional model. It was, however, impossible to set up a certain desired experimental condition so as to satisfy another necessary Euler's angle (ρ). In other words, the experimental data obtained are no more than the probability calculated only from altering the approaching angle of fish against the mesh surface. Therefore, in order to compare directly the theoretical results with the experimental results, it is necessary to modify the full equivalent of Euler's angle (ρ), which corresponds to the approaching direction toward the mesh. Although there is no theoretically adequate means to modify the experimental data, a generous modification could be acceptable to make the direct comparison from the reason cited below. Namely, by taking not only the symmetrical mesh shape such as a right hexagon but also the total number of model fish used, it must be noted that the ratios presented above may be as an average for all approaching diections. In addition to this, because as many as about 300 model fish were used in each series of experiments, the directional bias also was considered to be eliminate during the experiments. This means, in effect, that the model fish approached the mesh from all directions. Also, this is a very special reason why the hexagonal mesh shape was used. It may be concluded from the above fact that the averaged ratios of all inclination angles from zero to 90° can be used for the comparison. Moreover, this sort of modification would be permissible because many meshes of codend are spread over in all directions in fish's eyes and fish can approach them from all directions. Here, a single example of how to derive the averaged ratio is indicated below.

In case of the 45 mm mesh size, the midification for the ratio (R_1) can be made from its corresponding empirical equations derived previously. Now, let the modified ratio be replaced by (R_1'), then the averaged ratio of all inclination angles can be obtained in its lump from the following inetegral ;

$$R_1' = \frac{1}{\pi/2}\left[\int_0^{\tau_i} d\tau + \int_{\tau_i}^{\frac{\pi}{2}} 4.18\cdot 10^2 \cdot \tau^{-2.02} d\tau\right]$$

Where, τ_i is the critical angle which varies according to the mesh size.

The ratio (R_2) can also be modified in accordance with the same procedure as the above. Table 6 shows the modified ratios by mesh size. There is a little differences between the modified ratios, (R_1') and (R_2'), even in the case of the same mesh size. Since by definitions as to (R_1) and (R_2), the modified ratio (R_1') must be equivalent to the most probable selection ratio for the existing codends but the ratio (R_2) does not. The latter, the ratio (R_2'), if we must say, may be another index to the highest expectation of catch for a given mesh in the actual trawl fishery. The true value of (R_2') is hardly estimated by the field experiments and the theory. This sort of ratio can be estimated through the present visual observation only. Here, it is important to examine the differences between the modified two ratios because those differences will offer useful clues in order to evaluate the loss of small category of fish in the practical fishery and to estimate the more reliable lower selection points.

Table 6. The modified values (R_1', R_2') of selection ratio by mesh size.

Modified ratio	Mesh size (mm)		
	45	54	60
R_1'	0.41	0.32	0.26
R_2'	0.33	0.24	0.20

The modified ratios which were plotted in the theoretical ogives are shown in Fig. 19. It is apparent from Fig. 19 that all the modified ratios are within certain limited regions of raltive magnitudes. As was already stated, these regions were tentatively determined and devided according to the degree of relative mangitude for the convenience of estimating the lower selection points. The corresponding relative magnitudes for each mesh size and each relative magnitude shown in Fig. 19 are decided by the following method. As the right hexagon was used as an approximation of the circular mesh shape, it may safely be said that the average of the lengths of inscribed and circumscribed circles for the hexagon can be regarded as a perimeter of mesh. The relative magnitude to obtain can be calculated by this perimeter and the measured body depth ($2a$) of model fish. Fig. 20 shows the three sets of relative magnitudes calculated by mesh size and shape.

3.3.4. Estimation of more reliable lower selection points. Further discussion is necessary in regard with the lower selection points because of somewhat overestimation of those points based on the two dimen-

Table 7. The value of relative magnitude corresponding to the lower selection limit estimated from the experimental values, R_1' and R_2', which were plotted in Fig. 21, by mesh size and mesh angle.

Mesh angle (deg)	Mesh size (mm)		
	45	54	60
$\theta = 45°$	0.83	0.69	0.62
$\theta = 55°$	Do.	Do.	Do.
$\theta = 60°$	···	0.71	0.63
$\theta = 65°$	···	0.72	0.64

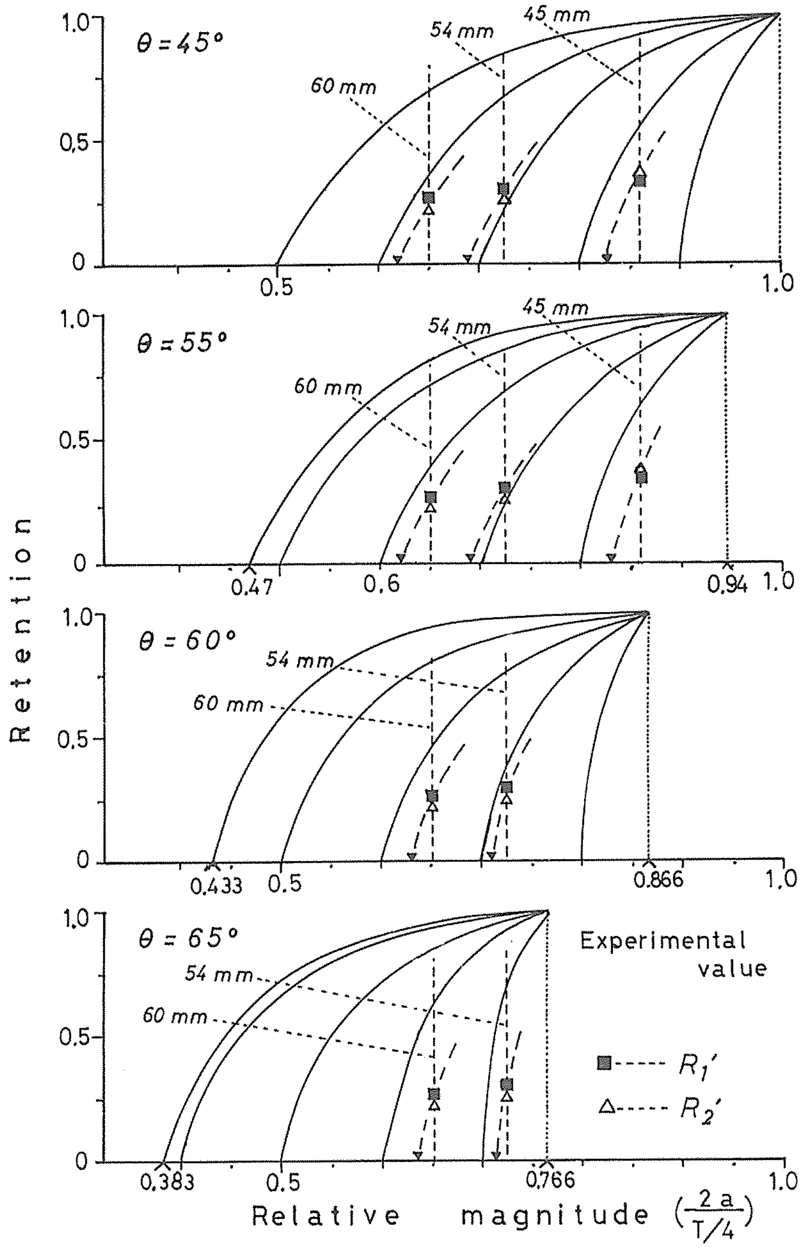

Fig. 19. The experimental results plotted in the theoretical selection curves.

sional nodel. For this, an attempt was made to estimate more reliable lower selection points using the modified ratios. This was done by means of graphical analysis which helped greatly toward estimating more reliable lower selection points. As Fig. 19 shows, all the modified ratios are situated on each dotted line. Accordingly, it is safe to consider that the intersections of the dotted lines and the abscissa correspond to the lower selection points. The readings for the intersection are listed in Table 7, by mesh size and angle. The values in Table 7 are regarded as to be the relative magnitudes corresponding to the more reliable lower selection points. From those values, it can be made clear that the lower selection points are affected considerably by the size of mesh, rather than the mesh angle. It is, however, true that the lower selection points are more or less affected by mesh angle. For the purpose of investigating the relation between

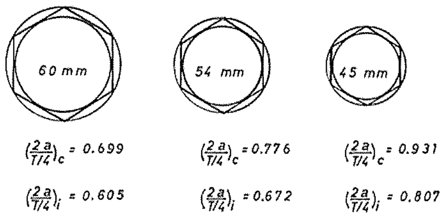

Fig. 20. The experimental values of relative magnitude calculated by the circumferences of circumscribed and inscribed circles of a hexagon for the same value of body depth of model fish.

Notes : $\left(\frac{2a}{T/4}\right)_c$ --circumcircle,

$\left(\frac{2a}{T/4}\right)_i$ --instribed cricle,

The experimental value in Fig. 19 shows the average value of $\left(\frac{2a}{T/4}\right)_c$ and $\left(\frac{2a}{T/4}\right)_i$.

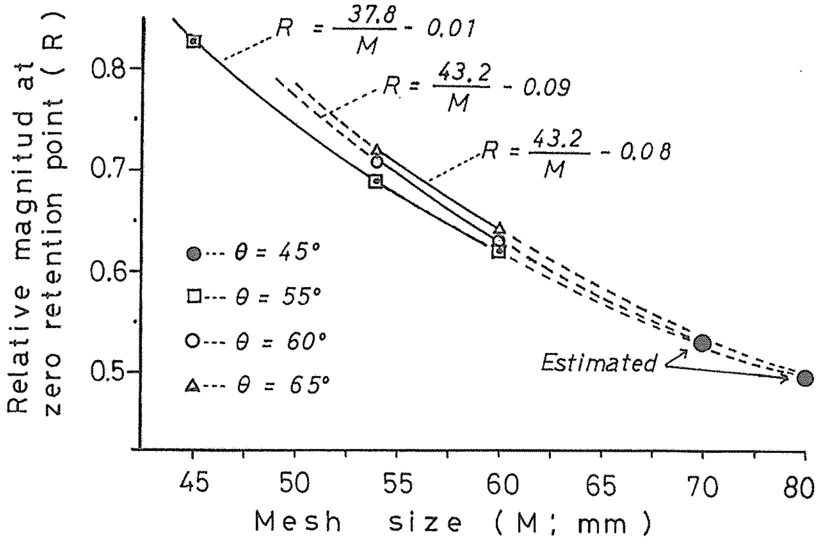

Fig. 21. Relation between the mesh size and the value of the relative magnitude corresponding to the lower selection limit, shown by mesh angle.

the lower selection points and the mesh size or mesh angle in more detail, the empirical equations between them were set up. As a rasult of investigation, hyperbolic equations were arrived at and shown in Fig. 21. By taking notice of the characteristics of the curves obtained, similar reliable lower selection points would be applicable to a little wider regions of mesh size for four mesh angles. Fig. 21. shows the lower selection points that were estimated by extending the respective curves toward their larger values of mesh size.

3.4. Approximate solutions for the mesh selectivity by applying a simple model, a dodecahedoron.

In this section, with an intention to not only make up some weak points but also follow simply the mesh selectivity characteristics, an attempt was made by using a simplified model, in which the author took advantage of the three dimensional model. Some weak points were pointed out previously, that is, the most reliable lower selection point could not be estimated by the two dimensional model and the three dimensional model alone. The two dimensional model has a significant weak point that the lower selection points expressed by Eq. (6) were considerable larger value than the real lower selection points. Also, Eq. (6) has another weak points. The lower selection points were decided irrespective of fish shape, i.e. the degree of ε values. Also, those points could not be correctly estimated using only the three dimensional analysis unless the detail visual observations were carried out. Here, the author adopted a simplified model, a dodecahedoron, as a simple three-dimensional expression of swimming action of fish. This model is based on the relation between the faces of dodecahedoron and the fish approaching those faces at right angles. It became clear that the results obtained also were applicable to the estimation of the mesh selectivity characteristics. Furthermore, the author made some corrections on the theoretical ogives shown in Fig. 9 by using the lower selection points derived from this simplified model.

3.4.1. Estimation of approximate lower selection points. When replacing the swimming action of fish into a simplfied model, a regular polyhedoron will serve the purpose of expressing them three-dimensionally. Here, consider the case where a diamond-like mesh is located at the center of polyhedoron and the fish approach the mesh through each face of polyhedoron. As the number of faces of polyhedoron increases, it becomes a sphere. This in turn is equivalent to the three dimensional analysis. On the contrary, if a regular polyhedoron having less number of faces is chosen as a model, it would be difficult

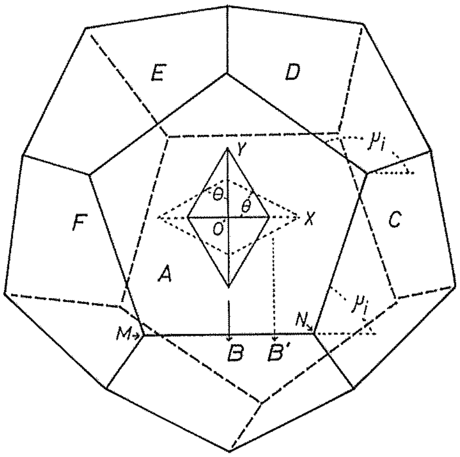

Fig. 22. A regular dodecahedoron used to estimate better theoretical lower selection limit, which can be calculated from the relation between the ellipse and the plane of projection of lozenge on the panel, $A, B, \cdots\cdots F,$.

to estimate better lower selection points. Considering the above, the author chooses a regular dodecahedoron as a simple model, in order to get approximate lower selection points. Fig. 22 shows a top-view of the diamond-like mesh in the dodecahedoron whose faces are the same regular pentagon.

Let consider the upper half of the dodecahedoron and give alphabetical letters, *A*,*B*, …*F*, to their faces. Next, assuming that the fish approach the mesh in a state which the body axis is kept at right angles against any face, the lower selection points can be approximately estimated by the following method. It is necessary, at first, to clarify the relation between the cross-section of fish body and the mesh shape projected orthogonally on each face. If the mesh is kept in such a state as shown by the solid line in Fig, 22, the projection on the face, (*D*) are the same as that on the face, (*E*). The same remark can be said to the faces, (*C*) and (*F*). With the projection on the face, (*A*), the necessary geometrical relation can be derived from the same procedure as the two dimensional analysis. In this analysis, one more projection was used because it was undesirable to use the above-said two congruent projections. This is the projection on the face, (*B'*) and the mesh shape for this case was drawn in a dotted line to distinguish it from the other faces as shown in Fig. 22. Following the manner of representation of mesh and ellipse in the previous section, the mesh shape projected on each face can be obtained solid-geometrically from Eqs. (4—2) and (4—3) which are shown in Appendix-(II)-(A). In this model, the dihedral angle, (ξ), of dodecahedoron in case where its two faces meet at a certain point is known by theorem. If the line (*MN*) in Fig. 22 is chosen as a base line, the external angle (μ_i) which varies according to the position of one side of pentagonal plane (*A*) also is naturally known. Because it is obvious that both dihedral and external angles, (ξ) and (μ_i), correspond to Euler's angles, (ρ) and (ϕ), in Eqs, (4-2) and (4-3), respectively, thus the lower selection points for the projected shapes of mesh can be obtained by the same way as shown in the two dimensional analysis. Table 8 shows the result of calculation. Among the various selection points, the minimum value must be chosen as the best lower selection point from the theoretical point of view. However, when comparing and contrasting all the lower selection points obtained through the two and three dimensional models, and the present simple model as well, the minimum value in Table 8 is rather too small. Also, this minimum must be

Table 8. The value of relative magnitude $\left(\frac{2a}{T/4}\right)$ corresponding to the lower selection limit, derived from the model shown in Fig. 22.

Plane of projection	μ value (deg)	Mesh angle (deg)		
		$\theta=55°$	$\theta=60°$	$\theta=65°$
B	0°	0.617	0.612	0.585
C	72°	0.490	0.433	0.370
B'	90°	0.499	0.470	0.453
D	162°	0.435	0.394	0.345
A	…	0.939	0.866	0.766
Average		0.596	0.555	0.504

Note : μ value is same to Fig. 22.

decreased according to increase in the number of faces of a polyhedoron. It would be better, therefore, to choose more practical lower selection points instead of the minimum. In other words, the other means of solving is required by determining the lower selection points practically. Synthesizing the theoretical results and experimental results derived so far, the author chooses the average value as an approximation of the practical lower selection points because those values are closer to the most reliable lower selection points presented in the foregoing sections. The average, as compared with the values obtained from Eq. (6), is smaller but can be regarded as the second best estimates of the real lower selection points.

3.4.2. Modification of the theoretical ogives. Some modifications were made for the theoretical ogives for $\theta = 55°$, $60°$ and $65°$, illustrated in Fig. 9, especially in their rising parts. The modifications were based on the above approximate values of the lower selection points. As a first approximation, the average values in Table 8 were rounded to the tenth's place, viz,

For $\theta = 55°$, $2a/(T/4) = 0.6$,
For $\theta = 60°$, $2a/(T/4) = 0.6$,
For $\theta = 65°$, $2a/(T/4) = 0.5$.

Those relative magnitudes were applied to the approximate lower selection points.

As for the ellipses ranging out of the selection range defined in the two dimensional model, it was necessary to investigate again the existence of the irregularity in the relation between the probability and the freely movable angle. This irregularity was left unsoloved for the range from the lower selection points defined newly to those calculated from Eq. (6). Fig. 23 shows the result of investigation about the irregularity by the same method explained previously. The curves in Fig. 23 have points of resembrance, so

Table 9. Comparisons between the values of the relative magnitudes obtained from Figs. 9 and 14.

ε	R. P. (%)	$\theta = 55°$	$\theta = 60°$	$\theta = 65°$
0.50	25	0.67 (0.95)	0.66 (0.88)	0.57 (0.79)
	50	0.75 (0.96)	0.74 (0.89)	0.66 (0.80)
	75	0.91 (0.98)	0.86 (0.91)	0.74 (0.81)
0.70	25	0.68 (0.97)	0.67 (0.91)	0.60 (0.81)
	50	0.79 (0.99)	0.78 (0.94)	0.70 (0.84)
	75	0.93 (1.04)	0.91 (0.98)	0.83 (0.88)
0.80	25	0.70 (0.98)	0.69 (0.92)	0.63 (0.83)
	50	0.84 (1.04)	0.83 (0.98)	0.75 (0.88)
	75	1.01 (1.11)	0.98 (1.04)	0.90 (0.96)
0.90	25	0.73 (0.98)	0.71 (0.94)	0.66 (0.87)
	50	0.90 (1.05)	0.86 (1.02)	0.83 (0.96)
	75	1.10 (1.15)	1.05 (1.14)	1.03 (1.07)
0.95	25	0.74 (1.00)	0.72 (0.96)	0.68 (0.90)
	50	0.91 (1.08)	0.88 (1.07)	0.86 (1.03)
	75	1.13 (1.20)	1.11 (1.21)	1.09 (1.17)
0.98	25	0.75 (1.01)	0.73 (0.98)	0.70 (0.92)
	50	0.93 (1.09)	0.90 (1.08)	0.89 (1.06)
	75	1.16 (1.22)	1.15 (1.26)	1.14 (1.24)

Notes : R.P ---- Retention points
The parenthesized values show the relative magnitudes from Fig. 9.

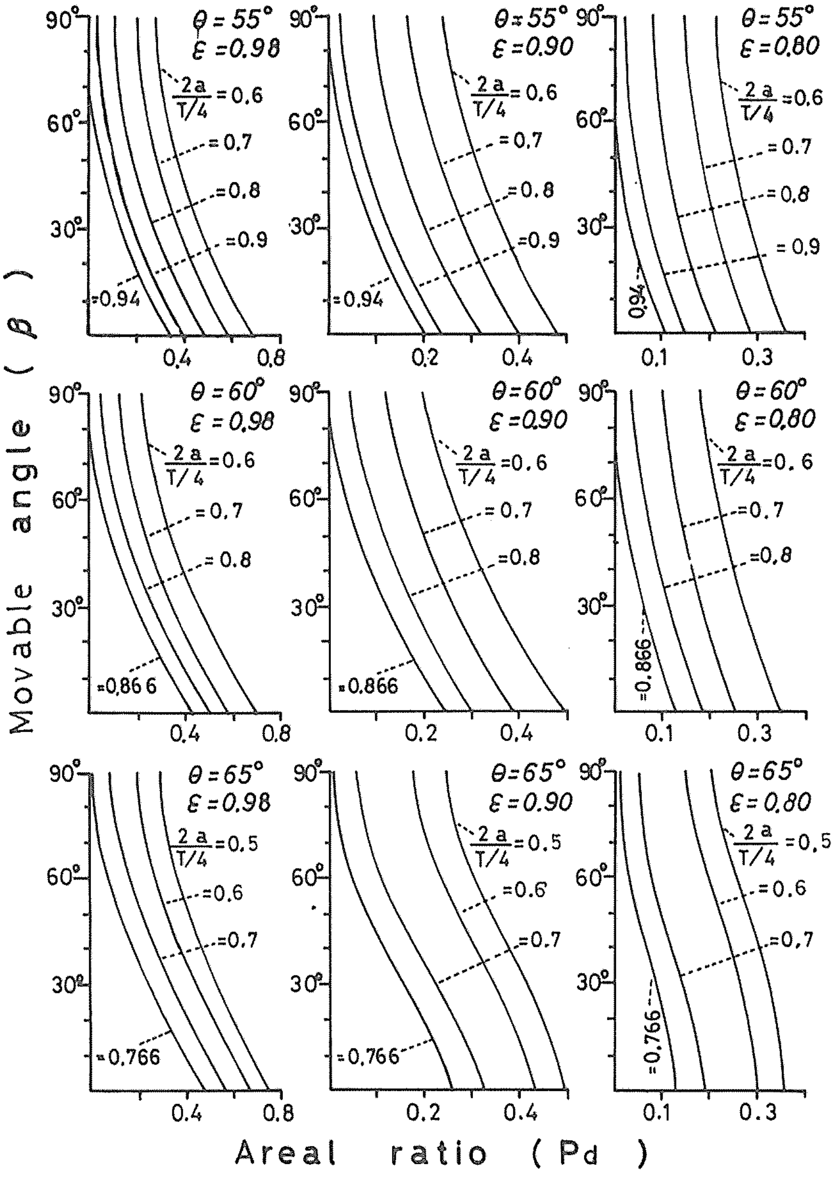

Fig. 23. Relation between the freely movable angle (β) of the ellipse and the areal ratio (*Pd*) within the range from the lower selection limits to the modified ones.

the probability of ellipses being retained was calculated from Eq. (11)′. Thus, the modified theoretical ogives were derived by substituting the rounded relative magnitudes for the new lower selection points, and are shown in Fig. 24. It is natural that the modified theoretical ogives have gentle slopes because they have wider selection ranges than the unmodified ones. From this, some differences arise in the value of relative magnitudes corresponding to the three main selection points, 25% R.P., 50% R.P. and 75% R.P., between the ogives in Figs. 9 and 24. Table 9 shows those differences by mesh angle and eccentricity, and supplies a usuful clue to justify whether either the ogives in Fig. 9 or those in Fig. 24 were accurate enough for the practical

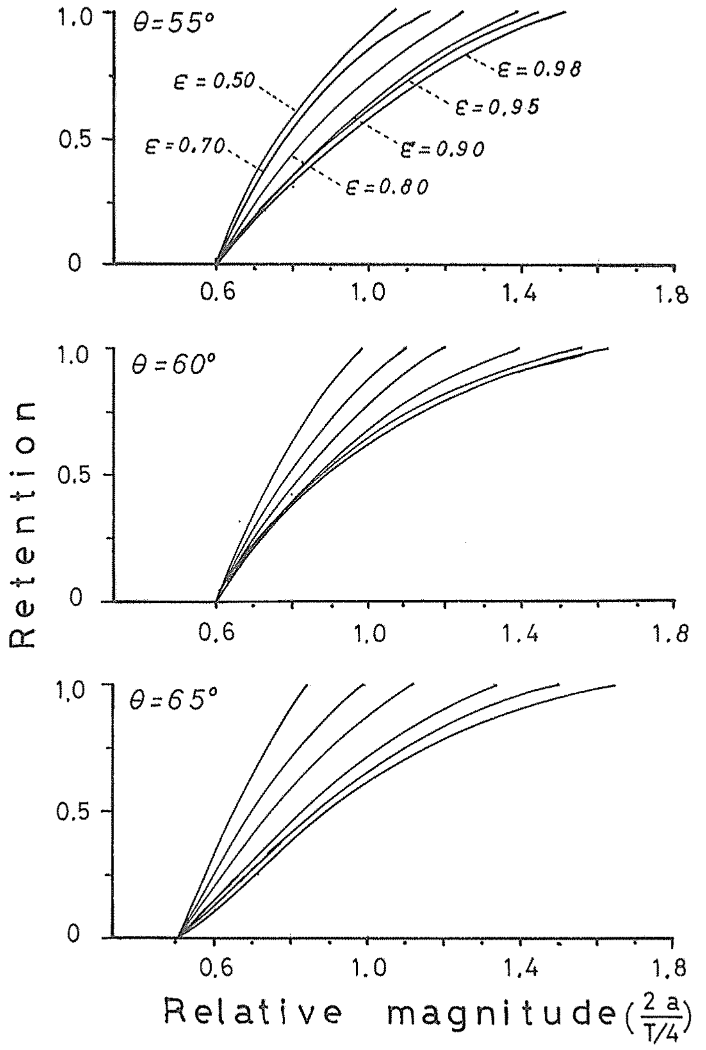

Fig. 24. Theoretical selection curves obtained from the modification of lower selction limits.

usage in order to estimate the mesh selectivity characteristics. Further investigation on this matter will be described below.

3.4.3. Validity of the modified ogives. So far, the modified and unmodified theoretical ogives were presented. With their validity, it may be concluded from the size of ε values as to which of these two ogives is better for practical usage. When the ogives are to be put into practice, careful attention should be paid out to the lower selection points. To decrease the relative magnitudes corresponding to the lower selection points put, in effect, to change the sign of fitting ratio (Q) from negative to positive and at the same time the Q values themselves increase if they are positive. The Q values are negative for the fish having the ε value being equal to or less than 0.8, when checking those values in Table 2 closely. For such species, the modified ogives are superior in the degree of approximation than the unmodified ones. On the contrary, in case of the fish having the ε value of 0.9 or more, the unmodified ogives are rather better than the modified ones in their lower parts below 50% R.P. The above examination indicates that the specific ε value, about 0.8, may be a standard of proper use. Here, some of ε values by species are given for reference ;

For the common fusiform fish such as Horse mackerel, *Trachurus japonicus*, and Allaska pollack, *Teragra chalcogramma*, their ε value is about 0.8, and then vertically slender fish such as Sea bream, *Chrysophrys major*, and Flat-fish, *Tanakius kitaharai*, far greater than 0.9.

Since the lower selection points could not be estimated quite well even in the field experiments, those points have a certain extent of lengths ranges unlike a constant point. If the experimental data for those points are incorrect, it is also to difficult to determine them correctly in the thoretical description. By considering the above experimental error, the rounded relative magnitudes were adopted as the approximations of the lower selection points. These newly obtained lower selection points differ from the values derived by Eq. (6). Thereupon, to what extent the approximation error exists between the two sets of the lower selection points was examined. The result of examination is shown in Table 10 in which the lower slection points were converted into the body length by using the regression equations. The examination was made only for the mesh angle of 60° and for the eight species among the ten species in Table 2 because the reliable experimental lower selection lengths could not be obtained for the remaining two species. As is apparent from Table 10, the error, the theory-and-experiment difference in the lower selection lengths would be negligible if the experimental lengths were precise. However, such a great difference was not found in the interquartile range after comparing both modified and unmodified ogives. Accordingly, it may be concluded that those two ogives will be useful to estimate the mesh selectivity characteristics for many species and various mesh size.

Table 10. Comparison of the 0% release length.

Species No. $*_1$	$\frac{T}{4}$	ε	0% release length (cm)			Error	
			Exp.$*_2$	Theory $*_3$			
			(A)	(B)	(C)	(A)−(B)	(A)−(C)
1	3.62	0.98	11.0	6.9	9.0	4.1	2.0
2	3.00	0.98	12.5	15.8	17.6	−3.3	−5.1
3	2.71	0.95	13.5	8.9	12.9	4.6	0.6
4	3.99	0.89	12.0	9.0	14.0	3.0	−2.0
5	2.71	0.87	10.0	6.3	9.2	3.7	0.8
6	2.71	0.85	9.5	10.7	13.2	−1.2	−3.7
	3.00	Do.	8.5	11.3	14.0	−2.8	−5.5
7	2.71	0.80	10.0	8.9	13.7	1.1	−3.7
8	2.71	0.50	10.5	12.8	17.6	−2.3	−7.1

Notes : $*_1$ The same to the Table 1.
$*_2$ Cited from Aoyama's report.
$*_3$ (B) and (C) are estimated from the Figs, 24 and 9, respectively.

3.5. Discussion.

When analyzing the mesh selectivity by using a probability model, it is necessary not only to introduce satisfactorily the swimming behaviour of fish in the model but also to express the pass-ability of fish against the mesh in a mathematical description. In the two dimensional probability model the mesh selectivity could be analysed by the plane geometrical method, on the assumption that the fish are kept their lateral lines of body at a vertical angle when they approach the mesh. In regard to this assumption, there are still some problems to be solved. That is to say, only a special phase of swimming behaviour is reflected in that model. In actual fishing operation, no matter how the fish entered into codend, a very limited space, it is safe to suppose that they have some extent of freedom in swimming about, Furthermore, some underwater observations on fish behaviour made clear that once they entered into the codend, many species tended to keep their heads so as to swim with the direction of towing. However, when trying to escape from the mesh during operation, they could not help swimming from side to side crossing the codend. Such a swimming action would describe considrably complicated-path and this sort of lateral swimming behaviour depends upon their own instincts and the towing condition of the gears. It is almost impossible to replace those complicated fish behaviour into a simple model. This is one of the major reasons why the three dimensional model was used in order to express those behaviours theoretically as they are. This could be regarded as being an effective approach from the methodological view-point. However, some problems to discuss remain in this three dimensional model, that is, a presupposition that the fish swim straight on the mesh surface. The validity of presupposition could not be made clear because the author forcused his attention on the momentary posture of fish just before passing through the mesh. As stated above, there is a room for improvement in the presupposition and formation of model. Meanwhile, even if the other elaborative models are adopted, some extent of approximation error can be avoided in the estimation of the theoretical ogives.

In the Chapter 2, the author took a serious view in estimating lower selection points. The reasons are ; Firstly, it is necessary to confirm whether or not the lower selection points used in the Chapter 2 are good. It may doubtful whether Eq. (6) is applicable to those points, while such a doubt would not arise about the upper selection points because of no great difference in both theoretical and experimental ogives ; Secondly, as expected, correct estimation of those points is necessary for conservation. The fact that to preserve undersized fish which are several times more than the number of fish corresponding to the upper selection point, lower selection points should not be overlooked for the rational management of fish population. Therefore, the lower selection points must be determined at as precise a level as possible with a view to preestimating of recruitment in the furture ; Finally attempts to do so will give useful clues to rectify the bias in population of fish due to the mesh selectivity especially in the smaller fish.

The laboratory experiments and visual observations using model fish were carried out for the purpose of examining closely the theoretical results as well as the investigation of the more reliable lower selection points. So far, work in experimental tanks is the best substitute for the lack of underwater information about fish behaviour and physical properties of trawl nets. And, many pending points, which were impossible to clarify only from the field researches, are being revealed through tank experimentations. Besides this, the interaction between the gear performance and the fish behaviour also was clarified by a variety of ways ranging from observations of fish behaviour pattern in laboratory to field researches with underwater cameras. On making the probability model, one of the most important task was the assumption on the fish behaviour, especially in step-by-step process of fish movement as it passes through the mesh. No detailed data is as yet published in regard to such a continuous process. To improve the underlying assumption and the probability model, it is necessary to investigate the fish behaviour in more detail. The necessary data would be obtained by the visual observations in laboratories along with the field reseraches. However, there are some set backs in the laboratory works, that is, the difficulty in the preparation of proper living environment for the test fish, such as visivility, temperature, bottom condition and so forth. Many fish which are subject to the trawl fishery usually inhabit in such a deep and dark layer that they may hardly discriminate the exact shape of gear or its mesh shape due to the less visivility.

Although there is nothing in particular to improve the probability model by using the model fish, some of the results are useful to evaluate how much undersized fish are probably able to escape from the codend. If the present experiments were carried out using a number of living fish instead of the model fish, the detailed data on the above-said continuous process could be made clear. As Table 5 shows, most of the model fish which come in contact with the mesh leg could pass through the mesh. Here, what is of particular importance is to foresee the possibilities of allowing the smaller fish to escape in healthy condition after passing through the codend. In connection with this, a trawl net with a cover-net or a specially designed device was used in the mesh experiments in order to collect such information as how to distinguish the catches in codend from those in its cover-net. This kind of experiments proved that the considerable amount of fish have the possibilities of escaping but little information was available on the ratio of "retain" to "escape". The experimental values, (N_{RT}) and (N_{PT}) in Table 5, would be useful to estimate the retain-and-escape ratio, though it is very difficult, in practice, to get this ratio from usual mesh experiments. A correct estimation of this ratio itself will come up as an important problem for furure study. In this sense, the ratio shown in the previous section, (R_1) and (R_2), are a conclusive factor for the estimation of the possibilities of returning back for the undersized fish. However, it cannot be concluded only from the present experimental results how many undersized fish entering codend escape safely in actual fishing operation. So the results shown in Table 5 should be modified on the basis of further field experiments.

The author presented the theoretical ogives for only the particular cross-section, $\varepsilon = 0$, because an indication of the generality of mesh selectivity was given from the two-dimensional analysis. The theoretical ogives for the other value of ε were derived and modified by making use of the result obtained through the simplified three-dimensional analysis along with the experimental results. One of the noticeable difference is that all the modified ogives have smaller value of lower selection points than the unmodified ones. After comparing both ogives, it was found out that the unmodified ogives were better approximation for the fusiform and the round-shaped fish but the modified ones were better only for the slendar fish. However, the differences between the theoretical ogives and the experimental ogives were so slight as to be negligible. To minimize such differences, it is desirable to thorize the important factors influencing the mesh selectivity which were pointed out in the Chapter 1. To theorize all of those factors would be very difficult, however. Another factors to consider are the theoretical approach on the assumption that each fish made only one attempt to escape. Better theoretical ogives will be estimated through further examination with regard to the probability of the fish being retained under the condition that several attempts to escape are made.

4. Results and general discussion.

According to the experimental results published so far, the mesh selectivity curves and their parameters were made clear with respect to some commercially important species. And the mesh size employed in the past experiments were within considerbly small range, i.e. mostly from 50 mm to 100 mm. During those experiments, it was often the case that the selection characteristics could not clearly estimated by reason of small catches even though relatively small mesh size was used. On the other hand, the species which traditionally have less commercial value may become important with a view of making the best use of them as food in the near future. However, the mesh selectivity curves for those species are not always clarified in detail in contrast with those for the important species. Possible efforts should be made and continued to investigate the mesh selectivity not only for the important species but also for the low-price and small fish. According to the author's observation, it would be impossible to make clear the mesh selectivity for all of those species by field experiments. To make up for such a weak point, better estimation for mesh selectivity must be made by other promising ways. This is one major reason why the author tried to make a first approximation to the mesh selectivity without recourse to field experiments. Further, the author feels that the mesh selectivity data are still far from being fully prepared in Japan, as compared with the other industrialized countries, in spite of the fact that the Japanese trawlers were operated in international fishing grounds or foreign fishery conservation zones. Failure to proceed further on experimental and theoretical studies will result in the great difficulty of the trawl fishery in Japan, in particular to the off-shore trawl fishery around Japan.

From the long-ranging view point, a new mesh regulation so as to permit the escape of many fish of the desired minimum size should be set forth sooner or later and eventually even for the coastal trawlers, followed by the exisiting international mesh regulations. It goes without saying that collecting the mesh selectivity data is necessary before enacting or revising the mesh regulations. By using the collected data which are revealed both experimentally and theoretically, a preestimation can be made out as for whether or not the regulation is proper, whether the effects of the regulation is significant, etc.

The most important objectives of mesh selectivity study are mainly twofold : (i) to put the results obtained for the conservation purposes and (ii) to offer basic data for the studies on the management of fishery resources. As for control measures in trawl fisheries in order to make semi-permanently the catch level most suitable, the following measures have been well known as practical and useful ones :

(i) Fishing effort restriction, such as vessel-and-day limit for fishing. This is, in effect, identical with the imposition of allowable catch quota.
(ii) Close season or area, or both.
(iii) Restriction concerning the type of fishing gear and method, except for the mesh size.
(iv) Minimum size limit of the species to be caught and specifying the prohibited species.

These measures were set forth jointly with the mesh regulation. Of all the known methods of the control, the last-mentioned is concerned deeply with the mesh selectivity study and occasionally includes the prohibition on the landing or sale of undersized species.

Although the mesh regulation is one of the best measures which brought forth good results for conservation purpose, it is very difficult to decide a criterion of desired size of mesh even if an optimum size of the species to be protected was confirmed experimentally. This is because the mesh selection curves vary with the species morphological characteristics and at the same time many species are taken simultaneously. In other words, there are great differences in the minimum size limit by species. Therefore, the mesh regulations enforced world-widely were based on the special mesh size which corresponded to 50% selection lengths of commercially important species[32,86]. Special emphasis should be laid on the fact that most of the existing mesh sizes enforced were determined on the basis of relatively old data of the past mesh experiments. The theoretical results will supply a new standard in changing the existiting mesh size or reconsidering whether existing mesh size is better or not. Moreover, there were drastic alterations and big changes in the netting materials used[52,87], size of gear and its design and construction, fishing vessels, etc. A long series of improvement of fishing gear, modernization of fishing vessels as well as scientific works on the engineering behaviour of the gear accomplished what was before apparently impossible, such as deep sea trawling. There is need, therefore, for further researches on the mesh selectivity by considering the present latest fishing gears and techniques. No matter how those researches are conducted, there is a problem awaiting solution ; that much more time is required to apply the results obtained through those researches to fishery management. In this sense, the theoretical results will play a still another important role in filling up such gap and in supplementing the lack of the latest mesh selectivity data.

The author proved that the modified and unmodified ogives for $\theta = 60°$ held to a fairly good approximation for many species. As is seen from the theory, those ogives could be derived from the four variables ($2a$, $2b$ or ε, $T/4$, θ). Among those variable, only two ($2a$, $2b$) are practically dealt with as unknown variables because the other two can be estimated from both given mesh size and the results of the past underwater observation of mesh angle. Accordingly, the theoretical ogives can be estimated only from the data of body depth and breadth at the greatest girth. As for the necessary number of those data, it is sufficient to measure them within the statistical confidence limits, including small size of fish as well as large ones. However, the body length is required to measure in examining the applicability of the theoretical ogives. That is, the regression equations between the body length and body depth become necessary for the comparison of the theoretical ogives with the experimental ogives. By the use of these regression equations, the relative magnitude can be converted in terms of selection factor (Sf). Consequently, it is very convenient not only to compare both theoretical and experimental ogives but also to estimate the selection characteristics. In connection with the selection characteristics, here the author mentions the relation between the various mesh sizes and 50% R.P. By making use of the characteristic curves shown in Fig. 11, it can be made clear that a pre-estimation on how far the enlargement of present mesh size exerts upon the lengths of fish corresponding to 50% R.P. at various mesh sizes.

As mentioned above, there are some advantages in the theoretical results and these depend greatly upon whether or not the theoretical ogives are accurate enough for practical usage. In this respect, the accuracy of the theoretical ogives were examined by means of comparing both theoretical and experimental ogives. As a result of comparison, it became clear that the error between them would be for practical use permissible. But again, there is a weak point in the comaprison that all the biometrical data of body depth, body breadth and body length used were not new data. If new data on the above bodily measurements will be collected jointly with the mesh selectivity experiments or other fishery researches, the verification of the theoretical results should be made stronger on the basis of those data. Further, next to the length of fish body, the girth is one of favourable characters of fish body in order to check the species-to-species difference in the mesh selectivity. Some results of girth measurements for serveral species were reported by the foreign researchers. However, the approximate equation such as Eq. (1) is to be recommended to estimate the girth owing to the tedious hand work of girth measurements. If the data on body depth and breadth are available, the approximate cross-sectional shapes of fish body can also be estimated[69,88] Consequently, the effect of variations in fish shape on the mesh selectivity becomes clear.

This study was made on the basis of various assumptions. Here the author discusses item by item a few points about the important items relating to the assumptions and then points out the necessary care to be taken and the problems encountered in applying the theoretical ogives.

(i) The mesh.

In the past, the mesh was regarded as being slightly flexible when the trawl net was in action. Also, the underwater observations showed that the mesh had a certain rhombic shape. As for the probability model employed, whether or not the mesh is deformed when the fish pass through it becomes a problem to discuss. Unfortunately, there is no published data on this matter. Theoretically, it must be noted that there are two different ways of thinking on the deformation of mesh. One is that the mesh is rigid and the deformation occurs only at the knots of mesh. This study is based on this way of thinking. Another is that the mesh has slight flexibility and is deformed slightly according to fish shape when the fish pass through it. Under this way of thinking, the deformation occurs in the very mesh that the fish pass through and its adjacent four meshes. The other meshes keep a certain rhombic shape.

With the flexibility of mesh under towing, according to the papers presented by LUCAS *et al*[54] and HODGES[76], the mesh was regarded as being rigid. While, according to the underwater studies made by CLARK[48], it could be considered that the mesh becomes more or less flexible if its size was more than 100 mm but under this size, the mesh is rigid. If the current mesh size enforced is enlarged to more than 100mm, it is necessary to consider the flexibility of mesh in the theoretical analysis as well as uneven shapes of meshes resulting from their flexibility. In other words, the probability model for analyzing mesh selectivity must be reconstructed on lines from the same-mesh principle to different-shape principle.

Next the author described the method of correction for the elongation of netting twine. If the elongation is large, the theoretical ogives require some corrections according to the extent of elongation. Generally, the netting twine tends to shrink at the initial stage of gear usage.[22,32] However, this tendency reverses and the netting twine tends to elongate in accordance with the long period of gear usage.[32] This elongation moves the theoretical ogives from low value of relative magnitude to high. Now, let a small elongation be $(\varDelta T)$ and the necessary correction can be made by substituting the real length of mesh $\left(\frac{T}{4}+\varDelta T\right)$ for the original length $(T/4)$ in the relative magnitude $\left(\frac{2a}{T/4}\right)$.

(ii) The fish shape.

When examining the effect of the variations of fish shape on the mesh selectivity, the theoretical ogives are rather favourable than the former experimental selection curves. The reason for this is to be found in the adoption of relative magnitude as abscissa instead of the body length. As is apparent from Figs, 9 and 24, the theoretical ogives for various species (various ε values) are all shown in one graph so that the above effects are easily known by comparing those curves. In order to make the theoretical ogives for wide use, it is of primary importance to investigate the cross-sectional shapes or the body depth and breadth of various species beforehand. At the same time, it must be concluded from such investigations that the cross-sections of many species can be approximated by an ellipse. At present, a few reports[69] presented merely the cross-section of several species. Such limited data on the fish shapes may be attributed to the tedious work in taking measurements. On referring to that cross-sections, a certain ellipse is very close to the original fish shape[69,78]. In this study, the author assumed that the cross-sections are similar at any position of fish body. This assumption is applicable to many species.

However, there are some exceptions. For example, according to the author's report[69], there were large differences in the ε values for Allask pollack, *Teragra chalcogramma,* between the position of head and that of the maximum girth. Namely, the ε value for this species took 0.55 at the posterior membrane of gill cover and 0.75 at the position of the greatest body girth. Further, some rare cases occur in which the body depth and breadth are smaller than the head depth and breadth, respectively. For such species, after calculating the ε value by using the larger depth and breadth among the above four measurements, the corresponding theoretical ogives for this ε value can be applied. Accordingly, it is advisable to measure not only the body depth and breadth but also the head depth and breadth in further researches. It is difficult to collect the necessary bodily measurements required to estimate the mesh selectivity, however, they are worth collecting for familiar types of fish species. To cite a typical example from Table 1, it can be seen that there is little difference in the values of ε between the yellow croaker, *Pseudosciaena manchurica*, and the white coraker, *Argyrosomus argentatus.* Since the difference is merely 0.02, the mesh selectivity characteristics for these two species can be estimated from their theoretical ogives if one of the measurements, body depth and breadth, is wanted.

(iii) The fish behaviour against moving net. Here, the author discussed a few problems in relation to the swimming posture of fish. The probability model used in this study includes one assumption that the figh go straight on the mesh surface, whatever the approaching directons and angles are. Besides this, there is another assumption that the fish approach and enter the meshes from their snouts first. If cases often occur in which the fish slip out of the mesh from their distal tips at first, the assumptions should be reconsidered because the difficulty differs between the escape from the snout and the slipping out from the distal tip. Some observation studies on the fish behaviour made in laboratories showed that whether or not the fish entered the mesh either from their snouts or from their distal tips depended mainly upon the relation between the fish size and the mesh size. In case where the mesh, as compared with the fish, is considerably large in their size, the slipping out from the distal tip seems to be probable[78,79] However, as a result of investigating the fish behaviour against moving nets reported so far,[54,58,59,75], it is safe to say that a great majority of fish species enteres the mesh with their snouts at first. And long-experienced trawlermen explained with examples that many meshed fish of different species exposed themeslves so that they sticked out their heads out of the meshes of codend. If many small fish stick their head out of the mesh, it should be investigate how much obstructive action arising from fins of fish, such as dorsal fin, ventral fin, pectral fin and anal fin, affects the mesh selectivity. Seemingly, those fins have reverse effects upon the mesh selectivity. Usually, when the fish enter head first in the mesh, the swimming action looks as if they make those fins and body comes closely into contact with the meshes during passing, so as to reduce hydrodynamic resistance and the frictional resistance against the netting twine to minimum. Consequently, they secceed in escaping by frequent beating of their distal fin only, which functions greatly as a means of propelling themself forward. The following method would be, for instance, available to modify the reverse effect of dorsal fin on the mesh selectivity. Namely, although the real body depth ($2a$) was used as a measure of fish body, if the dorsal fin has much effect on the mesh selectivity, an apparent measure of corrected body depth ($2a+\varDelta 2a$) in which the real body depth added to the height of the dordal fin ($\varDelta 2a$) may be reasonable for that modification.

As stated above, there are some incidental problems in the probability model and the underlying assumptions. These problems would be from the fact that it is very difficult to replace some complicated dynamic phenomena relating to the behaviour of gear and fish with a uniform or simple model. Further intensive researches from all approaches will be necessary to make those behaviours clear. If those behaviours become evident through the researches in the future, then such will help toward the improvement of the probability model and the underlying assumptions. The important points to improve include ; (i) the swimming character that the fish go straight on the mesh or not, (ii) the evaluation about the effect of meshes clogged by fish on the mesh selectivity and (iii) how many times do the fish try to escape from the meshes of codend for a certain duration of haul. If the fish succeed in escaping after several attempts of escape are made, the probability model must be reformed as such. Therefore, there is a room for improvement of probability model used in this study. However, since models were based on many experimental data, the resultant theoretical ogives are useful for estimations of various selection parameters of the exisiting trawl nets by taking the afore-said additional considerations described under (i) mesh, (ii) fish shape and (iii) fish behavior,

5. Summary.

This is a theoretical contribution, in which the author analyzed the mesh selectivity of trawl nets on the basis of a probability model. Since it is well known that the mesh selection curves are most typical manner of the representation of the mesh selectivity characteristics for many species at various mesh sizes, all-out efforts were concentrated on how to dedive the theoretical selection curves that held to a fairly good approximation for the existing trawl nets. In this paper, the author presented a trial as the first approach under the assumption that the pass-ability of fish can be considered as the probability depending largely upon the relative magnitude of fish shape to mesh shape. From the methodological standpoint, the theoretical approach can be divided into the two ; one is based on a two-dimensional model under the assumption that the fish always approach the mesh surface at right angles when they try to escape. Another is based on the three-dimensional model, assuming that the fish have a chance to approach the mesh from all directions and all inclination angles against the mesh. The latter is one of the suitable method of expressing the actual swimming action of fish against the moving net. A supplemental theoretical analysis on the mesh selectivity was made as a part of the three-dimensional analysis. A simplified model, a dodecahedoron, was used in the supplemental analysis.

In the theoretical approaches, it was assumed that the mesh is rigid diamond-shaped and the cross-sectional shape of fish body is an ellipse. The dimensions of fish and the mesh are denoted by the following symbols :

knot-to-knot length of a mesh by $(T/4)$,
larger included angle of a mesh by (2θ),
length of major axis of ellipse by $(2a)$,
length of minor axis of ellipse by $(2b)$,
and eccentricity of ellipse by (ε).

As is apparent from the text, the relative magnitude $\left(\frac{2a}{T/4}\right)$ can be expressed as a function of θ and ε. When applying the probability method and the geometrical relation between both fish and mesh shapes, the probability of the ellipse being retained can be expressed as a function of relative magnitude. In other words, by adopting the above function as an index of selection ratio, the theoretical selection curves can be derived for various combinations of θ and ε in the rectangular coordinate system with the relative magnitude as X-axis and with the selection ratio as Y-axis. Therefore, the mesh selectivity characteristics can be made clear for every mesh angles and fish shapes. Also, in cases where the theoretical selection curves for various mesh sizes become necessary, the necessary curves can be obtained by substituting the wanted mesh size $(T/4)$ into the denominator of the relative magnitude.

The theoretical selection curves have an enormous advantage in that they can be derived only from very limited biometrical data about the body depth and breadth. Namely, among the four variables $(T/4, 2\theta,$

$2a, 2b$) required to derive the theoretical selection curves, the latter two variables ($2a, 2b$) are necessary. As for the former two variables, the mesh size ($T/4$) is known, and the mesh angle (2θ) is unknown in general but its approximated angle can be considered to be some 60° according to the past underwater observations.

The utility value of the theoretical selection curves depends entirely upon their general validity. To examine this validity, the theoretical selection curves for $\theta = 55°$, 60° and 65° were compared with the experimental selection curves reported by other researchers. In making comparison, the author selected many species whose morphological characters differed much from species to species. Further, the experimental data used in the comparison were examined with various mesh sizes. As a result of comparison, it became clear that the theoretical selection curves could be considered to be fairly good approximations for many species. Therefore, the selection parameters which provide basic data for the mesh regulation can also be estimated for many other species whose mesh selectivity are left unsolved, by making use of the theoretical results. The rational exploitation of those species has caught world-wide attention because of a world-wide food problem lately. For that purpose, it is necessary not only to carry out fishery-oceanographic researches but also to collect the biological data. The important biological data such as body depth and breadth for many species can be easily obtained even by the usual fishery activity without recourse to the mesh experiments.

As essential prerequisites to a successful study, the author made some assumptions relating to the mesh, fish shape and fish behaviour in this study. However, much attention was devoted to make these assumptions so as to be reflected in their realistic conditions as nearly as possible. For this reason, there still remains some problems in these assumptions. Accordingly, it is necessary to take some additional considerations about these assumptions for the practical application of theoretical selection curves to the actual trawl fisheries. A few problems and their countermeasures were intensively presented and discussed in the Chapter 4. This will give useful hints to the problems described above.

Of all the various types of fisheries in Japan, the trawl fishery has took the leading and important position. In order to protect demersal species against excessive trawling activities, the well-known measures of fishery control were imposed upon the trawl fishery. The mesh regulation is only one of the control measures but this was widely accepted as an effective measure. However, since a new Sea-Order was brought about, deep-sea and off-shore trawlings around Japan are becomming important. The stronger control measures will certainly be imposed on those fisheries in the near future. The theoretical results obtained will give helpful suggestions as basic data to the imporvement or strength of the existing control measures.

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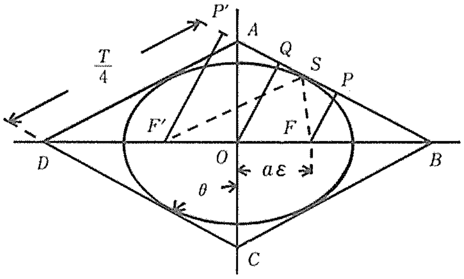
Appendices
Derivation of theoretical equations

[I]. Equations from Chapter 2.

(A) Derivation of the relative magnitude

The relative magnitude $\left(\frac{2a}{T/4}\right)$ stated in this paper can be obtained from the relationship between a lozenge (A, B, C, D) and an ellipse inscribed in the lozenge, as shown in App. fig. 1, together with their respective dimensions.



App. fig. 1. Relationship between lozenge $(A.\ B.\ C.\ D)$ and inscribed ellipse. Rectangular coordinates · system was expressed in the line $\overline{OB}$ as x-axis and the line $\overline{OA}$ as y-axis. The coordinate of S is $(x_i\ y_i)$ with center of ellipse at origin O. S and F, F' show a point of contact at the tangent line $\overline{AB}$ and forcal points of ellipse. $\overline{FP}$ $\overline{F'P}$ and $\overline{OQ}$ indicate the perpendiculars from the points F, F' and O to the line $\overline{AB}$.

Now, let S, O equal to the point of contact in the first quadrant and the center of both ellipse and lozenge, respectively, when the point O is the origin of the rectangular coordinate system with the side $\overline{OA}$ as the Y-axis and the side $\overline{OB}$ as the X-axis. The co-ordinate of $S(x_i,\ y_i)$ can be obtained as follows :

We can denote the universal expression for ellipse by the following form ;

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}=1 \qquad (1\text{-}1).$$

Where, $2a$ and $2b$ are the length of the longer and shorter axes of ellipse.

Differenciating y with respect to x, we get ;

$$\begin{aligned} \frac{dy}{dx} &= -\frac{b^2x}{a^2y} \\ &= -\tan\left(\frac{\pi}{2}-\theta\right) \end{aligned}$$

$$\therefore \quad \tan^2\left(\frac{\pi}{2}-\theta\right) = (1-\varepsilon^2)\frac{x^2}{a^2-x^2} \qquad (1\text{-}2).$$

Hence, the eccentricity (ε) of ellipse is given in the function of a and b,

$$\varepsilon = \sqrt{a^2-b^2}/a, \quad (0 \leq \varepsilon < 1) \qquad (1\text{-}3).$$

From the theorem on the ellipse, the four equations can be taken as follows ;

$$\overline{FP} = b\sqrt{\frac{a-\varepsilon x}{a+\varepsilon x}} \qquad \overline{F'P} = b\sqrt{\frac{a+\varepsilon x}{a-\varepsilon x}},$$

$$\overline{FS} = a-\varepsilon x\ , \qquad \overline{F'S} = a+\varepsilon x,$$

As the three triangles, $\Delta BFP, \Delta BOQ$ and $\Delta BF'P'$ are homologous one another, we can write ;

$$\begin{aligned} \overline{BF} &= \overline{BF'}\cdot\frac{\overline{FP}}{\overline{F'P'}} \\ &= (\overline{BF}+2a\varepsilon)\frac{a-\varepsilon x}{a+\varepsilon x} \\ &= \frac{a^2}{x}-a\varepsilon \qquad (1\text{-}4). \end{aligned}$$

and

$$\begin{aligned} \overline{BO} &= \overline{BF}+\overline{FO} \\ &= \left(\frac{T}{4}\right)\sin\theta \qquad (1\text{-}5). \end{aligned}$$

and

$$\overline{FP} = \overline{BF}\cos\theta$$

$$\begin{aligned} \left(\frac{a^2}{x}-a\varepsilon\right)\cos\theta &= b\sqrt{\frac{a-\varepsilon x}{a+\varepsilon x}} \\ &= a(1-\varepsilon^2)\sqrt{\frac{a-\varepsilon x}{a+\varepsilon x}} \qquad (1\text{-}6). \end{aligned}$$

By solving and rearranging for x of the above equations, we can obtain the co-ordinate of S, it becomes ;

$$x_i = \frac{a\cos\theta}{\sqrt{1-\varepsilon^2\sin^2\theta}}, \qquad y_i = \frac{a(1-\varepsilon^2)\sin\theta}{\sqrt{1-\varepsilon^2\sin^2\theta}}$$

From the equations and the co-ordinate of S derived so far, we can obtain the relative magnitude ;

$$\frac{2a}{T/4} = \frac{\sin 2\theta}{\sqrt{1-\varepsilon^2\sin^2\theta}} \qquad (1\text{-}7).$$

In this connection, the length of $\overline{OA}$ and $\overline{OB}$ may be stated ;

$$\overline{OA} = \frac{a\sqrt{1-\varepsilon^2\sin\theta}}{\sin\theta},$$

$$\overline{OB} = \frac{a\sqrt{1-\varepsilon^2\sin\theta}}{\cos\theta}$$

In case of the ellipse inscribed under the condition which the shorter diagonal line of lozenge coincides with the longer axis of ellipse, we have only to rearrange the variable θ by substituting $\left(\frac{\pi}{2}-\theta\right)$ into the equation (1—7). The results are as follows ;

$$\frac{2a}{T/4} = \frac{\sin 2\theta}{\sqrt{1-\varepsilon^2\cos^2\theta}}$$

(B) Derivation of areal ratio.

In order to derive the areal ratio which is used as an index of the selection ratio in the theoretical analysis, we let the ellipse revolve about the center of lozenge under the following conditions : In the course of revolving, the angle between the longer diagonal line of lozenge and the longer axis of ellipse is keeping at a certain given angle, ψ, in addition to this, the ellipse always revolves touching the inner sides of lozenge at the two or three points on the circumference of ellipse.

If we revolve the ellipse clockwise, the center of ellipse moves then from the point O_1 to the point O_4, followed by the points O_2 and O_3, along the dotted line as shown in App. fig. 2. Consequently the path of the center is described as a parallelogram after being revolved around the center fully once.

Next place, let $S(\psi)$ denote the area of the parallelogram and this can be obtained geometrically by using the following equation. That is :

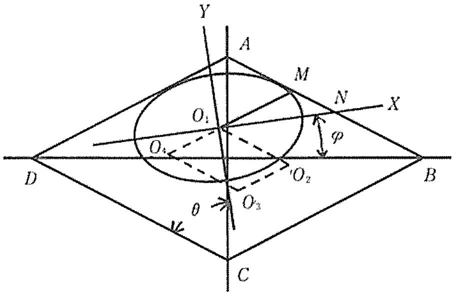
$$S(\psi) = \overline{O_1O_2}\cdot\overline{O_3O_4}\cdot\sin 2\theta \qquad (2\text{-}1).$$

Hence, $\overline{AD} \,/\!/\, \overline{O_1O_4} \,/\!/\, \overline{O_2O_3}$,

$\overline{AB} \,/\!/\, \overline{O_1O_2} \,/\!/\, \overline{O_3O_4}$

Here, we may consider the rectangular coordinate system $x-y$, with the longer axis of ellipse as x-axis and the shorter one as y-axis at the origin O_1. Moreover, let M denote the foot of the extension of a line $\overline{O_1O_4}$ dropped from the point O_1 and meeting a side of lozenge $\overline{AB}$, and also let N denote the foot of the extension of the longer axis of ellipse from the point O_1 and meeting the same side $\overline{AB}$.

Next we must obtain the two sides, $\overline{O_1O_4}$, $\overline{O_1O_2}$ by a functional form. On referring to the App. fig. 2, as well as the equations shown in the Appendices (I) and (III), the length of a line $\overline{O_1N}$ can be expressed by the following equation.



App. fig. 2. The path swept out by the center of ellipse. The path describes a parallelogram at the state which ψ is held constant. $\overline{O_1Y}$ and $\overline{O_1X}$ should be read along the y and x axis at the origin O_1, $\overline{O_1M}$ is parallel to the line $\overline{AD}$

$$\overline{O_1N} = \frac{a\sqrt{1-\varepsilon^2\sin^2(\theta-\psi)}}{\cos(\theta-\psi)}$$

and from the triangle, ΔO_1MN we get the length of $\overline{O_1M}$.

Then ;

$$\overline{O_1M} = \overline{ON}\,\frac{\cos(\theta-\psi)}{\sin 2\theta} = \frac{a\sqrt{1-\varepsilon^2\sin^2(\theta-\psi)}}{\sin 2\theta}$$

Hence, the angle between the line $\overline{O_1O_4}$ and the lines $\overline{O_1O_2}$ or $\overline{O_3O_4}$ take 2θ and $(\pi-2\theta)$ respectively.

With the relationship between the points, O_1 and O_3, we can easily find out that both points are symmetric to each other with respect to the line which passed through the center of lozenge and parallel to the longer axis of ellipse, therefore,

$$\begin{aligned}\overline{O_1O_4} &= \overline{AD}-2\overline{O_1M}\\ &= (T/4)-\frac{2a\sqrt{1-\varepsilon^2\sin^2(\theta-\psi)}}{\sin 2\theta}\end{aligned} \qquad (2\text{-}2).$$

We can obtain the length of line $\overline{O_1O_2}$, on the basis of the same procedure as that derived for the equation (2–2).

The result is ;

$$\overline{O_1O_2} = (T/4)-\frac{2a\sqrt{1-\varepsilon^2\sin^2(\theta+\psi)}}{\sin 2\theta} \qquad (2\text{-}3).$$

By using the equations (2—1), (2—2) and (2—3), the area surrounded by the path of ellipse's center can be rewitten as follows :

$$S(\psi) = \frac{(2a)^2}{\sin 2\theta}\left\{\frac{\sin 2\theta}{\left(\frac{2a}{T/4}\right)}-\sqrt{1-\varepsilon^2\sin^2(\theta-\psi)}\right\}\cdot\left\{\frac{\sin 2\theta}{\left(\frac{2a}{T/4}\right)}-\sqrt{1-\varepsilon^2\sin^2(\theta+\psi)}\right\} \qquad (2\text{-}4).$$

Therefore, the areal ratio stated in the Chapter 2 can be calculated from the following function.

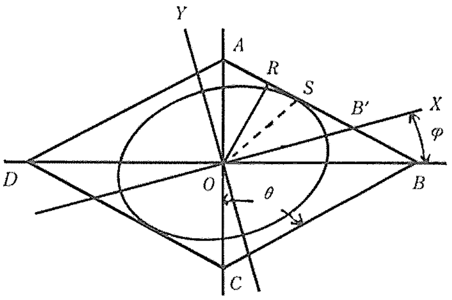
The areal ratio (P) ;

$$P = \frac{2}{\frac{\pi}{2}(\sin 2\theta)^2}\left(\frac{2a}{T/4}\right)^2\int_0^{\frac{\pi}{2}} S(\psi)\,d\psi$$

(C) Derivation from the movable angle.

When the size of ellipse is so small as the maximum one inscribed in the lozenge as shown in App. fig. 1 and the center of ellipse coincides just with the center of lozenge, this ellipse can rotate freely to some extent about the center of lozenge, corresponding to the value of the relative magnitude. We can calculate the degree of rotating angle which is also used as an index of the selection rate.

Now, let ψ denote a certain angle rotated to the utmost limit in the lozenge and we take the rectangular coordinate system $x-y$, following the App.fig. 2, with the longer axis of ellipse as x-axis and the shorter one as y-axis at the origin O as shown in App. fig. 3.



App. fig. 3. Turned ellipse in contact with the opposite sides of lozenge at the condition of ellipse coincided with that of lozenge. $\overline{OR}$ is a perpendicular from origin $\underline{O}$ to a side $\overline{AB}$. $\overline{OY}$ and $\overline{OX}$ are recutangular coordinate axies. at the origin O.

The co-ordinate of $S(x_i, y_i)$ which is one of the intersection of the sides of lozenge and the circumference of ellipse can be obtained on referring to the equations presented in App. (I)-(A), they are :

$$x_i = \frac{a\cos(\theta-\psi)}{\sqrt{1-\varepsilon^2\sin^2(\theta-\psi)}}$$

$$y_i = \frac{a(1-\varepsilon^2)\sin(\theta-\psi)}{\sqrt{1-\varepsilon^2\sin^2(\theta-\psi)}}$$

Next we take the point R, which is a perpendicular dropped from the origin and meeting the side of lozenge $\overline{AB}$, and also we take the point B', which is the intersection of the side $\overline{AB}$ and the extension of the longer axis of ellipse. The length of $\overline{OB'}$ can be obtained by the same way indicated in App. (I)-(A). It becomes.

$$\overline{OB'}=\frac{a\sqrt{1-\varepsilon^2\sin^2(\theta-\psi)}}{\cos(\theta-\psi)} \qquad (3\text{-}1).$$

From the triangles, $\varDelta ROB'$ and $\varDelta ROB$, the two sets of the length $\overline{OR}$ are given in different forms, they can be written ;

$$\overline{OR}=\overline{OB'}\sin\left\{\frac{\pi}{2}-(\theta-\psi)\right\} \qquad (3\text{-}2).$$

If we substitute in the equation (3-2) for $\overline{OB'}$, we get

$$\overline{OR}\ =a\sqrt{1-\varepsilon^2\sin(\theta-\psi)} \qquad (3\text{-}3).$$

and

$$\overline{OR}=\overline{OB}\ \cos\theta=(T/4)\frac{\sin 2\theta}{2} \qquad (3\text{-}4).$$

Eliminating the $\overline{OR}$ term from the both equation, (3−3) and (3−4), we get

$$\psi=\theta-\sin^{-1}\left\{\frac{1}{\varepsilon}\sqrt{1-\frac{(\sin 2\theta)^2}{\left(\frac{2a}{T/4}\right)^2}}\right\} \qquad (3\text{-}5).$$

In case of the relative magnitude ranging within the equation (4) in the Chapter 2, we have only to substitute $\left(\frac{\pi}{2}-\theta\right)$ in place of θ in the equation (3−5) in order to obtain the angle rotated to utmost limit in the lozenge.

[II]. Equations from Chapter 3.

(A) Derivation from areal ratio.

We assume that the arcal ratio used in the three dimensional analysis is given in the form of the following intergral. Let this ratio be replaced by P_2, the integral in the given case is :

$$P_2=\frac{\int_0^{\rho}\int_0^{\phi}\ \sin\phi\frac{(T/4)^2}{4VU}\left\{\sqrt{3}-\left(\frac{2a}{T/4}\right)\sqrt{U^2+V^2}\right\}^2 d\rho\, d\phi}{\frac{\pi}{2}\int_0^{\frac{\pi}{2}}\frac{xy}{2}\cos\phi\sin\phi\, d\phi} \qquad (4\text{-}1).$$

In the integral (4-1),

$$V=\cos\phi+(1-\cos\phi)\left(\cos^2\rho+\frac{\sqrt{3}}{2}\sin 2\rho\right) \qquad (4\text{-}2).$$

$$U=\sqrt{3}\cos\phi+(1-\cos\phi)\left(\sqrt{3}\sin^2\rho+\frac{1}{2}\sin 2\rho\right) \qquad (4\text{-}3).$$

In order to obtain the integration simply, we denote the numerator of the integral (4−1) by P_f and we shall perform its variables' transformation by introducing the Jacobian operator.
That is to say :

$$P_f\equiv\int d\rho\int\sin\phi\frac{(T/4)^2}{4VU}\left\{\sqrt{3}-\frac{2a}{T/4}\sqrt{U^2+V^2}\right\}^2 d\phi$$

$$P_f\equiv\iint\frac{(T/4)^2}{4VU}\left\{\sqrt{3}-\frac{2a}{T/4}\sqrt{U^2+V^2}\right\}^2 f(V,\ U)\frac{\partial(V,U)}{\partial(V,U)}dV\,dU$$

By partical differnciation of the equations (4–2) and (4–3) with respect to Euler's angles ρ, ϕ.

$$\frac{\partial(V,\ U)}{\partial(\rho,\ \phi)} = \begin{vmatrix} \frac{\partial U}{\partial \rho}, & \frac{\partial U}{\partial \phi} \\ \frac{\partial V}{\partial \rho}, & \frac{\partial V}{\partial \phi} \end{vmatrix}$$

$$\frac{\partial(V,\ U)}{\partial(\rho,\ \phi)} = \sin\phi\,(1-\cos\phi)\cdot(\sqrt{3}\sin 2\rho - 2 - \cos 2\rho)$$

Also, we can obtain the following expression from the equations (4–2) and (4–3), this is

$$(V-1)+\sqrt{3}\,(U-\sqrt{3}) = (1-\cos\phi)\,(\sqrt{3}\sin 2\rho - 2 - \cos 2\rho)$$

Therefore,

$$f(V,\ U)\frac{\partial(V,\ U)}{\partial(\rho,\ \phi)} = f(V,\ U)\sin\phi\,(V+\sqrt{3}\,U-4)$$

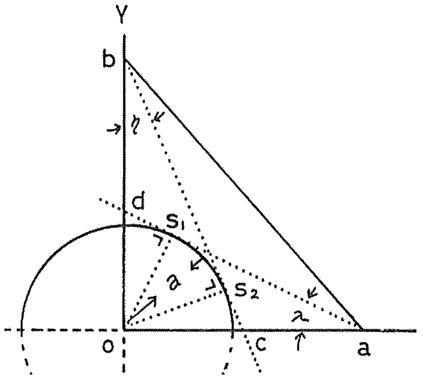
$$f(V,\ U) = \frac{1}{(V+\sqrt{3}\,U-4)}$$

Finally,

$$P_f = \int_{u_1}^{u_2}\int_{v_1}^{v_2} \frac{(T/4)^2}{4VU}\left\{\sqrt{3} - \frac{2a}{T/4}\sqrt{U^2+V^2}\right\}^2 f(V,\ U)\frac{\partial(V,\ U)}{\partial(V,\ U)}\,dVdU$$

Next place we must determine the area of integration due to the transformation of the integration variables (ρ, ϕ). App. fig. 4 shows the relation between the circular cross-section of fish body and the horizontal projection of the mesh shape formed by Euler's transformation about the standard space coordinate axes. In this figure, we consider that a fixed coordinate system X-Y is located on the horizontal plane and also consider only its first quadrant.

The both centers of the circle and the projection of mesh coincide with the origin, (o), each other precisely. Now, let (**d**) denote the foot of the tangent line, which touches the circle at the point s₁, dropped from the vertex (**a**) and meeting opposite side $\overline{\mathbf{bo}}$. In the same procedure as the above, let (**c**) denote the foot of the tangent line, which touches the circle at the point s₂, dropped from another vertex (**b**) and metting opposite side $\overline{\mathbf{oa}}$.



App. fig. 4. Tangent lines drawing from the vertices of lozenge that the center coincided with the center of circular cross-section.
$2a$: the diameter of circle,
s₁, s₂ : the points of contact.
η, λ : the angles between X, Y axes and tengent lines.

Referring to the figure and considering the given condition of $\theta = 60°$ (mesh angle), we shall be able to provide the area of inegration, or u_1, u_2 and v_1, v_2.

Initially, if rearranging with $X \to 0$, $x \to 0$ in both equations (12) and (13) presented in Chapter 3 and also comparing their interceptions on the Y and y axes together, u_1 and v_1 take the following values. They become ;

$$\sqrt{3}\,(T/4) \geq \frac{\sqrt{3}}{V}(T/4),$$

Therefore

$$v_1 \geqq 1\,.$$

Secondary, if rearranging and comparing their interceptions on the X and x axes with $Y \to 0$, $y \to 0$ in much the same way as the above, we obtain.

$$\frac{1}{2}(T/4) \geq \frac{\sqrt{3}}{2U}(T/4).$$

Therefore,

$$u_1 \geqq \sqrt{3}.$$

As for the terms u_2 and v_2 we can obtain them from the geometrical method. As is obvious from the App. fig. 4, whether or not the circle with radius (a) can pass through the given mesh's shape projected on the horizontal plane depends upon the following conditions which must be satisfied simulteneously. Namely,

(i)The y-interception of the tangent line $\overline{\mathbf{ad}}$ must be smaller than the length of $\overline{\mathbf{od}}$.

(ii)The x-interception of the tangent line $\overline{\mathbf{bc}}$ must be smaller than the length of $\overline{\mathbf{oc}}$.

Here, let the angle between the side $\overline{\mathbf{ao}}$ and $\overline{\mathbf{ad}}$ be replaced by λ and the angle between the side $\overline{\mathbf{ab}}$ and $\overline{\mathbf{bo}}$ be replaced by η respectivily, then the desired results can be obtained as follows ;

$$\tan\lambda = \frac{a}{\sqrt{\frac{(T/4)^2}{4} - a^2}},$$

$$\overline{\mathbf{od}} = \frac{a(T/4)}{2\sqrt{\frac{(T/4)^2}{4} - a^2}}$$

and

$$\tan\eta = \frac{a}{\sqrt{\frac{3(T/4)^2}{4} - a^2}},$$

$$\overline{\mathbf{oc}} = \frac{\sqrt{3}\,a(T/4)}{2\sqrt{\frac{(T/4)^2}{4} - a^2}},$$

Therefore,

$$\frac{a(T/4)}{2\sqrt{\frac{(T/4)^2}{4} - a^2}} \leq \frac{\sqrt{3}(T/4)}{2V},$$

$$v_2 \leq \sqrt{\frac{3}{\left(\frac{2a}{T/4}\right)^2} - 3}$$

and

$$\frac{\sqrt{3}\,a(T/4)}{2\sqrt{\frac{T/4)^2}{4} - a^2}} \leq \frac{\sqrt{3}(T/4)}{2U},$$

$$u_2 \leq \sqrt{\frac{3}{\left(\frac{2a}{T/4}\right)^2} - 1}$$

曳網類の網目選択性に関する理論的研究

藤石　昭生

各種曳網漁業の技術革新と近代化は漁業資源を枯渇させるほど促進された。網目選択性に関する調査の主目的は，資源の有効利用をねらいとした網目規制の基礎資料を得ること，および，資源量に対する網目規制の効果を判定することにおかれている。しかし，日本における網目選択性の調査資料は欧米のそれに比べて著るしく少ない。この欠陥を補うことを主眼として，網目選択性に関する綜合的な理論考察を行った。その結果，かなり，実用的な結論が得られたが，本理論の実地適用に当っては二，三の付加的考察を必要とする。