RESEARCH AND DEVELOPMENT OF TMD FOR LONG PERIODIC STRUCTURE USING AIR FLOATING TECHNIQUE

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Abstract

The structures with long periodic natural period such as high-rise building has been applied a response control device such as Tuned Mass Damper (TMD) with passive, semi-active and active type to reduce mainly a wind induced vibration. The additional mass type damper is basically constructed from a moving mass, spring element for tuning natural period and damping element. In generally, although there is a lot of type using a guide rail to support a dead load of mass, the static friction force is the most important design problem in a starting acceleration for long periodic TMD since the friction coefficient often becomes over about 5/1000. For example, if the moving mass is designed to be 10 ton with 5/1000 friction coefficient, the inertia force must be over 500 N to start the moving mass on a guide rail. Under this condition, the mass of TMD will not operate unless an acceleration of 5 gal or more is input to the building. Therefore, the starting acceleration of TMD depends on a friction coefficient of guide rail to support the movable mass.

This study has been examined about extremely low friction type TMD with under 0.01m/s^2 starting acceleration using an air floating system. The proposed TMD system is divided into two units. One is TMD unit and the other is air floating unit. TMD unit is composed of moving mass, spring and damping element. Moreover, air floating unit is constructed of compressor, controller for air pressure and compressed air piping. The compressed air is supplied to float a moving mass in the condition that acceleration is over against setting acceleration in trigger unit.

Feature of proposed TMD using air floating system is a simple mechanism and a high performance by low friction coefficient with safety improvement for combination with conventional supporting technique. Load support ratio is adjusted by changing an air pressure level. The mass part is supported by four load support springs in guiderail block, and also is connected eight tension coil springs. The support spring moves up and down along a guide pin. Prototype TMD is constructed following specification; Moving mass:1050 [kg], Air pressure:15~22 [kPa], Maximum floating height: 4 [mm]. Besides, the trigger acceleration sets to 0.03 [m/s^2] in this design performance specification. The specification of TMD is 1.0 Hz in natural frequency and ±100 mm in maximum displacement of movable region of the mass.

This paper describes the system concept, the loading test to confirm a friction characteristic of proposed system as a basic performance and shaking table test to examine an actual performance of floating speed against some acceleration trigger as a first step of the research and development. As a result, it was confirmed that the friction coefficient becomes 1.3/1000 in dynamic friction and 1.7/1000 in static friction by supporting load of mass using compressed air. Moreover, since the trigger reaction speed is almost 0.01 seconds, it is expected that proposed TMD can move the mass with minute acceleration in long period structure.

Keywords: TMD, Air Floating, Response Control, Long Period Structure, Shaking Table Test

1. Introduction

In long periodic buildings and bridges, a passive type and active type tuned mass damper (TMD) are applied as response control devices to reduce wind-induced vibration. TMD basically consists of a moving mass, a spring element for adjusting the natural period, and a damping element. In general, there are many types that use guide rails to support dead loads in mass, but the friction coefficient is often about 5/1000. For this reason, static friction is the most important design issue in the acceleration at the startup of long period TMD. For example, if the moving mass is designed to be 10 ton with a 5/1000 coefficient of friction, the inertial force must exceed 500 N to start the moving mass on the guide rail. Therefore, the startup acceleration of TMD depends on the friction coefficient of the guide rail that supports the moving mass.

On the other hand, there is the past research result [1] on human perception of horizontal translational vibration such as the perception start limit (1 Hz: 0.5 gal, 0.2 Hz: 1 gal, 0.1 Hz: 2 gal) and the comfort limit (1 Hz: 2 gal). gal, 0.2Hz: 4gal, 0.1Hz: 8gal). Therefore, a proposal of reducing small acceleration is desired for improving the living environment.

This study have been examined a low-friction type TMD using an air floating technique to reduce accelerations of less than 0.01 m/s^2. The technology of the floating system has been applied to a fluid dynamic conveyor for transporting coal, gypsum and ash at iron locations. In addition, floating systems for seismic isolation have already been applied to some structures. Sanpei Sakamoto has developed a levitation system for detached houses to lift in the event of an earthquake exceeding the trigger acceleration [2]. Professor Satoshi Fujita has applied an emergency earthquake prediction warning to seismic isolation systems for lightweight mechanical structures such as server racks [3].

This paper describes the concept of the system, a load test to confirm the friction characteristics of the proposed system as basic performance, and a shaking table test to examine the actual performance of floating speed with respect to a certain acceleration trigger as the first step of research and development. In addition, the outline of the TMD installed in the actual building and the preliminary analysis on response reduction are summarized.

2. Influence on response control effect of friction force in TMD

As the first step, the influence on response control effect of friction force in TMD is examined by using simple structure and TMD model. In here, the long periodic structure is modeled as 1DOF model for considering first mode of modal analysis. Equation of motion is shown as follow;

$$\left.\begin{aligned} & m_s^{*1}\ddot{x}_s + c_s^{*1}\dot{x}_s + k_s^{*1}x_s - c_d\left(\dot{x}_d-\dot{x}_s\right) - k_d\left(x_d-x_s\right) \\ & -\mu m_d g\cdot\mathrm{sgn}\left(\dot{x}_d-\dot{x}_s\right) = -m_s^{*1}\ddot{z}_H \\ & m_d\ddot{x}_d + c_d\left(\dot{x}_d-\dot{x}_s\right) + k_d\left(x_d-x_s\right) + \mu m_d g\cdot\mathrm{sgn}\left(\dot{x}_d-\dot{x}_s\right) = -m_d\ddot{z}_H \end{aligned}\right\} \quad (1)$$

in here,

m_s^{*1} : first modal mass in the structure

c_s^{*1} : first modal damping coefficient in the structure

k_s^{*1} : first modal stiffness in the structure

m_d : mass in TMD

c_d : optimal damping coefficient in TMD

k_d : stiffness of optimal tuning in TMD

μ : friction coefficient in TMD

g : gravity acceleration

x_s : relative displacement of structure from ground
x_d : relative displacement of TMD from ground
$\ddot{z}_H$: input wave

In time response analysis, mass ratio of TMD is 2% against the long periodic structure, natural period of structure is 4 seconds and friction coefficient of TMD sets to 5/1000 in normal case of guide rail and to 1/1000 in air floating case. Input wave is El Centro NS 100gal. As the result, although the maximum acceleration response is a small influence because of primary characteristic of TMD, it is confirmed that RMS responses in acceleration and response displacement in the structure is reduced in when a friction coefficient decreased from 5/1000 to 1/1000. This result has great significance to initial movable acceleration of TMD in long periodic structure, and to improvement of habitability in upper floor of high-rise building.

Table-1 Responses in normal and low friction coefficient

	Friction coefficient			
	5/1000		1/1000	
	Max	RMS	Max	RMS
Input acc. [m/s^2]	1.02	0.182	1.02	0.182
Resp. acc. in structure[m/s^2]	0.955	0.204	0.955	0.198
Resp. acc. in TMD [m/s^2]	0.989	0.221	1.06	0.261
Resp. disp. in structure [m]	0.0708	0.0309	0.0650	0.0245
Resp. disp. in TMD [m]	0.144	0.0463	0.164	0.0770

3. Concept of TMD using air floating system

Figure 1 shows a concept of TMD using a floating system. The system is divided into two units. One is TMD unit and the other is air floating unit. TMD unit is composed of moving mass, spring and damping element. Moreover, air floating unit is constructed of compressor, controller for air pressure and compressed air piping. The compressed air is supplied to float a moving mass in the condition that acceleration is over against setting acceleration in trigger unit.

Feature of proposed TMD using air floating system is a simple mechanism and a high performance by low friction coefficient with safety improvement for combination with conventional supporting technique. Moreover, load support ratio is adjustable by changing an air pressure level.

In the TMD, as shown in Fig.2(a), the moving mass with seal element is set in two guiderails on the base plate. The mass part is supported by four load support springs in guiderail block, and also is connected eight tension coil springs. The support spring moves up and down along a guide pin such as shown in Fig.2(b). The compressed air is supplied by compressed air piping to center of moving mass in which the measured acceleration on the base plate is over some trigger setting acceleration.

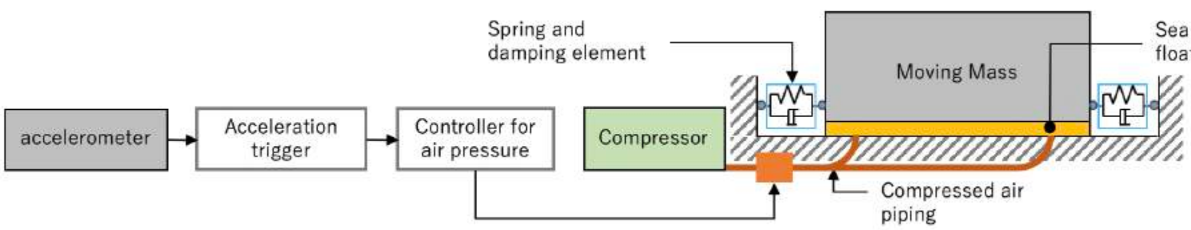
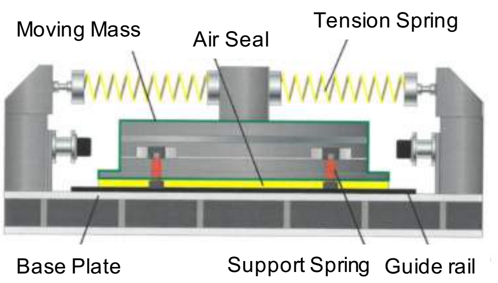
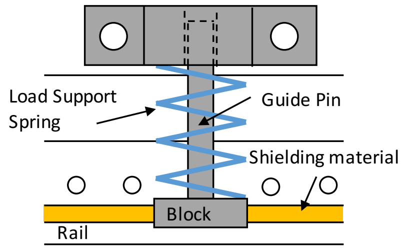


Figure-1 Configuration of TMD using air floating system



(a) Main constitution



(b) Load support part

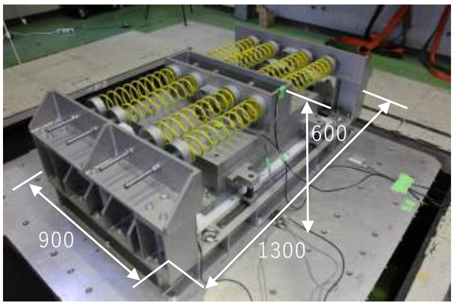
Figure-2 Detail concept of TMD using air floating technique

4. Loading test for investigating of basic performance

Figure 3(a) shows the test apparatus used for several tests. Table 1 shows mass, air pressure and specification of spring unit. In air floating condition, the moving mass is supported by the compressed air from 15 to 20 kPa. Besides, the trigger acceleration sets to 0.03 m/s^2 in this design performance specification. The specification of TMD is 1.0 Hz in natural frequency and ±100 mm in maximum displacement of movable region of the mass. This device has a fail-safe mechanism for function maintenance to support by the coil springs without air floating in some failure to behave predictably.

Figure 3 (b) shows experimental condition of TMD for loading test. Loading test is carried out by using electric loading test apparatus to evaluate the load-displacement characteristic in three different ways of load support method; coil spring support, coil spring and compressed air support and compressed air support. The load of a friction was measured by load sell in electric actuator. Table 2 shows the load support condition in the static loading test. In this time, 100 % coil spring support, 20 % coil spring and 80 % compressed air support and 100 % air support is set as the test parameters.

Figure 4 shows the load-displacement characteristics in each load support conditions. In the figure, black line shows only spring support without compressed air support, blue line shows spring and compressed air support and red line shows only compressed air support without spring support respectively. It is confirmed that the friction force is gradually reduced with increase of the compressed air support. Table 3 and Table 4 shows the friction coefficient in each support case. As the result, it was confirmed that the friction coefficient in the compressed air support is the lowest one about 1.3/1000 in dynamic friction coefficient and 1.7/1000 in static friction coefficient. Besides, the air support condition is included a friction in the linear guide.



(a) Test apparatus

(b) loading test

Figure-3 Air floating type TMD used for test and loading test condition

Table-1 Air floating type TMD used for test

Moving Mass	1050 [kg]
Air Pressure	15~22 [kPa]
Supporting Spring Constant	650 [N/mm]
Floating Height	4 [mm]
Natural Frequency	1.0 [Hz]
Max. Displacement	±100 [mm]
Acceleration Trigger	0.03 [m/s^2]

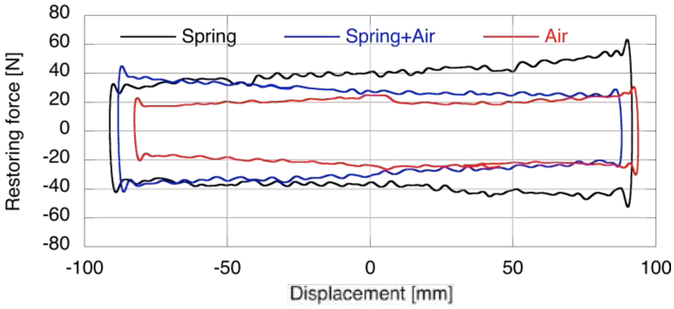


Figure-4 Load-displacement characteristic in each support type

Table-3 Load support condition in each support type

Support type	Air Support Load [kN]	Spring Deflection [mm]	Spring Support Load [kN]
Spring	-	3.5	8.9
Spring + Air	5.9	1.0	2.6
Air	8.4	0.0	-

Table-4 Friction coefficient in each support type

Support type	Dynamic Friction Coefficient	Static Friction Coefficient
Spring	4.0/1000	4.8/1000
Spring + Air	2.9/1000	3.6/1000
Air	1.3/1000	1.7/1000

5. Shaking table test for verifying basic performance

Performance verification test of proposed TMD is carried out by using shaking table. Figure 5 shows acceleration trigger system and measurement system. The acceleration trigger system is composed of accelerometer in horizontal and vertical direction on the base plate and acceleration trigger box. If the measured acceleration is over from setting acceleration in the trigger, compressed air in compressor and accumulator supplies to the space in between moving mass of TMD and base plate through the air injection switch part. The responses of displacement and acceleration in moving mass are measured by laser displacement gauge and accelerometer in horizontal and vertical direction. The voltage signal from laser displacement gauge and accelerometer are recorded in the data recorder though A/D converter. Sampling frequency sets to 100Hz. Input wave is sinusoidal wave and recorded seismic wave (JMA Kobe NS and Hachinohe NS). Besides, the trigger acceleration sets to 0.03 m/s^2 in shaking table test as the same of design specification.

Figure 6 shows responses of moving mass in Hachinohe NS 1.50 m/s^2. In the figures, (a) indicates response acceleration and (b) presents response displacement, and also black line shows only spring support without compressed air support, blue line shows spring and compressed air support and red line shows only compressed air support without spring support respectively. Table 5 shows the maximum responses and trigger acceleration. It was confirmed that the fundamental performance as a TMD in air floating does not affected to the support condition in spite of random vibration such as seismic wave. However, the response effect in air floating based on a lower friction was not obtained strongly against a large seismic input wave in this time.

Figure 7 shows an evaluation of initial responses after acceleration trigger. These figures are extracted the initial responses in Fig.7. The output voltage of green line in the figure increases at almost 4.45 seconds after reaching the 0.03 m/s^2 trigger acceleration. Soon after that, the moving mass moves after 1/100 seconds. Therefore, the proposed TMD using air floating system begins to move in a small acceleration input.

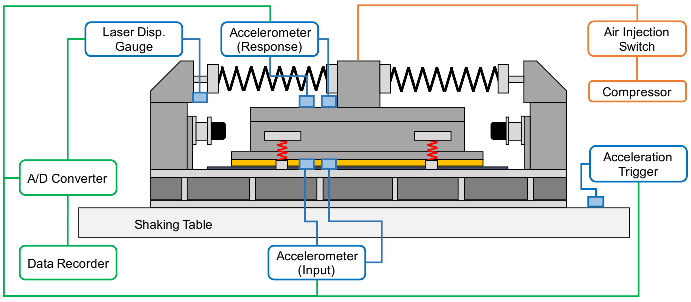
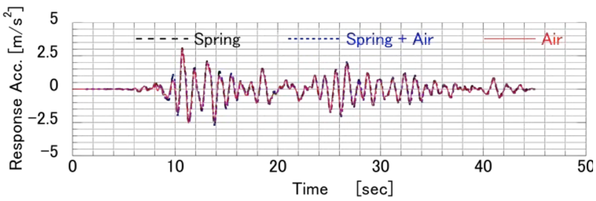
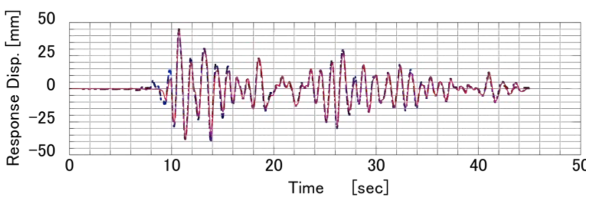


Figure-5 Acceleration trriger and measurement system



(a) Response acceleration



(b) Response displacement

Figure-6 Responses of moving mass in Hachinohe NS 1.5m/s^2

Table-5 Maximum responses in seismic wave input

	Load support ratio (Air:Spring)	Max. input acc. [m/s^2]	Max. resp. acc. [m/s^2]	Max. resp. disp. [mm]	Trigger acc. [m/s^2]
JMA Kobe NS	0% : 100%	1.56	4.11	61.5	-
	80% : 20%	1.55	3.98	59.0	0.06
	100% : 0%	1.46	3.65	53.7	0.04
Hachi-nohe NS	0% : 100%	1.10	3.08	44.9	-
	80% : 20%	1.12	2.99	43.8	0.03
	100% : 0%	1.07	3.01	44.2	0.02

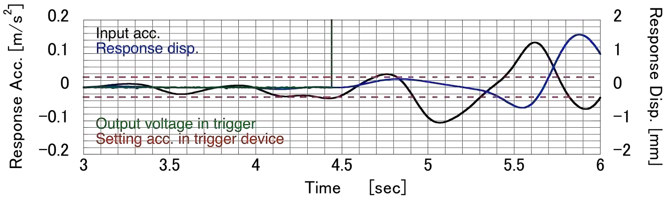


Figure-7 Initial responses of moving mass in Hachinohe NS 1.5m/s^2

6. TMD using air floating technique for actual building

As the next stage of research and development, TMD with air floating was applied to actual structures. Figure 8 (a) shows a TMD of a actual building type, which operates in two horizontal directions. The external shape is 2360mm in width, 1225mm in depth, and 2120mm in height. Besides, the air floating system is applied in the lower part of the 9.5 ton moving mass in the longitudinal direction, and the 12 ton upper part in the lateral direction is supported by a normal guide rail.

First, as shown in Fig. 8 (b), free vibration was measured from a rapid unloading test with an initial displacement of 30mm. Figure 9 shows the measurement results. Moreover, in here, the analytical model for simulating the dynamic behavior of air floating TMD as shown in Fig. 10 is examined and compared. Figure 10 shows the friction switching conditions in the analysis model. Figure 11 shows the measured free vibration waveform and the free vibration waveform obtained by analysis. Figure (a) shows the response waveform of the mass in the short direction at the top of the TMD, and Figure (b) shows the response waveform of the mass in the longitudinal direction at the bottom of the TMD. As shown in the results, the natural period of TMD was confirmed to be 1.0 Hz as designed. In addition, by comparing with the analytical results, it was confirmed that the friction coefficient of the mass part using the air floating in the free vibration waveform was reduced by about 1/2 from the friction coefficient of the mass part supported by the guide rail.

Figure 12 (a) shows the building installed the TMD. Figure 12 (b) shows the TMD installed in the building, and (c) shows the air pressure control system. The building is a 10-story structure with the first modal frequency of 1.3 Hz, the first modal mass of 430ton, and the first modal damping ratio of 1%.

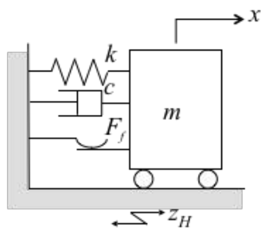
TMD in the analytical model obtained earlier is set to optimal tuning and optimal damping, and the performance is evaluated. Table 6 shows the specifications considering the optimal conditions of TMD. In order to evaluate the actual responses, the input force is induced to the building model, and also the input force set to be 4.28×10^4 [N] (equivalent to about 10 gal).

Figure 13 compares the response between without TMD and with TMD to estimate the vibration control effect. As a result, it was confirmed that the maximum response acceleration and the maximum response displacement are reduced to about 1/5 by installing TMD.

(a) Outer shape of practical used TMD

(b) Rapid unloading test condition

Figure-8 TMD with air floating was applied to actual structures



m : Mass in TMD

k : Spring constant in TMD

c : Damping coefficient in TMD

F_f : Friction force

x : relative displacement from floor

z_H : floor response displacement

Figure-9 Analytical model for evaluating actual performance of practical used type TMD

Switching condition（Stick → Slip）

Phase Ⅰ : $m\ddot{x} = -m\ddot{z}_H$

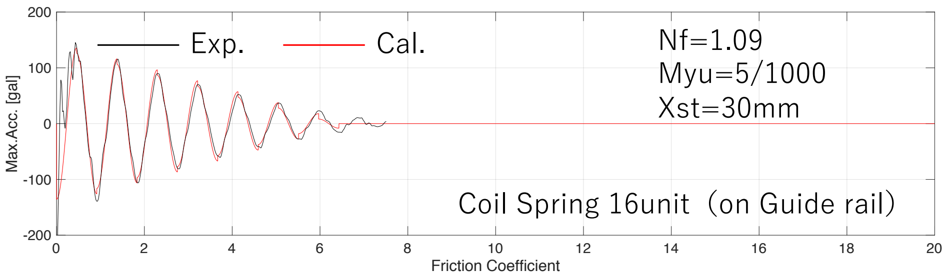
$\left|m\ddot{z}_H + kx + F_d(x)\right| > \mu mg$

Switching condition（Slip → Stick）

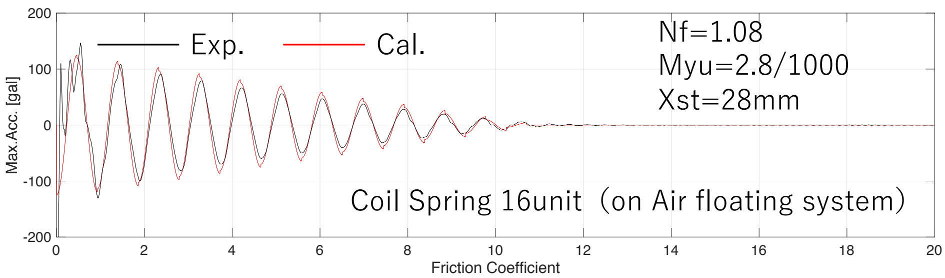
Phase Ⅱ : $m\ddot{x} + c\dot{x} + kx + F_f \cdot \mathrm{sgn}(\dot{x}) = -m\ddot{z}_H$

$x = 0$，かつ，$\left|m(\ddot{x} + \ddot{z}_H) + kx + F_d(x)\right| \leq \mu_s mg$

Figure-10 Switching condition of friction force for analytical model



(a) Guide rail



(b) Air floating

Figure-11 Free vibration wave measured in rapid unloading test using practical used type TMD

(a) Okayama Main Building

(b)Practical use type TMD with Air Floating

(c)Air pressure control system

Figure-12 Actual building applied TMD with air floating system

Table-6 Specification of analytical model for practical use condition

Item	specification
1st modal mass of building	427.6 [ton]
1st modal frequency of building	1.33 [Hz]
1st modal damping of building	0.01
Mass of TMD	9,632 [kg]
Natucal frequency of TMD	1.30 [Hz]
Equivalent damping ratio with friction damping	0.0910

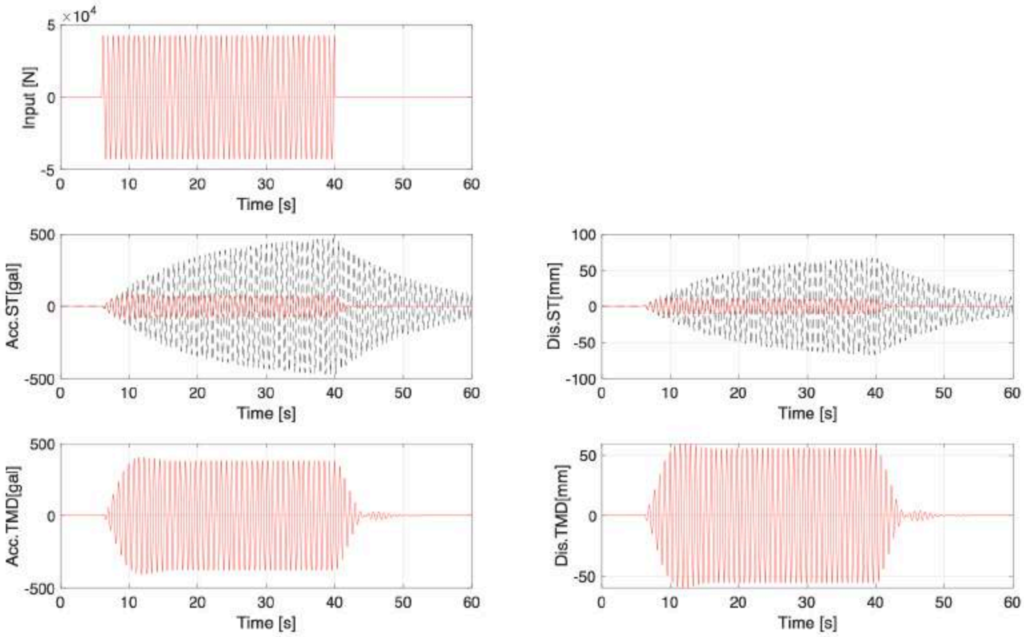


Figure-13 Preliminary performance investigation using the analytical model of TMD with air floating system

CONCLUSIONS

In this study, the air floating type TMD that can cope with longer periodic structures and improvement of living environment have developed. A feature of the proposed TMD is a very low friction coefficient by lifting by compressed air and moving the mass of the TMD with small input acceleration.

In the examination of basic performance by loading test and shaking table test, it was confirmed that the friction coefficient was 1.3 / 1000 for dynamic friction and 1.7 / 1000 for static friction by supporting the mass load using compressed air. Also, since the trigger reaction speed is almost 0.01 seconds, the proposed TMD can start moving mass with small acceleration for a long-period structure.

Moreover, the actual type TMD was verified the basic performance in a rapid unloading test, and examined the dynamic behavior using the analytical model to confirm the effectiveness. It was confirmed that the maximum response acceleration and the maximum response displacement will be reduced to about 1/5 by installing TMD using air floating type TMD.

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