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Seismic response control of a piping system using a semiactive damper with piezoelectric actuators

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ABSTRACT: The authors propose a new type of semiactive damper to control a seismic response of a piping system. The damper is composed of a ball screw and a disk brake with piezoelectric actuators. The brake force is controlled corresponding to the seismic response of the piping or an input acceleration. The damper does not restrict the thermal expansion of the piping because its brake force does not work during a gradual movement. The seismic responses of a L-shaped piping supported with the semiactive damper are calculated using a continuous system simulation language. Numerical results show that the damper can be used as an earthquake-proof device for piping systems practically.

1 INTRODUCTION

An earthquake-proof device for piping systems is required to restrain the movement of the piping during an earthquake. At the same time, it is not allowed to restrict thermal expansion, being a gradual movement, of the piping.

The mechanical snubber, which is composed of a ball screw, a flywheel and a disk brake, has been used as an earthquake-proof device for piping systems under high temperature. However, it is complicated in its structure and it is not easy to adjust the response sensitivity of the brake mechanism.

In this paper, we propose a new type of semiactive damper using piezoelectric actuators in order to obtain an earthquake-proof device having simple structure and large effect of vibration suppression. The brake force is controlled corresponding to the response of the piping or an input acceleration. Seismic responses of a L-shaped piping, which is fixed at both ends and supported with the damper at its bent section, are simulated using a continuous system simulation language. The restraint effect and effective control condition of the damper are also discussed.

2 STRUCTURE OF THE DAMPER

Figure 1 shows the construction of the semiactive damper with piezoelectric actuators which we will discuss in this paper. If a relative linear motion is given between the upper and lower mounting ears(1), the ball nut(2) attached to the telescoping cylinder(3) moves along the keyway(4). The linear motion of the ball nut is transformed into a rotary motion of the screw shaft(5) and the brake disk(6). The brake equipment is composed of the brake disk and a brake shoe(7), a brake lever(8) and two piezoelectric actuators(9). The brake lever is used for magnifying the displacements of the piezoelectric actuators.

If a voltage is applied to the piezoelectric actuators corresponding to the response of the piping, the actuators expand and push the brake lever, so that the brake shoe is pushed against the brake disk and a brake torque is generated in the brake disk.

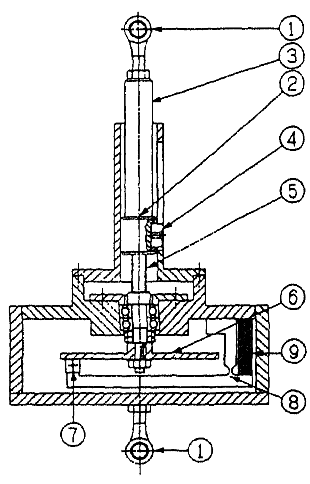

Fig.1 Construction of the damper

The main features of this damper are as follows:

1. Brake force is controlled corresponding to the response of the piping or an input acceleration.
2. Resistance force to a thermal expantion is very small because the disk brake does not work during a gradual movement.
3. The construction of the damper is simpler than that of the mechanical snubber.

3 EQUATION OF MOTION

Denoting the angle of rotation of the screw shaft by θ, the equation of motion for the damper can be written as

$$J\ddot{\theta} + Tb\ \mathrm{sign}(\dot{\theta}) = Ts \qquad (1)$$

where J is the summation of the moments of inertia of the brake disk and the screw shaft, Tb is the brake torque of the disk brake, Ts is the torque given by the ball nut and sign($\dot{\theta}$) is signum which takes -1,0 or 1 corresponding to a minus, zero or plus sign of $\dot{\theta}$. Relation between Ts in Eq.(1) and the axial force Fs acting on the screw shaft, that is the resistance force of the damper, can be written as

$$Ts = \frac{\ell \eta}{2\pi} Fs \qquad (2)$$

where ℓ is lead of the ball screw and η is mechanical efficiency of the ball screw. The brake torque Tb in Eq.(1) is given by

$$Tb = qr\mu Fb \qquad (3)$$

where Fb is the normal force that the brake shoe exerts on the brake disk, r is the distance between the center of the brake disk and the brake shoe, q is the number of the brake shoes, μ is the coefficient of friction. Relation between θ and the relative displacement u at the mounting position of the damper is given by

$$\theta = (2\pi/\ell)\ u \qquad (4)$$

Denoting the absolute acceleration of the piping and input accerelation by $\ddot{y}$ and $\ddot{y}_H$ respectively, the relative acceleration of the piping can be written as

$$\ddot{u} = \ddot{y} - \ddot{y}_H \qquad (5)$$

Substituting Eqs.(2)-(5) into Eq.(1), we obtain

$$Fs = \beta^2 J(\ddot{y}-\ddot{y}_H) + \beta qr\ \mu\ Fb\ \mathrm{sign}(\dot{\theta})\ /\ \eta \qquad (6)$$

where

$$\beta = 2\pi/\ell \qquad (7)$$

Figure 2 shows an analytical model of the L-shaped piping. The L-shaped piping is replaced by an eleven-masses system and they are linked by massless leaf springs. The upper and lower mounting ears of the damper are attached to the bent section of the piping (that is, the ith mass) and the foundation respectively. Expressing the equations of motion in matrix form, we have

$$\{u\} = -[A]([M]\{\ddot{y}\}+\{F\}) \qquad (8)$$

where $\{u\}(=\{y\}-\{y_H\})$ is the relative displacement vector, $\{y\}$ the absolute displacement vector, $\{y_H\}$ the displacement vector of the foundation, [A] the influence coefficient matrix, [M] the mass matrix and {F} the resiatance force vector, and they are given by

$$\{u\} = \{u_1, \cdots\cdots, u_n\}^T \qquad (9)$$

$$\{y\} = \{y_1, \cdots\cdots, y_n\}^T \qquad (10)$$

$$\{y_H\} = \{y_H, \cdots\cdots, y_H\}^T \qquad (11)$$

$$[A] = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} \qquad (12)$$

$$[M] = \begin{bmatrix} m_1 & & & 0 \\ & \ddots & & \\ & & m_i + \beta^2 J & \\ 0 & & & m_n \end{bmatrix} \qquad (13)$$

$$\{F\} = \{0, \cdots, f_i, \cdots, 0\}^T \qquad (14)$$

fi in Eq.(14) is given by

$$f_i = -\beta^2 J\ \ddot{y}_H + \beta\ q\ r\ \mu\ F_b\ \mathrm{sign}(\dot{\theta}) / \eta \qquad (15)$$

Using Eqs.(5) and (8), the equations of motion can be written as

$$\{\ddot{u}\} = -[M]^{-1}([A]^{-1}\{u\}+\{F\}) - \{\ddot{y}_H\} \qquad (16)$$

4 SEISMIC RESPONSES OF THE L-SHAPED PIPING

The digital simulation for the seismic responses of the L-shaped piping was carried out using a continuous system simulation language. Input accelerations used here are El Centro(1940)NS and Akita(1983)NS normalized to be $2m/s^2$ at the maximum acceleration as shown in Fig.3. The numerical conditions of the piping and the damper are given in Table 1.

The brake force is controlled by the following six conditions:
Brake force is kept at zero or a constant value Po corresponding to

(1) the relative displacement $|u_s|$,
(2) the relative velocity $|\dot{u}_s|$,
(3) the input acceleletion $|\ddot{y}_H|$,

and the brake force varies in proportion to

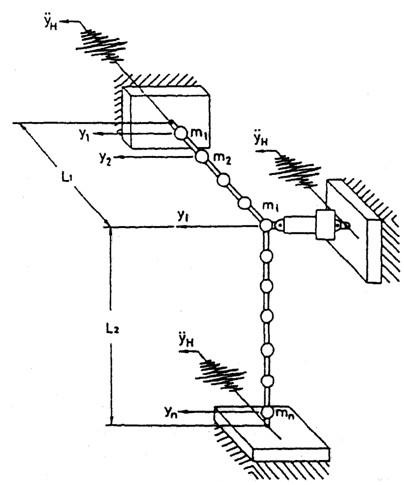

Fig.2 Analytical model of L-shaped piping

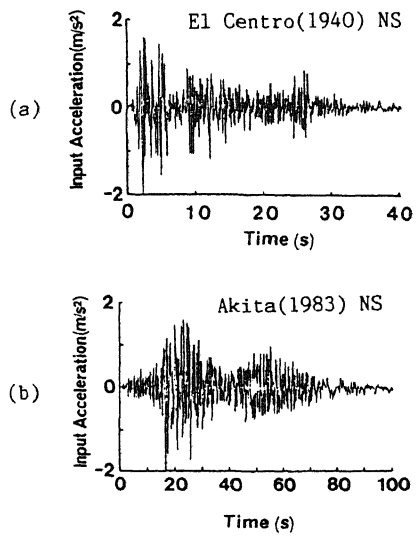

Fig.3 Input seismic acceleration

Table 1 Numerical conditions of the damper and the piping

Piping	Out diameter	139.88 mm
	Wall thickness	6.6 mm
	Weight	21.7 kg/m
	Length L_1	3600 mm
	Length L_2	5200 mm
Damper	Lead of ball screw ℓ	10 mm
	Moment of inertia J	1.86×10^{-4} kg·m^2
	Radius of brake disk r	60 mm
	Coefficient of friction μ	0.25

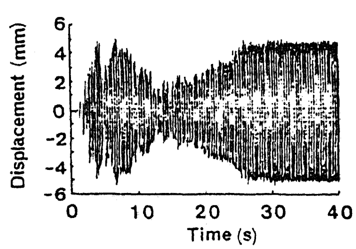

Fig.4 Response of the piping without the damper

(4) the relative displacement $|u_5|$,
(5) the relative velocity $|\dot{u}_5|$,
(6) the input acceleletion $|\ddot{y}_H|$

where u_5 and $\dot{u}_5$ are the relative displacement and the relative velocity at the bent section of the piping (that is, the fifth mass in Fig. 2) respectively. The conditions (1)-(3) and (4)-(6) are corresponding to on-off control and proportional control respectively.

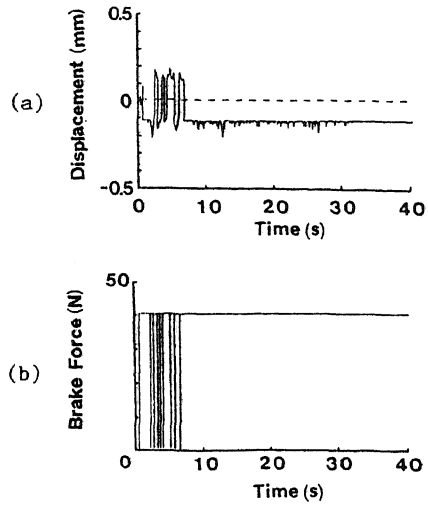

Fig.5 Response of the piping with the damper under the control condition(1)

The relative displacement time history of the piping for the case without damper when subjected to El Centro NS is shown in Fig.4. The relative displacement and brake force time history when the damper is controlled by the condition (1) are shown in Figs.5-(a) and (b) respectively. It will be seen from Figs.4 and 5-(a) that the seismic displacement response of the piping can be successfully reduced by the damper. However, the damper controlled by the condition (1) has such disadvantage that the disk brake keeps working till after the seismic disturbance as in Fig.5-(b), so that the piping does not restore to its original position. This means that the damper controlled by the condition (1) restrict even a gradual movement such as a thermal expansion of the piping.

For the case of the control conditions (2) and (6), the relative displacement, resistance force and brake force time history are shown in Figs.6 and 7 respectively. The damper controlled by these conditions are available for suppressing the seismic response of the piping.

It will be seen from Figs.6-(a) and 7-(a) that , the time history of the piping under the condition (2) differs from that under the condition (6) in wave shape. The reason is that the brake controlled by the condition (2) cannot work when the relative velocity response is less than a threshold value as shown in Fig.6-(c). On the other hand, the brake controlled by the condition (6) always work according to the input acceleration as shown in Fig.7-(c). As a result, the time history of the displacement responses in Fig.7-(a) is similar to the input acceleration in Fig.3-(a).

The maxima of the relative displacements

Table 2 Maxima of the relative displacements and accelerations of the piping and resistance forces of the damper

Control condition: Output force of an actuator	P_o (N)	A	El Centro (1940) NS: $\lvert u_s \rvert$ max ($\times 10^{-3}$ m)	El Centro (1940) NS: $\lvert \ddot{y}_s \rvert$ max (m/s^2)	El Centro (1940) NS: $\lvert F_s \rvert$ max (N)	Akita (1983) NS: $\lvert u_s \rvert$ max ($\times 10^{-3}$ m)	Akita (1983) NS: $\lvert \ddot{y}_s \rvert$ max (m/s^2)	Akita (1983) NS: $\lvert F_s \rvert$ max (N)
Without damper	—	—	5.27	16.00	—	7.68	22.38	—
(1) F_b=	10	—	0.95	3.14	210	0.79	2.73	134
{ P_o ($\lvert u_s \rvert \geqq 0.0001m$)	20	—	0.27	3.37	219	0.29	3.40	198
0 ($\lvert u_s \rvert < 0.0001m$)	40	—	0.22	6.20	328	0.20	6.31	247
(2) F_b=	10	—	0.71	2.34	183	0.69	2.31	121
{ P_o ($\lvert \dot{u}_s \rvert \geqq 0.001m/s$)	20	—	0.29	2.84	212	0.38	2.71	162
0 ($\lvert \dot{u}_s \rvert < 0.001m/s$)	40	—	0.25	4.62	262	0.32	4.48	207
(3) F_b=	10	—	1.00	2.55	195	1.56	2.53	199
{ P_o ($\lvert \ddot{y}_H \rvert \geqq 0.35m/s^2$)	20	—	0.95	3.29	234	1.68	3.52	302
0 ($\lvert \ddot{y}_H \rvert < 0.35m/s^2$)	40	—	0.96	5.74	292	1.44	5.86	365
(4) F_b= A · $\lvert u_s \rvert$	—	19600	0.99	3.94	244	0.92	3.76	194
	—	32667	0.78	4.74	273	0.74	4.50	199
	—	49000	0.55	4.86	296	0.47	4.03	200
(5) F_b= A · $\lvert \dot{u}_s \rvert$	—	1960	0.63	2.01	236	0.71	2.04	103
	—	4900	0.31	2.00	225	0.41	2.05	115
	—	9800	0.17	1.99	242	0.23	2.01	150
(6) F_b= A · $\lvert \ddot{y}_H \rvert$	—	4.9	1.28	3.06	202	1.46	2.60	136
	—	9.8	0.28	2.67	206	0.12	2.62	158
	—	24.5	0.14	5.77	256	0.08	5.51	229

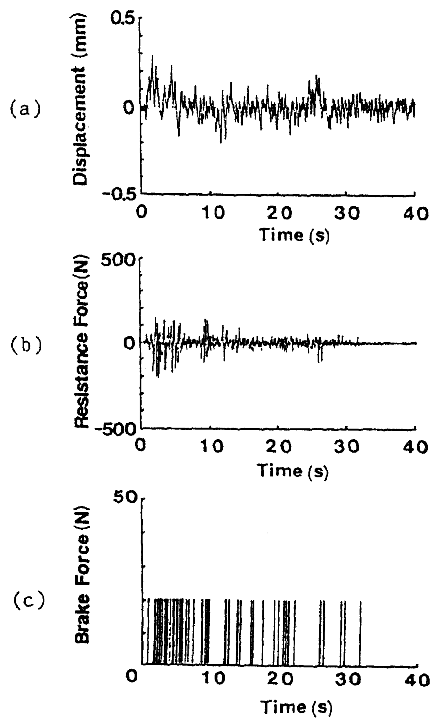

Fig.6 Response of the piping with the damper under the control condition(2)

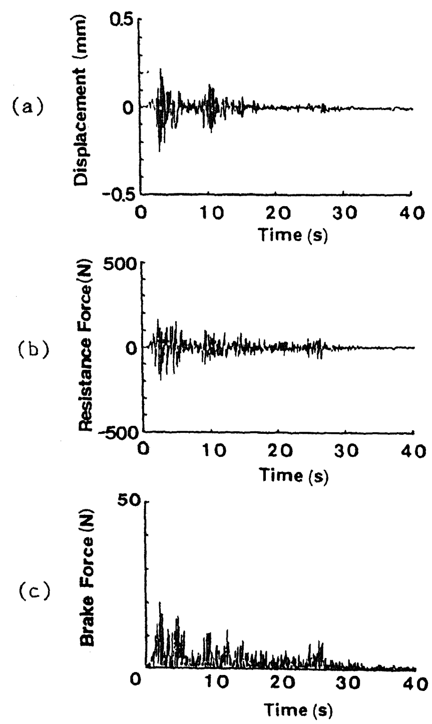

Fig.7 Response of the piping with the damper under the control condition(6)

and accelerations of the piping at the mounting position of the damper and the resistance forces of the damper for six types of control conditions are summarized in Table 2.

5 CONCLUSIONS

In this paper, the seismic response control of the L-shaped piping by a semiactive damper with piezoelectric actuators and the effective control condition of the damper are discussed numerically.

The results may be summarized as follows:

(1)The relative displacement response of the piping can be reduced successfully by the semiactive damper.

(2)The semiactive damper has the effect of vibration supprression even by simple control methods such as on-off control and proportional control.

(3)The brake force required for an actuator is 50N at most, so that commercial piezoelectric actuators can be used for the semiactive damper.

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