Balance Pan Damping Using Rings of Tuned Sloshing Liquids

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Abstract—**This paper describes a new method to damp out balance pan oscillations, even when the balance is operated in a vacuum. The key is to tune the wavelength of the damping liquid by adjusting the depth. The liquid is sealed in a vacuum-compatible container attached above the pan, and the time that the wave travels from one side of the container to the other can be adjusted for maximum damping at the natural pendulum frequencies of the pan. We are investigating the practical application of this damping approach in our respective watt-balance experiments. It is shown that the channels in the shape of rings filled with liquids to the optimum depth work well.**

Index Terms—**Damping control, vacuum control, watt balance, wave damping.**

I. Introduction

The CONNECTION between the SI electrical units and the mechanical units requires combining the high-accuracy electrical standards with the mechanical standards that are part of the SI. The watt balance experiment directly measures the electric power using the Josephson effect and the quantum Hall effect in terms of the mechanical power using the kilogram, meter, and second. One key to such an experiment is building a high-accuracy balance that works in a vacuum and near high magnetic fields and accommodates the unusual need to move the mass pan along the vertical axis. This requirement comes from the fact that in a watt balance one uses a balance to compare the force on a coil (with a current) in a magnetic field against the force from a mass in the earth's gravitational field. The magnetic field and the coil geometry are calibrated in a second experiment by moving the coil and measuring its velocity and the induced voltage. At the Laboratoire National de métrologie et d'Essais (LNE), this coil velocity is produced by vertically moving the precision balance with the coil hanging from this balance while the balance remains in its optimal horizontal position [1]. At the National Institute of Standards and Technology (NIST), a wheel balance that has bands, which works like a pulley system, allows for a vertical velocity [2]. In both laboratories, a passive damping system like this tuned liquid damper seems ideally suited for damping out the perturbations produced in the weighing mode. These perturbations are caused when masses are placed on or taken off the mass pan.

Tuned-sloshing-dampers have been studied both experimentally and theoretically for the application of damping out the skyscraper oscillations caused by the wind or earth movements [3], [4] as well as the applications used to stabilize the ships using anti-rolling tanks [5]. The basic idea is that the energy of oscillations can be transferred to the energy loss within the liquid. By adjusting the depth of the liquid and its container length, one can get a dramatic improvement in the damping efficiency. These techniques were also used in the damping of unwanted motions in early satellites [6]. This paper looks at damping when applied to the simple and double pendulum motion of pans on a balance. It is shown that the rings of the tuned liquids work well.

II. Design Considerations

A simple equation can be used to approximate when the frequency f_l of the pan motion is equal to that of a liquid in a straight channel [3], [4]

$$f_l = \frac{1}{2\pi}\sqrt{\frac{\pi g}{L}\tanh\left(\frac{\pi h_l}{L}\right)} \cong \frac{1}{2L}\sqrt{g h_l} \qquad (1)$$

where h_l is the liquid depth, L is the channel length, and g is the gravitational acceleration. We first studied the damping of mass pans using linear channels, and some of the results are shown in the 2008 Conference on Precision Electromagnetic Measurements (CPEM08) Digest [7]. In this paper, we experimentally investigate the circular channels and how they improve the damping of unwanted pan motion. By observation, we see that tilting a ring of liquid starts two waves that propagate around the channel and collide into each other on the opposite side. From this observation, we make an additional assumption that, for an annular ring, the effective length is half of the mean circumference of the ring $L = \pi r_m$, where r_m is the mean radius. Combining this with (1) can be used to estimate the best depth for the container (good to about 30%) and then

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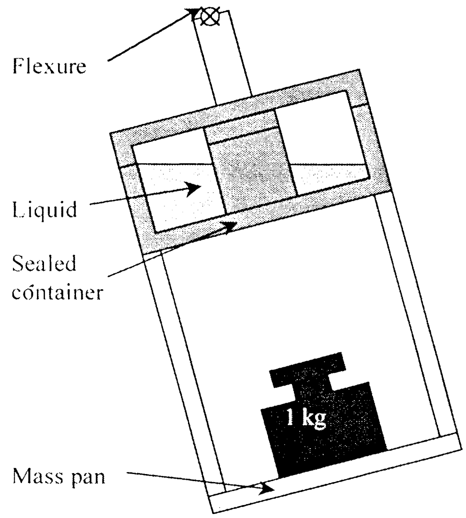

Fig. 1. Simple pendulum with a sealed container filled to the level of the highest damping. The damping is measured with the 1-kg mass on and off the pan.

empirically adjust the liquid level to optimize the damping of the pans. This equation has no firm theoretical footing, but as we will show, it is a reasonable estimator. Further theoretical analysis would be welcome.

Fig. 1 shows a sketch of a simple pendulum with the sealed damper. We show that the cylindrical design equally works for all the directions that might require damping. The wave motion starts on the high side of the ring with two waves traveling in opposite directions and colliding with each other on the other side of the ring. These equations give an approximate size for the ring, but we empirically tested several types of liquids and adjusted the depth of each liquid for maximum damping.

The range of frequencies common in the mass pans is a good match to this technique. For example, a pan used for the NIST test had $f_l = 1.35$ Hz, and (1) predicts $h_l = 7.6$ mm of liquid for $r_m = 32.5$ mm. We empirically found the maximum damping at 8 mm. Positioning the dampers is also critical. If the center of mass of all the weight on the pan is at the location of the liquid, then there is no motion of the liquid and thus no damping. In addition, if the damper is far above the flexure point, the liquid may be in an unstable equilibrium, where all the liquid shifts to one side. In a watt-balance experiment, it is common to make one weighing without any mass in the pan, and in this condition, the mass of the damper is likely to dominate the center of mass. Multiple channels (rings) can be machined, and the liquid depth in each channel can be adjusted to damp the various frequencies common in the pan system.

The weight of the damper can be a significant issue and is discussed in Section IV.

III. Requirements

The NIST watt balance experiment presently uses a single cross-flexure pivot that supports the mass pan, which creates a simple pendulum that must be damped to make good mass measurements. We are presently damping this pan motion by inserting a small vacuum-compatible rubber tubing in the holes that created the flexure elements, and this provides frictional

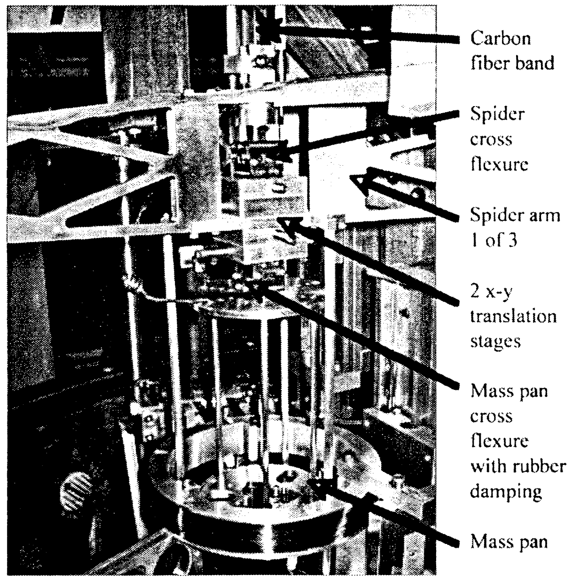

Fig. 2. NIST wheel balance showing the mass pan.

damping. This scheme has the potential to transmit unwanted torques through the flexure, and therefore, we plan to replace it with a liquid damper. This mass pan and flexure are attached to two translation stages to allow centering of the two flexures with respect to each other and the moving coil. The second (upper) flexure is at the center of a three-armed spider that holds the moving coil (see Fig. 2). The moving coil, which is in a magnetic field, can produce a force that is compared with the gravitational force of the mass placed on and off the mass pan as the coil current is reversed. This coil (not visible in Fig. 2) is connected by three 3-m rods to the spider. A small Helmholtz coil (only the upper section is shown in Fig. 2) maintains the standard mass near the zero field. It is not attached to the balance. The upper flexure connects both the spider and the mass pan forces. This spider flexure is attached to a carbon fiber band. Out of the picture, the carbon fiber hangs from a multifilament platinum–tungsten band that goes to a 60-cm diameter wheel balance. This wheel balance has a knife edge at the center and acts much like a pulley system, allowing 10 cm of linear vertical motion of the coil and mass pan. Thus, there are a number of flexure-type elements between the mass pan flexure and the balance. Because the coil has all 6 DOF critically damped by the electronic feedback, which also damps the motion of the pan flexure pivot, only the simple pendulum motion of the pan itself needs better damping. As we will see, the sloshing damper with only one channel is expected to work very well. There is also a mass pan on the counter mass side of the balance; therefore, two damper systems are needed. There are two frequencies associated with the NIST pans (one with the mass on and the other with the mass off), but they are very close; therefore, only one channel of liquid will be required.

The watt balance at the LNE employs a different method to produce the vertical coil displacement. Instead of a wheel balance, they have a linear displacement system that moves the balance along with the coil. This means that they use a state-of-the-art flexure balance that always operates at a fixed angle so that the two pan flexure pivot points are maintained

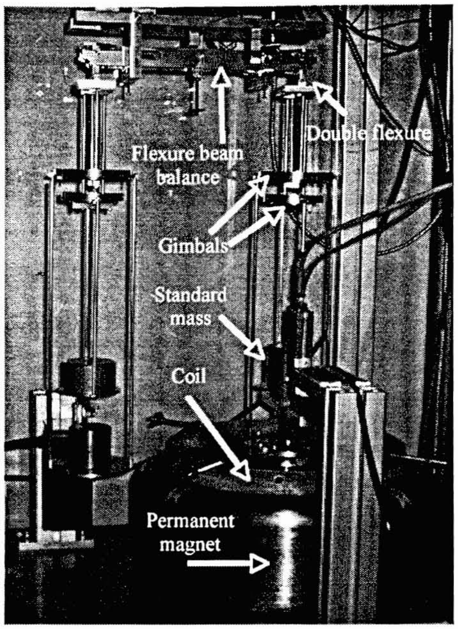

Fig. 3. LNE's first prototype without the translation stage that vertically moves the balance along with the coil.

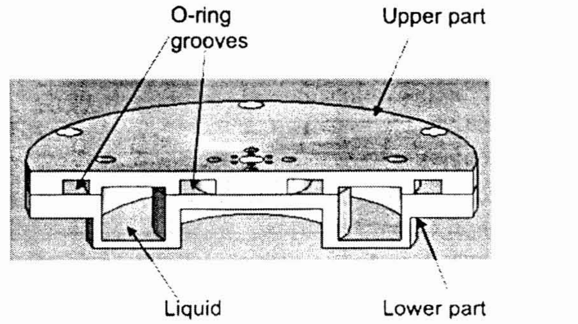

Fig. 4. Cross-sectional view of a damper. The liquid is sealed inside a 15-mm-wide channel. Two O-rings provide the vacuum seal.

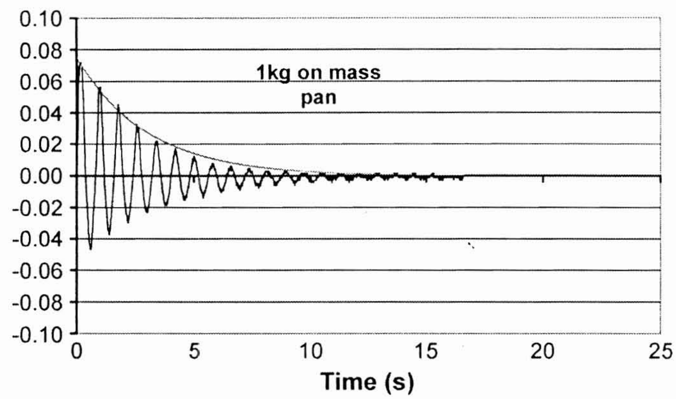

Fig. 5. Plot of the amplitude of balance pan swing in arbitrary units versus the time in seconds. The liquid is filled with 8 mm (22.5 ml), which is the optimum damping. The exponential curve is the best estimate of the decay rate. A 1-kg mass is on the pan.

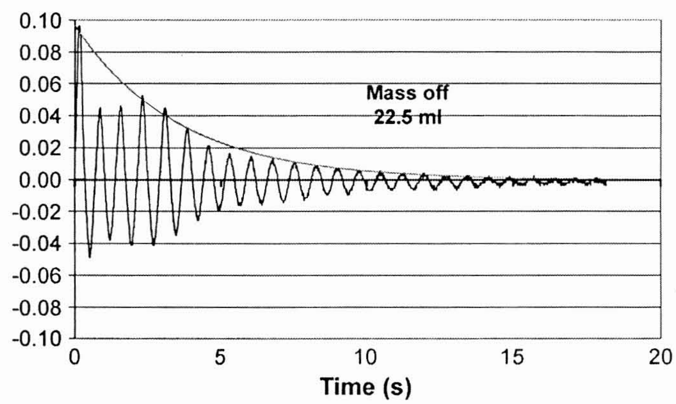

Fig. 6. Plot similar to Fig. 5 with 8 mm (22.5 ml) of liquid but no mass on the pan. The cause of the beating that is clearly seen is likely the mixing of the modes. This beating is only prominent when the liquid is near the optimal level. It has the effect of increasing the decay time.

in the same horizontal plane to the central flexure pivot point by servo control [8] (see Fig. 3). Two double flexures with one common pivot point are attached just below the pan flexures, which allow two forces to be combined at this central point of the double flexure pivot. One part of the double flexure is attached to the mass pan and the other to the coil system. The double flexure eliminates the need for the translation stage and the adjustments needed in the NIST experiment. Below the double flexure is another cross flexure to further reduce the torques being transmitted from the coils or mass pans. Thus, in the LNE experiment, the need is to damp a double pendulum motion. There are four such double pendula: one attached to the main coil and one with a mass pan on this same side. On the counter mass side, there are two more double pendula mass pans: one for a counter mass and one for a tare mass to balance the coil mass. A double pendulum has two frequencies, which change when the mass on the pan changes. It is likely that each double pendulum will need a tuned damper that has two or three channels to achieve the desired damping.

IV. Experimental Results

A. Simple Pendulum

The liquid used in the NIST damper is FC43 Fluorinert, which is a high-density 1860-kg $\times$ m^{-3} electronic fluid.[1] The channel width is 15 mm, and $r_m = 32.5$ mm. Fig. 4 shows a cutaway drawing of the damper under test, showing how the O-ring seals allow the damper with liquid in a vacuum. This damper with Viton O-rings was successfully tested for vacuum compatibility, but it has yet to be installed in the watt balance.

The damped oscillations are fitted to the following equations:

$$A = A_0 \sin(\omega t + \phi) e^{-t/\tau}. \qquad (2)$$

The amplitude of swing A is a product of a sinusoidal function and an exponential function. ω is the angular frequency, ϕ is the phase, and τ is the decay constant. The quality factor Q is defined to be the energy stored divided by the energy lost per

[1]Certain commercial materials are identified in this paper to adequately specify the experimental procedure. Such an identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials identified are necessarily the best available for the purpose.

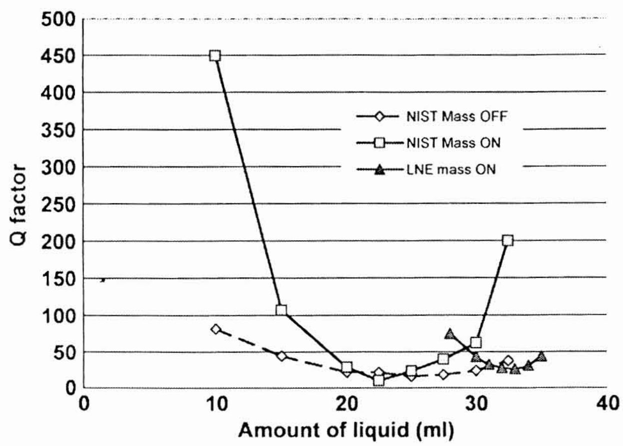

Fig. 7. Q as calculated from the estimated exponential fit of plots like Figs. 5 and 6. An 8-mm (22.5 ml) level of the electronic fluid will be used for the NIST system. The Q for no liquid is 14 000 when the 1-kg mass is on and 5000 when it is off. The LNE double pendulum has 5.9 mm (33 ml) of water as the maximum damping fluid.

cycle. For a two-pole oscillator with underdamped oscillation, Q is given by

$$Q = \omega\tau/2. \quad (3)$$

In both of the test setups in LNE and NIST, a mirror attached to the bottom of the mass pan deflects a vertical laser beam back to a linear displacement photo detector. It can detect either direction of the horizontal laser motion. Figs. 5 and 6 show a plot of this amplitude of the swing of the mass pan in arbitrary units versus time after a horizontal impulse has been applied to the pan. The exponential curve is our best fit for τ. The two plots are of maximum damping with a liquid level of 22.5 ml. One plot is with and one is without a 1-kg mass on the pan.

Fig. 7 shows a plot of the Q of the system as a function of the level of electronic fluid, which shows that the optimal level is 22.5 ml. The Q without any liquid and with 1 kg on the pan is about 14 000, and without the 1 kg on the pan, the Q is about 5000. This Q was measured in air. Two of the points on this graph come from the data shown in Figs. 5 and 6.

It is clear that the sloshing damper technique works well for this system, but the details for optimization are not simple. The damping depends on the liquid chosen, the width and diameter of the channels, and the location of the damper vertically. For this simple pendulum, there is just one mode in each orthogonal direction in which the pan can swing. The liquid, however, has many modes that can couple to this pan swing. This results in mixing and beating between the modes. It is easy to see this in Fig. 6, where the pan motion quickly damps and then builds before further damping. This beating is most apparent near the liquid level of the maximum damping. In an earlier test, we found that for a channel of width 12.5 mm, we achieved a maximum damping with the electronic fluid and only a little damping with water. When a larger width (22 mm) was tested, the electronic fluid had a lot of beating, which made this fluid less effective, whereas with water, the damping was much better. The damping with water in a 22-mm channel was equal to the damping of the electric fluid with a 12.5-mm channel. Because the LNE has a double pendulum, the damping requirements are even more complex.

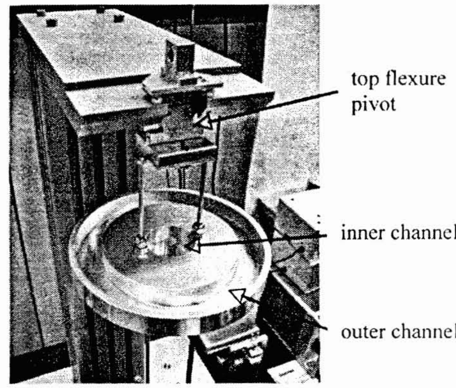

Fig. 8. LNE double pendulum with a damper having two channels for liquids. The pan with 1 kg is 340 mm below the damper.

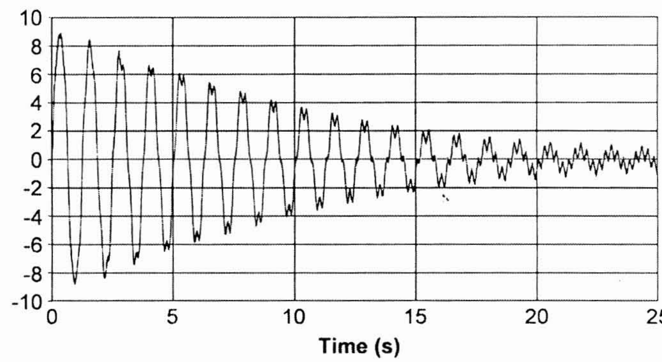

Fig. 9. This plot is from a double pendulum with a 1-kg mass on the pan. The 33 ml (5.9 mm) of water in the outer channel gives maximum damping of the lower frequency. The amplitude of swing is in arbitrary units.

B. Double Pendulum

At the LNE, a double-channel damper was tested with the inner channel having an inside radius of 4 mm and an outside radius of 16 mm, whereas the outer channel inside radius was 44 mm and the outside radius was 61 mm. Fig. 8 shows a photo of the damper, which is located 340 mm above the mass pan. The mass pan hangs from the second flexure pivot that is located 25 mm underneath the damper. All the data have been taken with a 1-kg mass on the pan. The damper mass is 200 g without liquid. The initial impulse is made on the mass pan perpendicular to the top flexure pivot.

Four liquids were tested with this system: ethanol (density of 791 kg $\times$ m^{-3}), white spirit (770 kg $\times$ m^{-3}), water, and trichloroethylene (1460 kg $\times$ m^{-3}). The trichloroethylene always caused a lot of beating, which slowed the damping. Fig. 9 shows the optimal damping with 5.9 mm (33 cm^3) of water in the external channel, and Fig. 10 shows that adding 4 mm (3 cm^3) of water to the interior channel effectively damps the higher frequency. Among the liquids tested at the LNE, water provided the best damping. Ethanol had a significantly less maximum damping with 50 cm^3 in the external channel and 5 cm^3 for the interior channel. The white spirit damping was in between water and ethanol, and having a maximum damping of 47 cm^3 for the external channel and 4 cm^3 for the interior channel. Using (1) and the assumption that $L = \pi r_m$, we predict that the exterior channel should have 40 cm^3, and the interior channel should have 4.7 cm^3.

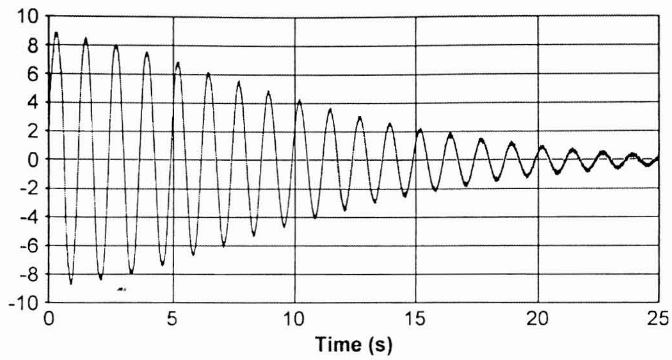

Fig. 10. Same as Fig. 9 but 3 ml (4 mm) of water is added to the inner channel damping out the higher frequency. The amplitude of swing is in arbitrary units.

C. *Weight of the Dampers*

The total weight of the NIST watt balance at the central knife edge is over 50 kg, and the dampers required to damp each mass pan are likely less than 300 g; therefore, the increased loading is not a major issue. As previously mentioned, the main coil system (22 kg) has an active damping system that can be turned off at critical times.

The LNE plans to keep the total mass on their central flexure an order of magnitude less than in the NIST experiment to increase the weighing sensitivity. With a double pendulum, they have a need for more channels that will increase the mass of these dampers. Weight is much more of an issue. As in the NIST experiment, these liquid dampers may only be used on some of the double pendula.

V. Conclusion

We needed a simple way to damp the motion of the mass pans. Starting with the various shapes of the containers, we quickly realized that wave motion was the key to producing a large amount of damping, which had already been well established for other applications. We found that square pans (four sides, open to center) worked better than round ones (one side). It is easy to see that the wave starting from a round object reaches the other side at different times, thus greatly decreasing the wave action that creates the damping. However, round objects are easier to seal with O-rings; therefore, we tried circular channels (two sides), and they worked very well, better than the linear channels described in the CPEM08 Dig., [7]. As the pan swings, the wave starts on the high side, traveling in both directions around the channel. When the liquid level is tuned for maximum damping, the two waves crash into each other at 180°, just as the pendulum is reaching its high point on that side. These circular channel dampers are symmetrical and work equally well for all directions. It is also easy to make multiple channels sealed into one container and tune the liquid level in each channel for each specific frequency that needs damping. A theory that better explains the damping including the beating effects and the dependence on the sample properties would be very useful. Tuned circular channel dampers work well for damping pan balances and are likely to work well in other applications.

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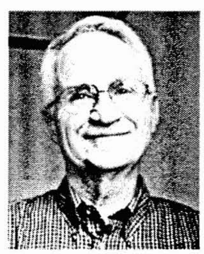

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