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DYNAMIC ABSORBER FOR ROPEWAY GONDOLA USING CORIOLIS FORCE

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Abstract. Wind-induced swinging of ropeway gondola can be reduced using dynamic absorbers. To maximize the performance of conventional dynamic absorbers, their location should be as high as possible. However, absorbers can not be installed at high positions due to interference issues with structures such as towers and stations. To address this problem, a new type of dynamic absorber that moves vertically is proposed. This absorber is composed of a mass supported by a spring. The mass moves in the radius direction (up and down) and it induces Coriolis force in the circumference direction to prevent the swing of gondola. If the natural frequency of the absorber is tuned to twice that of the gondola, the absorber moves spontaneously with a large amplitude due the resonance. This absorber is more effective when it is located at lower positions. The experiment with a small model and an actual gondola for 10 passengers were carried out and the results agreed well with the theoretical predictions.

1. INTRODUCTION

Wind loading often induces swinging of cable suspension carriers such as gondolas and chair lifts. In general, the operation of gondola is suspended for the wind speeds greater than 15m/s. There are two means for reducing swing of cable suspension carrier, dynamic absorbers and gyrostabilizers. Because the structure of the gyrostabilizers is complicated and requires a power supply, it is not suitable for cable suspension carriers. Alternatively, passive dynamic absorbers do not have such problems. Since their effectiveness is generally proportional to the square of the vibration amplitude, many researchers have tried to install dynamic absorbers at the bottom of carriers. In these setups, the absorbers worked very poorly, and it was believed that dynamic absorbers were not effective for reducing the swing of pendulum-type structures. However, Matsuhisa et al. [1] established a new theory regarding the location of dynamic absorber on pendulum structures in 1993. This theory revealed that their effectiveness is proportional to the square of the distance between the absorber and the center of oscillation. In the case of gondola, the center of oscillation is approximately the mid-point between the center of gravity and the bottom of the gondola. This means that absorbers located at the bottom of gondola do not work well and the absorber should be located as high as possible. Even if the absorber is above the fulcrum it works very well. This location theory is applicable for all kind of absorbers, which move in the circumference direction as shown in Figure 1. Since the first installation of the dynamic absorber on the ropeway chair lifts in 1995 (Japan), dynamic absorbers have been installed on about 20 ropeways in Japan [2]. However, there are many obstacles such as towers and stations that prevent installation of absorbers at a high position above the roof of gondola, then the actual absorbers are installed just above the roof without enough distance and they can not have good performance. In this paper, a new absorber that uses

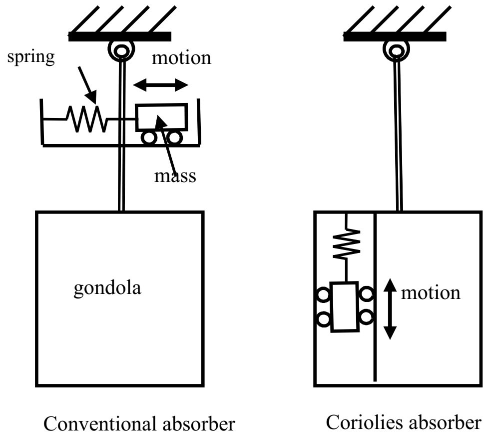

Fig. 1. Conventional and Coriolies absorbers on a gondola.

Coriolies force and moves in the radial direction of the pendulum-type structure as shown in Figure 1 is introduced. This absorber can be located at the low position of gondola. Because the Coriolies force is proportional to the mass, the angular velocity of swing, and the velocity of the absorber's mass in the radial direction, the effectiveness of absorber increases rapidly with the amplitude of swing. This phenomenon is opposite to the concept of pumping on a swing in a park, i.e., the swing angle increases very little when it is small, but it increases rapidly when it is large. Theoretical analysis and experiments with a small model were carried out and it was shown that the Coriolies absorber worked well. Then the Coriolies absorbers for an actual gondola was produced and its effect was investigated.

2. THEORETICAL ANALYSIS

2.1. Equations of motion

As shown in Figure 2, a ropeway gondola can be modeled as a simple pendulum (the center of oscillation and the center of gravity are assumed to be the same). The model parameters are defined as the following: m_1 is the mass, l_1 is the length between the gravity center G and the fulcrum (center of swing) O, c_1 is the damping coefficient, θ is the rotational angel of the pendulum, u is the displacement of the absorber, l is the distance between the fulcrum and the absorber in the static condition, and g is the acceleration of gravity; m_2, k and c are mass, spring constant and damping coefficient of the absorber, respectively. Assuming that the cable does not move, the locations of the gondola and dynamic absorber masses are

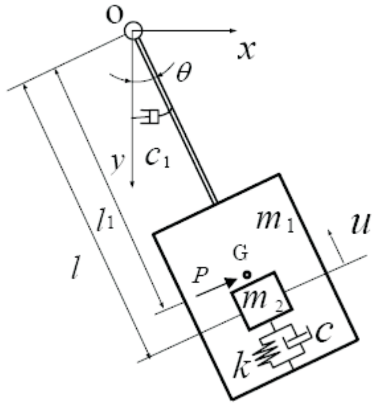

Fig. 2. Schematic diagram of pendulum with a Coriolis dynamic absorber

$$x_1 = l_1 \sin\theta, \tag{1}$$
$$y_1 = l_1 \cos\theta, \tag{2}$$
$$x_2 = (l - u) \sin\theta, \tag{3}$$
$$y_2 = (l - u) \cos\theta. \tag{4}$$

The kinetic energy T and the potential energy V are

$$T = \frac{1}{2} m_1 l_1^2 \dot{\theta}^2 + \frac{1}{2} m_2 \left\{ (l-u)^2 \dot{\theta}^2 + \dot{u}^2 \right\}, \tag{5}$$

$$V = m_1 g l_1 (1 - \cos\theta) + m_2 g (l-u)(1-\cos\theta) + \frac{1}{2} k u^2. \tag{6}$$

The energy dissipation function is

$$F = \frac{1}{2} c_1 \dot{\theta}^2 + \frac{1}{2} c \dot{u}^2 \quad . \tag{7}$$

The Lagrange's equations of motion are obtained from Eqs. (5), (6), and (7) as

$$m_1 l_1^2 \ddot{\theta} + m_2 (l-u)^2 \ddot{\theta} + c_1 \dot{\theta} - 2 m_2 (l-u) \dot{u} \dot{\theta} + (m_1 g l_1 + m_2 g l - m_2 g u) \sin\theta = P l_1 e^{j\omega t}, \tag{8}$$

$$m_2 \ddot{u} + c \dot{u} + k u + m_2 (l-u) \dot{\theta}^2 - m_2 g (1 - \cos\theta) = 0, \tag{9}$$

where, P is the external force assumed to acts on the gravity center G.

The fourth term of Equation (8) is the moment caused by the Coriolis force $2m_2\dot{u}\dot{\theta}$ that acts as a damping force. The fourth term of Equation (9) is centrifugal force that is proportional to $\dot{\theta}^2$ and this force drives m_2. Therefore, the Coriolis force is approximately proportional to $\dot{\theta}^3$. The fifth term $m_2 g(l-u)\sin\theta$ in Equation (8) is the moment given by the gravity force, and this moment is also non-linear due to variation of the arm length $(l-u)$. Because the fourth and fifth terms in Equation (9) are the driving force on m_2, the displacement u has a resonant peak at the damped natural frequency that is two times that of the frequency of θ. Considering the non-linearity of the damping force, the Coriolis absorber works poorly for small swing angles, but remarkably well for large angles. This phenomenon can be experienced when one pumps a swing in a park by moving his body up and down.

2.2. Frequency response and optimum tuning

The distance of the absorber mass m_2 from the fulcrum O is $l-u$, and u is a variable. However, it is assumed that u is small enough compared with l and the distance is l. The equivalent arm length of the combined pendulum of the main mass m_1 and the absorber mass m_2 is

$$l_e = \frac{m_1 l_1^2 + m_2 l^2}{m_1 l_1 + m_2 l}, \tag{10}$$

The natural frequencies of the gondola and absorber are

$$\omega_1 = \sqrt{\frac{g}{l_e}}, \tag{11}$$

$$\omega_a = \sqrt{\frac{k}{m_2}}. \tag{12}$$

The following non-dimensional parameters are introduced.

$$\mu = \frac{m_2}{m_1},\ \gamma = \frac{l}{l_e},\quad f = \frac{\omega_a}{\omega_1},\quad h = \frac{\omega}{\omega_1},\quad \varsigma_1 = \frac{c_1}{2m_1 l_e^2 \omega_1},\quad \varsigma = \frac{c}{2m_2\omega_1},\quad \Theta = \frac{P}{m_1 g}$$

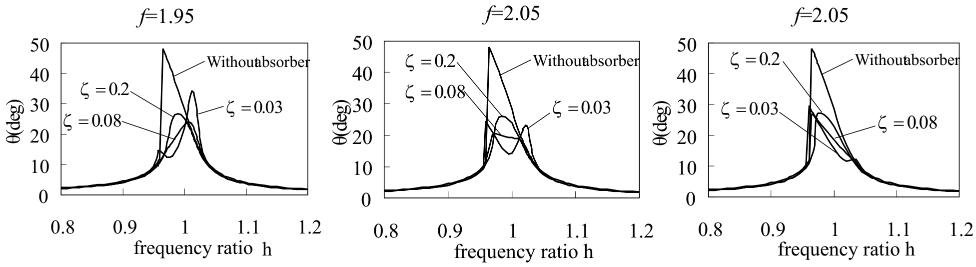

Fig. 3. Frequency response of the pendulum with Coriolis absorber

Because this system is nonlinear, its response to sinusoidal excitation is numerically calculated. The calculated frequency responses with parameters $\mu = 0.1$, $\gamma = 1$, $\Theta_{st} = 0.015$, $\zeta_1 = 0.005$, f=1.95, 2.001, and 2.05 and ζ= 0.03, 0.08 and 0.2 and are shown in Figure 3. The peak response is significantly reduced by the absorber and its magnitude depends on f and ζ. In general, the optimum values f_{opt} is 1.99 and ζ_{opt} is between 0.06 and 0.1. When the damping is zero, f_{opt} must be 2.0. However, f_{opt} is decreased by a small amount by the damping. When the exciting force is large, ζ_{opt} becomes large. The effectiveness of the absorber depends on its mass and location. Figure 4 and 5 shows the frequency responses for various mass ratios μ and location parameters γ, respectively, where f =2.0, ζ=0.08, Θ_{st}=0.015, μ=0.1, and γ=1.0. The effectiveness of the absorber is proportional to the mass ratio. The location of the absorber also has a large influence on its effectiveness. Because motion of the absorber is caused by the centrifugal force, the absorber must be attached to a place far from the center of swing.

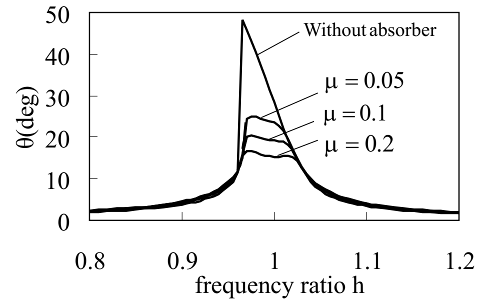

Fig. 4. Effect of mass ratio on frequency response

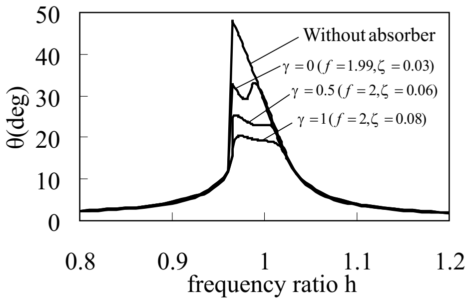

Fig. 5. Effect of location on frequency response

2.3. Free response

The free response of a gondola with an initial angle of $\theta = 30°$ is shown in Figure 6 for f =2.0, ζ=0.1, μ=0.1, $\zeta_1 = 0.005$ and γ=1.0. This figure shows that the absorber oscillates with twice the frequency of the pendulum. In the case of a linear system, the damping ratio is independent on the amplitude of oscillation. However, because the Coriolies absorber is non-linear, the damping ratio depends on the magnitude of the oscillation. Figure 7 shows the damping ratio for each period of oscillation for three different initial angles: 30, 35 and 40 degrees. This figure shows that when the oscillation is small, the damping ratio is negligible, but it increases with the magnitude of the oscillation.

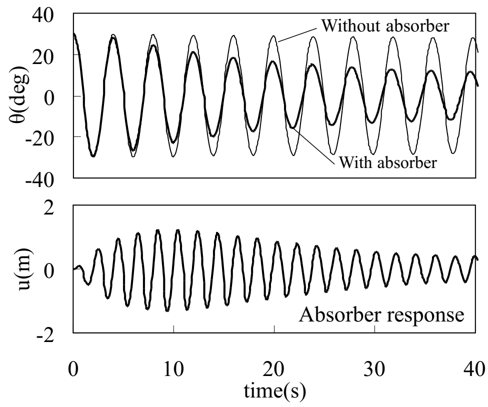

Fig. 6. Free response of pendulum with Coriolies absorber

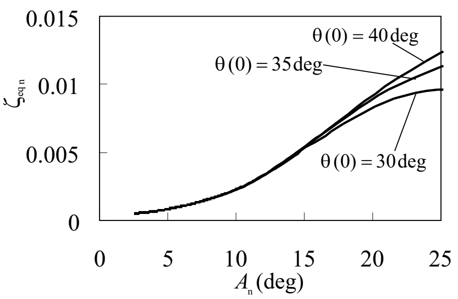

Fig. 7. Damping ratio calculated for each period of free vibration

2.4. Random response

Random wind force is imposed on the carrier using Davenport's [3] formulations. The wind-induced vibration of a gondola with Coriolies absorbers for wind velocities of 15, 20, and 25 m/s are shown in Figure 8. In these calculations, values for parameters are selected to model a middle-size gondola (12 passengers) as m_1=790 kg (without passengers), l_1=3.8 m, ζ_1=0.01, f =2.0, ζ=0.1, μ=0.1, and γ=1.0. The results show that the absorber works very well. Typically, the operation of gondola without absorbers is suspended for the wind velocity greater than 15 m/s. However, for a gondola with the Coriolies absorber, operation is feasible up to wind speeds of 20 m/s.

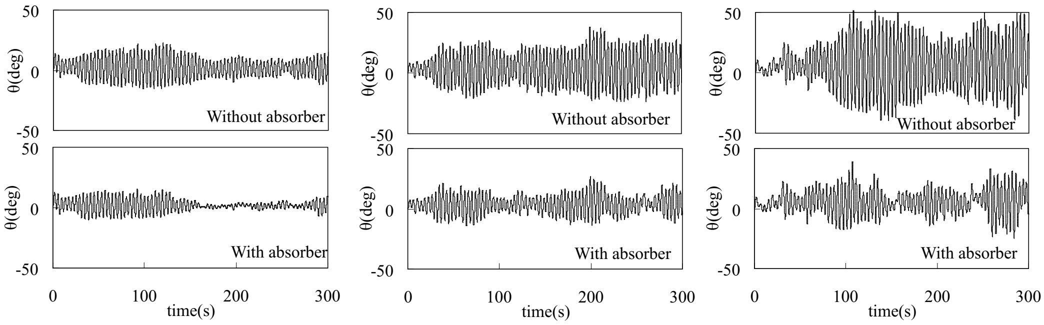

Fig. 8. Wind induced vibration of a gondola for three wind velocities

3. EXPERIMENT WITH A SMALL MODEL

Figure 9 shows an experimental apparatus composed of a pendulum and a passive Coriolies absorber. The absorber is placed in parallel with the pendulum and its mass is suspended by two coil springs (one is above the mass and the other is below). The damping is provided by the electromagnetic force that is induced by a permanent magnet attached to the absorber mass and aluminum bar on the pendulum. The swing angle is measured using a potentiometer at the fulcrum. Values for the system parameters are: m_1=0.93 kg, l_1=0.67 m, ζ_1=0.002, m_2=0.2 kg, l=0.65 m, μ=0.24, f=2.0, and ζ=0.045.

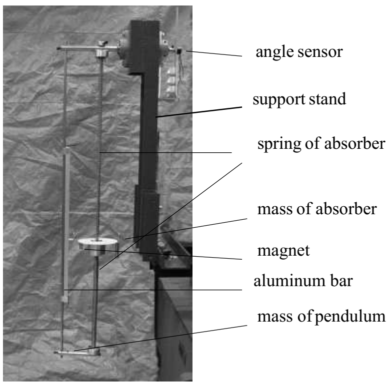

Fig. 9. Pendulum with a Coriolies absorber

Figure 10 shows the free response of the experimental system. This response agrees well with the theoretical prediction. Figure 11 shows the system's frequency response. In this experiment, instead of the external force P, the fulcrum is moved horizontally with harmonic displacements. The resonant peak value is significantly reduced.

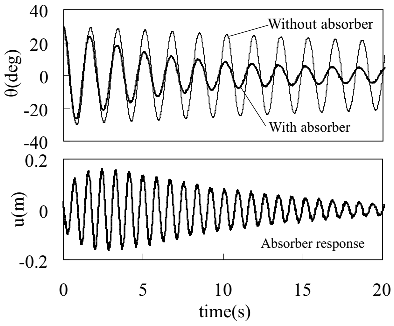

Fig. 10. Experimental results of free response

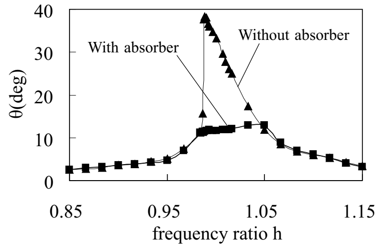

Fig. 11. Experimental results of frequency response

4. EXPERIMENT WITH AN ACTUAL MODEL

Figure 12 shows an gondola with two Coriolies absorbers. The mass of absorber is suspended by two coil springs and the damping is given by electromagnetic induced force with permanent magnet on the moving mass and aluminum guide. The mass of gondola is

Fig. 12. Pictures of gondola with absorbers

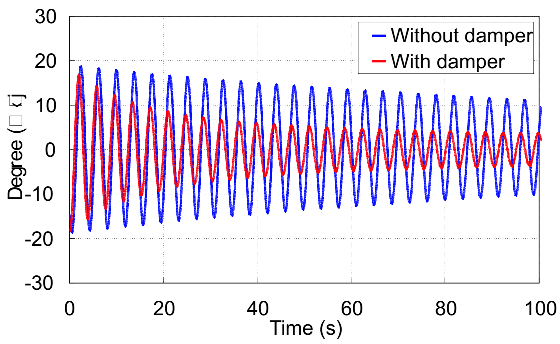

Fig. 13. Free responses of gondola with and without absorber

650 kg, the natural frequency is 0.262 Hz and damping ratio is 0.0035. The mass of absorber is 145 kg, the moving mass is 75 kg, the natural frequency is 0.531 Hz and damping ratio is 0.055. Figure 13 shows the free response. In the first several periods, the absorber works well, however after that the amplitude of the swing of gondola becomes small and the absorber does not work well. This is resulted by the non-linearity of the Coriolies force. Therefore the Coriolies absorber can reduce the large amplitude as 20 degrees to middle amplitude as 10 degrees.

5. CONCLUDING REMARKS

In this paper, a passive absorber that uses Coriolies force to reduce vibration is introduced. This absorber moves in the radial direction of a swinging pendulum. Therefore, it has many differences with conventional absorbers that move in the circumference direction. For example, the relationship between the absorbers' effectiveness and their location is opposite. In the case of conventional absorber on a gondola, the location should be as high as possible, but for the Coriolies absorber, it should be as low as possible. The damping ratio of the conventional absorber is constant, but that of the Coriolies absorber increases rapidly with the magnitude of vibration. Considering the absorber's characteristics, it is applicable to many systems such as gondola, boats, and cranes.

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BỘ HẤP THỤ ĐỘNG LỰC SỬ DỤNG LỰC CORIOLIS LẮP CHO CABIN CÁP TREO

Sự lúc rung do gió của cabin cáp treo có thể được giảm bớt nhờ việc sử dụng bộ hấp thụ động lực. Để tối ưu hóa hiệu quả, bộ hấp thụ động lực thông thường cần có vị trí càng cao càng tốt. Tuy nhiên, bộ hấp thụ không thể đặt ở vị trí cao do sự cản trở của các kết cấu khác như tháp treo cáp hoặc các trạm dừng. Để giải quyết vấn đề này, một dạng bộ hấp thụ động lực mới, chuyển dịch theo phương thẳng đứng, đã được đề xuất. Bộ hấp thụ này bao gồm khối lượng đỡ bởi lò xo. Khối lượng chuyển động theo hướng bán kính (lên và xuống) và nó gây ra lực Coriolis theo hướng chuyển động tròn và sẽ hạn chế sự lắc lư của cabin. Nếu tần số riêng của bộ hấp thụ được điều chỉnh gấp 2 lần tần số của cabin thì bộ hấp thụ sẽ chuyển động với biên độ lớn do cộng hưởng. Bộ hấp thụ này càng hiệu quả nếu được đặt ở vị trí càng thấp. Thí nghiệm với một mô hình thu nhỏ và một cabin thật dành cho 10 hành khách đã được thực hiện và các kết quả phù hợp tốt với các dự đoán lý thuyết.