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Induced current damping for the suspension system of a gravitational-wave detector

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The damping technique is necessary to control a suspended mass used for an interferometric gravitational wave detector. Here we introduce a new damping method, called ''induced current damping,'' which has a simple mechanical and electric design and a desirable attenuation performance of pendulum. The fundamental concept of the induced current damping is a conversion of the mass motion to the Joule heat of an external coil. To realize an optimal Joule heat the effective internal resistance of the coil used for the induced current damping is reduced by connecting a negative resistance circuit to the coil. We built a one-dimensional suspension system with the induced current damping and demonstrated that the system worked as expected. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1510547]

I. INTRODUCTION

In 1917, Einstein predicted the existence of space-time ripples which are called gravitational waves. In the 1970's, it was recognized that a Michelson interferometer would be a superior means to detect gravitational waves. Currently several projects in the world are working towards the detection of gravitational waves with large-scale interferometers such as TAMA in Japan, Virgo and GEO, in Europe and LIGO in the USA. The first detection of gravitational waves could be achieved within a few years by these detectors.

The reason why gravitational waves have not yet been detected is that the effect of gravitational waves on the distance between masses is so small that it hides itself under various kinds of noise in the detectors. Among those noise sources, it is seismic fluctuations that limit the sensitivity at low frequencies ($\leqslant$ about 100 Hz). Optical components in a laser interferometric gravitational wave detector are suspended as pendulums to be isolated from seismic noise. The motion of a pendulum at its resonant frequency, however, would be an obstacle for the control of the interferometer. This resonant motion must be damped.

Currently there are two types of damping systems in use: active and passive. Although both systems are working well enough in the existing detectors, they require complicated optical or mechanical designs to optimize the performance of the systems. Here we show a completely new method that is simple and flexible. It is ''induced current damping.''

II. THEORY

A. Conventional damping system

The transfer function of a pendulum from the motion of the suspension point to the motion of the mass has a steep peak at its resonant frequency and rolls off as $\sim f^{-2}$ above the resonant frequency. Since this f^{-2} rolloff is essential for seismic attenuation, any damping system for the resonant peak should not impair this attenuation performance.

Let us first consider velocity damping, where a force proportional to the velocity of the mass is applied as a damping force on the mass. If the velocity of the mass is measured with respect to the suspension point, the attenuation performance of the pendulum is degraded by the velocity damping. This is because the damping force, which consists of the velocity signal of the mass and the suspension point, is dominated by the velocity signal of the suspension point above the resonant frequency. This makes the transfer function of the pendulum f^{-1} instead of f^{-2} at higher frequencies.

LIGO uses an active damping system,[1,2] where a position sensor consisting of a LED and a photodetector and an actuator consisting of a magnet and a coil are used. Since the position sensor is attached to the suspension frame, the at-

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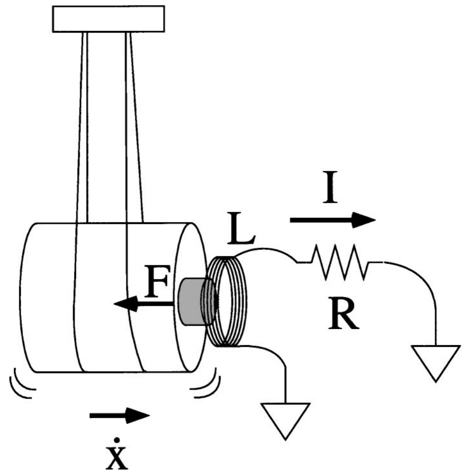

FIG. 1. Pendulum and coil with negative resistance circuit. A magnet is attached to the suspended mass.

tenuation performance of the pendulum would be degraded if the velocity signal is directly applied to the mass. In order to avoid this, a low-pass filter is incorporated in the servo system so that the damping system is inactive at higher frequencies. Although this system allows a flexible design of the frequency dependent servo system, a delicate optical design for integration of both the position sensor and the actuator into the system is required. Moreover, the interaction between the scattered laser light by the mirror and the photodetector of the local sensor could cause a serious problem.

TAMA uses a passive damping system.[3] A strong magnet is placed near an intermediate metal mass from which the mirror is suspended. An eddy current is generated on the surface of the intermediate mass with its amplitude linear to the velocity between the magnet and the mass. This eddy current produces a magnetic force and damps the motion of the mass. Since the motion of the mirror is strongly coupled with the motion of the intermediate mass, the mirror motion is automatically damped by this mechanism. Because this eddy current damping is a kind of velocity damping, the attenuation performance of the pendulum would be degraded if the magnet is attached to the same frame as the suspension point. In order to avoid this, the magnet is also suspended as a pendulum which has a higher resonant frequency than the pendulum of the main mass, so that the damping force is no longer proportional to the velocity with respect to the suspension point at higher frequencies. Although this system does not require an electronic servo system, a complicated mechanical design is required to optimize the performance of the damping system.

B. Induced current damping

We developed a new damping system which has a flexibility for incorporating frequency dependence while remaining simple in design. The new system has a magnet attached on the mass and a coil attacted to the suspension frame with relative position which maximizes the interacting force (Fig. 1). The mass motion generates an induced current in the coil which produces Joule heat, if the coil is connected to a normal resistor. This motion–heat conversion makes damping

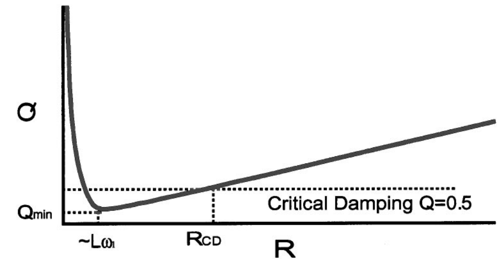

FIG. 2. Q factor as a function of total resistance R. Q takes minimum value when $R \sim L\omega_1$. R_{CD} is smaller than the internal resistance, which is required to realize the critical damping.

possible. A difference from the eddy current damping is that any circuit can be connected to the coil to easily realize any desired frequency dependence.

When the magnet on the mass approaches the coil with a velocity $\dot{x}$, the voltage of $V=\alpha_1\dot{x}$ is induced. So the current in the coil is described by the differential equation

$$\alpha_1\dot{x}-RI=L\frac{dI}{dt}, \tag{1}$$

where R is a series resistance including the internal resistance of the coil, $I(t)$ is the current in the coil, and L is the inductance of the coil.

The force F applied to the magnet is proportional to the magnetic moment of the magnet M as well as the magnetic field produced by the coil, which is proportional to the current of the coil. Here the equation of motion is derived to be

$$m\ddot{x}=-m\omega_0^2x-\alpha_2MI, \tag{2}$$

where m is the mass of the test mass and α_2 is the coupling parameter which depends on the number of windings, the radius of the coil, relative position of the magnet, etc.

Equations (1) and (2) indicate that the resonant frequency shifts from ω_0 to ω_1:

$$\omega_1^2=\omega_0^2+\beta\frac{L\omega_1^2}{R^2+L^2\omega_1^2}. \tag{3}$$

With this new resonant frequency, the quality factor of the pendulum Q is

$$Q=\frac{\omega_1}{\beta}\frac{R^2+L^2\omega_1^2}{R}. \tag{4}$$

Here the coefficient $\beta=\alpha_1\alpha_2M/m$ represents the coupling strength between the magnet and the coil. The quality factor reaches its minimum value roughly when $R\simeq L\omega_1$ (Fig. 2). This means that the quality factor of the pendulum is large either when R is large and thus the current is small or when R is small with the series impedance of the coil limited by the inductance and thus no energy is dissipated in the coil.

C. Negative resistance

Since typical coils have an internal resistance that is much larger than the resistance required to realize significant damping, we have to connect a negative resistance circuit to the coil (Fig. 3). In this circuit the input voltage V_{in} has the opposite polarity to the input current I, hence the effective resistance value of the circuit is negative.[4,5]

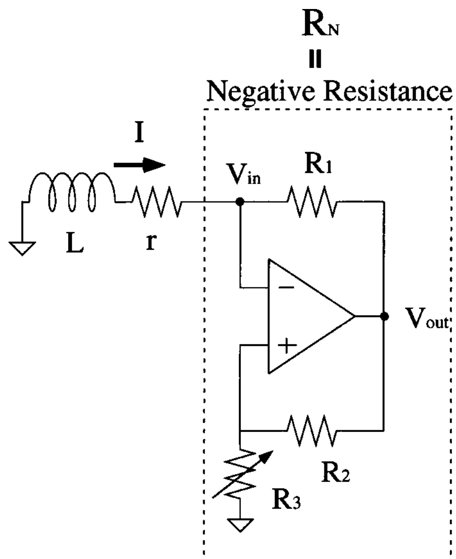

FIG. 3. Negative resistance circuit.

$$R_N = -\frac{R_1 R_3}{R_2}. \tag{5}$$

It is important to maintain the following two conditions to avoid instability. One is to keep the total resistance positive, i.e., $r > R_1 R_3 / R_2$, otherwise the system generates energy instead of dissipating it. The other is to keep the sum of the OP amp feedback negative. To satisfy both conditions, the damping coil must be connected to the negative terminal of the OP amp.

D. Transfer function

Figure 4 shows the transfer function of the pendulum using various kinds of damping systems. The transfer function for the eddy current damping system with the damping magnets fixed with respect to the suspension point shows an f^{-1} slope above the resonant frequency, whereas the damping system using a coil and negative resistance shows an f^{-2} slope above a threshold frequency. This is because the impedence of the coil increases at higher frequencies limiting the current in the coil.

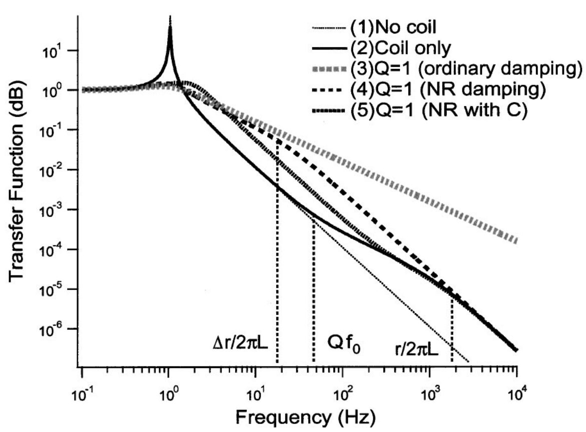

FIG. 4. Calculated transfer function. (1) No coil; (2) internal resistance of the coil defines the Q value. Damping kickback starts at $f = Qf_0$ and ends at $f = r/2\pi L$, from which the inductance becomes dominant; (3) in eddy current damping system, the kickback continues forever and the attenuation is degraded; (4) resistance is small enough that the inductance becomes dominant much earlier allowing the curve to steeply decay. (5) The capacitor has canceled the kickback so the attenuation performance is improved.

The attenuation performance can be further improved with a capacitor C_3 in parallel with R_3 (or R_1), which inactivates the negative resistance circuit at higher frequencies. In the figure, the transfer function using the capacitance shows a significant improvement in the attenuation performance.

It should be noted that the addition of capacitance enhances the resonant frequency by changing the effective resistance and inductance of the circuit as follows:

$$R \rightarrow r - \frac{R_1 R_3}{R_2} \frac{1}{1 + R_3^2 C_3^2 \omega^2}, \tag{6}$$

$$L \rightarrow L + \frac{R_1 R_3}{R_2} \frac{R_3 C_3}{1 + R_3^2 C_3^2 \omega^2}. \tag{7}$$

Thus there exists an optimal capacitance for each Q value desired.

It may be possible to further improve the performance of the system by connecting a more complicated frequency-dependent impedance, such that damping at the pendulum resonance is achieved while not affecting the attenuation at higher frequencies. Problems to be studied are stability of the electronic circuit and electronic noise.

E. Noise problem

In addition to the attenuation performance, the noise performance of the damping system is also very important. The Johnson noise, the thermal noise of the resistors, in the damping circuit using the negative resistance generates a noise current I_J in the coil:

$$I_J = \frac{\sqrt{4kT[R_2^2(R_3 + r) + R_3^2(R_1 + R_2)]}}{R_2(L\omega i + r) - R_1 R_3}. \tag{8}$$

If there is no damping circuit, I_J is $\sqrt{4kTr}/L\omega i$ at higher frequencies since the coil inductance L is dominant. Comparing with this, Eq. (8) indicates larger Johnson noise, but the noise level can be reduced to the same level by incorporating the capacitance to R_3, which makes R_3 negligible at higher frequencies.

The OP amp noise in the damping circuit can be also reduced since the impedance of the inductance of the coil is larger at higher frequencies.

III. EXPERIMENT

A. Experimental setup

To verify the theory and usefulness of the induced current damping, we prepared a single pendulum system, where a metal mass is suspended with two wire loops from a suspension frame. The pendulum length from the suspension point to the center of the mass is 19 cm, so the pendulum mode has a resonant frequency of 1.15 Hz. The test mass was chosen to be relatively light, ~60 g, for convenience of the experiment. The pendulum system was assembled with a special care so that no undesirable mechanical resonances

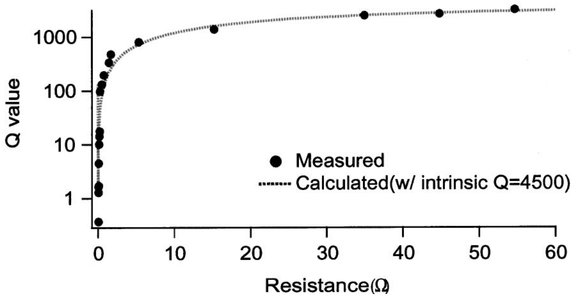

FIG. 5. Q vs R.

disturbs the measurement. For example, the pitch resonant frequency of the mass is set to be higher than 10 Hz, while the yaw resonance is set to be close to the pendulum resonance so that the effect of the yaw motion can be neglected compared with the pendulum motion.

A magnet is attached onto the center of the back surface of the mass, and a coil is attached to the suspension frame near the magnets in such a way that a part of the magnets is inserted in the coil. This pair of the magnet and coil is used to execute the induced current damping. The magnet is 2 cm long. The radius of the coil a is 0.5 cm and the number of windings N is 200, and the coil has an inductance of $L = 0.221$ mH and an internal resistance of $r = 4.05\ \Omega$. One side of the coil is connected to a negative resistance circuit and the other (shown as grounded in Fig. 3) is connected to a coil driver whose output impedance is zero.

The whole suspension system is placed on a metal plate, which is connected to a mechanical shaker for the actuation purpose. The metal plate sits on a frictionless translation stage to ensure one-dimensional motion. On the top of the suspension frame and below the test mass knife edges are attached. The position of the knife edges can be measured by photosensors, which are attached tightly onto an independent breadboard to avoid undesirable mechanical resonances and cross coupling from the shaker. This actuation and sensing system is used to measure the transfer function of the pendulum.

B. Experiment and results

We first measured the quality factor of the pendulum mode with various damping conditions. Higher damping was realized by tuning the negative resistance circuit, while lower damping was realized by adding an external series resistance to the coil. For the lower damping case (higher quality factor) we measured a ringdown time of the pendulum mode after exciting the mode to obtain the quality factor of the system. For the higher damping case (lower quality factor) we measured a transfer function of the pendulum from force to the mass motion with sweeping the frequency of applied voltages to the coil driver to obtain the quality factor. Figure 5 shows the result. It is shown that the quality factor of the pendulum system is successfully decreased to the level of critical damping by the negative resistance circuit. The measured quality factor agrees with the calculated value.

These measurements also lead us to find the value of β which gives the minimum of Q and the optimum of R and C_3

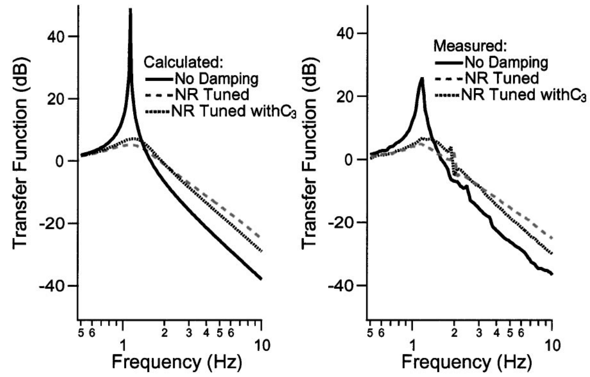

FIG. 6. Measured transfer functions show a good coincidence with calculated curves.

for each Q. In this experiment, $\beta = 0.043$ and nominal $Q_{\min} = 1.1$ when $R = 0.0045\ \Omega$.

We then measured the transfer function of the pendulum from the ground motion to the mass displacement under various damping conditions. We did it by shaking the whole system and measuring the position of the suspension frame and the mass with respect to the independent breadboard. Figure 6 shows the measured transfer functions together with the calculated ones. A curve rolls off as f^{-2} without damping and as f^{-1} with a simple induced current damping (which would roll off as f^{-2} because of the increasing impedence of the coil inductance at higher frequencies, but we could not measure it because of many mechanical resonances above 10 Hz). The most important result is that an induced current damping with a capacitor gives a curve that rolls off f^{-2} without any prominent resonances, which agrees with the theory. This indicates that we successfully prove the usefulness of the implementation of a capacitor into the negative resistance circuit to realize a good attenuation performance of a pendulum with the induced current damping.

We have demonstrated that the induced current damping is a simple and desirable method to damp the pendulum motion effectively without degrading the attenuation performance of the pendulum. Use of this system can simplify damping in all sorts of multipendulum suspensions for advanced gravitational wave detectors.

ACKNOWLEDGMENTS

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