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DEVELOPMENT OF THE PASSIVE NEGATIVE STIFFNESS DAMPER FOR REDUCING ABSOLUTE RESPONSES OF RAILWAY STRUCTURES

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Abstract

In this paper, a new vibration control device realizing negative stiffness in a passive manner is proposed in order to reduce the absolute response of structures under strong seismic motions. The developed device consists of a sliding plate with a PTFE portion, and they are vertically pressurized by coil springs. The shape of the sliding plate is convex, by which the control force is negatively proportional to the deformation. In addition, the proposed device comes with supplemental friction energy dissipation between the sliding plate and the PTFE in order to prevent a significant increase in the displacement of the damper. The prototype of the proposed device was assembled, and its performance was investigated through both sinusoidal and hybrid loading tests. It was found from the periodical loading tests that the proposed device generated the designated negative stiffness as well as friction energy dissipations in a good accuracy. It was also confirmed from the hybrid loading tests assuming the viaduct equipped with the damper device that the proposed device significantly reduced the absolute and relative responses of the slab and base shear of the column. It consequently follows that the proposed negative stiffness damper could be applicable to railway structures, assuring structural damage reduction and running safety of trains simultaneously.

Keywords: Negative stiffness control; passive damper; hybrid loading tests

1. Introduction

In the seismic design standard for railway structures in Japan revised in 2012, the “Robustness against Crises” was determined as indispensable performance for every railway structure [1]. It is referred to as the inherent performance of the structures that should not be vulnerable under very strong earthquakes, even if the intensity of the motion exceeds the prescribed design level. This concept arose from the lessons drawn from the past earthquakes, such as the 1995 Kobe Earthquake, the 2004 Niigata-ken Chuetsu Earthquake and the 2011 Great Tohoku Earthquake. Railway structures are now required to be properly designed and/or retrofitted to meet such a concept more than ever. Among the variety of countermeasures available to satisfy this requirement, use of the structural control is regarded as one of the most promising options to keep the structure intact by the vibration energy dissipation. In recent years, various types of structural control methods and devices have been developed and employed on railway bridges, road structures and buildings [2-6].

Here, desirable features of a control device for railway structures should include the reduction of both the absolute acceleration and absolute displacement simultaneously.Whereas the reduction of the absolute acceleration contributes to the damage reduction of structures, suppressing the absolute displacement is another key feature particularly for railway structures, since the damage of the track on which the vehicles are running is affected by the absolute displacement.

Based on this background, a new control device which is suitable for a railway structure by making use of the "negative stiffness" control method is proposed in this paper. One of the advantages of this control technique over traditional methods is that it reduces the absolute acceleration and displacement, by which the requirements with regard to the structural invulnerability and the running safety of the train are met simultaneously. In this paper, the basic concepts of the negative stiffness control and the real device realizing the control by a simple

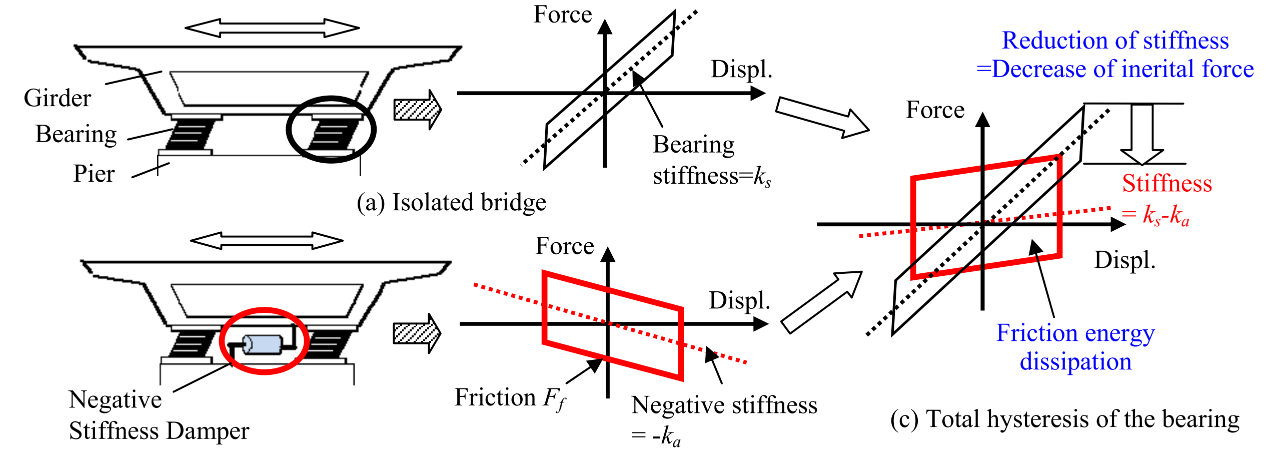


Fig. 1 Effect of the negative stiffness damper installed in an isolated bridge

passive mechanism were proposed, and its efficacy on seismic response reduction was investigated through series of periodical and hybrid loading experiments.

2. Overview of the negative stiffness control

The negative stiffness control is one of the structural control methods where the control force is negatively proportional to deformation. Unlike other methods, negative stiffness control makes it possible to decrease the total stiffness of the structure, thereby suppressing the absolute acceleration and absolute displacement.

Assuming a bridge with an isolation bearing having a linear positive stiffness (=k_s) as shown in Fig. 1(a). In this structure, the force-displacement relation of the bearing is represented by Fig. 1 (c). It is obvious from the figure that the force acting between the girder and the pier is proportional to the deformation of the bearing. It follows that the unexpected damage of the structure might take place if the displacement of the bearing exceeds the prescribed design level due to an extreme earthquake. It is possible to decrease the acting force by reducing the stiffness of the bearing itself. However, such a design is not necessarily a feasible solution, since the soft bearings might not have enough vertical stiffness to support the weight of a girder.

In order to overcome such a difficulty, the new "negative stiffness" device is proposed that is installed parallel to the bearing as shown in Fig. 1(b). This device has a capability of generating a force (=F_D) which is negatively proportional to the displacement (= x), namely,

$$F_D = -k_a x \tag{1}$$

Where $-k_a$ is the stiffness of the device ($-k_a$<0). Since the total stiffness of the bearing is represented by the summation of the stiffnesses with regard to the bearing and the device, it is reduced to $k_s - k_a$ by using the device (see Fig. 1(c)). As this reduction of the bearing stiffness is directly related to the force acting between a girder and a pier, the proposed device could reduce the absolute acceleration or the inertial force of the girder accordingly. The advantages of the negative stiffness control over traditional methods were theoretically and numerically examined [6-8].

Decreasing the total stiffness of the bearing, however, might increase its displacement, depending on the characteristics of the structures and the seismic motion. It follows that negative stiffness control should come with supplemental damping such as a friction energy dissipation system to prevent a significant increase in bearing displacement. Consequently, the nonlinear behavior of the damper device to be developed is expressed by the combination of the negative stiffness and the friction damping, that is,

$$F_D = -k_a x + F_f(\dot{x}) \tag{2}$$

Where $\dot{x}$ is a velocity of the device and F_f is the friction force. Fig. 1(b) shows the schematic of this relation.

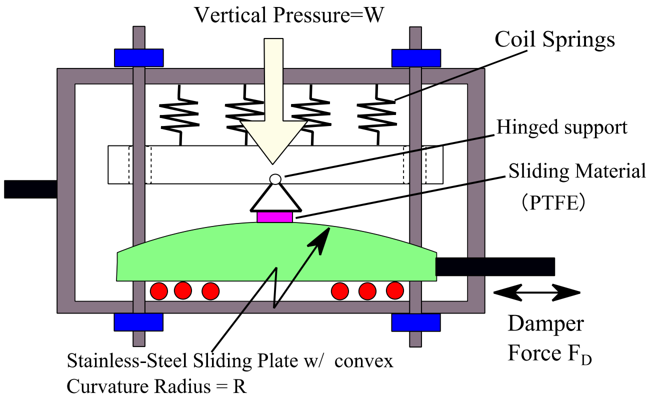


Fig.2 Schematic of the proposed negative stiffness damper

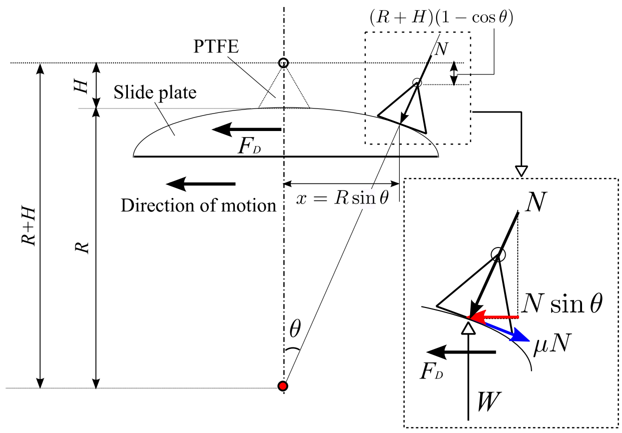


Fig.3 Free body diagram of the sliding plate and the PTFE

3. Proposed damper realizing the negative stiffness

3.1 Overview of the damper device

The negative stiffness device needs to generate its force to accelerate displacement, whose mechanism is contrary to ordinal dampers. It follows that building an actual damper device has been achieved by using active controlled actuators or semi-active devices with controllers and sensors[5,6]. Recently, the passive mechanism realizing the negative stiffness by a combination of a planar frame with a pre-loaded springs was also proposed[7]. For application to existing railway structures, however, those control systems are not regarded as alternatives to the widely-used passive dampers, in terms of the long-term robustness and the costs of installation and maintenance. Simpler and more economical devices are needed.

On the basis of these requirements, a new mechanism providing negative stiffness control in a simple passive manner was developed. Fig. 2 shows the overview of the damper device. The developed device consists of a stainless-steel sliding plate with a PTFE portion, and they are vertically pressurized by coil springs. As shown in Fig. 2, the shape of the sliding plate is a convex, by which the device force is negatively proportional to its displacement. Apart from generating the vertical pressure, the coil springs are also employed to absorb the vertical displacement between the sliding plate and the PTFE according to the horizontal displacement of the device. As shown in Fig.2, the PTFE were attached to coil springs using the gadget. Since one end of which was a hinge, the PTFE could maintain the planar contact with the curved stainless-steel plate even when a large displacement took place. In addition, this device was also designed to dissipate the vibration energy by the friction force acting between the sliding plate and PTFE.

In fact, a similar negative stiffness damper for the bridges has already been proposed by authors, in which the weight of a girder was used as an alternative to the coil springs [8]. This device, however, is less applicable to various structures such as viaducts where the pressurizing weight is not available. On the contrary, the proposed device in this paper is the standalone and does not require any external force. The improved device is referred to as the "negative stiffness damper" in the following discussions.

3.2 Modeling of the damper device

A mathematical model representing the device force as functions of displacement and velocity is needed for designing the damper. Fig. 3 shows the forces acting on the sliding plate, assuming the sliding plate is moving leftwards. From this figure, the horizontal control force of the device is given by the equilibrium with regard to the horizontal direction as,

$$F_D = N\left(-\sin\theta + \mu\cos\theta\frac{\dot{x}}{|\dot{x}|}\right) \tag{3}$$

Where F_D is the device force, N is the contact force perpendicular to the surface of the sliding plate, μ is the friction coefficient of the PTFE and the stainless-steel plate, x and $\dot{x}$ are displacement and velocity of the device. In addition, θ depicted in Fig. 3 represents the horizontal location of the PTFE that is related to the displacement x and the curvature radius of the sliding plate R as,

$$\sin\theta = \frac{x}{R} \tag{4}$$

Considering the equilibrium with regard to the vertical direction, the contact force N is expressed by the pressurizing force of the coil spring W as follows.

$$N = W\cos\theta \tag{5}$$

$$W = -k_{spg}(R+H)(1-\cos\theta) + W_{init} \tag{6}$$

Where k_{spg} and W_{init} are the spring constant and the initial induced force of the coil spring at $x=0$, respectively. Note that W is dependent on the displacement since the coil spring is expanded according to the horizontal motion of the convex sliding plate. By substituting Eqs. (4) and (5) into Eq. (3), the horizontal force of the device is obtained as,

$$F_D = -\frac{W}{R}\cos\theta \cdot x + W\mu\frac{x}{|\dot{x}|}\left(1-\left(\frac{x}{R}\right)^2\right) \tag{7}$$

Assuming the displacements in the horizontal and the vertical directions are infinitesimal, Eq. (7) is simplified as follows.

$$F_D = -\frac{W_{init}}{R}\cdot x + \mu W_{init}\frac{\dot{x}}{|\dot{x}|} \tag{8}$$

Eq. (6) is also used for deriving Eq. (8). By comparing Eq. (8) with Eq. (2), it is obvious that the desirable negative stiffness is realized by properly determining the ratio of the initial induced force of the coil spring (=W_{init}) to the curvature radius of the sliding plate (=R). In addition, the amount of friction energy dissipation is controlled by an induced force W_{init} and the friction coefficient μ.

4. Verification tests of the basic features of the damper

In order to verify the effectiveness of the proposed mechanism generating the negative stiffness, the prototype was designed and manufactured as shown in Fig. 4. The size of the PTFE portion was width 40mm x depth 40mm x thickness 8mm. The curvature radius R of the stainless-steel sliding plate was 497mm, and the maximum allowable displacement was ±60mm. A total of six coil springs were employed to generate the vertical pressure of W_{init}=24 kN between the PTFE and the sliding plate. According to Eq. (8), the expected negative stiffness was -48.3 N/mm. In addition, the friction coefficient μ between the PTFE and the stainless-steel sliding plate was expected to be from 0.1 to 0.15, referring to past research [9].

The fundamental performance of the constructed device was then investigated by cyclic loading tests. The test was carried out using the displacement-controlled hydraulic actuator, and sinusoidal motions were applied to the device. The test setup is shown in Fig. 5. The loading frequencies were 0.01Hz, 0.1Hz and 1.0 Hz. The maximum displacement values for each loading frequency were set at ±20mm, ±30mm, ±40mm and ±50mm.

Fig. 6 and Fig.7 show the measured force-displacement relation for when the loading frequencies were 0.01Hz and 0.1Hz, respectively. As clearly seen in these figures, the proposed device displayed the downward-sloping hysteresis with stable friction. It follows that the device generated the force negatively proportional to the deformation, i.e. negative stiffness.

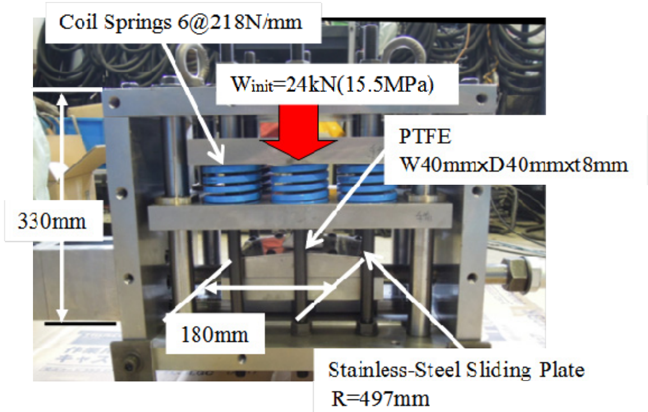


Fig.4 Schematic of the prototype damper

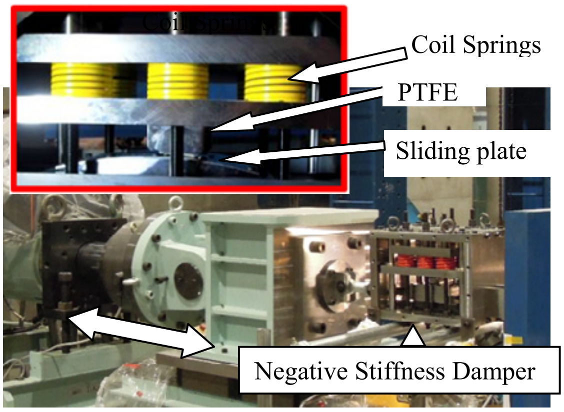


Fig.5 Test setup using the actuator

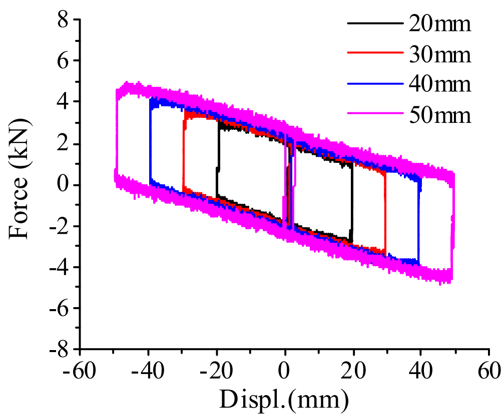


Fig.6 Force-displacement relation under sinusoidal loading (0.01Hz)

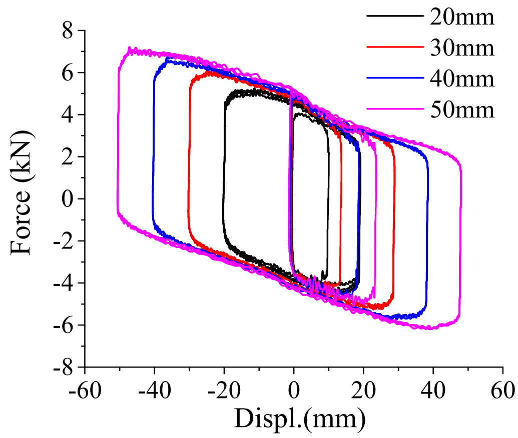


Fig.7 Force-displacement relation under sinusoidal loading (0.1Hz)

In order to evaluate the performance of the damper device quantitatively, the experimental results were fitted to the mathematical model Eq. (8) by employing the non-linear least square method. In this procedure, the negative stiffness and friction force were identified so as to minimize the evaluation function shown in Eq.(9).

$$E = \int_0^T \left(F_{Dm}(t) - F_{De}(t; -k_a, F_f) \right) v(t) dt \tag{9}$$

Where $F_{Dm}(t)$ and $v(t)$ are the measured force and loading velocity, T is the loading duration, and $F_{De}(t)$ is the estimated damper force from Eq.(2), which is the function of the negative stiffness and friction coefficient. The identified negative stiffness, friction force and corresponding friction coefficient for all tests are shown in Fig. 8 and Fig. 9, respectively. In these figures, design values (-48.3 N/mm for the negative stiffness and 0.1-0.15 for the friction coefficient) are also depicted by dashed lines, for reference.

From Fig. 8, it is found that the proposed device successfully generated the desired negative stiffness in a good accuracy. With regard to the friction force and corresponding friction coefficients in Fig. 9, they were increasing according to the loading frequency. It is due to the velocity dependency of the friction coefficient that is generally observed in a sliding material [9]. Nevertheless, the produced friction forces were almost within the prescribed range. From these results, it is confirmed that the proposed damper mechanism made it possible to produce the designated negative stiffness and friction energy dissipation with considerable accuracy.

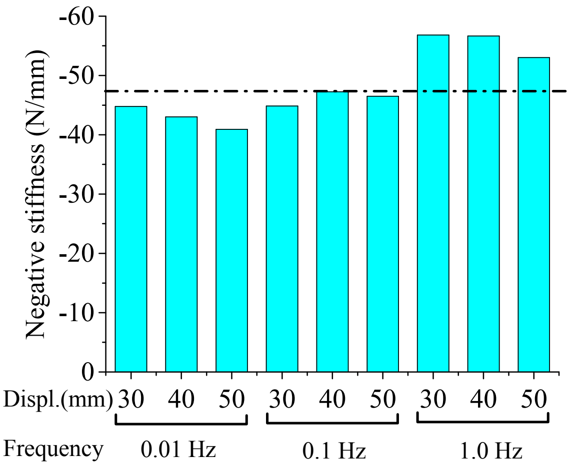


Fig.8 Identified negative stiffness

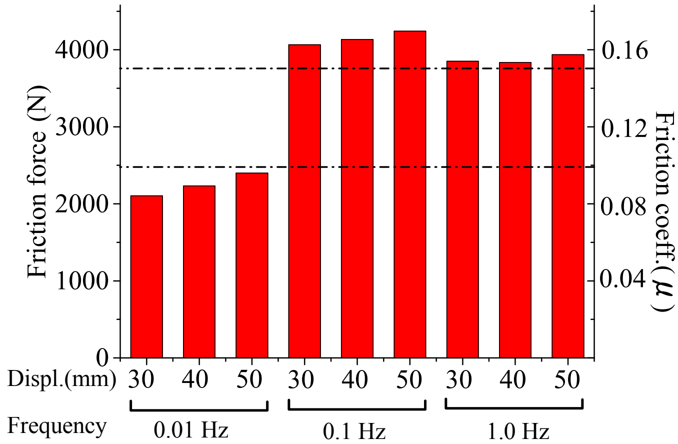


Fig.9 Identified friction force and corresponding friction coefficient

5. Hybrid loading tests for evaluating structural response reduction

On the basis of the performance verification tests, the effectiveness of the proposed damper device embedded in a structure was investigated. As shown in Fig. 10, a two-degree-of-freedom bridge model consists of a pier (node 1) and a girder (node 2) was assumed, and the proposed device was installed in between the nodes. The dynamic behavior of the bridge with the damper device was investigated under earthquake loadings, considering the interaction between the device and the structure. This test was carried out by employing the hybrid loading technique, in which the numerical simulation of the structure and the loading of the device were combined simultaneously. That is to say, the device was excited by a displacement-controlled actuator, and the measured force was incorporated into the numerical calculation of the structure. The resulting displacement of the damper device was then given to the actuator as the next target position. Repetition of this procedure permitted a precise investigation of the seismic behavior of the device installed in the structure.

A digital signal processor was utilized to instantaneously carry out the complex operations, including the measurement of the force and the displacement of the damper device, the calculation of the equation of motion and the operation of the actuator. Those procedures were carried out with a sampling frequency of 1 kHz. In addition, modified operator splitting method assuring the precise numerical integration without time-consuming iteration was adopted to solve the equation of motion [10].

The parameters of the hypothetical structure were selected as shown in Fig. 10 based on the preliminary numerical simulations. These values were determined to enable tests to be performed while meeting the device's maximum displacement and force constraints. In addition, this structure was assumed to be a linear system to emphasize the vibration reduction effect due to the device's nonlinear behavior. The natural frequencies of the structure in the 1st and 2nd modes were 0.96 Hz and 2.0 Hz, respectively. A damping ratio of 3% was given to each mode to express the structure's inherent damping. Two different types of acceleration were selected as the inputs for the tests. The one was the Level 2 motion Spectrum II for G3 ground condition whose maximum acceleration was scaled to 150 gal. This motion has been widely used for verifying the safety and restorability of railway structure constructed on a good ground condition. The other was sinusoidal motion, the frequencies of which were swept from 0.3 Hz to 2.0 Hz in 30 sec while keeping a maximum acceleration of 80 gal. These motions are referred to as "L2 motion" and "swept motion" hereafter.

As a representative result, Fig. 11 shows the force-displacement relation of the damper device under swept motion. Figures 12 and 13 represent the absolute acceleration time histories and the corresponding frequency responses with respect to node 1 and node 2. In these figures, responses without the device obtained from preliminary simulations are also depicted.

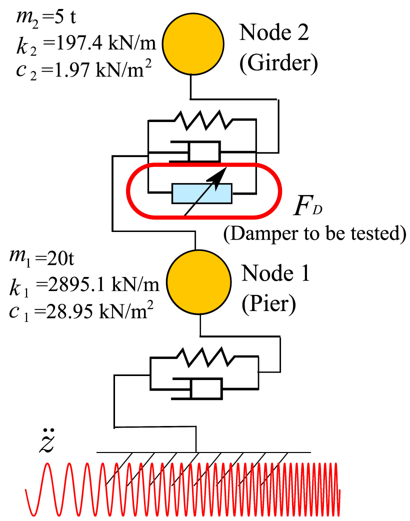


Fig.10 A 2DOF model for hybrid loading tests

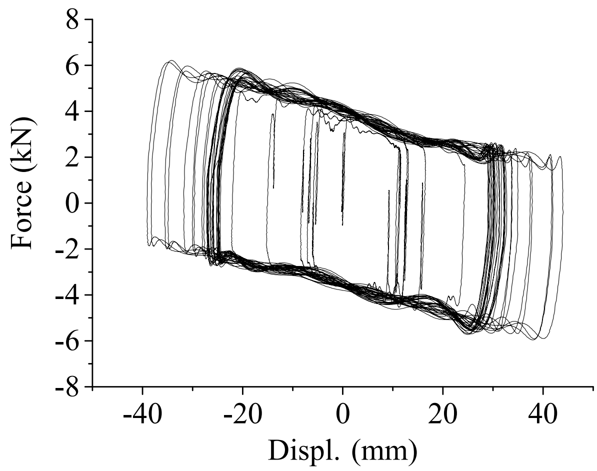
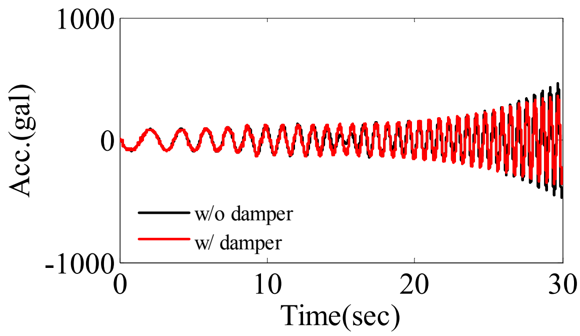
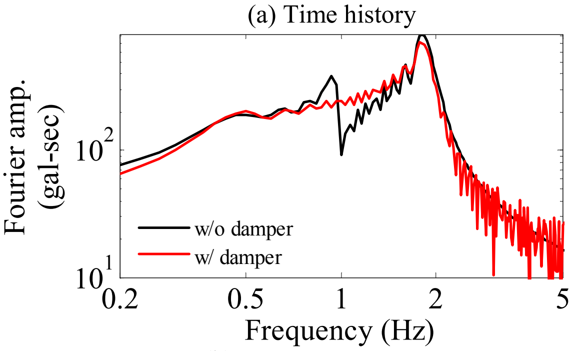


Fig.11 Force-displacement loop under swept motion

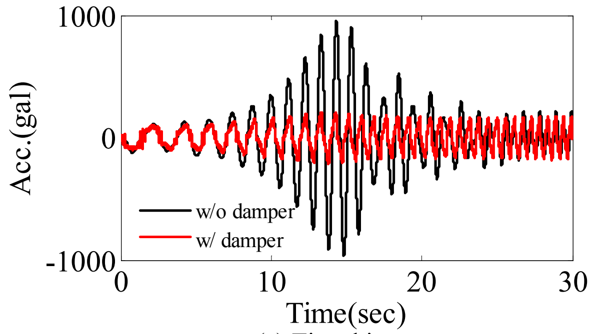


(a) Time history

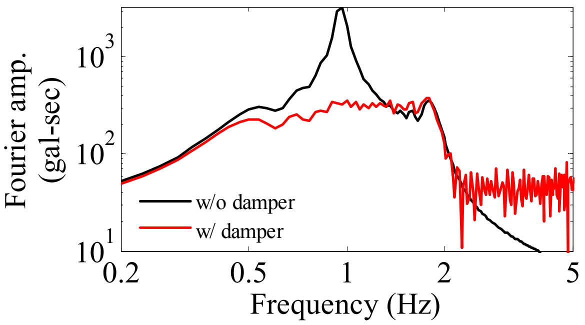


(b) Frequency response

Fig. 12 Comparison of the absolute acceleration response of node 1 with and without the device under swept motion



(a) Time history



(b) Frequency response

Fig.13 Comparison of the absolute acceleration response of node 2 with and without the device under swept motion

As clearly seen in Fig. 11, the proposed device generated the stable negative stiffness and friction damping even under nonstationary motion. It is also found from Fig. 12 and Fig. 13 that the resonance motion at around 1st mode frequency was sufficiently suppressed by the damper's negative stiffness and the friction damping. With regard to the frequency characters of the response with the device, it was assumed that the negative stiffness decreased the total stiffness of the structure and the resulting peak response was expected to

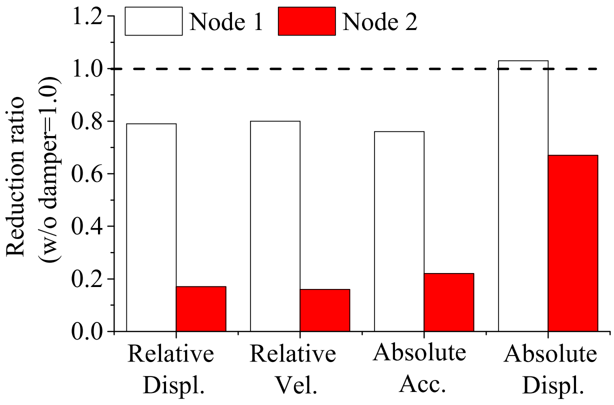


Fig. 14 Maximum response reduction ratios under swept motion

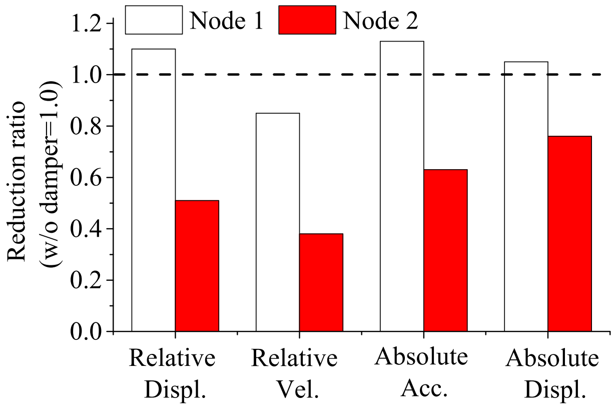


Fig. 15 Maximum response reduction ratios under L2 motion

appear at the lower frequency than that without the device. Fig. 13 shows, however, that there was no clear peak response due to the friction damping that smoothed its peak response.

The effectiveness of the damper device was also evaluated on the basis of the maximum response reductions with regard to the relative displacement, relative velocity, absolute acceleration and absolute displacement. The reduction ratio, I, was introduced for the evaluation as,

$$I = \frac{\max\left(\left|R_{w/d}\right|\right)}{\max\left(\left|R_{w/od}\right|\right)} \tag{10}$$

Where, $R_{w/d}$ and $R_{w/od}$ are the responses with and without the device. It follows that the damper device suppresses the response if the index I is less than unity. Fig. 14 and Fig. 15 show the reduction ratios under the swept motion and the L2 motion, respectively.

These figures show that significant reductions in absolute responses were observed at node 2. These reductions were possibly caused by the following effects: 1) the reduction of the apparent stiffness and the interaction force between nodes 1 and 2 due to the negative stiffness suppressing the absolute acceleration and displacement transmitting from the pier to the girder; and, 2) the friction damping dissipating the vibration energy of the structure and suppressing the displacement of the device itself. In particular, more reduction effect was observed in case of the swept motion, where the number of repetitions and resulting cumulative energy dissipation was relatively higher than for L2 motion. On the contrary, no apparent reduction effects were observed in node 1 responses. As seen in the frequency response in Fig. 12, the frequency response without the device decreased at around 1 Hz. The same figure shows that this fluctuation was smoothed by introducing the damping, and the transfer ratio rose accordingly. This smoothing effect could have caused the increase in the response in the 1st mode frequency that dominated the total response of node 1.

It is concluded from these experimental results that the proposed damper device generated stable negative stiffness and friction energy dissipation, and contributed to reducing the girder response. This effect could improve not only the vulnerability of the structure but also the train running safety, they are affected by absolute responses. It should be noted, however, that such a significant reduction could take place partly because the structure is assumed to be a linear system, in which the response of the structure without a damper device would be drastically increased by the resonance. Nonlinear structural models will be employed for hybrid loading tests in further research, in order to carry out verification tests on the damper in more practical situations. In addition, improvement of the damper capacity such as maximum force and displacement is also required in the further research.

6. Conclusions

In this paper, a new vibration control device realizing negative stiffness in a passive manner was proposed in order to reduce the absolute response of structures under strong motions. A prototype of the proposed device was assembled, and its performance was investigated through both sinusoidal and hybrid loading tests. Several conclusions are summarized and remarked as follows:

(1) A new vibration control device realizing negative stiffness by a simple mechanism was proposed for railway structures. The developed device consists of a convex sliding plate with a PTFE portion, vertically pressurized by coil springs. Since this device generates negative stiffness in a passive manner, it is possible to attain significant vibration reduction while suppressing the manufacturing and maintenance costs.

(2) The prototype of the proposed device was assembled, and its performance was investigated through sinusoidal loading tests. It was found that the proposed device generated the designated negative stiffness as well as friction energy dissipations in a good accuracy.

(3) It was confirmed from the hybrid loading tests assuming the bridge equipped with the damper device that the device significantly reduced the maximum absolute and relative responses of the girder under both design earthquake and periodical motion. It consequently follows that the proposed damper contributes to the improvement of structural vulnerability and train running safety during earthquakes.

In applying the negative stiffness device to the real structures, however, preliminary numerical simulations considering the nonlinear behaviors of the structure and damper are needed. The combined model of the negative stiffness and friction shown in Eq. (8) is used for the simulation, since the precisely manufactured convex and coil springs will realize the designated negative stiffness in a good accuracy as shown in this paper.

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