PROPOSAL OF GENERATION-TYPE TMD WITH ELECTROMAGNETIC DAMPING DEVICE AND ITS APPLICATION TO AN ACTUAL BRIDGE UNDER SERVICE

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In this study, a power generation-type Tuned Mass Damper (TMD) with an electromagnetic damping device that enables power generation and easier damping adjustment is proposed as an alternative to the conventional TMD with oil dampers installed on expressway bridges in service. A road traffic vibration test on an actual bridge in service was carried out to verify its damping effect and effect on reducing low-frequency noise. Numerical simulations were carried out to show that by changing the electric resistance of the electromagnetic damping device, various types of power-generating TMDs can be designed, which focus on vibration control, energy absorption or power generation. In the experiment, using an actual bridge, the damping effect of the power generation-type TMD was confirmed to, on the whole, agree with the numerical simulation and the electric resistance design was proven to be useful. The results indicates that it is possible to use the power generation-type TMD, with the same level of damping effect as that of the oil damper, on an actual bridge.

Key Words : *tuned mass damper (TMD), low-frequency noise, bridge-vibration, real bridge experiment*

1. INTRODUCTION

In recent years, environmental problems along expressways caused by low-frequency noise emitted from bridges have been reported, and their causes and remedies are now under study. Tokunaga et al.¹⁾ analyzed frequency characteristics of low-frequency noise emitted from road bridges, carried out field studies, and found that the primary mode of vertical vibration on bridges had a high correlation with the reciprocal of span length. Kawada and Kawatani²⁾ replicated the acoustic characteristics of the actual

sound field and confirmed the effects of countermeasures, applying theoretical analysis of low-frequency noise using the boundary element method. Countermeasures for low-frequency noise from road bridges were studied and reported by Osafune, Yamamoto³⁾ and Fukada⁴⁾.

Tuned Mass Damper (TMD) and Impact Mass Damper (IMD) are countermeasure technologies for low-frequency noise. In this system, weight, or mass, is added to the bridge through dampers and springs to control vibration. And by adjusting the weight of the mass and the rigidity of dampers and springs, the sys-

tem restrains bridge-vibration by best tuning the eigenfrequency and damping. A past study⁵⁾ proved that the system was useful in minimizing bridge-vibration and generation of low-frequency noise, and the system has been installed and is in operation on expressway bridges throughout Japan. However, inspections of TMDs have not been carried out after they were installed, which has been an issue. Followings have been reported in past studies: (a) The vibration frequency and damping constant of a bridge change over the years it is in service⁶⁾, (b) the eigenfrequency change as gaps in concrete structures develop⁷⁾ and (c) vibrations from large-vehicles, amplified by running over rugged road surfaces are coupled with bridge-vibration, causing cyclic road surfaces, and this changes the vibration characteristics⁸⁾. Since bridge eigenfrequency and damping constant change over the years due to the aging of pavement, floor slabs, and other members, it is necessary to reset TMDs to the target frequency and damping ratio. Therefore, TMDs need to be easy to adjust, and be preferably equipped with a monitoring system to check frequency and damping.

Many methods to best control vibration using TMDs have been proposed. The following designs with a wider bandwidth in the target frequency have been proposed. Abe and Fujino^{9),10)} offered a design method using Multiple Tuned Mass Damper (MTMD) that has an eigenfrequency of many tuned mass dampers, which are distributed within a certain bandwidth around the eigenfrequency of the target structure. Yoshinaka and Kawaguchi¹¹⁾ proposed a dispersed TMD that controls multiple modes. However, they are hard to introduce to the single mass point TMD^{3),5)} installed on many road bridges.

Therefore, the authors focused on adjusting the damping ratio of the TMD. One approach was to use the two mass point generation-type Tuned Mass Generator (TMG)¹²⁾ that replaces the oil damper of the TMD, which we have designed, with an electromagnetic damping device and controls damping with the resistance of the electric circuit. TMG parameters can be changed easily, so designing it to control vibration or for vibration-powered generation is possible by changing the electric resistance of the electromagnetic damping device. The study in reference 12) aimed at power generation and designed and carried out verification tests of the two mass point TMG with 104kg main mass and 12kg sub mass. Since replacing oil dampers with electromagnetic damping devices is easy, it is expected that this method may be applied to TMDs with single mass point systems and mass weight of 1,500kg class, which are widely installed on expressway bridges to control bridge-vibrations.

In this study, we replaced the single mass point TMD of about 1% mass ratio with an oil damper,

which is installed on expressway bridges in service as an environmental measure, with a generation-type TMD with electromagnetic damping devices. We verified that its performance was equal to that of the single mass point TMD. We also conducted traffic vibration tests on an actual bridge in service to find out the generation-type TMD's damping effect, low-frequency noise reduction, and amount of power generation. Prior to the tests, TMDs focusing on (a) reduction of peak vibration, (b) energy absorption, and (c) power generation were designed and the most suitable electric resistance for each type was calculated. To compare three types of data taken with different traffic volumes, bridge-vibration damping effects and low-frequency reduction effects were analyzed by standardizing the traffic volume of large-vehicles that very much contribute to bridge-vibration. By doing so, we clarified the parameters needed to dampen bridge-vibration by proposing an electromagnetic damping device for generation-type TMD and verified the reduction effects of bridge-vibration and low-frequency noise by testing on an actual bridge.

2. BRIDGE USED IN THE TEST

We designed a generation-type TMD with electromagnetic damping devices to replace TMDs using oil dampers that are installed on expressway bridges in service. To validate its damping effect and power generation, an actual bridge in service, where vehicles running on the bridge provided constant vibration, was selected for the test.

(1) Outline of bridge used in the test

The test was conducted on a 4-main plate girder steel bridge ($L=35\text{m}$) with a simple structure using simple girders. The bridge was equipped with TMDs. The superstructure was reinforced with three vertical reinforcing girders, one between each main girder. A general drawing of a bridge is shown in **Fig.1**. The bridge was located near a residential area, so 4m-high noise barriers and backside acoustical boards under the main girders were installed. **Fig.2** illustrates of the environmental measures. Since low-frequency noise around the test bridge caused by bridge-vibration was creating environmental problems, three TMDs were installed, one between each main girder, to minimize the problem. This TMD was designed to counter the first mode of bridge-vibration, and its specifications are shown in **Table 1**, installation location in **Fig.3**, and detail drawing in **Fig.4**. The bridge used for the test was equipped with the same type and same number of TMDs on both the inbound and outbound lanes. However, the tests were carried

Fig.1 General drawing of bridge.

Fig.2 Environmental measures (Noise barrier and backside acoustical board).

Table 1 TMD specifications

Mass(per unit)	1,500 kg
Eigenfrequency	3.45 Hz
Damping ratio	4.2 %

Fig.3 Position of TMD.

out on the inbound lanes where a traffic counter was installed nearby.

(2) Vibration characteristics of the bridge used in the test

First, to find out the bridge's vibration characteristics with the TMDs installed, we measured the vibrational acceleration and pressure level of the low-frequency noise. A layout of the sampling points is shown in Fig.5. To analyze frequency characteristics and prepare vibration modes, vibrational acceleration was measured at five points, including two at the end of the main girder span, one at the center of span, and two at 1/4 from the end of span, using a piezoelectric-type vibration level meter (Rion VM-53). The pressure level of the low-frequency noise was measured at the center of span 1.2m high on the acoustical board, using a vibration-level meter (Rion LN-62).

Fig.4 Configuration and dimensions of installed TMD¹³⁾.

Fig.5 Sampling point layout.

Generally, pressure levels of low-frequency noise are measured at 1.2m high from the ground. But because this test was meant to evaluate the vibration characteristic of the inbound lanes only, the noise pressure level was measured from the backside acoustical board, where noise from the outbound lanes would not affect the measurement. Vibrational acceleration and low-frequency noise pressure level were simultaneously recorded by a data recorder (Rion DA-21) at a sampling frequency of 256Hz. Sample measurements were taken with all three TMDs (a) in operation and (b) not in operation. The results of the FFT analysis for vibrational acceleration at the 1/2 point of the main girder span are shown in Fig.6 and the vibration mode for the dominant frequency in Fig.7. Fig.6 shows the results of the analysis carried out between 0Hz and 128Hz with the frequency resolution at 0.25Hz, the sampling frequency at 256Hz, time length of analysis at 4 seconds, and the window function as rectangle. Fig.7 shows the results of the analysis carried out for 0Hz to 128Hz with the frequency resolution at 0.0625Hz, the sampling frequency at

(a) TMD in Operation (b) TMD Not in operation
Fig.6 Frequency characteristics of main girder vibrational acceleration (at 1/2 of span).

Fig.7 Vibration mode.

256Hz, time length of analysis at 16 seconds, and the window function as rectangle. From the frequency characteristics, superiority is seen around 3.5Hz and 19Hz. The vibration mode graphs indicate that they are each vibration primary mode and vibration secondary mode in the bridge axis direction. As for TMD's target eigenfrequency around 3.5Hz, we saw a reduction in the superiority of the vibration primary mode when TMD was in operation. The time history of waveforms for vibrational acceleration and low-frequency noise level at 1/2 point of span are shown in **Fig.8**. Although there are differences in the amplitude equality, the waveforms are almost the same and we can see that the emission of low-frequency noise is caused by the propagation of bridge-vibration into the atmosphere.

3. OUTLINE OF GENERATION-TYPE TMD

Fig.9 shows an analysis model of the single mass point generation-type TMD and bridge, created referring to a past study ¹⁴⁾. This is a model of a single mass point tuned mass-type generation device, structured with springs, electromagnetic damping devices and a single mass added to an equivalent mass M . The equivalent mass M of bridge is supported by springs of spring constant K and dampers of damping constant C_M . When harmonious outer force $F(t)=F_0\sin(\omega t)$ acts on mass M , displacement of mass M is $X(t)$ and displacement of Mass m_1 of generation-type TMD is $x_1(t)$. m_1 to M mass ratio μ_1 is 1%. Since the characteristics of damping force $F_e(t)$, created by

Fig.8 Time history waveform of vibrational acceleration and low-frequency noise pressure level.

Fig.9 Analysis model of single mass point tuned mass type generation device and bridge.

Fig.10 Electric circuit of generation-type TMD with electromagnetic damping device.

an electromagnetic damping device, change depending on the electric circuit connected to the internal structure of the electromagnetic damping device, we designed the electromagnetic device including the electric circuit.

(1) Control by resistance R of electric circuit

We tested the electric circuit's internal resistance to verify if the electromagnetic damping device could control damping like the oil damper.

Fig.10 shows the equivalent circuit of the electromagnetic damping device and resistance R , and the electric circuit of the generation-type TMD with internal resistance r and self-inductance L .

The formula for the electromotive force $E(t)$ of the

Table 2 System specifications.

Excitation device	Transcend	MTS810
Data logger	KEYENCE	NR-600 HV04 unit
PC for data storage	Panasonic	Let's note CF-SX3
Distortion-type load cell	Tokyo Measuring Instruments Lab.	TCLZ-5KNA
Dynamic distortion meter	Tokyo Measuring Instruments Lab.	DPM-711B

Table 3 Settings of NR-600HV04 logger and resolution.

Settings	
Sampling rate	1000 Hz
AD resolution	14 bit
Measurements	Measurement resolution
Moving part Displacement [mm]	6.10 μm
Load acting on moving part [N]	15.3 mN
Generated electromotive power [V]	1.22 mV

electromagnetic damping device can be expressed as follows, applying the change rate of magnetic field $d\phi/dt$ from Faraday's law of electromagnetic induction:

$$E(t) \propto \frac{d\phi}{dt} \quad (1)$$

The induced electromotive force can be expressed as follows, when magnetic field variance and velocity change dx/dt of moving parts are proportional:

$$E(t) = -k_{emf} \frac{dx}{dt} \quad (2)$$

The value k_{emf} shows the ratio of electromotive force to velocity. When the inductive electromotive force coefficient is $[\text{V.s/m}]$, the equation of the equivalent circuit of the electromagnetic damping device (**Fig.10**) and the damping force $Fe(t)$ of the electromagnetic damping device can be expressed as follows.:

$$E(t) = (R+r)I(t) + L \frac{dI(t)}{dx} \quad (3)$$

$$F_e(t) = k_{emf} I(t) \quad (4)$$

Generated power $W(t)$ and power loss $W_{loss}(t)$ are as follows:

$$\begin{aligned} W(t) &= RI^2(t) \\ W_{loss}(t) &= rI^2(t) \end{aligned} \quad (5)$$

Damping force caused by power generation of the electromagnetic damping device and equivalent damping coefficients c_{eh} and c_{el} of damping by power

Fig.11 Electromagnetic characteristics test of electromagnetic damping device.

loss are expressed by the following formulas:

$$\begin{aligned} c_{eh} &= \frac{k_{emf}^2}{r} \frac{R_r}{(1+R_r)^2} \\ c_{el} &= \frac{k_{emf}^2}{r} \frac{1}{(1+R_r)^2} \end{aligned} \quad (6)$$

Here, $R_r = R/r$ is resistance ratio. Therefore, the equivalent damping coefficient c_e can be represented by the sum of c_{eh} and c_{el} .

$$c_e = c_{eh} + c_{el} \quad (7)$$

From the above, it is clear that damping force $Fe(t)$ of the electromagnetic damping device and generated power $W(t)$ contribute to the equivalent damping coefficient c_{eh} derived from power generation of the electromagnetic damping device. This shows that the damping effect (vibration control) and power generation of the generation-type TMD may be controlled by changing resistance R within the electromagnetic damping device.

(2) Verification test for power generation and mechanical characteristics

Laboratory tests using a vibration table were carried out to determine the power generation and mechanical characteristics of the electromagnetic damping device, which will be used for testing on an actual bridge. **Fig.11** is a sketch of the test system, and the specifications of the test system are shown in **Table 2**. We used MTS810 as the excitation device. As shown in **Fig.12**, the electromagnetic damping device is fastened to the MTS810 frame by a single-purpose jig tool, and the shaft is fixed to the vibration table with the distortion-type load cell placed in between. The vibration table is controlled by the MTS810 controller, and the displacement [mm] of the vibration table output from MTS810, the load [N] output from distortion-type load cell, and the electromotive force [V] output from the electromagnetic damping device were measured using the NR-HV04 unit of the

Fig.12 Electromagnetic damping device installed in excitation device.

NR-600 series. **Table 3** shows the settings of the logger.

To find the relationship between the electromotive force coefficient and displacement calculated in the experiment, the electromotive force was measured after applying constant velocity excitation, created by a triangle waveform, to the moving part. **Fig.13** shows, from the top, the displacement time history of the moving part of the electromagnetic damping device, the time history of the velocity derived by differentiating the displacement of the moving part with the frequency domain, and the time history of power generation voltage of the electromagnetic damping device. The excitation velocity was 5mm/s, and the vibration width was ± 20 mm.

Fig.14 shows the generation voltage waveform derived from the experiment and the electromotive force coefficient k_{emf} of the electromagnetic damping device calculated from the moving-part velocity. The vertical axis in **Fig.14** is electromotive force coefficient k_{emf} and the horizontal axis shows the position of the moving part when the upside of the electromagnetic damping device is positive. The red line represents electromotive force coefficient when the moving part moves downward. The blue line represents electromotive force coefficient when the moving part moves upward. The small divergence between the red and blue lines is likely caused by the hysteresis characteristic of the electromagnetic damping device. The influence of the hysteresis characteristics is small in the single-digit Hz low-frequency band, and therefore, it was ignored in the numerical analysis of this study. From the above, we used the relationship between electromotive force coefficient k_{emf} and moving part position x [mm] obtained by the test, shown in **Fig.14**.

Fig.13 Time history of moving part displacement, time history of moving part speed, and time history waveform of generated electromotive force.

Fig.14 Relation between electromotive force coefficient of electromagnetic damping device and position of moving part.

Fig.15 shows the relationship, obtained by the test, between the reaction force that the moving part receives when it is activated and the position of the moving part. The vertical axis in **Fig.15** represents the reaction force received by the moving part (upward positive), and the horizontal axis represents the position of the moving part when the upside of the electromagnetic damping device is positive. The inside of the trajectory made by the reaction force and moving-part displacement is the energy loss caused by dynamic friction. The upper trajectory is for when the moving part moves up and down. The lower trajectory is for when the moving part moves downward. Since a half of the difference between the upper trajectory and lower trajectory is considered dynamic friction force, we calculated the dynamic friction force and showed its relationship to the position of the moving part in **Fig.16**. As shown in **Fig.16**, the peak frictional resistance of the moving part is observed around the neutral position of the moving part, and the frictional resistance lowers as the moving part

Fig.15 Displacement time history of load acting on moving part of electromagnetic damping device.

Fig.16 Relation between dynamic friction force and position of moving part of electromagnetic damping device.

Fig.17 Relation between magnetic spring and position of moving part of electromagnetic damping device.

moves away from its neutral position. It is thought that gravitation in the centrifugal direction between the magnet of the moving part and the yoke of the fixed part is strongest near the neutral position. This suggests that there is increasing friction generated at the bearing. The mean dynamic friction is about 6N within the $\pm 10\text{mm}$ range of the vibration, estimated for most vibration-powered generation. The reaction force generated by the magnetic spring may be calculated by subtracting the influence of dynamic friction (**Fig.16**) from the relation between reaction force received by the moving part and the position of the

moving part (**Fig.15**). **Fig.17** shows the relationship between the reaction force of magnetic spring and the position of the moving part. When the moving part is within a $\pm 2\text{ mm}$ range, the magnetic spring exhibits a positive spring behavior, and within a $\pm 2\text{ mm}$ to $\pm 8\text{ mm}$ range, the magnetic spring exhibits a negative spring behavior. This indicates that the absolute value of the magnetic spring's maximum reaction force is held small by having complex characteristics that alternate between positive and negative spring behavior. The results show that the magnetic spring's influence on the tuning of the vibration frequency of the generation-type TMD becomes relatively small.

4. STUDY BY NUMERICAL SIMULATION

We studied the resistance of the electric circuit to determine the vibration control and power generation characteristics of the electromagnetic damping device installed on the TMD of the bridge used in the test. To verify how damping effect and amount of power generation is controlled, the following three types of electromagnetic damping devices were examined to calculate the ideal electric resistance value:

- (a) A type focusing on reducing peak vibration that keeps the peak of the frequency spectrum of the vibrational acceleration to minimum.
- (b) A type focusing on energy absorption that maximizes the absorbed energy using attenuation of the electromagnetic damping device.
- (c) A type focusing on power generation that generates maximum energy.

(1) Outline of numerical simulation model

Fig.8 shows the numerical simulation model. The target frequency of the bridge was set as $f=3.4\text{ Hz}$, considering primary vibration mode characteristics of the test bridge. The effective mass of the bridge's target vibration mode is $M=205000\text{ kg}$. The mode damping ratio of the bridge tends to depend on the vibration stroke. However, the damping ratio shall be $\zeta=3.0\%$, which was obtained by formula (8) applying the free damping waveform representing vibrations at about 50 to 100 gal deemed to be typical vibrations caused by an average traffic load on actual bridges. The mass of a 1500kg generation-type TMD is $m_1=1560\text{kg}$, considering the mass of the adjusting mass; the natural frequency is $f_1=3.45\text{ Hz}$.

A numerical simulation was carried out to calculate the mechanical damping ratio of the spring mass using $\zeta_1=2.0\%$, which was obtained from formula (8) using the free damping vibration waveform. Four electromagnetic damping devices, the maximum number possible, were installed. We used nonlinear characteristics obtained from the experiment for both

the electromotive force coefficient k_{emf} and magnetic spring characteristic F_g . (**Fig.14, Fig.17**). The internal resistance of the electromagnetic damping device is $r=10.3\Omega$. The frictional resistance generated in the electromagnetic damping device or friction caused by imperfect alignment of axis, when an electromagnetic damping device is installed on TMD, affect the damping characteristics of the generation-type TMD. Though it is considered that these also influence tuning of the electric resistance, it is difficult to measure the entire friction resistance σ_g of the generation-type

Fig.18 Simulation model of bridge with generation-type TMD.

Table 4 Numerical simulation parameters.

Bridge			Generation-type TMD		
f	3.40	Hz	f_1	3.45	Hz
M	205,000	kg	m_1	1,560	kg
ζ	3.0	%	ζ_1	2.0	%

σ_g	10N, 30N, 50N	r	10.3 Ω
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Fig.19 Excitation force by traffic load (19 hours)(Red frame indicates excitation force used for numerical simulation in **Fig.20**).

TMD in an experiment. Therefore, in this study, we set three conceivable patterns of frictional resistance σ_g of the entire generation-type TMD and examined which resistance was suitable to the purposes of these patterns. The three frictional resistances (σ_g) studied are 10N, 30N and 50N.

$$\zeta = \frac{C_M}{2\sqrt{MK}}, \quad \zeta_1 = \frac{C_1}{2\sqrt{m_1 k_1}} \quad (8)$$

$$\text{Bridge damping energy} = \int C_M \dot{X}^2 dt \quad (9)$$

$$\text{Energy absorption} = \int \left\{ \sigma_g |\dot{x}_1 - \dot{X}| + (c_1 + 4 \cdot c_e)(\dot{x}_1 - \dot{X})^2 \right\} dt \quad (10)$$

$$\text{Power generation} = R(r+R)^{-1} \int 4 \cdot c_e (\dot{x}_1 - \dot{X})^2 dt \quad (11)$$

Generation damping coefficient c_e , which represents attenuation of power generation by the electromagnetic damping device, is given in the following formula:

$$c_e(x) = \frac{k_{emf}^2(x)}{r+R} \quad (12)$$

All necessary parameters for numerical simulations are shown in **Table 4**.

First, to analyze the influence of frictional resistance and resistance value R of electric circuit to bridge-vibration, an equivalent excitation power caused by vehicle traffic is applied to the model of bridge with generation-type TMD, shown in **Fig.18**. Equivalent excitation power was calculated using the method proposed by Taguchi et al.¹⁵⁾, derived from measured vibration acceleration data. In this analysis, we used four hours' worth of equivalent excitation force indicated by the red frame in **Fig.19**. The power spectrum density of bridge acceleration for that time is shown in **Fig.20**.

Black lines (original) represent regular TMD in operation. **Fig.20** shows three simulation results for each friction resistance and how the spectrum varies when electric resistances are changed in each case. The black line shows the power spectrum density derived from acceleration data actually measured at the test bridge with conventional TMDs using viscous dampers. We see that attenuation by power generation of electromagnetic damping device increases as

electric resistance grows. When the total friction damping force of generation-type TMD is 10N, the maximum value of spectrum turns minimal by setting electric resistance R at 70Ω . On the other hand, when the total friction damping force is 30N, the maximum value of spectrum turns minimal at around 120Ω . When the total friction damping force is 50N, attenuation by friction becomes dominant and diminishes the damping effect by power generation.

(1) Study on resistance value settings for specific purposes

Next, to analyze influences of electric circuit resistance on vibration of bridge and power generation, we studied the relationships between resistance and peak vibration, energy absorption, and power generation, which were the design targets of the three types of electromagnetic damping devices. We referred to past documents^{(12),(14)} for the calculations, shown in formulas (9) to (11). For the calculation, excitation force (19 hrs.) of traffic load was applied to the simulation model of the bridge installed with the generation-type TMD (**Fig.18**). Also, (a) the maximum peak value of power spectrum density of bridge acceleration when electric resistance R was changed between 0Ω and 1000Ω , (b) vibration energy absorbed by generation-type TMD damping device, and friction damping using formula (9), and (c) power generation using formula (10) were each calculated, applying the numerical analysis results. The results are shown in **Fig.21** to **Fig.23**.

Fig.21 is for when frictional resistance is 10N, **Fig.22** is for 30N, and **Fig.23** is for 50N. Focusing on controlling the vibration of bridge when the frictional resistance is 10N, the maximum value of power spectrum density function of bridge acceleration becomes minimum when electric resistance is 80Ω . And power generation is maximum when electric resistance is 70Ω . From the case studies of the actual bridge test, we found that the optimum electric resistance for vibration control and that for power generation are close when the friction resistance is small (equivalent to 10N). On the other hand, focusing on energy absorption of the power generation-type TMD, electric resistance is maximum at around 200Ω . We see that the absorbable amount of energy barely changes at electric resistance of 200Ω or more.

When focusing on controlling the vibration of bridge when the friction resistance is 30N, electric resistance is 140Ω when the maximum value of power spectrum density function of bridge acceleration becomes minimum. And power generation becomes maximum at electric resistance 70Ω . The test results show different optimum values of electric resistance for controlling vibration and for power generation when friction resistance is equivalent to 30N. On the

(a) Total friction resistance of generation-type TMD is 10N

(b) Total friction resistance of generation-type TMD is 30N

(c) Total friction resistance of generation-type TMD is 50N

Fig.20 Spectrum density function and resistance setting when generation-type TMD is installed on bridge.

other hand, focusing on energy absorption of the power generation-type TMD, electric resistance becomes maximum near 400Ω . And the amount of energy absorption barely changes at electric resistance 400Ω or more. When focusing on controlling vibration of the bridge when the friction resistance is 50 N, electric resistance is around 500Ω when the maximum value of the power spectrum density function of bridge acceleration turns minimum. We see that the maximum value of the power spectrum function

Fig.21 Maximum peak value of power spectrum density function of bridge acceleration, results of energy absorption and power generation (Total friction resistance 10N).

Fig.22 Maximum peak value of power spectrum density function of bridge acceleration, results of energy absorption and power generation (Total friction resistance 30N).

Fig.23 Maximum peak value of power spectrum density function of bridge acceleration, results of energy absorption and power generation (Total friction resistance 50N).

barely changes at electric resistance of 500Ω or more. On the other hand, power generation energy reaches its peak at electric resistance 70Ω. An optimum electric resistance that maximizes energy absorption of generation-type TMD does not exist between 0Ω and 1000Ω, and energy absorption barely changes at 300Ω or more. This means that frictional resistance is large and dominant, and it is likely that the influence of tuning by electric resistance on power generation-type TMD is relatively small.

The simulation results of each friction resistance are shown in **Table 5**. When the purpose is (a) peak vibration damping to control vibration, peak vibration can be minimized by setting electric resistance high when the frictional force of power generation-type TMD is high. When the purpose is (b) energy absorption to control vibration, energy absorption can be maximized by setting the electric resistance high if the frictional force of the generation-type TMD is high. But when the friction is around 50N or less, the influence of friction is dominant and energy absorption does not change when resistance is 400Ω or more. On the other hand, if the purpose is (c) power generation, the most suitable electric resistance does not depend on the frictional force of the 1500kg power generation-type TMD and is 70Ω.

In this study, to minimize the tests affecting surrounding areas, we used just two electromagnetic damping devices and the remaining two were oil dampers. Although electromagnetic damping devices A and B used in the experiment have different frictional forces, 6N and 20N, near the center, we used these two since the frictional forces were relatively small. Therefore, the total friction of the 1500kg power generation-type TMD equipped with electromagnetic damping devices A and B is considered to be around 30N, considering misalignment in assembling. The relationships between the most suitable electric resistance R_4^* , based on the numerical simulation result using four electromagnetic damping devices and the most suitable electric resistance R_2^* to get equivalent power-generation damping when two electromagnetic damping devices are used can be derived by formula 13 as follows.:

$$R_2^* = (R_4^* - r) / 2 \quad (13)$$

The most suitable resistances were set for each case as follows, considering total friction resistance 30N when two electromagnetic damping devices are installed:

- (a) Aiming to reduce peak vibration level : 100Ω
- (b) Aiming for energy absorption : 200Ω
- (c) Aiming for power generation: 100Ω

Table 5 Summary of generation-type TMD power generation, maximum value of power spectrum density function of bridge acceleration and energy absorption.

Friction of generation-type TMD	(a) Focusing on peak vibration damping			(b) Focusing on energy absorption			(c) Focusing on power generation		
	10N	30N	50N	10N	30N	50N	10N	30N	50N
Optimum electric resistance	80Ω	140Ω	500Ω	200Ω	400Ω	300Ω	70Ω	70Ω	70Ω
Peak vibration level [gal^2/Hz]	9.42	9.65	10.04	10.63	10.44	10.46	9.89	12.24	14.36
Energy absorption [%]	29.77	28.24	25.95	31.60	29.23	25.71	29.14	25.60	22.02
Power generation [mWh]	1,775	1,172	415	1,361	645	602	1,778	1,330	1,036

5. EXPERIMENT ON AN ACTUAL EXPRESSWAY BRIDGE IN SERVICE

(1) Outline of experiment

Experiments were carried out to verify the usability of the numerical simulation design for expressway bridges in service. The bridge used in the test stood near a residential area and was causing environmental problems. So, to minimize environmental problems caused by the tests, of the three TMDs installed, we replaced one TMD at the center in the perpendicular direction to the bridge axis with a power generation-type TMD. The tested TMD is shown in **Fig.24**. The electromagnetic damping devices used to replace oil dampers were the two devices, A and B, adopted for designing. They were diagonally placed as shown in **Fig.25**. We used a variable resistor to make it easier to set the three electric resistances derived from numerical simulations. To determine the damping amount of the generation-type TMD, we installed a vibrational accelerometer in the center of the upper side of the generation-type TMD mass. And a displacement gauge was installed to measure the relative displacement between power generation TMD mass and the cross beam of the installation rack. The measured damping amount is shown in **Fig.26**. To determine the damping effects and reduction of low-frequency noise, we installed vibrational acceleration meters and low-frequency level meters as shown in **Fig.5**.

(2) Test results and examination of the results

In the experiment, we tested three electric resistances, each for a week. We measured the vibrational accelerations and low-frequency noise of bridge and TMD, and the amount of power generation.

Based on the measurements, we calculated the damping damping device (right) amount. For bridge-vibration damping and low-frequency noise reduction, we compared the oil damper and the electromagnetic damping device and analyzed the usefulness of the numerical simulation results.

Fig.24 Tested TMD.

Fig.25 Generation-type TMD (left) Electromagnetic.

a) Damping amount

For the free vibration waveform to confirm damping ratio ζ_A of vibrational acceleration of the generation-type TMD installed on the test bridge, we used the waveform that was shaped when the vibration mass of the TMD settled after being vibrated by traffic disturbance via the bridge. For the measurements, we used a vibrational acceleration meter installed on the generation-type TMD mass, as shown in **Fig.26**. For the analysis, we extracted stable points of the free vibration start acceleration, using data of the vibrational acceleration meter installed on the vibration mass, and checked the free vibration waveform using formula (14).

In this measurement, the free vibration start acceleration of the vibration mass was also set at 200cm/s^2 . As for calculating the damping ratio ζ_A , we extracted values of 4 to 5 wave length from the free vibration waveform of the relative displacement, which were measured simultaneously with acceleration, after the start of analysis. We calculated each damping ratio

$$\zeta_A = \sqrt{\frac{1}{\left\{ \frac{2\pi}{\ln\left(\frac{x_n}{x_{n+1}}\right)} \right\}^2 + 1}} \quad (14)$$

from the three waveforms and evaluated the average as damping ratio ζ_A . Calculation examples of damping ratio ζ_A are shown in **Fig.27** and **Table 6**.

b) Damping effect

To verify bridge-vibration damping and low-frequency noise reduction effects of power generation-type TMD, we measured the vibrational acceleration and low-frequency noise to determine the vibration characteristics of the bridge by operating the TMD's oil damper part under the follow conditions: (a) using oil dampers, setting electric resistance at (b) 30 Ω , (c) 100 Ω and (d) 200 Ω . Sampling points are at 1/2 span as shown in **Fig.5**. The vibrational acceleration meter was installed on the flange under the reinforcing vertical beam, and the low-frequency noise level meter was placed on the backside acoustical board. Measurements were taken during the test periods and 10 minutes of each test period when there was heavy large-vehicle traffic.

Frequency characteristics of the measured vibrational acceleration are shown in **Fig.28**. When looking at TMD's target eigenfrequency around 3.5Hz, although no damping effect is observed at 30 Ω and superiority in the power spectrum value is seen, superiority in the power spectrum value is diminished by the damping effect of the oil damper, and similar damping effects can be seen for both 100 Ω and 200 Ω . But since the measurements were taken under different conditions, such as time and day and external forces owing to traffic conditions, the power spectrum values could not be compared and evaluated. Therefore, we calculated the total power spectrum values for each frequency between 10Hz and 30Hz, which were out of the target natural frequency range of TMD and compared them with large-vehicle traffic during the test period (**Table 7**). Their correlations are shown in **Fig.29**. Since the total power spectrum value and large-vehicle traffic volume show a high correlation, we standardized traffic conditions by multiplying the ratio with the average large-vehicle traffic volume. We likewise calculated the power spectrum value from 3.25Hz to 3.5Hz, which were around the target eigenfrequency of TMD, and using the ratio to the total power spectrum between 10Hz and 30Hz, evaluated the damping capacity of the power generation-type TMD. The results are shown in **Table 8**, **Fig.30**, and **Fig.31**.

When focusing on power generation, the damping

Fig.26 Measuring damping amount.

Fig.27 Calculation example of damping Ratio ζ_A using free vibration waveform.

Table 6 Calculation results of damping ratio ζ_A .

No. of tests	(1) 30 Ω	(2) 100 Ω	(3) 200 Ω
1	6.87 %	5.27 %	5.04 %
2	6.58 %	5.30 %	4.88 %
3	6.60 %	5.96 %	4.83 %
Average	6.68 %	5.51 %	4.92 %

effect is small at 30 Ω , though the power spectrum ratio between 10Hz and 30Hz is large. The damping effect at 100 Ω , aiming at reducing peak vibration, is at the same level as the damping effect of oil dampers. Energy absorption is the focus for 200 Ω , which shows damping effect but is lower than that of oil dampers and at 100 Ω .

We also analyzed low-frequency noise, in the same way that we did for vibrational acceleration. The measured frequency characteristics of vibrational acceleration are shown in **Fig.32**. We calculated the total power spectrum values for between 10Hz and 30Hz and compared them with large-vehicle traffic volumes. The results are shown in **Table 9**, and the correlation is shown in **Fig.33**. After calculating the power spectrum values for between 3.25Hz and 3.5Hz in the same way, we evaluated the damping effects of power generation-type TMD using the ratio to the total power spectrum value of between 10Hz and 30Hz. The calculated results are shown in **Table 10**, **Fig.34**, and **Fig.35**.

Though the correlation between the total value of power spectrum and large-vehicle traffic volume is not as high as that with vibrational acceleration, the time history waveforms of vibrational acceleration and low-frequency noise appear almost the same, as shown in **Fig.8**. Since bridge-vibration propagates into the atmosphere and emits low-frequency noise, the same tendency as vibration acceleration can be

Fig.28 Frequency characteristics of vibrational acceleration.

Table 7 Total power spectrum value between 10Hz and 30Hz and large-vehicle traffic.

	Oil damper	30 Ω	100 Ω	200 Ω
Power Spectrum (m/s ²)	0.754	0.761	0.685	0.750
Heavy Vehicle (cars)	278	288	247	282

Fig.29 Correlation of total power spectrum between 10Hz and 30Hz and large-vehicle traffic.

Table 8 Total power spectrum ratio between 3.25 and 3.5Hz to 10Hz and 30Hz.

	Oil damper	30 Ω	100 Ω	200 Ω
(1) 3.25-3.5 Hz	0.066	0.108	0.062	0.072
(2) 10-30 Hz	0.754	0.761	0.685	0.750
(3) Ratio	1.016	1.052	0.902	1.030
(1) / (2) × (3)	0.089	0.149	0.082	0.099

Fig.30 Power spectrum ratio around target eigenfrequency of TMD.

Fig.31 Frequency characteristic of vibrational acceleration standardized by large-vehicle traffic volume.

Fig.32 Frequency characteristics of low-frequency noise.

Table 9 Total power spectrum between 10Hz and 30Hz to large-vehicle traffic volume.

	Oil damper	30 Ω	100 Ω	200 Ω
Power Spectrum (Pa)	0.099	0.110	0.087	0.094
Heavy Vehicle (cars)	278	288	247	282

Fig.33 Correlation of total power spectrum between 10Hz and 30Hz to large-vehicle traffic.

Table 10 Total power spectrum ratio between 3.25Hz and 3.5Hz to 10Hz and 30Hz.

	Oil damper	30 Ω	100 Ω	200 Ω
(1) 3.25-3.5 Hz	0.720	1.254	0.712	0.802
(2) 10-30 Hz	8.304	8.728	7.383	7.961
(3) Ratio	1.016	1.052	0.902	1.030
(1) / (2) × (3)	0.088	0.151	0.087	0.104

Fig.34 Power spectrum ratio around target eigenfrequency of TMD.

Fig.35 Frequency characteristics of low-frequency noise standardized by large-vehicle traffic volume.

Table 11 Comparison of power generation characteristics focusing on power generation per resistance (30, 100, 200 Ω).

		30 Ω	100 Ω	200 Ω
Power generation	Total power generation [mWh]	3384.03	4574.53	3147.71
	Hourly average (mWh)	27.51	27.23	18.74
Large-vehicle traffic	Total traffic volume [cars]	51779	82959	82753
	Hourly average [cars/h]	421.0	493.8	492.6
Per 1 large-vehicle				
Unit power generation		59.9	53.7	35.7
(Total)[μ Wh/cars]				

seen. Low-frequency noise damping at 100 Ω , which aims at reducing the peak vibration level, was equivalent to that of the oil damper.

From the above, we see that the damping effect mostly matches the numerical simulation result, so we can say that it is possible to design the power generation-type TMD in the same way as the ordinally-type TMD.

c) Power generation

Table 11 shows the amount of electricity generated during the test periods for each electric circuit resistance 30 Ω , 100 Ω , and 200 Ω . We used power generation for large-vehicle traffic to compare the amount of power generated for each resistance setting, focusing on the correlation between large-vehicle traffic and bridge-vibration energy. The average power generation per hour per large-vehicle was calculated by dividing power generation per hour by large-vehicle traffic per hour. We define unit power generation as [μ Wh/car]. **Table 11** shows the average measuring period of unit power generation for each resistance. Comparing unit power generation for each resistance, we see that the unit power generation is maximum at resistance 30 Ω , which is the resistance setting aimed for power generation. From this, we see that power generation can be controlled by adjusting resistance settings. This fact was displayed through power generation testing on an actual bridge. The test also verified the usability of the resistance design for power generation-type TMD by numerical simulation.

6. CONCLUSION

TMDs are in operation on expressway bridges as an environmental countermeasure. In this study, we proposed a power generation-type TMD using electromagnetic damping devices and carried out road traffic vibration tests on an actual bridge in service to

determine the damping effect and amount of power generation. As a result, the following were clarified.

- 1) We proposed a power generation-type TMD with electromagnetic damping devices that replace oil dampers and carried out tests on road traffic vibration on an actual bridge in service. In the test, we found that the power generation-type TMD was suitable for practical application since the bridge-vibration damping effect and low-frequency reduction effect of TMDs using oil dampers and those of power generation-type TMDs using electromagnetic damping devices, which focused on peak vibration damping, were the same.
- 2) We found that the electromagnetic damping device may be designed to focus on peak vibration reduction, energy absorption, or power generation by adjusting its electric resistance setting. We also found through power generation tests on an actual bridge that power generation could be adjusted by changing the electric resistance setting, since the unit power generation reached maximum at 30 Ω , which was a resistance setting focusing on power generation.
- 3) By testing on an actual bridge, we found that the power generation-type TMD's capacity in damping bridge-vibration mostly matched the numerical simulation results and low-frequency noise also decreased. This shows that it is possible to design a power generation-type TMD as a measure to control vibration and reduce low-frequency noise of road bridges, like the conventional TMD.

By replacing oil dampers of TMDs installed on bridges, with electromagnetic damping devices to control vibration as an environmental measure, bridge-vibration damping, and low-frequency noise reduction may be managed easily through electromagnetic control. Therefore, depending on the time zone, such as when there is heavy large-vehicle traffic or when environmental issues tend to arise, TMD settings can be adjusted according to the purpose, such as to control bridge-vibration, reduce low-frequency noise, or to generate power. TMDs are installed as an environmental measure, and further improvements may be expected by adding the ability to generate power that can be used to supply power to frequency and damping monitoring systems and also to health monitoring systems, which are considered effective in prolonging the life of a bridge.

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REFERENCES

- 1) Tokunaga, N., Fukushima, A. and Nishimura, A.: Study on acoustic characteristics of low-frequency noise generated from elevated roads, *Committee of Infrastructure Planning and Management Papers*, No. 17, 2000.
- 2) Kawada, N. and Kawatani, M.: Theoretical analysis of low-frequency noise caused by road bridge traffic vibration by the boundary element method, *Japan Society of Civil Engineers Papers A*, Vol. 62, No. 3, pp. 702-712, 2006.
- 3) Osafune, T. and Yamamoto, M.: Noise and vibration measures for highway bridges, *Bridge and Foundation Engineering*, November 2011 Issue, 2011.
- 4) Fukada, S.: Countermeasure technology for vibration and low-frequency noise of bridge generated by travelling vehicles, *Souonseigyo* (noise control), Vol. 40, No. 2, pp. 61-64, 2016.
- 5) Murai, T.: Experiment on bridge vibration and low -frequency noise reduction of TMD on an actual bridge, *Bridges Vibration Colloquium, '01 Papers*, 2001.
- 6) Mikami, S., Takagi, Y., Yamazaki, T., Tubota, Y. and Oshima, T.: Study on changes of vibrational characteristics of bridge in service for seven years, *Japan Society of Civil Engineers Hokkaido Branch Papers and Reports*, Vol. 62, pp. 61-62, 2005.
- 7) Kaito, K., Abe, M., Fujino, Y. and Kumasaka, K.: Void detection of concrete structure focusing on local vibration characteristics, *Japan Society of Civil Engineers Papers*, No. 690/V-53, pp. 121-132, 2001.
- 8) Fukada, S., Muroi, N., Momiyama, Y. and Kajikawa, Y.: Effects of cyclic road surface on bridge evaluated from long-term monitoring before and after road repair, *Japan Society of Civil Engineers Papers A1*, Vol. 67, No. 1, pp. 121-136, 2011.
- 9) Abe, A. and Fujino, Y.: Efficiency and design formulas of multiple-tuned mass damper (MTMD), *Japan Society of Civil Engineers Papers*, No. 465/I-23, pp. 87-96, 1993.
- 10) Abe, M. and Fujino, Y.: Formula for performance evaluation of multiple-tuned mass damper (MTMD), *Japan Society of Civil Engineers Papers*, No. 465/I-23, pp. 97-106, 1993.
- 11) Yoshinaka, S. and Kawaguchi, K.: Study on distributed TMD based on MMD method for multiple-mode control in large-span structures, *Architectural Institute of Japan Structural System Papers*, Vol. 586, pp. 123-130, 2004.
- 12) Takeya, K., Sasaki, E., Iwabuki, H., Osafune, T., Hora, H. and Nagoya, T.: Development of tuned mass-based power generation device for bridge vibration and its application to real bridges, *Japan Society of Civil Engineers Papers A1*, Vol. 72, No. 2, pp. 290-301, 2016.
- 13) Tokkyokiki Corporation, http://www.tokkyokiki.co.jp/pdf_new/tokkyokiki_catalog_54%20md.pdf, 2017.10.1.
- 14) Takeya, K. and Sasaki, E.: Study on structure type and design of the tuned mass-based power generation device for bridge vibration, *Japan Society of Civil Engineers Papers A1*, Vol. 71, No. 2, pp. 267-276, 2015.
- 15) Taguchi, N., Hanasato, T. and Ishida, R.: Study on excitation force characteristics of road traffic vibration and prediction method of environmental ground vibration, *Architectural Institute of Japan Environment Papers*, Vol. 73, No. 633, pp. 1241-1247, 2008.

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