Study on Damping Performances of New Link Device using Granular Materials

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Abstract

Noise reduction and vibration controls of high-speed railways are required to improve the inter-noise characteristics of aluminum car body systems, such as Shinkansen and express trains. However, it becomes difficult to maintain the vibration control of the traction rod between the car body and the car bogie. In this paper, to improve the damping performance of the traction rod, we have proposed the new type of noise-reduction link mechanism using granular materials. Factors that affect the damping performance are examined through an experimental study. A new type of noise-reduction link mechanism is considered via examining the damping performance with granular mass and friction effects. Finally, in the experiment of the vibration bench test, a new type of noise-reduction link mechanism is improved by max. 11 dB in comparison with the conventional one.

Key Words : Damping, Vibration Control, Noise Reduction, Granular Materials, One Link Device, Railways

1. Introduction

As trains become faster, high-speed railway vehicles are increasingly required to provide a low noise passenger car environment as well as lightweight car bodies, better energy-saving performance and improved ride comfort (1) (2).

However, there are a number of disadvantages in reducing indoor noise, such as increased vibration and noise stemming from high-speed operation, and the reduced sound isolation and absorption performance of lightweight car body structures. Another problem currently in focus is the low-frequency indoor noise caused by low-frequency vibration in coasting (3). In particular, it is necessary to reduce the n-fold components of low-frequency vibration (160 to 315Hz) that are found in the revolution of motors and gears in the truck driving system. This makes it important to research cutting vibration transmission routes (such as the traction rod and yaw dampers arranged between truck and car body) and drastically reduce their vibration transmissibility.

Shiohata et al. (4)(5) proposed a method to evaluate the radiation noise of low-frequency vibration in the 200Hz band that propagates from car bogie to car body, based on tests using a life-size model of car body structure. It was demonstrated that application of a damping material in the panel section of the car body structure improved the damping effect. Tanaka et al. (6) improved the aluminum car body and inner structures for high-speed railways to reduce noise, proposed the indoor noise reduction technique adopted in their study, and discussed the practicality of the aluminum car body structure with a damping material applied to panel sections.

Oda et al. (7) developed a method of predicting indoor noise and a noise reduction technology to apply the method, and clarified its noise reduction effect in running tests. The three of them alike attempted to establish a noise prediction method and proposed a low-noise car body structure using a

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number of damping materials in hollow aluminum sections. However, the method of using bulk damping materials makes the car body heavier and requires a design that incorporates optimal arrangement of the damping materials.

This study is aimed at minimizing increases in car body weight, noting that about 70% of indoor noise is caused by longitudinal vibration propagating from the truck driving system to the under-floor car body bolster beams through the traction rod. The study also clarifies the characteristics of the vibration transmissibility. A traction rod using granulars (i.e., a noise reduction link device) was devised to drastically reduce the vibration transmittal ratio in the 200Hz band (8).

Araki et al. (9) implemented basic research in the advanced field of granulars, clarified the damping characteristics of granular impact dampers, and attained a damping effect on a horizontal vibration system in the 7.5Hz band.

Sato et al. (10)- (12) used a multi-impact damper to clarify the damping effect of a cantilever beam in the 2Hz band. However, no discussion was made on damping caused by the friction behavior of granulars.

In researching a granular impact damper using a cylindrical vessel, Saeki (11) determined the damping effect in the 10Hz band through calculation and testing. Any of these three cases are reported in theses discussing the damping effect of several hertz bands.

This paper discusses the composition of a noise reduction link device for high-speed railway vehicles, the basic characteristics of the granulars contained in the link, element tests, and another damping effect in the 200Hz band.

2. Problems with one link device and the purpose developing a new link device

2.1 Problems with one link device

The truck for railway vehicles(see Fig.1) is a running gear consisting of truck frames, wheels, axles, a primary suspension system (elements connecting bearing boxes and truck frames), a secondary suspension system (air springs, left and right yaw dampers, a one link device and other elements connecting truck frames and car body), a traction motor, gears, couplings and brakes. The elements that connect the car body and the truck are air springs, yaw dampers and a one link device. There are two air springs (one each on the left and right of the truck frame) to support the car body weight, and two yaw dampers (one each on the front and rear between car body and truck) to improve the stability of lateral motion. The one link device is an element to transmit longitudinal forces (vertical, lateral and yawing) from the truck to the car body.

Figure 2 shows the characteristics of passenger car noise in a high-speed railway vehicle running at 270km/h. The figure indicates that the indoor noise level is the highest in powering and coasting at 160 to 250Hz in the 1/3 octave central frequency band. More specifically, the sound pressure is significantly higher (about 3dB in terms of the overall OA value) in coasting than in powering, though this is not shown explicitly in the figure (13). The low-frequency vibration at the peak noise of 160 to 250Hz is caused by the motors, gears, couplings and other devices in the rotating system. This vibration resonates with that of the car body-fixing point and propagates through the one-link mechanism. As a result, the low-frequency vibration in the low-frequency band propagates from the truck driving system to the car body through the one link device, and is emitted in passenger cars. It is this vibration that needs to be reduced.

2.2 Purpose developing a new link device

The conventional one link device transmits vibration from the truck driving system directly to the car body. With this mechanism, therefore, damping can be expected only by applying rubber vibration isolators to both ends in the peak frequency band. To offset this drawback, the authors devised a system whereby approximately a million granulars are enclosed in a hollow space in the link. This converts the truck's vibration energy into kinetic energy in the granulars, and accelerates friction damping among the granulars and between the granulars and the link side wall. The transmittal ratio of the truck's vibration to the car body is thereby reduced (see Fig. 3 for the composition of the noise reduction link device).

The granulars placed in the link are excited by vibration (on the left of the figure) and move in a lateral direction, reducing vibration at the car body fixing point on the right. In the case of a conventional one link device, the rubber vibration isolators (with a spring constant of 8,620MN/m) at both ends were softened, shifting the peak frequency (eigenvalue) to the low-frequency side to affect damping. Since a fluctuating force of several tons works in the longitudinal direction, however, the softened rubber vibration isolators posed a problem in terms of strength and reliability.

The authors therefore devised a noise reduction link mechanism without changing the hardness of the rubber vibration isolators, and used it to reduce the vibration level in the peak frequency band (at an eigenvalue of about 200Hz). Figure 4 shows the principle of the noise reduction link mechanism. The following equations give the energy of the whole system of multiple granulars moving laterally in the figure.

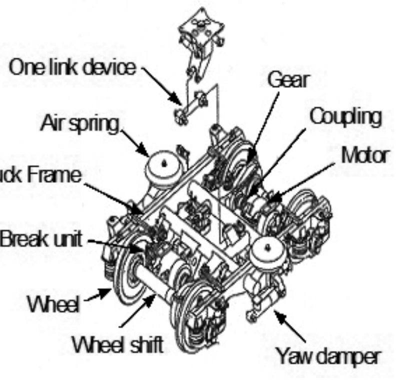


Fig.1 Configuration of railway truck

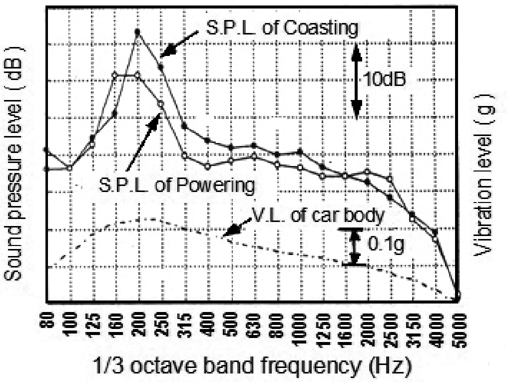


Fig.2 Noise and vibration result of running

$$\frac{1}{2}m_0\dot{y}^2+\frac{1}{2}K(y-x)^2+\sum_{i=1}^{n}\frac{1}{2}m_iz_i^2=-\int C(\dot{y}-\dot{x})\dot{x}dt-\int K(y-x)\dot{x}dt\int C(\dot{y}-\dot{x})^2dt$$
$$-\int kn_1(-z_1+y)^{2/3}(\dot{y}-\dot{z}_1)dt-\int kn_2(-z_2+z_1)^{2/3}(\dot{z}_1-\dot{z}_2)dt-\int kn_3(-z_3+z_2)^{2/3}(\dot{z}_2-\dot{z}_3)dt\cdots\cdots$$
$$-\int kn_i(-z_i+z_{i-1})^{2/3}(\dot{z}_{i-1}-\dot{z}_i)dt\cdots\cdots$$
$$-\int kn_n(-z_n+z_{n-1})^{2/3}(\dot{z}_{n-1}-\dot{z}_n)dt-\int kn_{n+1}(-z_{n+1}+z_n)^{2/3}(\dot{z}_n-\dot{z}_{n+1})dt$$
$$-\int cn_1(-\dot{z}_i+\dot{y})(\dot{y}-\dot{z}_i)dt-\int cn_2(-\dot{z}_2+\dot{z}_1)(\dot{z}_1-\dot{z}_2)dt-\int cn_3(-\dot{z}_3+\dot{z}_2)(\dot{z}_2-\dot{z}_3)dt\cdots\cdots$$
$$-\int cn_i(-\dot{z}_i+\dot{z}_{i-1})(\dot{z}_{i-1}-\dot{z}_i)dt\cdots\cdots$$
$$-\int cn_n(-\dot{z}_n+\dot{z}_{n-1})(\dot{z}_{n-1}-\dot{z}_n)dt-\int cn_{n+1}(-\dot{y}+\dot{z}_n)(\dot{z}_n-\dot{y})dt\cdots(1)$$

$$k_{ni}=\frac{\sqrt[4]{\dfrac{r_i-(r_{i-1})}{r_i+r_{i-1}}}}{3}\left(\frac{1-\nu_i^2}{E_i}+\frac{1-\nu_{i-1}^2}{E_{i-1}}\right)^{-1}\cdots(2)$$

$$c_{ni}=\frac{1}{2\pi}\ln\frac{1}{e^2}\sqrt{1.24\cdot m_i\cdot k_{mi}}\cdot\left|\delta_n\right|^{1/4}\cdots(3)$$

The symbols in the above equations are defined as follows:

m0: Mass of one-link mechanism
K: Spring constant of rubber vibration isolator
C: Damping coefficient of rubber vibration isolator
x: Forced displacement
y: Displacement of mass m0
zi: Displacement of granulars mi (i = 1, 2, ..., n)
Ei: Young's modulus
νi: Poisson's ratio
ri: Radius of granular
δn: Displacement in normal direction at collision
e: Restitution coefficient

The restoring force spring constant and damping coefficient of the granulars when they collide with each other or with the inner wall of the one-link mechanism (Kni and Cni in equations (2) and (3)) were derived from equations (4) and (5) in reference (11). However, these values will be set at 0 when collision does not occur.

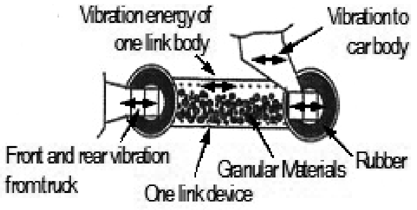


Fig.3 Conceptual configuration of noise reduction link mechanism

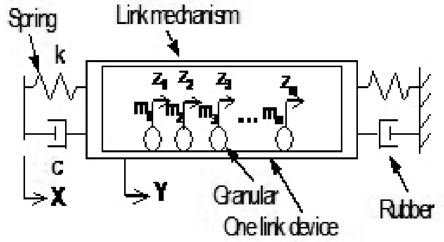


Fig.4 Model of noise reduction link mechanism

In equation (1), the first and second terms on the left side represent the energy of the one link device. The third term gives the energy of multiple granulars. On the right, the first and second terms represent the energies put into the mechanism by forced displacements from outside. The third term gives the energy dispersed by the damping elements of the mechanism. The fourth and following terms represent strain energy, dispersed energy and other energies at collision. To reduce the energy put into the one-link mechanism from outside by forced displacements, therefore, the energy of the granulars and the energy damped by the one-link mechanism have only to be increased.

The purpose of this study is to use granulars contained within a noise reduction link device to damp the low-frequency vibration (160 to 250Hz) that propagates from the truck to the car body, or to drastically reduce the vibration transmittal ratio of the noise reduction link device.

3. Noise reduction link device and element tests

3.1 Method of element tests

Figure 5 shows the element test apparatus for the noise reduction link device. Fig. 6 shows the apparatus for measuring the vibration transmittal ratio. The noise reduction link device is set at the position of the supports on the truck and car body sides. It is excited by an electrodynamics exciter fixed to the right side, and outputs a swept sine wave signal at 160 to 350Hz. Here, the authors installed a vibration accelerometer on the link and another on the truck, and measured the vibration transmittal ratio between the two sides with an FFT analyzer to clarify the damping effect of the noise-free link device.

In this element test, the authors adopted two systems (inside and outside granular placing systems) and clarified the damping effect of the noise reduction link device with different granular masses, materials and filling ratios. The granular filling ratio is taken as 100% when the hollow space of the link is completely filled with granulars. The inside granular placing system (Fig. 7) inserts multiple granulars into the hollow space of the link (mass: 18.3kg). This system prevents the granulars from being scattered by flying stones or degraded by rain or other environmental conditions. The outside granular placing system (Fig. 6) arranges multiple cylinders filled with granulars around the link. This system makes it possible to freely increase or decrease the granular mass, thereby facilitating verification of the damping effect at different masses. To maximize the damping effect of the granulars, the authors fixed hollow cylinders around the link wrapped with a rubber sheet.

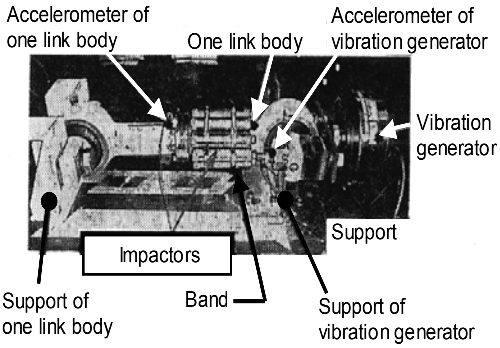


Fig. 5 Experimental setup using vibration generator

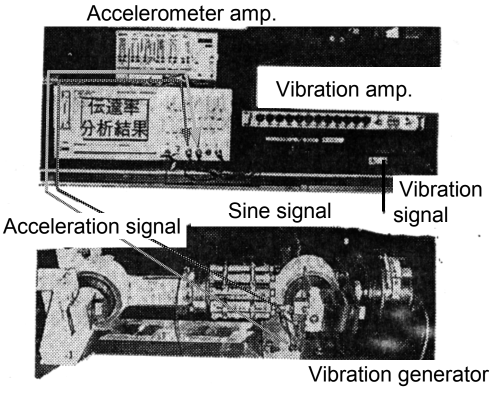


Fig. 6 Photographs of measuring apparatus

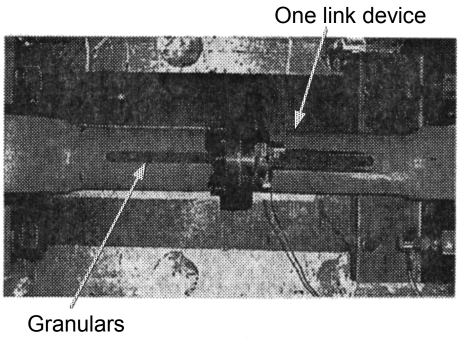


Fig. 7 Photographs of sealed in granulars

3.2 Characteristics of granulars

The authors used spherical and non-spherical granulars of 1mm in diameter (used for ball bearings) made of iron, plastic and lead.

To measure their basic characteristics (material constant, compression ratio and the restitution coefficient related to the damping effect), the authors performed a strength test, applying a compressive load of 4.9N to the granulars with micro-compression tester from Shimadzu Corporation (Figs. 8 to 10). Figure 8 shows the appearance of a spherical lead specimen after the test, with spherical configuration restored, although showing some deformation. Figure 9 (a) shows the relationship between the compressive load and the displacement of a spherical lead specimen, which was linearly deformed to 20μm by the compressive load but returned to 18μm when the load was removed. The average compression ratio of three lead granulars was 1.62%, and the average restoring ratio was 0.21%. The non-spherical lead granular shown in Fig. 9 (b) showed non-linearity at the start of compression. It deformed to 23μm under a compression load of 4.9N, and returned to 24μm when the load was removed. The average compression ratio was 2.27%, and the average restoring ratio was 0.18%. These results indicate a larger hysteresis characteristic and easier energy conversion with non-spherical lead granulars than with spherical ones.

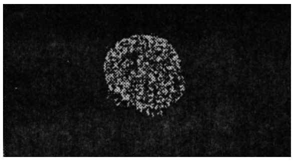
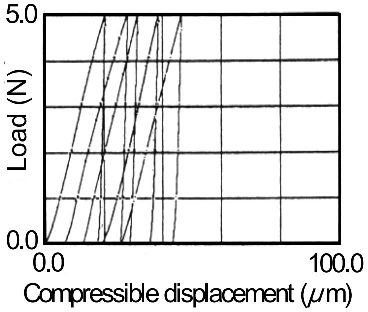
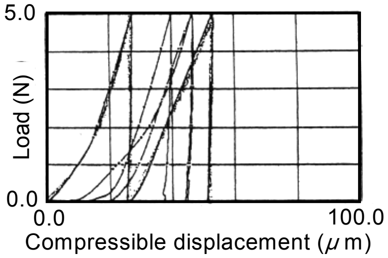


Fig. 8 Photographs of granular after experiment



(a) Load-compressible displacement using spherical granular material



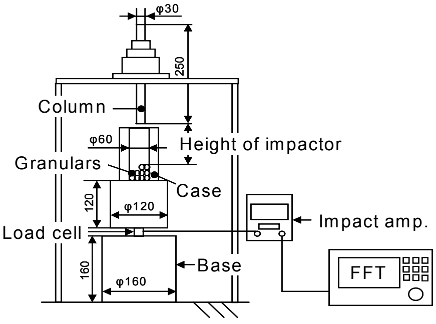
(b) Load-compressible displacement using spherical less granular material

Fig. 9 Static characteristics of granulars

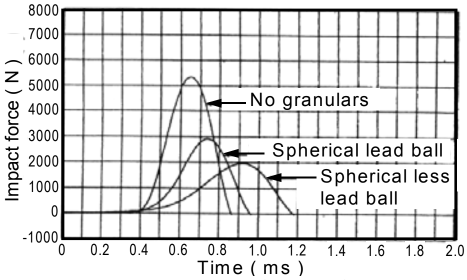
Figure 10 (a) shows the test apparatus manufactured by the authors to verify the collision damping effect of granulars, and Fig. 10 (b) the test results obtained with the apparatus.

The authors dropped an unconstrained iron column (mass: 1,500g, material SK 3) onto multiple lead granulars (diameter: 1mm, total mass: 50g, both spherical and non-spherical) contained in a case, and measured the impact damping characteristics of the granulars with a load cell at 1ms sampling (see Fig. 10(a)). Multiple lead granulars are contained in a case, colliding with the dropping iron column. Thus, there were three test conditions: containing spherical lead specimens, non-spherical lead specimens and no specimens.

The impact force determined from the impact-time waveforms was 5,300N (Max.) with empty case, 2,900N(Min.) with case containing spherical specimens and 2,000N(Max.) with case containing non-spherical specimens. The convergence time was the shortest with the empty case and the longest with the case containing non-spherical specimens. The impact force of the non-spherical specimens was smaller than that of the spherical ones. Because the kinetic energy of the column mass was converted into the friction energy of the granulars, or because the restitution coefficient was smaller due to the column not rebounding after hitting the granulars. The impact force (by trapezoidal integration) was 0.82Ns with the spherical specimens and 0.78Ns with the non-spherical specimens.



(a) Experimental setup using granulars



(b) Time-history of impact force

Fig. 10 Experimental result of impact force using impactor and granulas

Table 1 summarizes the above results and shows basic specifications of the granulars used in this study. When judged from the material's constant and measured characteristics, non-spherical specimens had the largest specific gravity and damping effect (small impact and restitution coefficient), where the ratio of the column height at the start of dropping to the restitution height was taken as the restitution coefficient.

Table 1 Specification of granular materials

		Elastic factor			Damping parameters			
		Specific gravity (-)	Young's modulus (GPa)	Poisson's number (-)	Compress Ion (%)	Retaining (%)	Impulse (N･S)	Rebound coefficient (-)
Steel ball		7.88	20.5	0.39	0.27	0.24	-	0.5
Plastic ball		1.14	0.24	0.31	7.87	4.1	-	0.22
Lead ball	Sphere	11.4	14	0.39	1.62	0.21	0.82	0.09
	Sphere less	11.4	14	0.39	2.27	0.18	0.78	0.04

4. Test results and discussion

4.1 Damping effect of the inside granular placing system

Figures 11 and 12 show the test results with different granular diameters, materials and granular filling ratios. Figure 11 shows the damping force output from the electrodynamics exciter in Fig. 5, where vibration level 4 (which generates the maximum damping force of about 2m/s2) was set to output a damping force 18dB higher than that at vibration level 1. Each vibration level was set to make the damping force flat at 160 to 250Hz.

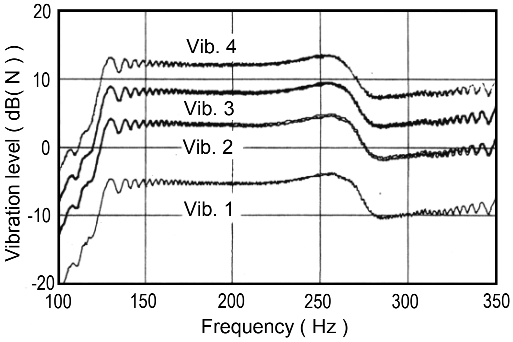


Fig. 11 Vibration spectrum of vibration generator

Figure 12 shows the damping performances of spherical lead granulars (diameter: 1mm, mass: 3.05kg, mass ratio: 16.7%, filling ratio: 90%). When the exciting frequency was increased from a value lower than the natural frequency (peak frequency 230Hz) of the noise reduction link device as shown in Fig.11, a damping effect gradually emerged (or the vibration transmission ratio decreased). With a large exciting force (vibration level 4), the vibration transmittal ratio decreased as the frequency approached the peak of 230Hz. The damping effect produced a value of -3dB in comparison with the conventional device without granulars. Here, this demonstrates that the vibration transmission ratio does not change when a noise reduction link device without granulars is used, even when the exciting force is increased from vibration level 1 to 4.

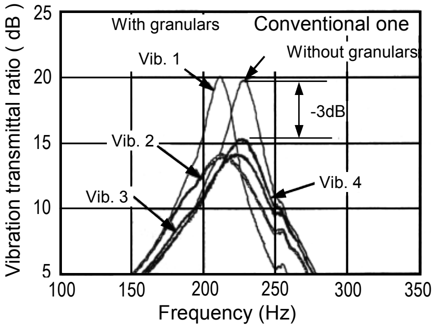


Fig. 12 Comparison of damping performances with inner spherical granulars

Therefore, when the exciting force is small, the vibration energy of the noise reduction link device is hardly converted into the kinetic energy of granulars at all, as they do not move very strongly. In other words, no damping effect emerges, as the mass of the granulars works as an additional mass to that of the noise reduction link device. In contrast, when the exciting force is large, the granulars work as dispersed masses, thus increasing the energy conversion efficiency. The peak frequency therefore tends to approach the natural frequency of the noise reduction link device. When the damping force increases further, the vibration energy of the noise reduction link device is transmitted to the granulars, which repeatedly collide. This increases their kinetic energy and gradually reduces the vibration energy of the noise reduction link device. As a result, the vibration transmittal ratio decreases. Compared with the test results of a link using spherical steel granulars (density: 7.86g/cm3), the above link using lead granulars (density: 11.4g/cm3) reduces the vibration transmittal ratio to a larger degree (not shown in the figures). Smaller granulars increase the filling ratio of granulars in the hollow space of the link, which in turn increases the granular mass and tends to increase the damping effect.

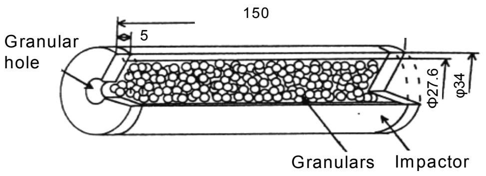


Fig. 13 Impactor with built in granulars

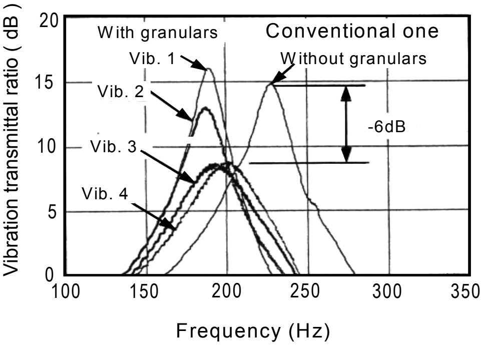


Fig. 14 Damping performances with other impactor

4.2 Damping effect of the outside granular placing system

Figures 13 to 16 show the composition of the cylinder used for the outside granular placing system and its test results. The cylinder, with an outer diameter of 34mm and a length of 150mm, contains 1-mm granulars as well as other types. It aims to convert its vibration energy into the kinetic energy of granulars or friction energy between granulars.

Figure 14 shows the damping effect with the nine cylinder sets shown in Fig. 13 (cylinder mass: 5.08kg, granular mass: 3.58kg, total mass: 8.66kg) directly placed around a link. The figure shows that a peak frequency exists around 190Hz at vibration level 1, which is about 40Hz lower than that (230Hz) of the conventional link device without granulars. As the exciting force increases, the peak frequency shifts to the high-frequency side (200Hz) as outlined above. This improves the damping effect by about -6dB compared to a conventional link device without granulars.

Figure 15 shows the damping effect of the whole of the nine cylinders (mass: 8.66kg) in Fig. 14 when it is placed around a link wrapped with a rubber sheet 1mm thick. As the damping force increases, the peak frequency shifts to the high-frequency side (200Hz), providing a damping effect of -3dB and -9dB in total, which is better than the case above without the rubber sheet. It can therefore be thought that the rubber sheet between the cylinder and the link's outer surface causes a shearing action which effects damping, subsequently improving the damping effect.

Figure 16 shows the damping effect of nine solid cylinders (mass: 5.08kg) without granulars arranged directly around a link. As the peak frequency does not shift to the high-frequency side even when the exciting force increases, no damping effect emerges with this link device. The link therefore transmits its total vibration energy to the solid cylinders but moves in the same phase as the cylinders. This keeps the peak frequency of 190Hz unchanged, and no damping effect is seen.

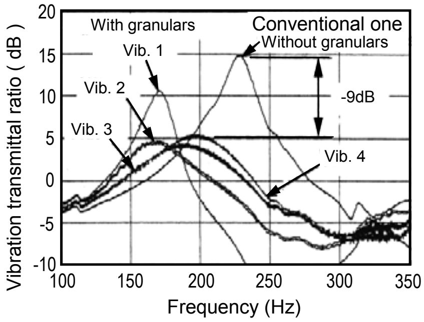


Fig. 15 Damping performances with other impactor and rubber seats

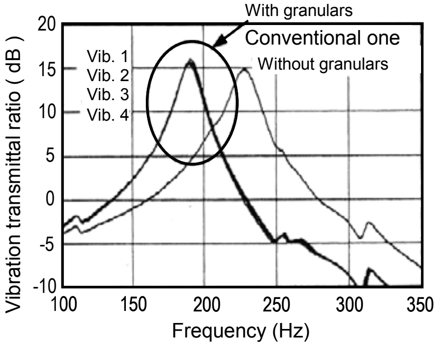


Fig. 16 Damping performances with other impactor using no granulars

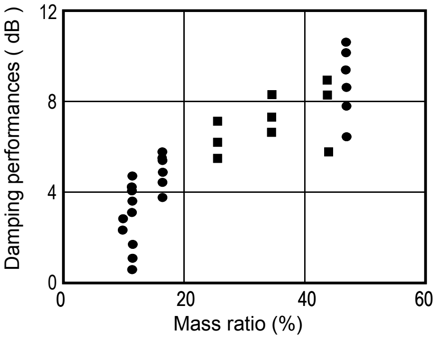


Fig. 17 Relationship between mass ratio and damping performances

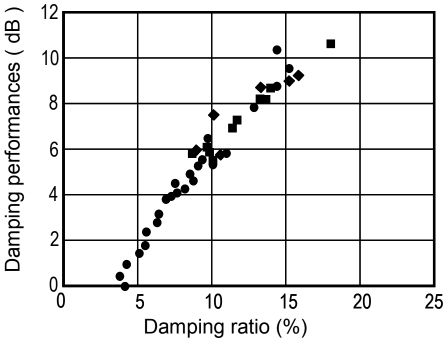


Fig. 18 Relationship between damping ratio and damping performances

4.3 Damping effect at different granular masses and damping ratios

Figures 17 and 18 summarize the results obtained in Section 4.2, and clarify the damping effect of the noise reduction link device at different granular masses and damping ratios. Increasing the granular mass ratio in the total mass of the link using granulars improves the damping effect (see Fig. 17).

The maximum damping effect was -10dB at a mass ratio of 0.5 (link: 18.3kg, granular containing cylinder: 5.08kg, granulars: 3.58kg, total: 9.2kg) and a filling ratio of 95%. This shows that increasing the granular mass is the most effective way of improving the damping effect. The authors regard the damping effect of a non-granular solid cylinder wrapped with a rubber sheet as -3dB, which is compared to a conventional link device, taking into account the effect of rubber sheet shearing.

The relationship between the damping effect and the damping ratio in Fig. 18 shows that they are approximately proportional. At damping ratios of 10% and 15%, the damping effect was -6dB and -9dB respectively, showing an improvement over links without granulars. As shown in the figures, the maximum damping effect in this study was -11dB when the link was wrapped with a rubber sheet 1mm thick and nine cylinders containing multiple granulars (mass: 8.66kg) were arranged. Further, although this is not shown in figures, it was found that the damping effect holds linearity up to a damping ratio of 11%, but this effect tends to saturates above this percentage(13).

5. Conclusion

The authors devised two types of noise reduction link device to reduce the low-frequency noise at about 200Hz that propagates from the railway truck to the car body of high-speed railway vehicles. One method involves an inside granular placing system whereby multiple granulars are inserted into the hollow space of the conventional one-link mechanism. The other method consists of an outside granular placing system whereby granular containing cylinders are arranged around the link. The test results of these two systems are summarized below.

(1) The damping effect of the outside granular placing system is up to -11dB compared to that of the conventional one link device without granulars. Approximately one million non-spherical lead granulars of 1mm in diameter are contained in the hollow space of the link, and multiple cylinders are arranged around the link wrapped with a rubber sheet 1mm thick.

(2) The damping effect of the inside granular placing system is -3dB compared to that of the conventional one-link device. The link contains spherical lead granulars of 1mm in diameter at a filling ratio of 90%. However, the damping effect does not improve when the exciting force is small.

(3) The damping effect of the outside granular placing system is -6dB, compared to that of the conventional one-link device.

(4) The damping effect is proportional to the granular mass ratio and the damping ratio. Larger masses and the use of a rubber sheet are effective in improving the damping effect.

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