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EVALUATION OF PERFORMANCE OF MULTI-SUSPENDED PENDULUM ISOLATION (MPI) SYSTEM WITH SPATIAL TRUSS STRUCTURE

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SUMMARY

This paper is concerned with a new seismic isolation device, called Multi-suspended Pendulum Isolation (MPI) system with spatial truss structure, newly developed by author. MPI system is according to the principal of single pendulum, and is consisting of main pendulum, several secondary pendulums and base flame structure. Main pendulum to support superstructure, is multi-suspended by several secondary pendulums and last secondary pendulum is suspended by base flame structure mounted on ground, therefore MPI system provides horizontal flexible interface connection between superstructure and ground.
Since MPI system is based on the principal of single pendulum, predominant natural period of MPI system is according to total length (l) of respective suspension and independent from weight of superstructure, given by following equitation;

$$T^{(1)} = 2\pi * \sqrt{l/g}$$

In MPI system, all pendulums are suspended vertically with respective suspension members and this gives all pendulums to oscillate parallel with ground, therefore the force induced by weight of superstructure is vertical one to all pendulums, as well as to ground. In addition to this, spatial truss structure is applied to all secondary pendulums, force transmitted to those pendulums are only axial force, by means of compression or tensional force.
As a result of experimental oscillation tests, acceleration recorded at main pendulum is reduced 1/27 for El Centro earthquake ground motion and 1/6 for Hyougoken-nanbu (Kobe) earthquake ground motion. In addition to these, MPI system has certain decay of oscillation due to multi-suspension and shape of pendulums, having 0.22 of logarithmic decrement (0.035 of damping ratio) recorded by triple suspension experimental model.

INTRODUCTION

Since Hyougo-nanbu (Kobe) earthquake in 1995, many discussions have been held regarding review of building structural analysis and current Building Code contents, and durability of buildings against earthquake has become most concerned subject in public. During Kobe earthquake, two buildings with seismic isolation system were recorded no damages on neither structures nor building internal equipment, and after Kobe earthquake more than four hundreds buildings with seismic isolation system have been constructed or under construction in Japan, comparing with about forty buildings before this earthquake. Therefore seismic isolation system has been considered one of most ideal method to have building durability especially for low-rise buildings, because strengthening strategy inevitably brings larger masses and response acceleration of stiff structured buildings is much greater comparing with one of buildings with seismic isolation system.
There are several seismic isolation methodologies being under developing, however these are classified into two categories; natural period controlled type and base-isolation one. Rubber bearing methodology is one of natural

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period controlled and now a days, lead rubber bearing (LRB) is most commonly applied methodology in Japan for seismic isolation system, however this has disadvantages still remain to be solved; its natural periods being related with weight of superstructure.
Multi-suspended Pendulum Isolation (MPI) System is new isolation system developed by author recently, and in this system, isolation aim can be established by supporting superstructure by main pendulum, of which is multi-suspended by several secondary pendulums. All pendulums are vertically and respectively suspended, and rested on the ground, therefore MPI system provides horizontally flexible connection between superstructure and ground. And the principal of pendulums is referred for this MPI system so that the natural period of MPI system and superstructure will be predetermined and according to the total suspending length of pendulums and independent from a weight of superstructures.
In our study, we aim to develop new base-isolation system of which has predetermined natural period independent from a weight of superstructure, and this paper describe the preliminary experimental results through oscillation tests by sinusoidal wavemotion and several earthquake wavemotion.

MULTI-SUSPENDED PENDULUM ISOLATION SYSTEM

Multi-suspended Pendulum Isolation system is consisting of main pendulum, secondary pendulums, supporting base structure and suspending members. Superstructure is mounted on main pendulum (P-1) of which is suspended by secondary pendulum (P-2), octahedron shape of spatial truss frame, and P-2 is suspended by next secondary pendulum (P-3). P-3 is same shape as P-2 and suspended by next secondary pendulum (P-4). Same skim repeats and last secondary pendulum (P-n) is suspended by supporting base structure mounted on ground, providing all connection between pendulum and suspending members is pivot. For experimental oscillation tests, steel made experimental model (triple-suspended pendulum) is manufactured and its features are shown on Figure 1 and 2.

In general, it is understood that oscillation system of suspended structure is according to simple pendulum and shows following behaviour, i.e. 1) cycle oscillation by gravity, 2) regardless amplitude, a natural period to be

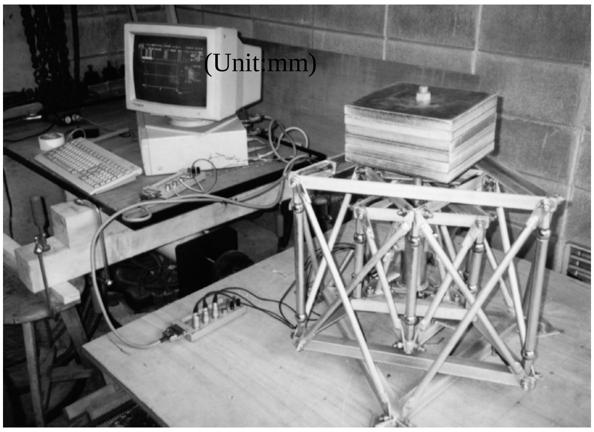
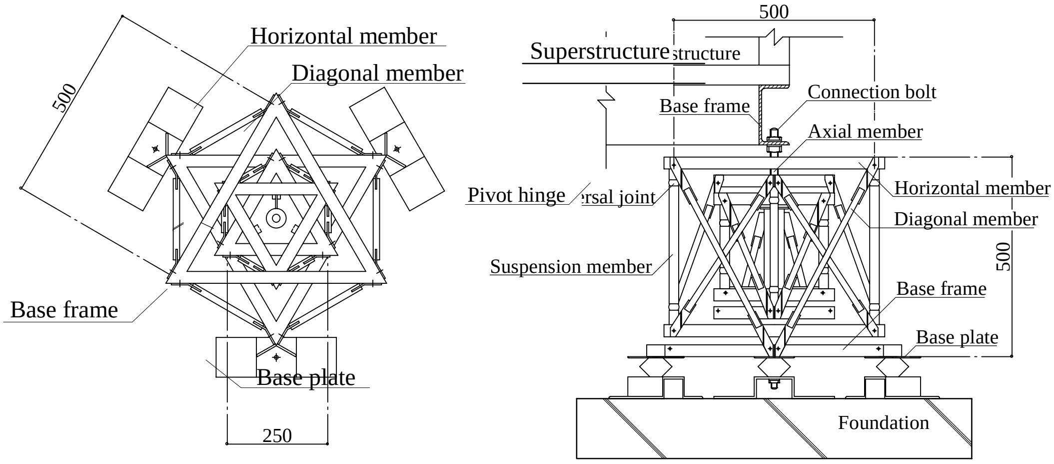


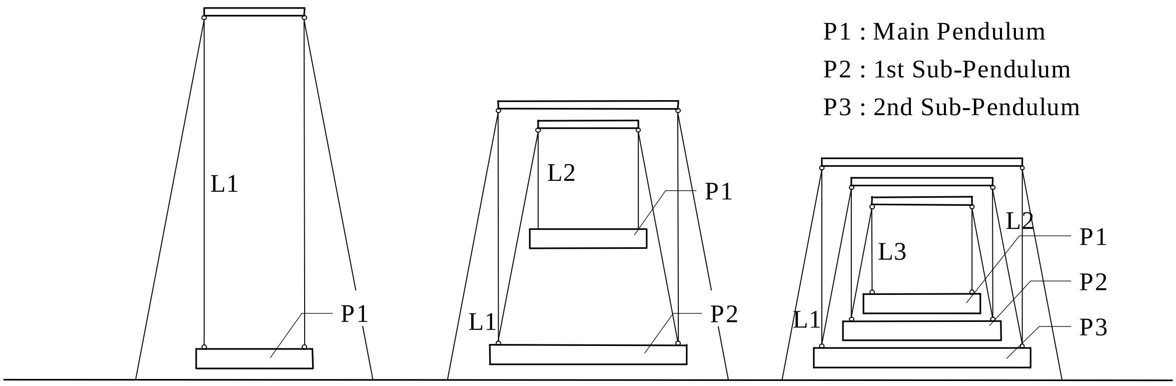
Figure 1: Photograph of experimental model used for experimental oscillation tests

constant when amplitude is small. Theory of MPI system is shown on Figure 3, and total suspension length of MPI system is given by sum of respective suspension length. This multi-suspension theory is maximise total suspension length within certain limited height.
MPI system is consists of several pendulums, as lumped masses and whose positions are independent of one another, therefore this oscillation system is considered as multi-degree-of-freedom (MDOF) system and the oscillatory motion of MPI system is governed by following equitation;



(a) Plan **(b) Elevation**

Figure 2: Experimental model (Steel made, triple-suspended pendulum)



(a) Single suspension **(b) Double suspensions** **(c) Triple suspensions**

Figure 3: The comparison of Multi-Suspended Pendulum Base Isolations

$$\begin{bmatrix} m_1 \cdots & m_i \cdots & m_n \\ & \vdots & \vdots \\ & m_i \cdots & m_n \\ & \vdots & \vdots \\ & & m_n \end{bmatrix} \begin{bmatrix} \ddot{x}_1 \\ \vdots \\ \ddot{x}_i \\ \vdots \\ \ddot{x}_n \end{bmatrix} + \begin{bmatrix} C_1 \\ \vdots \\ C_i \\ \vdots \\ C_n \end{bmatrix} \begin{bmatrix} \dot{x}_1 \\ \vdots \\ \dot{x}_i \\ \vdots \\ \dot{x}_n \end{bmatrix} + \begin{bmatrix} K_1 \\ \vdots \\ K_i \\ \vdots \\ K_n \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_i - x_{i-1} \\ \vdots \\ x_n - x_{n-1} \end{bmatrix} = \begin{bmatrix} M_1 \\ \vdots \\ M_i \\ \vdots \\ M_n \end{bmatrix} \ddot{x}_g \quad (1)$$

The term $K_i * (x_i - x_{i-1})$ is a horizontal force to produce the displacement x_i, and this is given by following equitation;

$$K_i * (x_i - x_{i-1}) = m_i * g * \tan\theta_i \quad (2)$$

Where θ_i is rotation angle of i^{th} pendulum and g is gravity acceleration, when small value of θ_i is given, K_i can be approximated;

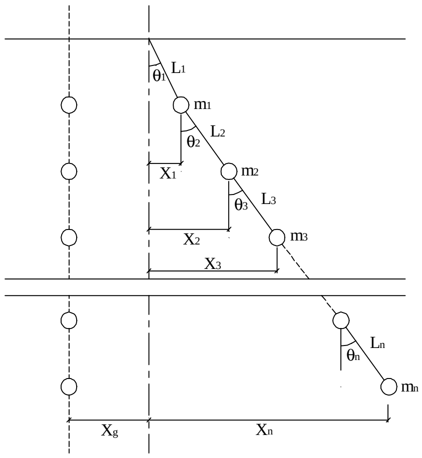


Figure 4: MDOF oscillation model

$$K_i = \frac{m_i}{l_i} * g \qquad (3)$$

Of which,

m_i	: Lumped mass of ith pendulum

According to equitation (1), the oscillation of MPI system has nth order of natural circular frequencies ($\omega^{(n)}$) and 1st order of natural circular frequencies ($\omega^{(1)}$) can be approximated, $\omega^{(1)} = \sqrt{g/l}$, when small value of θ is given. Accordingly 1st order of natural period ($T^{(1)}$) of MPI system is given by following approximation;

$$T^{(1)} = 2\pi * \sqrt{l/g} \qquad (4)$$

In MPI system, all pendulums are suspended vertically with respective suspension members and this gives all pendulums to oscillate parallel with ground, therefore the force induced by weight of superstructure is vertical one to all pendulums, as well as to ground. In addition to this, spatial truss structure is applied to all secondary pendulums, force transmitted to those pendulums are only axial force, by means of compression or tensional force.

According to above mentioned, the features of MPI system are summarized herewith;

1) To have its natural period independent weight of superstructure
2) To predetermine its natural period by total length of suspension
3) To restore the displacement by means of gravity
4) To have flexibility to horizontal displacement
5) To have inherent damping

EXPERIMENTAL TESTING METHOD AND RESULTS

Table 1: Dimension of experimental models

		Prototype Model			**Experimental Model**
Number of suspension		Single	Double	Triple	Triple
Material		Aluminium			Steel
Length of suspension (mm)	l_1	850.0	600.0	345.0	285.0
	l_2		250.0	285.0	225.0
	l_3			220.0	160.0
	Total l	850.0	850.0	850.0	670.0
Weight of Lumped Mass (kgf)	m_1	0.0255	0.0255	0.0765	2.2959
	m_2		0.0510	0.0510	1.5306
	m_3			0.0255	0.7653
	Total m	0.0255	0.0765	0.1530	4.5918
Natural period calculated		1.85 seconds			1.64 seconds

To evaluate and verify fundamental performance of new MPI system, following experimental oscillation tests has been performed with steel made experimental model and aluminium made prototype model, all dimensional features are shown on Table 1;
And for oscillation test, shaking table engaged is one of single axial with maximum displacement of ±75.0mm and manipulation of oscillation to be by means of amplitude.

Resonance of multi-suspension and MPI system:

To verify and compare resonance frequency of systems, following wave-motion is applied to shaking table and response acceleration of each system is recorded. According to Fourier analysis of acceleration spectra as shown on Figure 5 and 6, predominant resonance frequencies are verified and known, as linear natural frequency of systems (reciprocal is natural period).

Input wave-motion	Sinusoidal (0.2Hz to 5.0Hz, continuous)
Amplitude	10.0 % (Maximum displacement ±7.5mm)
Weight applied	For Prototype model 0.4082 kgf
	For experimental model 3.0612 kgf

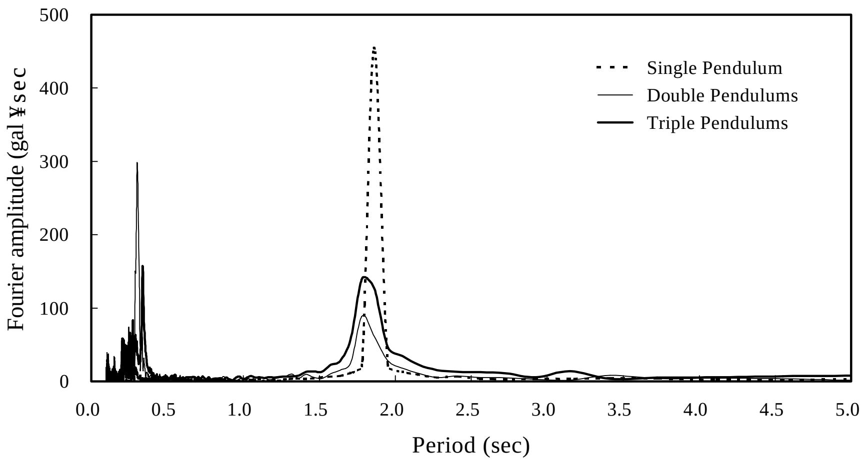


Figure 5: Fourier Spectrums (Prototype Model)

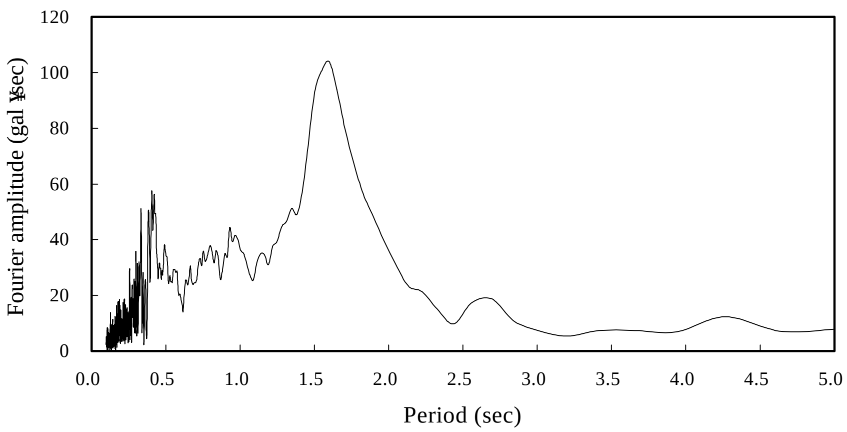


Figure 6: Fourier Spectrum (Experimental Model)

Response acceleration by actual earthquake motion:

To verify the effectiveness of MPI system against earthquake, ground motion of following earthquakes is applied to shaking table as input wave-motion and time historical acceleration is recorded and results as shown on Figure-7, 8, 9 and 10.

Input wave-motion	El Centro 1940 NS components
	Hyougokenn-nanbu (Kobe) 1995 NS components
	Hachinohe 1968 NS components
	Kushiro 1961 NS components
Amplitude	20.0 % (Maximum displacement ±15.0mm)
Weight applied	3.0612 kgf

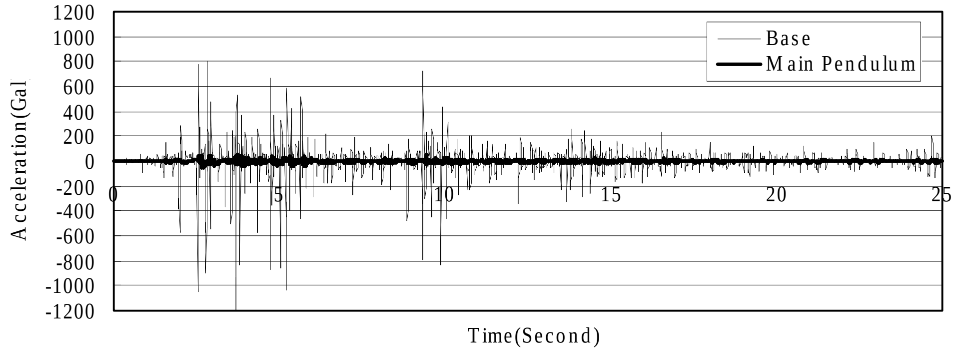


Figure 7: Acceleration response time histories of ElCentro 1940 NS components

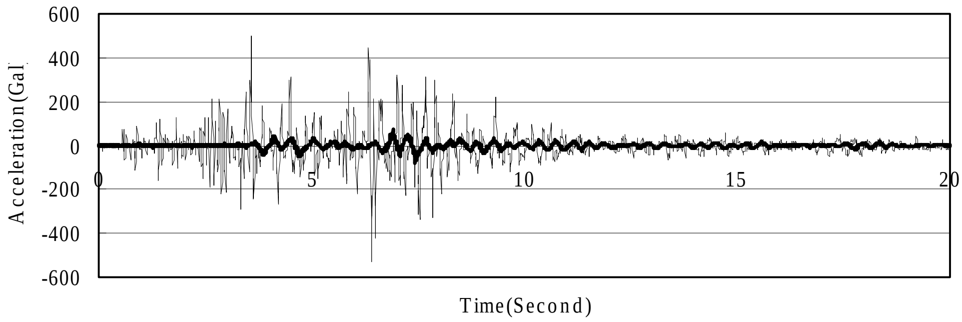


Figure 8: Acceleration response time histories of Hyogo-ken Nanbu(Kobe) NS components

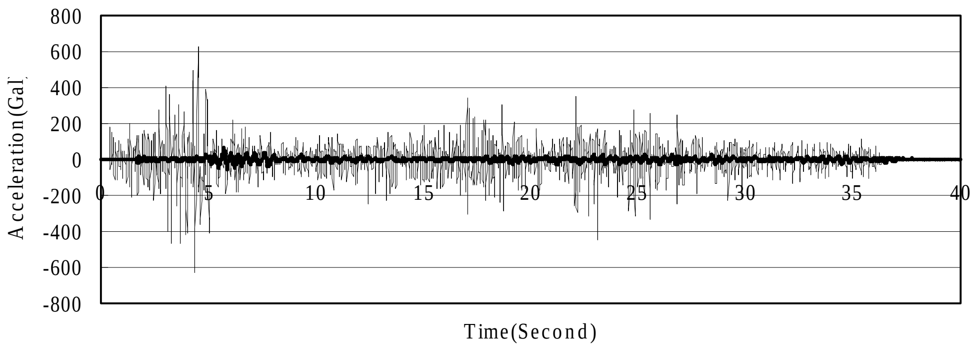


Figure 9: Acceleration response time histories of Hachinohe 1968 NS components

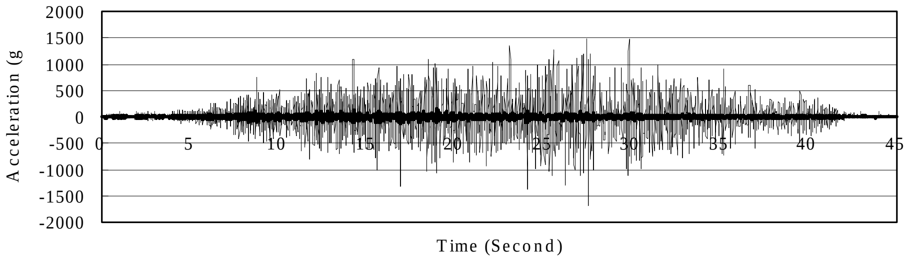


Figure 10: Acceleration response time histories of Kusiro 1961 NS components

Damping effect of multi-suspension system:

To verify and compare damping effect of multi-suspension system, following wave-motion is applied to shaking table for approx. 20 seconds and decay of oscillation of each systems (single suspension, double suspension and triple suspension) are recorded and results as shown on Figure 11.

Input wave-motion	Sinusoidal (Frequency 0.6Hz)
Amplitude	10.0 % (Maximum displacement ±7.5mm)
Weight applied	0.4082 kgf

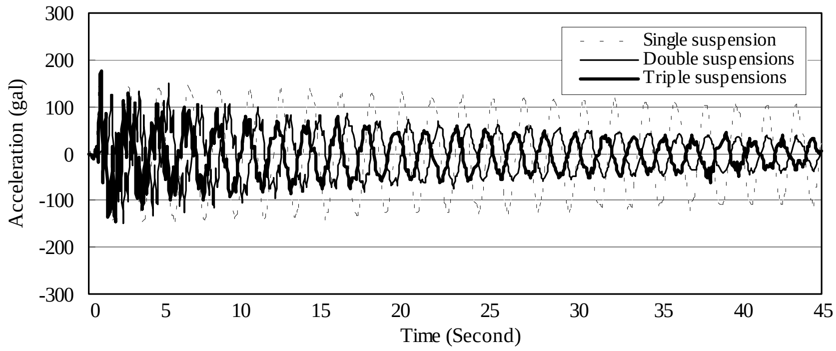


Figure 11: Comparison of damping effect

EXPERIMENTAL TEST RESULTS AND FINDINGS

Resonance of multi-suspension and MPI system:

According to experimental results as shown in Figure 5, common resonance frequency for three prototype models is observed 0.56Hz (1.8 seconds as fundamental natural period). This is almost same as one calculated according to total length of suspension as shown on Table-1, and this is considered as 1st order of natural period of system. Beside above, there are another resonance are observed on double and triple suspension, 0.4 and 0.45 seconds respectively, and which are considered as 2nd and /or 3rd order of natural period of system. Steel made experimental model has also resonance frequency of 0.61Hz (1.64 seconds as natural period) as almost same as one calculated according to the total length of suspension.

Response acceleration by actual earthquake motion:

Comparison of measured response acceleration at main pendulum and input acceleration to experimental model is shown on Table2. Depending upon type of earthquake, decrement of response acceleration at main pendulum is variable, 1/6 for Hyougoken-nannbu (Kobe) pattern to 1/27 for El Centro pattern, however effectiveness is significant for all type of earthquake.

Table 2: Peek value of Acceleration

Type of Earthquake	Peak value of Acceleration (gal)		Reduction Ratio
	Input (Base)	Main Pendulum	
El Centro 1940 NS	1208.0	43.5	1/27
Kobe 1995 NS	532.0	80.0	1/6
Hachinohe 1968 NS	629.0	64.0	1/9

Note) Level of input acceleration to be controlled by means of shaking table amplitude.

Damping effect of multi-suspension system

According to time historical of oscillation decay shown on Figure 12, damping ratio and logarithmic decrement are calculated and shown on Table 3.

Table 3: Damping ratio and logarithmic decrement

Type of suspension	Single	Double	Triple
Damping Ratio (h)	0.0058	0.019	0.035
Logarithmic Decrement (In d)	0.0365	0.1194	0.2200

CONCLUSION

The object of this paper is to evaluate and verify the fundamental behaviors and characteristics of multi-suspension system of which will be applied for development of Multi-Suspended Isolation (MPI) System.
According analysis and experimental results of multi-suspension system, followings are summarised,

1) 1st order of natural period ($T^{(1)}$) of MPI system is given by following approximation and independent of weight of superstructure;

$$T^{(1)} = 2\pi * \sqrt{l/g} \qquad (4)$$

2) Oscillation decrement due to multi-suspension system and shape of pendulum, and those of triple suspension is;

Damping ratio 0.035
Logarithmic decrement 0.22

And as a result of experimental oscillation test by actual earthquake ground motion, significant effectiveness of seismic isolation is verified as, 1/6 for Hyougoken-nannbu (Kobe) pattern to 1/27 for El Centro pattern.

It is concluded that newly developed Multi-suspended Isolation (MPI) system is preliminary verified as effective as seismic isolation device and of which has 1st natural period independent of weight of superstructure and decay of oscillation by itself.

For our further development, it is understood that following listed subjects to be clarified;

1) Resonance due to predominance order of nth natural period
2) Effectiveness of oscillation decrement due to multi-suspension
   - Relation with suspending order
   - Respective length of each suspensions
3) Effectiveness of oscillation decay due to shape of pendulum
4) Relation between displacement and respective lumped masses

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