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HYBRID MAGNETO-MECHANICAL SUSPENSION FOR PRECISION EXPERIMENTS

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A novel suspension system using both magnetic and mechanical springs is described. The suspension is capable of isolating the test mass of, say, a seismometer, with an upper (magnetic) spring natural frequency of 10 to 30 Hz, and a lower (mechanical) spring frequency of 1 Hz, or less. The upper spring can be critically damped by adjusting the derivative gain of the feedback system used to stabilize the magnetic suspension.

1. Introduction

The mass-spring system is the classical method for vibration isolating precision scientific instruments[1]. Passive vibration isolation typically involves a heavy mass (say, a stone table) that rests on three or four soft springs with a resulting cut-off frequency of 3 to 5 Hz. If pneumatic springs are used, elastomeric hysteresis in the bladder material can produce damping of the resonant oscillations. While this limits the quality factor of the system, it removes the oscillatory energy and permits the isolated mass to approach its noise-limited rest position.

Active vibration isolation, on the other hand, uses feedback to electronically reduce the cut-off frequency of the isolation system. This technique has been used extensively in seismic noise filtering systems, for gravitational wave detectors, precision electro-optical assemblies and inertial instrument test platforms. In all such instruments to date, however, the isolated mass has necessarily been in mechanical contact with the feedback system's actuator. White not a problem in principle, such contact can provide leakage paths for noise currents, transmit normal-mode vibrations, and make possible the existence of other types of perturbing effects.

Magnetic suspension, however, provides a technique whereby a test body can be completely free of mechanical contact with its surroundings. By servo-controlling the magnetic field acting on the test mass, a magnetic lifting force can be produced which will exactly offset the gravitational force on the mass, thereby making possible free, stable levitation of the test mass. The dynamics of the suspension, i. e., its stiffness and damping rates, can be controlled by adjusting the integral, derivative and proportional gains of the servo-loop. This, in turn, makes it possible to tune the natural frequency of the suspension over a relatively large range without ever having to physically substitute one suspension spring for another.

The technique of magnetic suspension is making possible several interesting types of novel scientific instruments, including high precision rotational pyrometers[2], photomechanical laser power meters[3] and several other devices. By using a standard mechanical spring to suspend a test mass from an already magnetically suspended »basemass«, one might hope to incorporate the best properties of both types of vibration isolators (i. e., active and passive) into a single package. The resulting system would be free of mechanical contact with its platform, be electronically tunable over an order of magnitude or more in frequency and, eventually, be amenable to multi-axis control of the base-mass. In what follows, a working example of one such system is described.

2. *Experimental arrangement*

Fig. 1 shows the operating principle of a standard[4] magnetic suspension system. The position of the test mass, M, is sensed by a transducer, T. In practice, T might be a photo-optical detector or a pick-up coil. The transducer's output is sent to a feedback amplifier, A, which differentiates the signal, amplifies it and then uses it to drive the suspension coil, S. As gravity pulls down on the suspended body, the feedback works to magnetically raise it, and vice versa. If properly adjusted, the feedback circuit can maintain the vertical position of a suspended body stable in space to $< 10^{-9}$ m.

One realization of such a feedback circuit is shown in Fig. 2. Assuming that T is a photodiode (see Ref. 3, for instance), the output of the detector is operated on by offset and gain amplifiers before differentiation and, thereafter, further amplified before being used to drive the suspension coil. The result is shown in Fig. 3a, where a steel ball is shown floating freely in space (a close-up is shown in Fig. 3b). Attached to this steel ball is a delicate mechanical spring from which a second steel ball is hanging, with the entire assembly thus constituting a hybrid magnetomechanical suspension.

The spring constant of the mechanical spring was measured to be ≈ 4 N/m (i. e., $\approx 4 \times 10^3$ dynes/cm) and its mass was 0.25 gram. The mass of the upper sphere was 16.3 grams and that of the lower sphere was 8.5 grams. The mechanical oscillator was undamped, except for atmospheric drag and some residual magnetic damping from the fringing fields of the suspension coil. Its natural period was approximately 1/3 s, but this could be lengthened by replacing the lower sphere with a heavier mass. The natural frequency of the magnetic oscillator (without the mechanical oscillator attached) could be tuned over the range of roughly 10 to 30 Hz by adjusting the proportional gain of the feedback circuit. Clearly, the magnetic spring was several times stiffer than the mechanical spring.

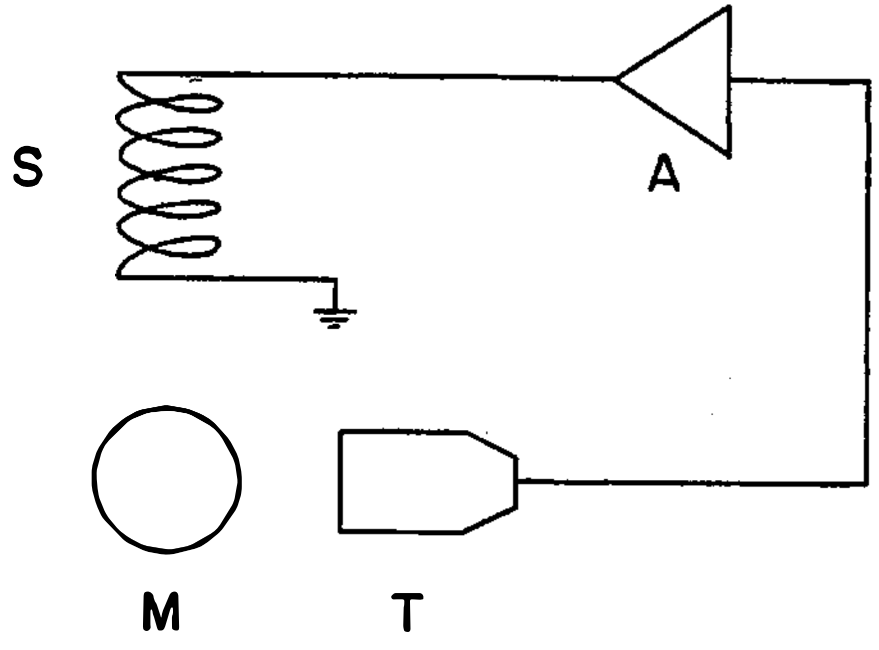

Fig. 1. Schematic block diagram of the operation of a magnetic suspension, showing the suspended body, M, the system's motion transducer, T, the feedback network and amplifier, A, and the suspension coil, S.

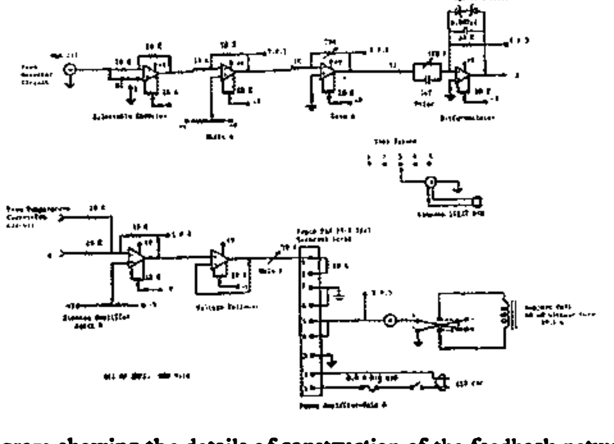

Fig. 2. Circuit diagram showing the details of construction of the feedback network and amplifier.

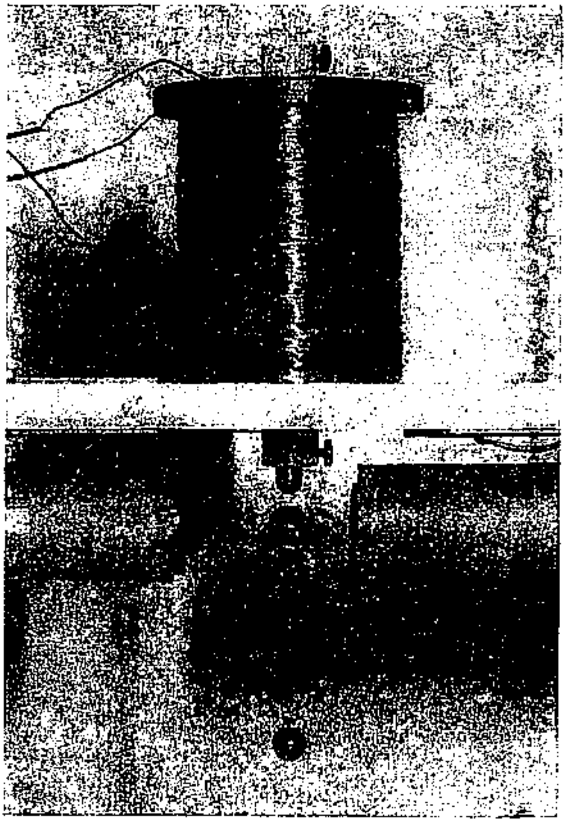

Fig. 3a. Full view of the magnetic suspension apparatus showing the magnetic spring suspending the mechanical oscillator.

3. *Results and discussion*

Stable suspension of this isolation system could be achieved quite easily over the proportional gain range of $V_0/V_i = 13$ to 18. If the magnetic suspension were operated at higher gain settings, the upper sphere would exhibit gain-unstable oscillations about its equilibrium position, as viewed through a 6x telescope. The mechanical suspension filtered these oscillations, though, such that no motion of the lower sphere could be observed through the same telescopic arrangement. Under normal operating conditions (no gain-unstable oscillations), the upper sphere could not be seen to move at all.

Once the apparatus was constructed, a variety of elementary experiments were conceived for it. In what follows, one of the more interesting of these will be discussed.

The application originally foreseen for such a system was its use as a free-body seismometer. In such a device, a corner-cube retro-reflector constitutes the

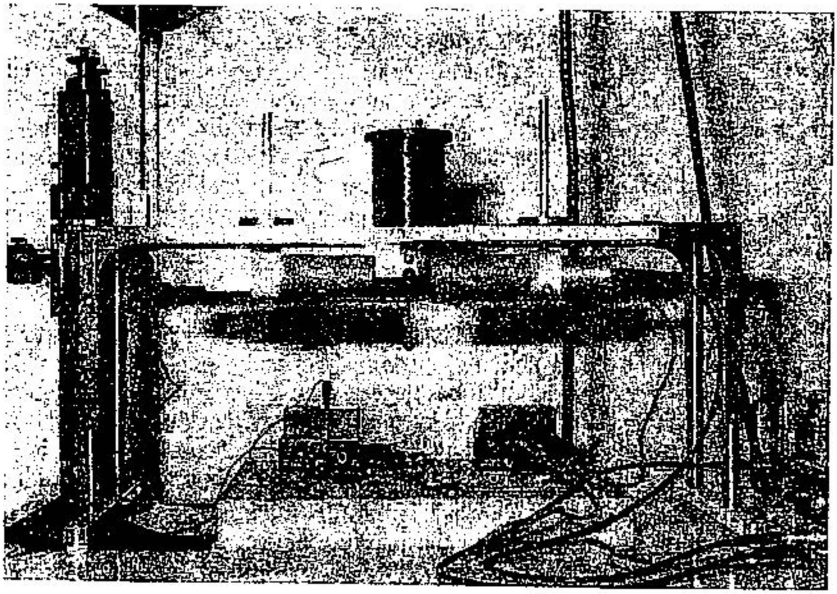

Fig. 3b. Close-up view of the magnetic and mechanical oscillators.

lower (inertial) mass suspended by the hybrid spring, and it serves as the movable arm of a Michelson laser interferometer. A significant advantage of such a system is that instrumental calibrations and measurements of suspended mass transient response would be facilitated by simply summing the appropriate control signal into the magnetic suspension circuit. Moreover, the entire hybrid spring assembly (magnetically suspended mass, mechanical spring and corner-cube) could be hermetically sealed inside a transparent, bakeable vacuum vessel thereby eliminating radiometer effects, etc.

As a first step towards realizing the construction of such a device, an Edmund Scientific Co. model J42,388 corner-cube retro-reflector was obtained. It had a reflection deviation angle of typically 5 minutes of arc and a clear aperture of 25 mm. The corner cube could be attached to a mechanical spring via a threaded hook mounted at its apex. This assembly had a mass of 30.95 grams and, when mounted on the particular mechanical spring selected for this work, the system's natural frequency was 1.87 Hz. This was measured by timing 100 oscillations, totalling 53.46 seconds.

This frequency is $\approx$ 10 times less than the midpoint of the tuning span of the magnetic component of the elementary version of the hybrid spring described above. In principle, then, a hybrid spring-based seismometer using components such as these should exhibit excellent filtering characteristics against the usual types of man-made vibrations, typically dominated by electric motor-driven floor noise (the dominant spectral peak for which is 30 Hz in North America, where the electrical power line frequency is 60 Hz).

One disadvantage to a seismometer of this kind might be the fact that the suspended corner cube will have a natural pendulum frequency. For a spring extended under load to a length of, say, 5 cm, the pendulum oscillations would occur at a rate of 2.23 Hz (assuming small angle, rigid rod-like oscillations), very close to the natural vertical oscillation frequency of the suspended corner-cube. This implies that there could be mode-coupling and subsequent masking of the seismometric interference fringes. If it were only a question of directional fidelity in the reflected ray this would not matter since, with a corner-cube, the incident and reflected light beams are nominally collinear. The problem, of course, is that the pendulum oscillations would constitute a path-length change and this, in turn, would be responsible for the masking of the seismometric signal. Clearly, it will be necessary to provide mode-selective damping in any version of such a seismometer where the two frequencies would be so close together.

The vibration isolation characteristics of the hybrid spring are governed by the dynamics of the two coupled oscillators. Ultimately, the quantity of interest is the natural frequency of the combined mass system, since motion in the individual oscillators can be excited by driving forces resonant with this frequency. An elementary mathematical argument, due to Prentis[5], will serve to model this system.

Let the magnetically suspended mass be called m_1 and let the spring constant of the magnetic suspension be called k_1. The lower mass is then m_2 and the mechanical spring has strength k_2. Assume that the upper coupling point of the magnetic suspension is immovable, but that m_1 moves through some displacement x_1 and that m_2 moves through some displacement x_2. If we let the differentiation operator $\mathrm{d}^2/\mathrm{d}t^2 = D^2$, then we can write the equations of motion for m_1 and m_2 as:

$$m_1 D^2 x_1 = k_2 (x_2 - x_1) - k_1 x_1 \tag{1}$$

$$m_2 D^2 x_2 = -k_2 (x_2 - x_1). \tag{2}$$

Solving these two equations to eliminate x_2, we find:

$$[D^4 + ((k_1 + k_2)/m_1 + k_2/m_2) D^2 + k_1 k_2/m_1 m_2] x_1 = 0. \tag{3}$$

If there are driving forces $P_1(t)$ and $P_2(t)$ acting on m_1 and m_2, respectively, then Eq. (3) becomes:

$$[D^4 + ((k_1 + k_2)/m_1 + k_2/m_2) D^2 + k_1 k_2/m_1 m_2] x_1 =$$
$$= (D^2 + k_2/m_2) P_1(t)/m_1 + k_2 P_2(t)/m_1 m_2. \tag{4}$$

Typically, though, such applied forces will be impulses at $t = 0$ with $P_1 = P_2 = 0$ for $t < 0$. Assuming a harmonic solution to Eq. (3), the natural frequency for the system can then be written as:

$$\omega^2 = \frac{1}{2}\left(\frac{k_1}{m_1} + \frac{k_2}{m_1} + \frac{k_2}{m_2}\right) \pm \sqrt{\frac{1}{4}\left(\frac{k_1}{m_1} + \frac{k_2}{m_1} + \frac{k_2}{m_2}\right)^2 - \frac{k_1 k_2}{m_1 m_2}}. \tag{5}$$

Evaluation of Eq. (5) in the appropriate special cases proves consistent with reduction of the problem to one where either the magnetic or mechanical spring, for instance, is dynamically dominant over the other. An extension of this reasoning to the situation where the anchor point (the point of attachment) of the magnetic suspension is moving is available elsewhere[6].

It is useful to compare the properties of this type of hybrid suspension with those of other high precision, active vibration isolation systems described in the literature. In an active isolation system, feedback is used to reduce the cut-off frequency of the transmitted vibrations. The goal is usually (but not always) to reach cut-off frequencies in the 1 to 10 mHz range, a part of the noise spectrum dominated by natural earth microseisms[7].

There are several types of stable, closed-loop, electromechanical vibration isolation systems. The salient features of some typical examples are listed in Table 1 and compared against the hybrid electromechanical system described in this article. These systems fall into two broad categories with respect to their application: isolators for the test masses in gravity wave experiments, and stabilized platforms for electro-optical instrument or inertial sensor testing. For reasons having to do with the dynamics of the process under study, some of these isolation systems are tuned to frequencies well-above the natural earth microseism band. In its present state of development, the hybrid spring falls roughly mid-range between the two frequency extremes. By virtue of its magnetic suspension system,

TABLE 1.

author	method	operating/cut-off frequency (Hz)	test mass size (kg)	purpose
Del Fabbro et al.[8]	gas spring oscillator	10	430	gravity wave detection
Saulson[9]	fedback inertial platform	0.04	<5	gravity wave detection
Robertson et al.[10]	fedback pendulum	0.0016	0.47	gravity wave detection
Giazotto et al.[11]	fedback pendulum	10	100	gravity wave detection
DeBra et al.[12]	magnetically served platform	0.050	630	zero-g satellite simulation
Lamont and Toler[13]	pneumatically servoed platform	0.160	20, 500	inertial sensor test platform
Rinker and Faller[14]	servo-controlled vertical spring	0.02	0.5	gravimetry
Turachek[15]	servo-controlled inertial table	0.100	65	instrument isolation
Gillies	hybrid spring (demonstration)	<1	≈ 0.01	exploratory studies

Comparison of various servo-controlled, active vibration isolation systems.

though, it is the only such device to date that is completely decoupled mechanically from the other parts of the isolator structure. The present exploratory version of the hybrid spring was designed with a weak spring capable of carrying only small loads; this for convenience of manipulation. Of course, a much more robust system could be built using other magnetic suspension technologies that have been designed to suspend truly substantial masses[16].

The use of feedback to dampen higher frequency mechanical vibrations and noise in extended structures is usually called »electronic cooling«. A well-known technology based on this principle has come into existence and has been used by Forward, among many others, to reduce the vibrational amplitudes in instrumens such as resonant gravity gradiometers[17] and delicate membrane mirrors[18]. If the position of the lower mass in the hybrid spring arrangement were continuously monitored, an appropriate feedback signal to the magnetically suspended mass would enable electronic cooling of the vibrations driving the lower one. Except for the noncontacting suspension, this scheme would then be very similar to that of Rinker and Faller's[14] »superspring«. Vibration isolation in this maner at very low (microseismic) frequencies, however, depends critically upon the proportional gain of the feedback loop[14]. As pointed out by Ritter and Gillies[19], this is a different situation than the standard, derivative gain-based, electronic cooling vibration control problem. In fact, their article[19] explores the classical limit of mechanical thermal noise reduction by feedback, paying particular attention to the nature of the »McCombie limit«[20].

4. *Conclusions*

A magnetically suspended mechanical oscillator can be made to serve as a hybrid active/passive vibration isolation device. Such a system has been built with the magnetic suspension being tunable over a relatively large range of frequencies and with the mechanical suspension (mass/spring system) then providing a second level of filtering. A dynamical model of the system provides a clear explanation of the nature of the coupling between the two masses involved in the design.

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MAGNETO-MEHANIČKO OVJEŠENJE ZA PRECIZNA MJERENJA

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Opisujc se nov način ovješenja tijela primjenom magnetske i elastične sile Ovom metodom može se mehanički izolirati tijelo, npr. uteg seizmometra, s gornjom rezonantnom frekvencijom (od magnetskog ovješenja) između 10 i 30 Hz i donjom rezonantnom frekvencijom (od mehaničkog ovješenja) od 1 Hz i nižom. Magnetsko ovješenje može se lako podesiti da se postigne kritično gušenje mijenjanjem derivacijskog pojačanja u povratnoj vezi sistema koji služi za stabilizaciju magnetskog ovješenja.