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Tuned Mass Damper for long-period buildings

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ABSTRACT: A new type response control devices for long-period buildings were developed. This device is two mass system, one is a pendulum and another is a horizontal moving mass that is connected to pendulum. The natural period of this device can be longer than a natural pendulum that has same rod length. And powered-passive type was developed by adding the control force to passive type. The effectiveness of these devices were confirmed by shaking table tests.

1 INTRODUCTION

Tuned Mass Dampers (TMD) have been installed to reduce the vibration of structures such as tall buildings. Pendulum type TMD is one of such devices. But, a natural period of pendulum depends on only a rod length. For example, a pendulum with natural period 5sec needs a rod length of 6.2m. We developed a new pendulum type TMD, named Pendulum Connected Mass Damper (PCMD). This PCMD has two mass. One mass is a pendulum, and another mass, which is allowed only horizontal motion by linear guide, is connected to the pendulum by means of vertical sliding bush. This device can reduces the length of pendulum according to a ratio of the horizontal moving mass to the pendulum mass (β : mass ratio). It is compact enough to be set in one floor height for long-period buildings. We developed a passive type PCMD and powered-passive type PCMD, which can increase passive type effectiveness. This paper presents the results of shaking table tests of these devices and analytical studies.

2 PASSIVE TYPE PENDULUM CONNECTED MASS DAMPER

A natural period of the PCMD (T:sec) is determined by following equation (1).

$$T = 2\pi\sqrt{\frac{l(1+\beta)}{g}} \qquad (1)$$

where β is mass ratio ($\beta = m_2 / m_1$), and l(cm) is a length of pendulum, and g(cm/sec^2) is gravitational acceleration. Fig.1 shows a length of pendulum which is required by this PCMD. For example, a length of 6.2m pendulum has a natural period of 5sec, however a length of this PCMD can be reduced to, only one third, 2m in case of β = 2. Moreover, the period of this device can be tuned easily by changing the value of mass ratio and length of pendulum.

2.1 EXPERIMENTAL PROCEDURE

Fig.2 shows the prototype of passive type PCMD. A mass of pendulum is 0.97tf, and another mass, which can do in any horizontal motion, are 1.75tf in x direction and 1.9tf in y direction respectively. A natural period of this device are 3.28sec in x direction and 3.36sec in y direction respectively.

This device was set on the three dimensional shaking table and shook by sinusoidal waves and by floor displacement response of two dimensional seismic excitation. The sinusoidal wave input tests were conducted to observe a value of acceleration that this device started moving, and frequency response curve of this device. Resonance curve were measured for input amplitude of 12mm and 6mm. Input frequencies varied from 0.20Hz to 0.40Hz at 0.02Hz intervals.

The floor response waves were calculated by using El Centro 1940 ground motions and a natural period of 3.3sec and damping factor of 1%. For tests, floor response waves were normalized to be 10mm at maximum displacement. And, input waves were NS

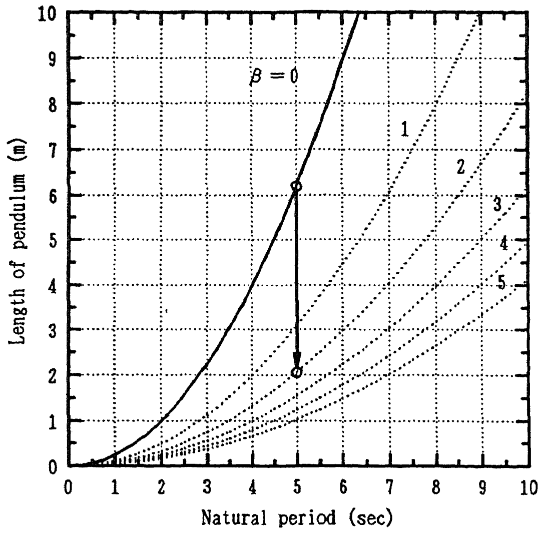


Fig.1 Relationship between mass ratio and rod length

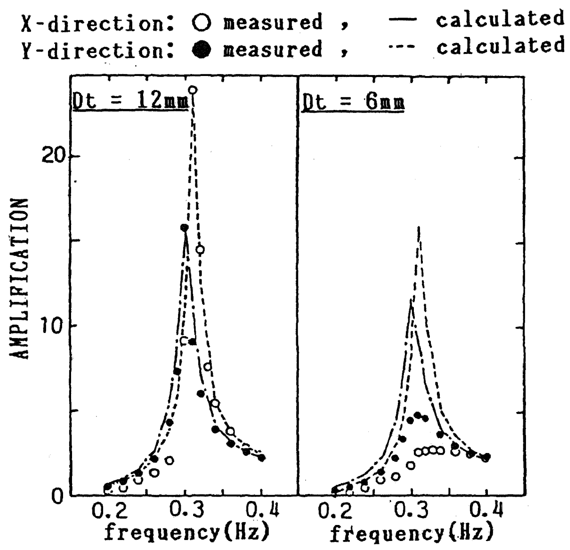


Fig.3 Frequency response of passive type PCMD

component in x direction and EW component in y direction respectively.

The displacement of shaking table and horizontal moving mass of this device were measured by displacement transducer, and acceleration by accelerometer. The value of acceleration, when this device started moving, was found by displacement of mass that was measured by analog pen-recorder.

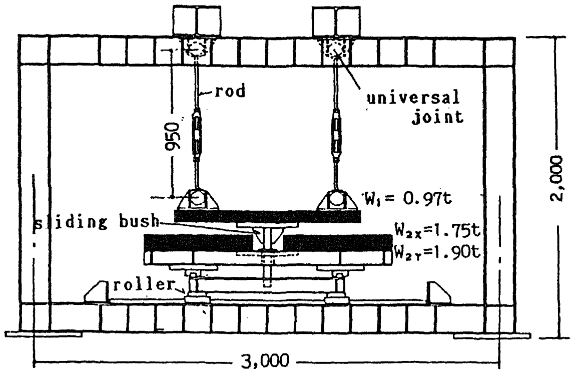


Fig.2 Prototype of passive type PCMD

2.2 EXPERIMENTAL RESULTS

This device started moving at small acceleration in each direction. This device was moved by small vibration of structures, but response amplification of this device was small. This result shows that an apparent damping factor of this devise was increased by friction when values of excitation were small. Fig. 3 shows comparison between measured response and calculated response of this devise. They represented that natural periods of this device, in each direction, can be calculated using equation (1). The resonance amplification of this device in x and y directions were different, because friction factors differentiate in each directions. When amplitude of input wave was small, measured resonance curve was lower than calculated curve, because response were more affected by friction when vibration of structure was small.

Fig.4 show time histories of displacement of this device. In these figure, measured displacement response were compared with calculated displacement response which considered the effect of friction on this device. Calculated results show that the displacement response of this device was calculated independently in each direction and was not affected by another direction.

3 POWERED-PASSIVE TYPE PENDULUM CONNECTED MASS DAMPER

3.1 EXPERIMENTAL PROCEDURE

Powered-passive type PCMD was developed by adding the control force to passive type PCMD. Fig.5 shows a test model of powered-passive type PCMD. This model has total mass weight of 50kgf and a natural period of 2sec, the mass ratio of β = 1.43. A horizontal moving mass was driven by a boll screw with an AC servo motor. This model

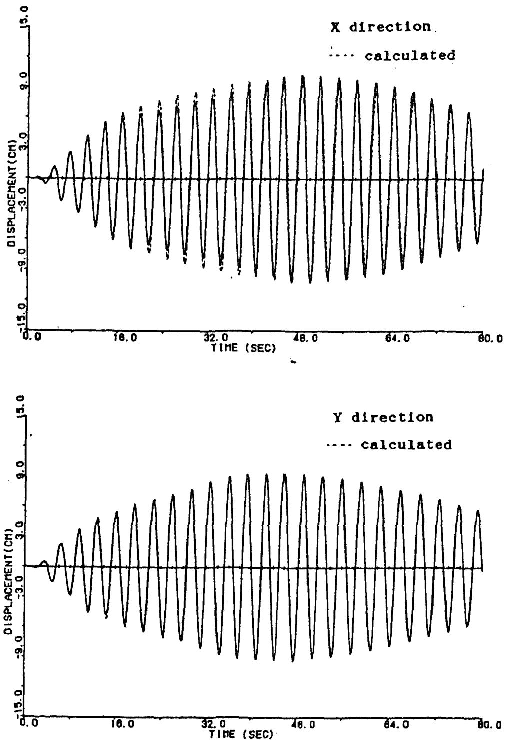


Fig.4 Time histories of response of passive type PCMD

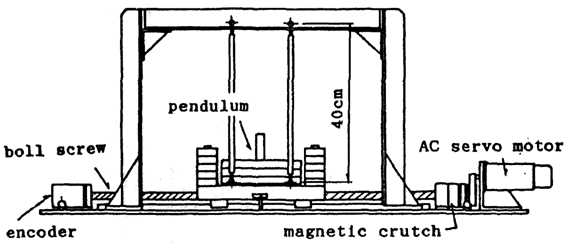


Fig.5 Test model of powered-passive type PCMD

Table.1 Specifications of experimental model

$m = 2.04$ kgf/cm/sec^2	$m_d = 0.0510$
$k = 20.14$ kgf/cm	$k_d = 0.5036$
$c = 0.128$	$c_d = 0.0608$

$$Q = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{vmatrix}, \quad R = 0.1 \qquad \begin{vmatrix} G_1 \\ G_2 \\ G_3 \\ G_4 \end{vmatrix} = \begin{vmatrix} 2.475 \\ 0.000 \\ -0.068 \\ -0.038 \end{vmatrix}$$

moves in one direction, and the maximum stroke is 20cm. When this devise is used as passive type PCMD, it is released from driver unit by magnetic crutch.

The powered-passive type PCMD used the optimum control theory. A state variable vector **X** and the control force **u** of this system are as follows.

$$\dot{\mathbf{X}} = \mathbf{AX} + \mathbf{Bu} + \mathbf{f} \qquad (2)$$

where,

$$\mathbf{A} = \begin{vmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -k/m & k_d/m & -c/m & c_d/m \\ k/m & -(k_d/m+k_d/m_d) & -c/m & -(c_d/m+c_d/m_d) \end{vmatrix}$$

$$\mathbf{B} = \begin{vmatrix} 0 \\ 0 \\ -1/m \\ 1/m+1/m_d \end{vmatrix}, \quad \mathbf{X} = \begin{vmatrix} x \\ z \\ \dot{x} \\ \dot{z} \end{vmatrix}, \quad \mathbf{f} = \begin{vmatrix} 0 \\ 0 \\ f/m \\ -f/m \end{vmatrix}$$

where m, c, and k represent, respectively, mass, damping coefficient and stiffness of structure. And m_d, c_d, k_d are mass, damping, stiffness of PCMD, and $\dot{x}$, x are velocity and displacement of structure, and $\dot{z}$, z are the velocity and displacement of the PCMD relative to the structure, and f is external excitation. Where a control force u is assumed as follows.

$$u = G_1x + G_2z + G_3\dot{x} + G_4\dot{z} \qquad (3)$$

It determine the gain values of G_1, G_2, G_3, G_4 by minimizing the objective function defined by equation (4).

$$J = \int (X^T QX + u^T Ru)dt \qquad (4)$$

where Q, R are the weight matrix.

Fig.6 shows schematic of experimental apparatus. A pendulum, which simulated a long-period structure, has a natural period of 2sec and weight of 2tf. A powered-passive type PCMD is mounted on this pendulum, and these were set on shaking table and shook by sinusoidal waves and seismic excitations. Input values of sinusoidal amplitude was 3mm. And for seismic excitation input waves, El Centro NS 1940, Taft EW 1952 and Hachinohe EW 1968 ground motion records were used. Input waves of maximum accelerations were set at 50gal or 100gal.

For state variables, absolute velocity of structure and PCMD by velocity transducer, and relative displacement of structure and PCMD by encoder were used. Table 1. show the specifications of experimental model.

3.2 EXPERIMENTAL RESULTS

Fig.7 show the comparison between frequency response curve without PCMD, with passive

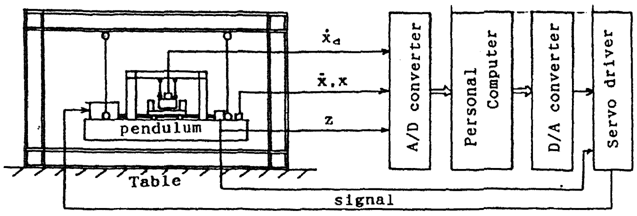


Fig.6 Schematic of experimental apparatus

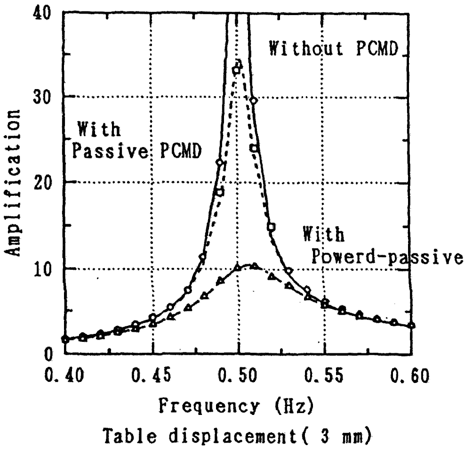


Fig.7 Experimental results of frequency response

type PCMD and with powered-passive type PCMD. And in this figure, the calculated response curves were obtained using apparent damping factor which simulated the experimental results. Though a model of structure has low damping, these results show that the damping of passive type PCMD is about 5 times of structural model and the powered-passive type is 16 times of structural model.

Fig.8 show , the time histories of displacement response of structure by seismic excitations, with and without PCMD. Powered-passive type PCMD can reduce the maximum displacement to 60% of without PCMD for every earthquake waves. And after main shock vibration, powered-passive type PCMD can reduce to 20%, which were more effective. Passive type PCMD have various reductions for every earthquake waves, but powered-passive type PCMD has similar reductions for every earthquake waves.

In these tests, the passive type PCMD didn't move at small values of displacement response of structure, because this experimental model was small size and the linear guide had relatively large friction. But, powered-passive type PCMD has small effect of friction, and moved at small displacement of structure by control force using driver unit. But, calculated results are different from experimental results. Therefore, it is necessary to consider effect of the friction.

4 ANALYTICAL MODEL FOR PCMD

Fig.9 shows the analytical model of PCMD that consider the effect of friction.
The equations of motion are as follows. Where phase.1 is moving condition and phase.2 is stopping condition.

$\dot{z} > 0$ and $\dot{z} < 0$ ---- Phase.1

$$\mathbf{M}\ddot{\mathbf{X}} + \mathbf{C}\dot{\mathbf{X}} + \mathbf{K}\mathbf{X} = -\mathbf{M}\ddot{y}_o + \mathbf{I}u - \mathrm{sgn}(z)\mathbf{I}F$$

$\dot{z} = 0$ -------- Phase.2

$$(m+m_a)\ddot{x} + c\dot{x} + kx = -(m+m_a)\ddot{y}_o$$

where,

$$\mathbf{M} = \begin{vmatrix} m & 0 \\ 0 & m_a \end{vmatrix}, \quad \mathbf{C} = \begin{vmatrix} c+c_a & -c_a \\ -c_a & c_a \end{vmatrix}, \quad \mathbf{K} = \begin{vmatrix} k+k_a & -k_a \\ -k_a & k_a \end{vmatrix}$$

$$\mathbf{I} = \begin{vmatrix} -1 \\ 1 \end{vmatrix}, \quad \mathbf{X} = \begin{vmatrix} x \\ x_a \end{vmatrix}$$

x_a : absolute displacement of PCMD ($z = x_a - x$)
$F = \mu m_a g$: friction force
sgn( ) : indicates the algebraic sign of its argument
μ : coefficient of friction
$\ddot{y}_o$: the acceleration of ground motion

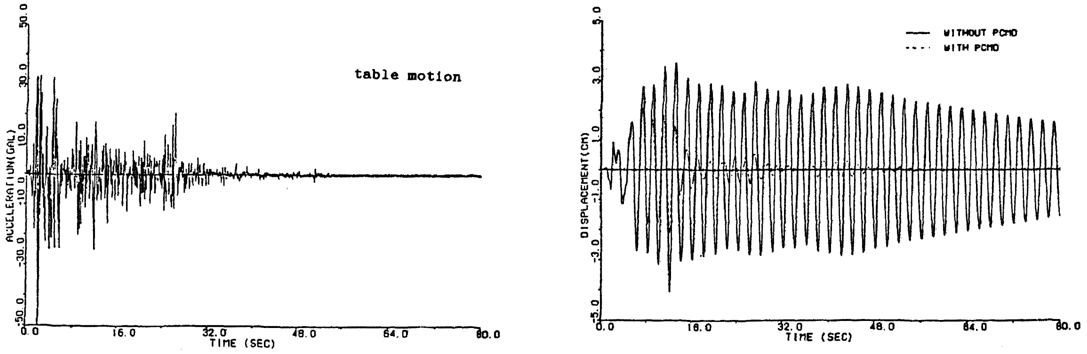
condition
from phase.2 to phase.1 is

$$| m_a(\ddot{x}+\ddot{y}_o) + k_a z - u | > \mu m_a g$$

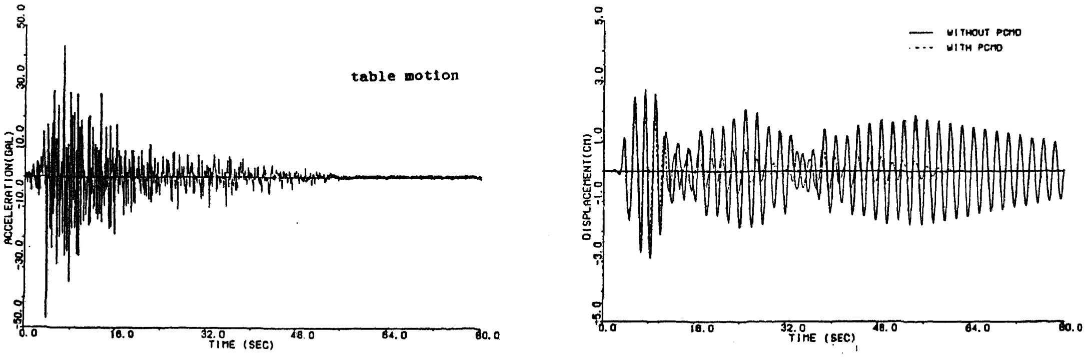
from phase.1 to phase.2 is

$$| m_a(\ddot{x}+\ddot{y}_o) + k_a z - u | \leq \mu m_a g \quad \text{and} \quad \dot{z}=0$$

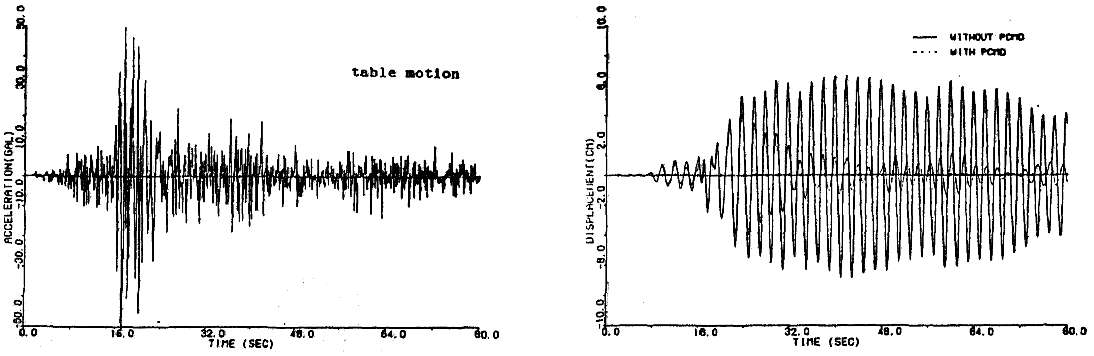
Fig.10 shows the comparison between calculated results of sinusoidal excitation tests and experimental results. They are similar to each other when excitation is large. When excitation is small, they are different from each other. These results show that the coefficient of friction were changed to decrease with increasing velocity



(1) El Centro NS 1940



(2) Taft EW 1952



(3) Hachinohe EW 1968

Fig.8 Time histories of response and table motions

of PCMD. They show that response of large excitations aren't subject to the influence of friction, but response of small excitations are affected by friction.

Fig.11 shows the comparison between the time history of calculated displacement of structure and experimental results. The latter part of calculated results are not simulated the experimental results. Because, the coefficient of friction of PCMD test models were changed on the way. Therefore, greater accuracy can be achieved if the variable coefficient of friction are considered.

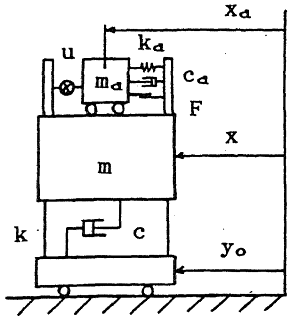


Fig.9 Analytical model

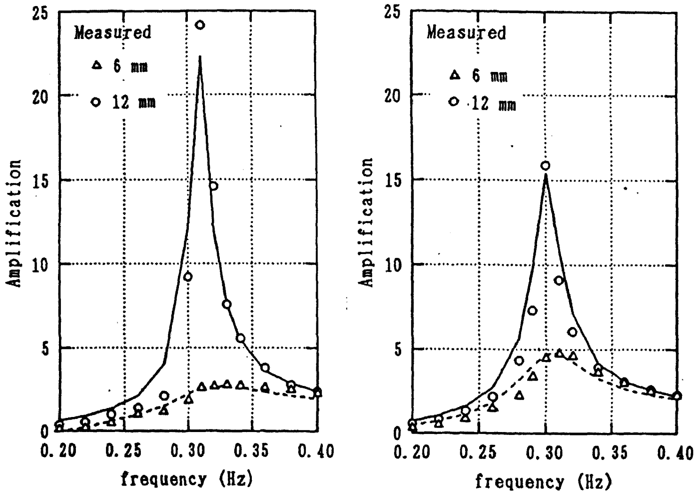


Fig.10 Comparison between experimental results and calculated results

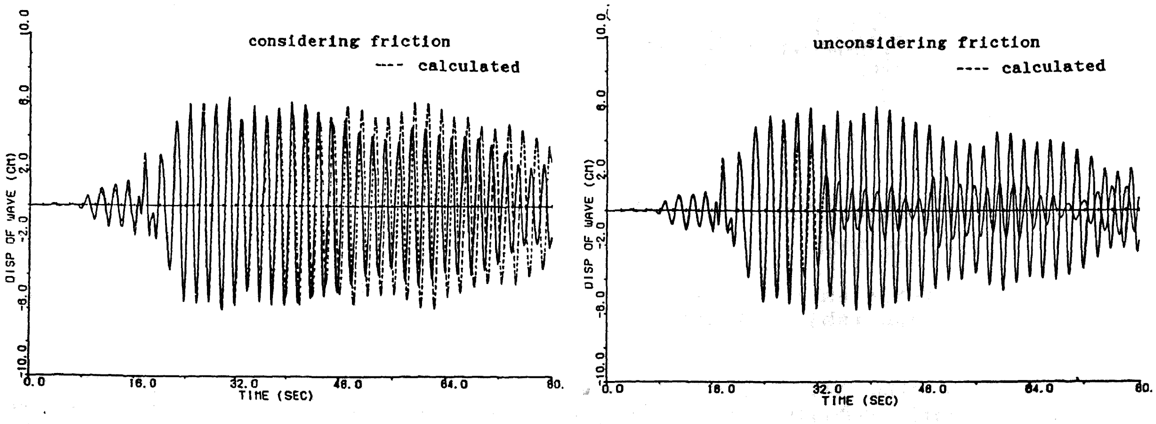


Fig.11 Time histories of displacement response

5 CONCLUSION

The results of these studies show that,

1)A natural period of the PCMD is determined by equ.(1), and the response of this devise is calculated independently in each direction.

2)The passive type PCMD started moving at small acceleration. But their effectiveness are small. These results show that the responses of PCMD are affected by friction, when excitation are small.

3)The powered-passive type PCMD has more than two times effectiveness of passive type PCMD. Using control forces is an effective way to reduce the structural vibration and are not influenced by friction.

These PCMD can reduce the vibration of structures such as long-period buildings. A passive type PCMD is necessary to improve on the effect of friction. And we will propose a powered-passive type PCMD controlled using the modern control theory and using a large scale model at a next opportunity.

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