SMiRT-12 / K. Kussmaul (Editor)

K25/6

APPLICATION OF ACCELERATED LIQUID FLOW DAMPERS TO BASE ISOLATION OF REACTOR BUILDINGS

S. Kawamata[1], M. Ohnuma[1], T. Toda[2] and T. Makita[2]

[1]Tohoku Institute of Technology, Sendai, Japan
[2]Technical Research Institute, Hazama Corporation, Tsukuba, Japan

ABSTRACT

"Accelerated liquid flow damper" utilizes turbulent flow resistance of liquid which is driven into small tubes by a piston-cylinder system and is characterized by very large force capacity and nonlinearly increasing resistance against structural vibration of large amplitude. Resisting force rules are derived by excitation test of the damper and applicability of the damper to base-isolated reactor buildings is examined by earthquake response analyses of the damped system.

1. INTRODUCTION

It has been widely recognized that base isolation is a powerful mean of seismic design of reactor buildings. Being characterized by enormous mass of the building and very high design earthquake, the isolation system necessitates installation of effective damping devices.

The authors developed "accelerated liquid mass damper" for the purpose of passive control of structural vibration[1), 2)] and its effectiveness was proved by tests of small scaled structural models.

To apply the dampers of this type to structures having large mass, the ratio of sectional area of the cylinder to the one of the discharge tube must be large enough to obtain high velocity and high pressure gradient of liquid flow. By excitation of a damper of half scale to prototype, it was found that, for very rapid flow in tubes, inertial resistance of liquid mass became negligible compared to high viscous resistance of turbulent flow and the latter exhibited strong nonlinearity to flow velocity.

In virtue of the nonlinearity of its resistance, the damper is able to suppress the amplitude of resonant response to earthquakes without detracting the action of isolators to filter the earthquake components of high frequency. This property, together with its large capacity of resisting force and displacement stroke, provides the accelerated liquid flow damper with noteworthy advantages in the application to base-isolated reactor buildings.

In this paper, empirical rules of pressure gradient of liquid flow in a tube are derived based on the results of excitation tests of the damper and the damping factor of single mass vibration system is evaluated. Also, applicability of the damper to base-isolated reactor buildings is examined by analyzed steady and earthquake responses of model structures.

2. RESISTING FORCE TEST OF DAMPER

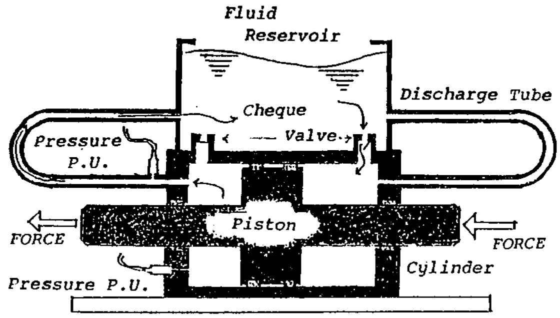

Fig.1 Scheme of accelerated liquid flow damper

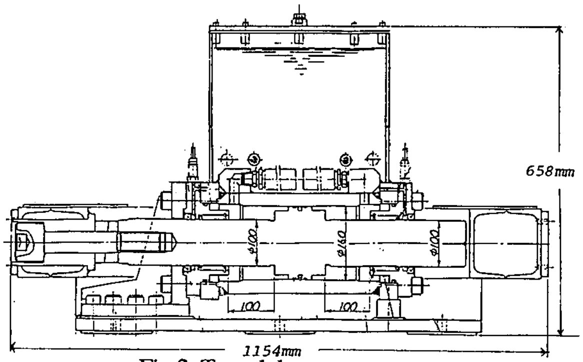

Fig.2 Tested damper

As shown in the scheme of Fig.1, an accelerated liquid flow damper is composed of a fluid reservoir with cheque valves, piston-cylinder and discharge tubes. The liquid flow in the tubes becomes intermittent transient one by the action of the cheque valves and its flow rule is not known.

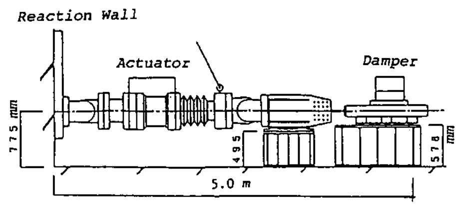

Fig.3 Test setup

To investigate the flow resistance rule, a damper shown in Fig.2, which was designed in half prototype scale, was subjected to sinusoidal excitation by the use of a hydraulic actuator in a manner shown in Fig.3. Damper oil was filled in and discharge tubes of 6.25*mm* and 9.4*mm* inner diameter were used. Exciting frequency ranged from 0.33 to 3.0Hz with displacement amplitude up to ±60*mm*.

Fig.4 shows an example of loops of actuator force and inner pressure in relation to piston displacement. Relation of pressure in discharge tube at zero displacement to piston velocity, shown in Fig.5, indicates that the pressure gradient along tubes does not depend on the exciting frequency and it has strong nonlinearity to sectional mean velocity of the fluid flow.

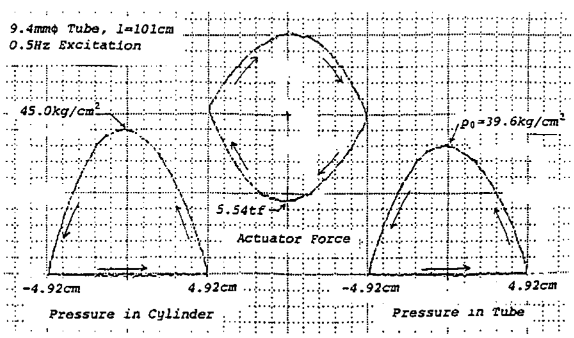

Fig.4 Force / pressure- displacement loops

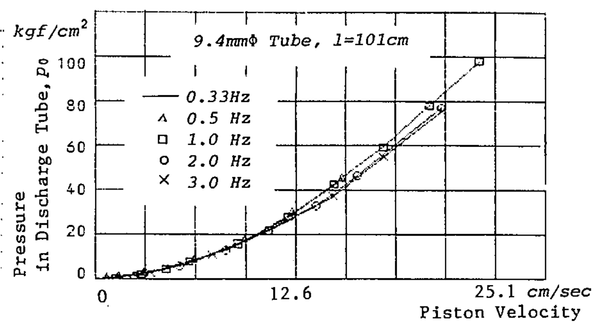

Fig.5 Pressure-velocity relation

As practiced in the analysis of steady flow data, the measured pressure in the tube at zero displacement was represented in term of pipe friction factor, by which the pressure drop along tube is given as

$$\Delta p_T = \frac{\rho l}{2D} \cdot u_m^2 f \tag{1}$$

where, Δp_T : pressure drop in tube, D : inner diameter of tube
ρ : density of fluid, u_m : mean velocity of pipe flow
l : length of tube, f : friction factor

Fig.6 shows the friction factors obtained for both the tubes in terms of Reynolds number defined by diameter of tube, R, where

$$R = u_m D / \nu \,, \qquad \nu \ : \text{kinematic viscousity} \tag{2}$$

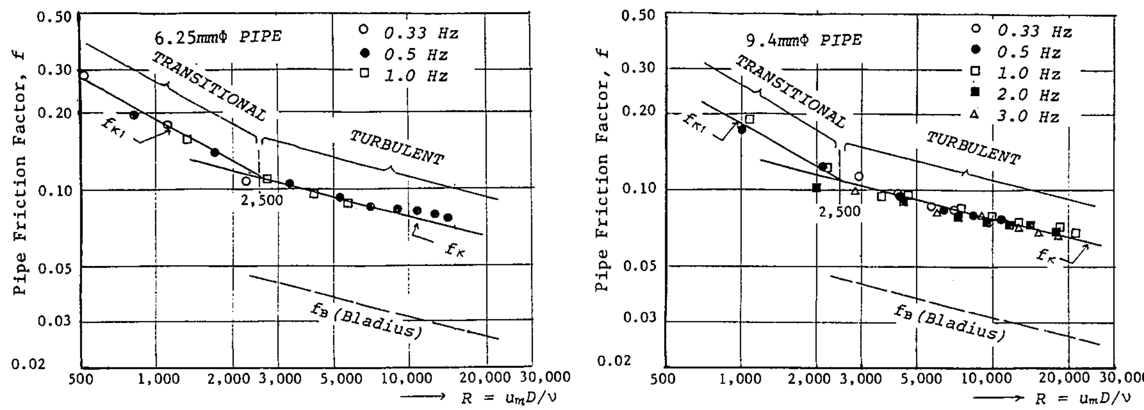

Fig.6 Relation of pipe friction factor to Reynolds number

3. FLOW RULES AND EVALUATION OF DAMPING FACTOR

As shown in Fig.6, plots of pipe friction factor to Reynolds number can be represented by two straight lines: f_K corresponding to turbulent flow region and f_{KI} for transitional region, which can be formulated as

$$f_K = 0.762\,R^{-0.25} \qquad \text{for } 2{,}500 \le R \text{ (turbulent)} \tag{3}$$

$$f_{KI} = 9.49\,R^{-0.57} \qquad \text{for } R < 2{,}500 \text{ (transitional)} \tag{4}$$

Comparing to the known H. Bladius' formula for turbulent steady flow in circular pipes,

$$f_B = 0.316\,R^{-0.25} \qquad \text{for } 2{,}300 \le R \text{ (turbulent)} \tag{5}$$

f_K in Eq.(3) has the same dependence on Reynolds number but has 2.4 times greater coefficient.

In the excitation test, the pressure drop from the outlet of the discharge tube to the surface of the liquid reservoir was not observed separately and was included in the pressure drop in the tube. Therefor, Eq.s (3) and (4) should be interpreted as tentative representations. Transition points from flow resistance linear to velocity into the transitional phase were not recognized in the test: they seemed to be in the region of very small displacement amplitude.

The pressure drop from inside of the cylinder up to inlet of the discharge tube was obtained as the pressure difference between pick up points in the cylinder and in the tube. It can be represented in the term of mean velocity of fluid in the tube as

$$\Delta p_C = 0.661\,\rho\, u_m^2 \tag{6}$$

where, Δp_C : pressure drop in cylinder

The pressure drop in the cylinder may vary according to the design of fluid conduit up to the inlet of the tube.

According to Eq.s (1) , (2) and (3) , pressure in the tube is proportional to the 1.75th power of mean velocity of fluid in the point of zero displacement. However, for the whole phase of sinusoidal flow, the flow rules should be examined separately.

By the analysis of the shape of observed pressure-displacement loops, it was concluded that the 1.75th power rule of pipe flow could be applied for the whole process of the flow without losing accuracy of response analyses of structural systems. By the same reasoning, flow rules of Eq.s (4) and (6) were also assumed to be valid for the whole flow process.

Now, let the damping factor for a single mass vibration system with the damper shown in Fig.7 be evaluated. Resisting force of the damper is given by

$$F_D = A\,(\Delta p_C + \Delta p_T) \tag{7}$$

where, F_D : resisting force of damper
A : pressure receiving area of piston-cylinder

The mean velocity of liquid flow in the tube is represented in the term of responding velocity of the structural system as

$$u_m = \frac{A}{a}\dot{x} = \frac{4A}{\pi D^2}\dot{x} \tag{8}$$

where, a : sectional area of discharge tube
x : relative displacement of system

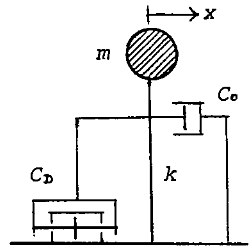

Fig.7 Damped system

The resisting force of Eq. (7) can be evaluated by the use of Eq.s(1)~(6) and Eq.(8). Consequently, damping coefficient and damping ratio to the critical can be obtained as follows:

$$C_D = F_D / \dot{x}, \qquad h_D = C_D / 2\,\omega_0\, m \tag{9}$$

where, C_D : damping coefficient, h_D : damping ratio
m : mass of system, ω_0 : natural frequency

As the resisting force of the damper is nonlinear to velocity, the damping ratio of Eq.(9) should be evaluated in every step of time integration for response analysis and be added to a viscous damping ratio, $h_0 = C_0 / 2\,\omega_0\, m$, proper to the structural system.

4. ANALYSIS OF STEADY RESPONSE TO GROUND MOTION

To investigate the response characteristics of structures provided with the accelerated liquid flow dampers to ground motion, steady response of a single mass system with the damper to sinusoidal ground acceleration was analyzed. Parameters of the subject system is given in Table 1.

Table 1. Parameters of analyzed system

Structure	
Weight of mass, W	500ton*
Natural period, T_0	2.0sec
Proper damping, h_0	0.02

* Weight of area covered by single unit of damper

Damper (1/2 scale model)	
Pressure area, A	122.5cm^2
Diameter of tube, D	0.94cm
Length of tube, l	200cm
Density of liquid, ρ	0.88$gram/cm^3$
Kinematic viscosity, ν	0.26cm^2/sec

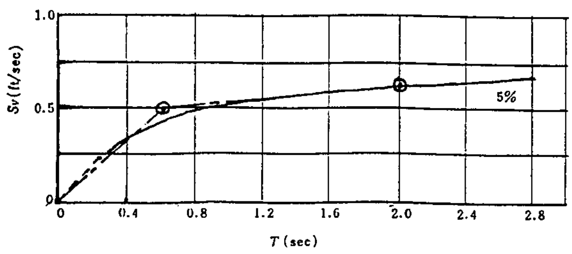

Fig.8 Mean velocity response spectrum (H. Umemura)

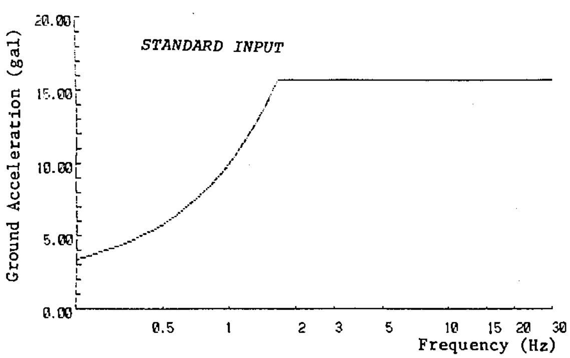

FIg.9 Standard ground-acceleration spectrum

To reflect general character of earthquake motion, a standard input acceleration spectrum was prepared. Mean velocity response spectrum of 5% damping system by H. Umemura, shown in Fig.8, was represented by bi-linear approximation as shown in the same figure. The standard input ground acceleration spectrum shown in Fig.9 was decided as the one by which a single mass system with the same damping produces the specified velocity response in resonance. Steady vibration was analyzed not only with regard to the standard input but also to those amplified by 2 times and 4 times to see the effect of nonlinear resistance of the damper.

Resonance curves were obtained applying the well known theory of steady vibration, where harmonic response was assumed and viscous damping whose energy dissipation was equivalent to the nonlinear resistance of the damper was searched for by an iterative procedure of prediction and correction.

Fig.10 shows resulted transmissibility for the three levels of input acceleration compared with the cases of constant viscous damping, the corresponding equivalent viscous damping of the system being presented in Fig.11.

It is worthwhile noting that the peak transmissibility in resonance decreases to the input of higher level, while the one to the components of higher frequency is kept far smaller than the cases of viscous damping.

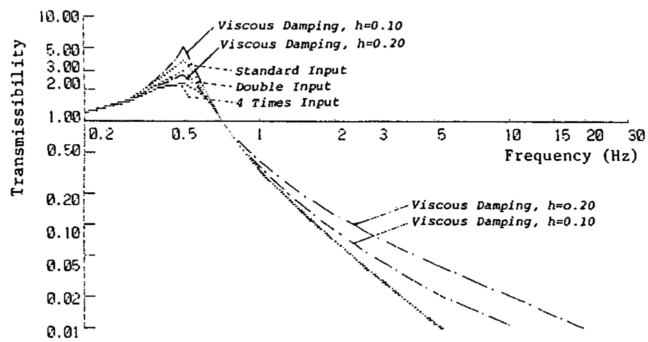

Fig.10 Transmissibility

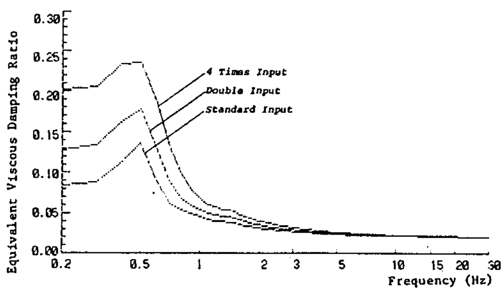

Fig.11 Equivalent damping ratio

5. ANALYSIS OF RESPONSE TO EARTHQUAKE

Single mass systems with an accelerated liquid flow damper of full scale were subjected to analyses of response to two representative recorded earthquakes. Time histories of response were obtained by Runge-Kutta method.

Parameters of the analysis are listed in Table 2. In all cases $h_0 = 0.02$ was assumed.

Table 2. Parameters of full scale damper and structural systems

Inner Diameter of cylinder:	$30cm$*	Diameter of tube:	$2.5cm$	Liquid density:	$0.88 gram/cm^3$
Diameter of piston rod:	$15cm$*	Length of tube:	$4.0m$	Kinem. viscosity:	$0.23 cm^2/sec$

System A	Natural period:	$T_0 = 2.0sec$	Weight of mass:	W = 1,000ton **
System B	Natural period:	$T_0 = 4.0sec$	Weight of mass:	W = 2,000ton **

* Pressure receiving area: 350 cm^2 ** Weight covered by a unit of damper

Ground acceleration of El Centro-NS and Hachinohe-EW was input in real amplitude and in double amplitude. Table 3 shows the maximum values of the inputs and resulted responses. An example of the time histories of response is presented in Fig.12.

From the results of the analysis, it can be seen that the base-isolated systems with the damper realize very low amplification factors of responding acceleration with the displacement of isolators well within their allowable limit, and also that factors of responding acceleration and displacement decrease to the higher level of input in general. The maximum inner pressure of the damper is the order of $300 kgf/cm^2$ and is acceptable in the design of the damper.

Table 3. Maximum responses to earthquake inputs

Input earthquake		ELCentro-NS		Hachinohe-EW	
		Real amplitude	Double amplitude	Real amplitude	Double amplitude
	Acceleration	342 *gal*	683 *gal*	183 *gal*	366 *gal*
System *A* To = 2.0 *sec* W = 1,000*ton*	Acceleration	144 *gal*	269 *gal*	145 *gal*	262 *gal*
	Amplification factor	0.421	0.394	0.792	0.719
	Displacement	14.0 *cm*	23.9 *cm*	14.4 *cm*	23.8 *cm*
	Inner pressure	$102 kgf/cm^2$	$253 kgf/cm^2$	$107 kgf/cm^2$	$314 kgf/cm^2$
System *B* To = 4.0 *sec* W = 2,000*ton*	Acceleration	45 *gal*	84 *gal*	51 *gal*	102 *gal*
	Amplification factor	0.132	0.123	0.279	0.279
	Displacement	14.1 *cm*	23.3 *cm*	19.1 *cm*	33.1 *cm*
	Inner pressure	$111 kgf/cm^2$	$337 kgf/cm^2$	$85 kgf/cm^2$	$261 kgf/cm^2$

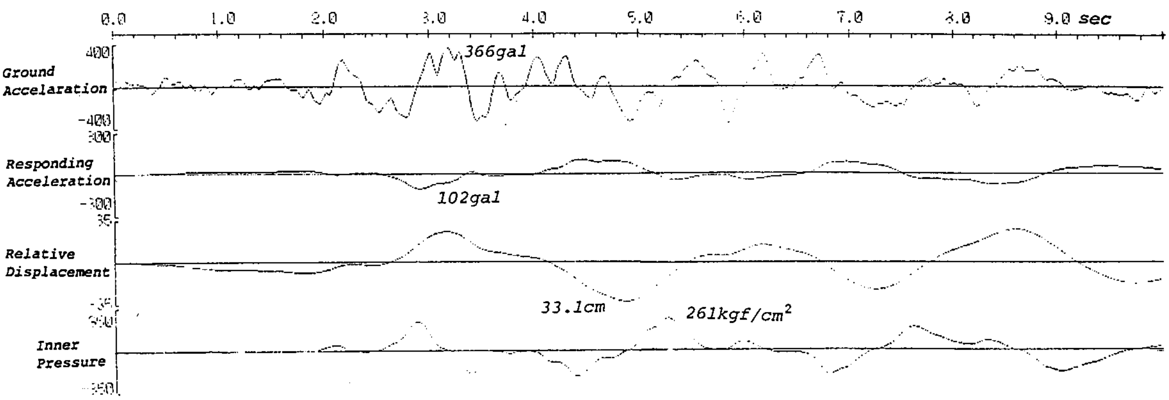

Fig.12 Response time history of System *B* to Hachinohe-EW, double amplitude

6. CONCLUSION

Resisting force rules of the accelerated liquid flow dampers in turbulent and transitional phases were derived from the results of excitation tests of a 1/2 scale model. Also, damping factors of single mass systems provided with the dampers were evaluated.

Analyses of response to ground motion demonstrated the effectiveness of the damper to control structural response for wide range of input level. The damper whose resisting force increases nonlinearly to responding velocity, together with its large capacity of resisting force, seems to provide many advantages for the use in base isolation of reactor buildings.

REFERENCES

1) Kawamata,S.,1987. Accelerated liquid mass damper and principles of structural vibration control. Trans. SMiRT-9, Lausanne, Vol.K: pp.737-742
2) Kawamata,S.,1992. Seismic control of multi-storied buildings by means of accelerated liquid mass damper. Proc. 10WCEE, Madrid, Vol.4: pp.2319-2324