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LOSSES IN PENDULAR SUSPENSIONS DUE TO CENTRIFUGAL COUPLING

Sangita N. Pitre and S. V. Dhurandhar

Inter University Centre for Astronomy and Astrophysics,

Post Bag 4, Ganeshkhind, PUNE-411007, INDIA

and

D. G. Blair and Ju Li

Department of Physics, University of Western Australia, Nedlands, WA 6009,

AUSTRALIA

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Abstract

We present an analysis of the centrifugal coupling of a simple pendulum to a dissipative support. We show that such a coupling leads to an amplitude dependent quality factor. For amplitudes which could be present in laser interferometer gravitational wave detector suspensions, this mechanism could limit the quality factor of the test mass suspension significantly to 10^{10} and should be considered in the design of advanced LIGO type detectors.

1. Introduction

Large scale laser interferometer gravitational wave detectors are being planned(see J. Hough et al 1989; A. Brillet, A. Giazotto et al 1992; the Australian proposal 1990; D. G. Blair, D. M. McClelland and H. Bachor 1992; H. Bachor et al 1990) and constructed (A. Abramovici et al 1992). Such detectors require extremely low amplitudes of vibrational noise in their mirror suspensions. The chief sources of noise are seismic vibrations and thermal noise. The former can, in principle, be reduced to arbitrarily low levels by suitable filter design. Thermal noise however is generated internally, by the accoustic losses in the mirror and by the losses in the mirror suspension. Internal mirror losses generally give rise to a thermal noise peak in the kHz range (assuming a suitable shape for the mirror). Pendulum losses give rise to a noise amplitude which, in the frequency range $\sim$ 1-100 Hz is generally expected to dominate the noise of a large scale detector.

In Figure 1 we show the predicted thermal noise of a 100 kg, 1 Hz pendulum for a range of Q-factors. There would clearly be a great advantage in using pendula with Q-factors$> 10^{10}$. Losses in such pendula are normally considered to arise from elastic losses in the flexure or hinge from which the pendulum is supported. However, even if the elastic loss was reduced to nearly zero using suitable materials and configurations, losses in practice can remain due to the coupling of the pendulum to its support structure. There are two ways in which this coupling can arise. One is a simple linear horizontal coupling of the suspension point to its support structure. This can be modelled by conventional linear analysis and is accounted for in most isolation system designs. The second is a loss which arises from the centrifugal(vertical) coupling of the pendulum to vertical losses in

the support structure. This is a non-linear problem, surprisingly difficult to solve. Here we present the solution to this problem, and give examples of the limiting Q-factor in various situations.

The dominant and relevant effect of a high quality factor is to reduce the thermal noise of the pendulum suspension. The dependence of the thermal noise spectral density on the quality factor has been derived earlier (see J. Hough et al 1989). The thermal noise is given in terms of the quantity $\tilde{h}^2$ where the *tilde* denotes the Fourier transform of the quantity below it. The quantity h is the metric perturbation of the gravitational wave one is trying to detect. The thermal noise is given in terms of this metric peturbation. Thus,

$$\tilde{h}^2_{thermal} \sim \frac{16kT\omega_p}{mQ_{eff}\omega^4 l^2}.$$

Here k is the Boltzmann constant, T the absolute temperature, l the length of the arm of the laser interferometric detector and ω the frequency of the thermal noise. The $\tilde{h}$ falls off as $Q_{eff}^{-\frac{1}{2}}$ and therefore a higher Q_{eff} has the effect of reducing the thermal noise. If we observe the noise profiles for burst or continuous wave sources (see J. Hough et al 1989) of laser interferometric gravitational wave detectors, the thermal noise is present at the lower end of the band of detectable frequencies. Increasing the Q_{eff} will push this thermal curve 'downwards' reducing the noise at lower frequencies near the seismic cut-off. This will have the effect of increasing the signal to noise ratios for sources which emit gravitational waves predominantly at lower frequencies. For example coalescing binaries which radiate more power at lower frequencies will have their signal to noise enhanced if the quality factor is boosted.

2. The equations of motion

We consider here a simple model of a seismic isolator which consists of a pendulum attached to a spring. The spring motion has a dissipative element in it while the dissipation in the pendular motion is neglected. We set up the classical equations for the system which turn out to be non linearly coupled. We then solve this system of equations numerically and find that under the assumption that the amplitudes of the motion are small, analytic approximations are possible and an analytic but approximate solution can be derived. We finally compute an effective quality factor for the pendular motion which now depends on time because the motion is not damped according to the usual exponential law.

Consider the system as shown in the figure 2. The two dynamical variables are x and θ which are defined as follows: x is the extension of the spring beyond its normal length and θ is the angular displacement of the pendulum. The Lagrangian for the system is,

$$\mathcal{L} = \frac{1}{2}M(\dot{x}^2 - {\omega_s}^2 x^2 + l^2\dot{\theta}^2) - Ml\sin\theta\dot{x}\dot{\theta} + Mg(x + l\cos\theta) \tag{2.1}$$

where M is the mass of the bob of the pendulum, l is the length of the pendulum, ω_0 is the natural frequency of the spring and g is the accelaration due to gravity. We assume that the damping of the spring is proportional to the velocity which means that the damping force Q_x is of the form,

$$Q_x = -2\frac{M}{\tau}\dot{x}, \tag{2.2}$$

where τ is the damping time constant. We now use the Euler-Lagrange equations to get the equations of motion. The x - equation is,

$$\ddot{X} + \frac{2}{\tau}\dot{X} + {\omega_s}^2 X = \sin\theta\ddot{\theta} + \cos\theta\dot{\theta}^2 + {\omega_p}^2, \tag{2.3}$$

where, $X = \frac{x}{l}$ and ${\omega_p}^2 = \frac{g}{l}$. The equation may be simplified somewhat further by defining another variable z where,

$$z = X - \frac{{\omega_p}^2}{{\omega_s}^2} \tag{2.4}$$

Since θ is normally very small only terms quadratic in θ can be retained, the equation for z then becomes,

$$\ddot{z} + \frac{2}{\tau}\dot{z} + {\omega_s}^2 z = \theta\ddot{\theta} + \dot{\theta}^2 \tag{2.5}$$

The equation for the second variable θ can again similarly be obtained from the Lagrangian by the Euler-Lagrange equations. We assume that the damping for the θ motion can be neglected. Therefore, there is no generalised force for this generalised coordinate. With these assumptions, the θ equation is,

$$\ddot{\theta} + {\omega_p}^2 \sin\theta = \sin\theta\ddot{X} \tag{2.6}$$

In terms of z and for θ very small, the equation for θ is,

$$\ddot{\theta} + {\omega_p}^2\theta = \theta\ddot{z} \tag{2.7}$$

We can still make a further simplification by going over to a dimensionless time coordinate. We may choose to measure time in terms of either of the frequencies ω_s or ω_p. Suppose we take the former, defining,

$$T = \omega_s t \quad , \quad Q = \frac{1}{2}\omega_s \tau \quad , \quad \alpha = \frac{\omega_p}{\omega_s} \tag{2.8}$$

we have the following dynamical equations,

$$\ddot{z} + \frac{1}{Q}\dot{z} + z = \theta\ddot{\theta} + \dot{\theta}^2 \tag{2.9a}$$

$$\ddot{\theta} + \alpha^2\theta = \theta\ddot{z} \tag{2.9v}$$

where the dot is the time derivative with respect to the dimensionless time T. *The aim is to compute the quality factor Q_{eff} of the θ motion.*

To make further progress, we need to know roughly the numerical values of $\omega_s, \omega_p, and \tau$ (or an equivalent set of quantities).. The equations are too complex to solve in full generality. However, if the actual values are known for these parameters then it is possible to obtain approximate analytic solutions.

The above equations are nonlinearly coupled and do not possess any exact solutions. Therefore we may guess approximate analytic solutions by first solving the equations numerically. There are basically only two parameters, namely, α and Q. All the other quantities have been thrown into the background by resorting to dimensionless units.

3. The numerical solution

The numerical method we resort to is the fourth order Runge-Kutta which consists of converting each of the above coupled second order differential equations to two first order equations. To this end we define, $\dot{\theta} = \Omega$ and $\dot{z} = v$, then we have a set of four first order differential equations,

$$\dot{\theta} = \Omega, \quad \dot{z} = v, \quad \dot{\Omega} = -\alpha^2\theta + f, \quad \dot{v} = f \tag{3.1}$$

where,

$$f(\theta, z, \Omega, v) = \frac{\Omega^2 - \alpha^2\theta^2 - z - v/Q}{1 - \theta^2}. \tag{3.2}$$

Supplying the values to the four variables at an initial time t_0 determines the solution to the problem. We however need to choose the time step judicially. It should be small

enough to take care of the variations in the parameters adequately, but at the same time the step should be large enough so that the number of operations are reduced. It is found that the variation in the parameters is more or less sinusoidal. We take about 20 time steps for the smallest cycle which is so for the variables z and v. We restrict our attention to the problem when θ is small. This simplifies the problem and we can get approximate analytic solutions for large times when the transients have died out. We have experimented with several initial values for the parameters (with the proviso $\theta_0 << 1$ where $\theta_0 = \theta(t_0)$) and have found that the solutions have certain common features that are of interest to us. With this in mind we make the following choice for the initial values (denoted by the subscript '0') for the variables:

$$z_0 = v_0 = \Omega_0 = 0, \quad \theta_0 = 0.05 \tag{3.3}$$

We assume several values of α and Q and solve the equations numerically. Although the values we have chosen do not correspond to actual situations, observing the salient features of the solutions provides useful guidelines in searching for analytic solutions.

We observe the following features:

(i) At early times $\theta \sim \theta_0 \cos \alpha t$. At late times the motion is seen to be damped. We have taken the computation far enough upto $T = 10^4$ so that the damping is appreciable.

(ii) For lower values of α and θ_0 the damping is slower and is not easily seen. For such values we have taken the computation upto $T \sim 10^6$. However the results are not qualitatively different.

(iii) The z- motion consists of two superimposed oscillations:

(a) The cycles are at a frequency 2α. This is due the quadratic nonlinearity, namely, θ^2

forcing the z motion.

(b) On these oscillations is superimposed a transient of about unit frequency which is damped at the rate $e^{-T/2Q}$. At late times the transients die out and the spring oscillates with the frequency 2α.

At late times both the θ and z oscillations are slowly damped. The damping is not exponential but slower and is quantified in the next section. It is remarkable that in the regime of interest, analytic solutions to this system of equations are possible.

4. The analytic solution

A. The transients and the particular solution

Since the θ displacement is small we start with a trial solution

$$\theta(T) = \theta_1 \cos(\alpha T) \qquad (4$$

so that at $T = 0$ the θ displacement is maximum, namely, $\theta_1 = \theta_0$. θ_1 here is assumed to be constant although it happens to be a slowly varying function of time on the time scale of the rate of damping. For a few cycles this assumption is alright during which little decay in the amplitude occurs. The oscillation time scale is of course of the order of α^{-1}. This solution assumes that $\theta\ddot{z} \sim 0$ which is justified later. We further proceed to compute the right hand side of the z equation from equation (4.1). Thus,

$$\ddot{z} + \frac{1}{Q}\dot{z} + z = -\alpha^2\theta_1^2 \cos 2\alpha T \qquad (4.2)$$

which means that the z motion is forced at twice the frequency of the θ oscillation. The total solution for $z(t)$ is obtained as a superpostion of the transient solution and the forced

solution. Thus,

$$z(t) = z_{transient}(t) + z_{forced}(t) \tag{4.3}$$

where,

$$z_{transient} = e^{-T/2Q}(A_1 \cos\beta T + A_2 \sin\beta T) \tag{4.4}$$

where, $\beta = (1-\frac{1}{4Q^2})^{\frac{1}{2}}$, and A_1 and A_2 are to be determined from initial conditions imposed on the full solution. The forced solution is,

$$z_{forced} = z_1 \cos(2\alpha T + \Phi_1) \tag{4.5}$$

where,

$$z_1 = -\alpha^2\theta_1^2/A \ , \ \tan\Phi_1 = \frac{2\alpha}{Q(1-4\alpha^2)} \ , \ A = [(1-4\alpha^2)^2 + 4\alpha^2/Q^2]^{\frac{1}{2}}. \tag{4.6}$$

Again here the behaviour of z_1 is analogous to θ_1. The transient solution dies out in the timescale Q^{-1} so that at late times ($T \gg Q^{-1}$) only the forced solution survives.

The trial solution for $\theta(T)$ as given in equation(4.1) can be justified in the following way. We observe that if we choose $\alpha \sim 1$ or less and $Q \sim 1$ to 100 then $z \sim \alpha^2\theta_1^2$. Since the z motion is also sinusoidal with frequency 2α , $\ddot{z} \sim \alpha^4\theta_0^2$. Thus, the term $\theta\ddot{z}$ will be of the order of $\alpha^4\theta_0^3$ which is very small. Therefore the assumption of neglecting this term in our trial solution for θ is not unjustified.

B. Damped motion

The motion is damped since the system loses energy because of the dissipation in the spring. We analyse the damping from energy considerations. We need to evaluate first the total average energy of the system and then relate it to the rate of loss of average

energy. Since the dissipative element is in the spring the system loses energy *only* through the z- motion. However, the θ- motion will also be damped because of the coupling. The instantaneous energy is the Hamiltonian of the system and is given in dimensionless units by,

$$E = \frac{1}{2}\dot{z}^2 + \frac{1}{2}\dot{\theta}^2 - \theta\dot{\theta}\dot{z} + \frac{1}{2}z^2 + \frac{1}{2}\alpha^2\theta^2 \tag{4.7}$$

We now substitute the late time solutions,

$$z = z_1(T)\cos(2\alpha T + \Phi_1) \quad , \quad \theta = \theta_1(T)\cos\alpha T \tag{4.8}$$

where θ_1 and z_1 are 'slowly' varying functions on the timescale of α^{-1} in equation (4.7) and compute the average energy per cycle of the oscillations. We however need to consider the average energy per cycle of the variables. The calculation leads to,

$$\langle E\rangle = (\alpha^6\theta_1^4 - \frac{1}{4}\alpha^4\theta_1^4 + 2\alpha^6\theta_1^4)A^{-2} + \frac{1}{2}\alpha^2\theta_1^2 \tag{4.9}$$

Since θ_1 has been assumed to be small, $\langle E\rangle \sim \frac{1}{2}\alpha^2\theta_1^2$. The rate of loss of energy is computed by first differentiating the expression for the Hamiltonian and then using the equations of motion. We then have,

$$\frac{d}{dT}E = -\frac{1}{Q}\dot{z}^2 \tag{4.10}$$

The average loss of energy per unit time can then be computed from equations (4.6) and (4.8) and averaging the trigonometric functions over unit time. Thus,

$$\frac{d}{dT}\langle E\rangle = -\frac{2\alpha^6\theta_1^4}{A^2Q} \tag{4.11}$$

From the equations (4.9) and (4.11) we get a differential equation for the decay of the average energy, or equivalently for the amplitude θ_1 :

$$\frac{d}{dT}\theta_1^2 = -\frac{4\alpha^4\theta_1^4}{A^2Q} \tag{4.12}$$

Solving this equation with the initial conditions $T = 0$, $\theta = \theta_0$, we have,

$$\theta_1(T) = \frac{\theta_0}{B(T)} \tag{4.13a}$$

where,

$$B(T) = (1 + \epsilon T)^{\frac{1}{2}} \quad , \quad \epsilon = \frac{4\alpha^4\theta_0^2}{A^2Q}.$$

The decay of the z-motion is obtained from equation (4.6). We get,

$$z_1(T) = -\frac{\alpha^2\theta_0^2}{AB^2(T)} \tag{4.13b}$$

Therefore we notice that the z motion is damped at a faster rate than the θ motion. This behaviour remains true for various values of α, Q and θ_0 as has been verified on the computer and cross checked with the above formulae. But if α and θ are very small then enormous length of time is required on the computer to produce appreciable damping as can be seen from the foregoing discussion. The analytic solution then helps in predicting the damping profile.

C. The effective Q for the pendular motion

Consider a damped simple harmonic oscillator with natural frequency ω_0 and damping time constant τ. Then the time dependence of the amplitude is $\sim e^{-t/\tau \pm i\omega_0 t}$. The quality factor Q is then given by the formula: $Q = \frac{1}{2}\omega_0\tau$. In terms of the dimensionless time T the effective quality factor Q_{eff} for general damped motion, which is not necessarily an exponential decay, is given by,

$$Q_{eff} = \frac{1}{2}\alpha[-\frac{d}{dT}(ln\theta_1(T))]^{-1} \tag{4.14}$$

Using equation (4.13a), the above expression leads to the result,

$$Q_{eff} = \alpha \frac{(1+\epsilon T)}{\epsilon}. \tag{4.15}$$

Therefore in this case the quality factor is a function of time which is to be expected since the damping is not exponential. We observe that, the Q_{eff} increases with time. At early times, i.e. when $\epsilon T \ll 1$ the Q_{eff} is given by,

$$Q_{eff} \sim \frac{\alpha}{\epsilon} = \frac{A^2 Q}{4\alpha^3 \theta_0^2}. \tag{4.16}$$

We observe that at early times Q_{eff} is a constant and hence in this regime the system behaves like a normal damped harmonic oscillator i.e. the amplitude θ_1 decays exponentially with time $\theta_1(T) \sim e^{-\alpha T/2Q_{eff}}$. However when $T \sim \epsilon^{-1}$ the decay of the amplitude is slower than the exponential rate. Figure(3) compares the decay of the amplitudes of the two oscillators:

(a) exponentially damped,

(b) pendular, which corresponds to the system under consideration.

In the figure, $\alpha = 0.3, Q = 2$ and $\theta_0 = 0.01$ which corresponds to $\epsilon \sim 10^{-6}$. It is convenient to use logarithmic scales for depicting the behaviour. We plot $-log_{10}(-log_{10}\theta_1)$ verses $log_{10}T$. The usual case of the exponentially damped oscillator appears as a straight line with slope =-1. This curve is labelled as *exponential*. The intercept on the vertical axis turns out to be $log_{10}Q_{eff} - log_{10}(\frac{1}{2}\alpha log_{10}e) - log_{10}(-log_{10}\theta_0)$ which increases with Q_{eff}. We observe that when $T \sim \epsilon^{-1} \sim 10^6$ the pendular curve departs from the exponential and the decay is slower.

For the case of the spring constant $k \sim 10^7$ kg.sec^{-2} , $M \sim 10^3$ kg , $l \sim 1$ metre and Q say 10, we have the following values for the relevant parameters : $\omega_s \sim 100, \omega_p \sim 3, \alpha \sim$

0.03 and $A \sim 1$. From the equations (4.13) and (4.15) we get an amplitude dependent quality factor for the pendular motion. Thus,

$$Q_{eff} = \frac{A^2 Q}{4\alpha^3} \times \frac{1}{\theta_1^2} \tag{4.17}$$

Figure (4) displays this behaviour in which $log_{10} Q_{eff}$ is plotted against $log_{10}\theta_1$. For the values of the parameters mentioned above, the constant $A^2Q/4\alpha^3 \sim 10^5$. The tendency is for the Q_{eff} to increase with the decrease of amplitude. Therefore a value of $Q_{eff} \sim 10^{10}$ is not impossible under the circumstances.

5. Discussion

We have shown that the coupling of a pendulum to a lossy support structure can create an amplitude dependent Q-factor and this can significantly degrade the Q of an intrinsically high Q pendulum if care is not taken in the design. Since metal and rubber vibration isolator elements have intrinsically low Q, these can contribute particularly large amplitude dependent losses. The coupling of noise into such a suspension will occur through *parametric amplification* type processes more familiar in optical and radio frequency parametric amplifiers. Some interferometer designs have proposed a suspension point servo which uses a secondary interferometer to lock together the pendulum suspension points. Such a suspension does not eliminate seismic noise, but forces it into common mode so that there is no differential motion. In such a situation residual seismic amplitudes could be large enough to degrade the suspension Q through the mechanism discussed here.

Acknowledgement

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Figure Captions

1. The frequency dependence of the thermal noise predicted for a 1 Hz pendulum for various Q-factors.A pendulum with Q=10^{10} would allow a strain sensitivity of about $10^{-23}/\sqrt{Hz}$ at 35 Hz in a 1 km laser interferometer gravitational wave detector.

2. A schematic diagram of a simple model for a seismic isolator is shown which consists of a pendulum attached to a spring. The spring motion is damped with the damping force proportional to the velocity.

3. The figure depicts the decay of the amplitudes with time for the standard exponential case and for the model considered here (pendular). The parameters have the following values $\alpha = 0.3, Q = 2$ and $\theta_0 = 0.01$.

(a) *exponential*: The amplitude is damped exponentially with time. This appears as a straight line with slope $= -1$ on the logarithmic scale.

(b) *pendular*: In the model considered the amplitude decays slower than in the standard case (a).

4. The figure shows that the quality factor Q_{eff} is amplitude dependent for the model considered here. The Q_{eff} is plotted verses the amplitude θ_1 on a logarithmic scale. We find that the Q_{eff} increases as the inverse square of the amplitude. In this figure the relevant parameters have the values $Q = 10, \alpha = 0.03$ and hence the constant $A^2Q/4\alpha^3 \sim 10^5$.

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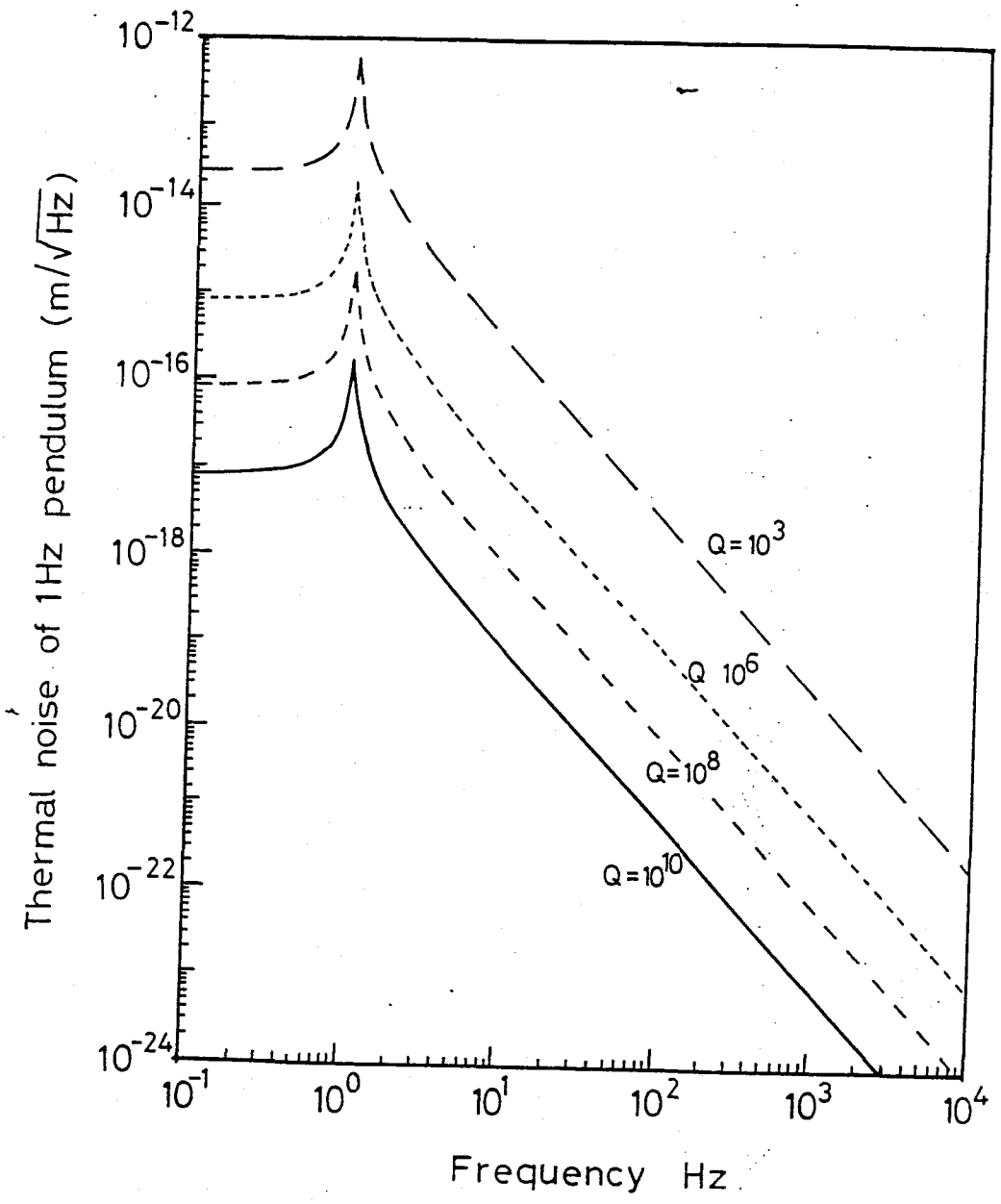
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10^-12
10^-14
10^-16
10^-18
10^-20
10^-22
10^-24
10^-1
10^0
10^1
10^2
10^3
10^4
Frequency Hz
Q=10^3
Q 10^6
Q=10^8
Q=10^10

Figure - 1

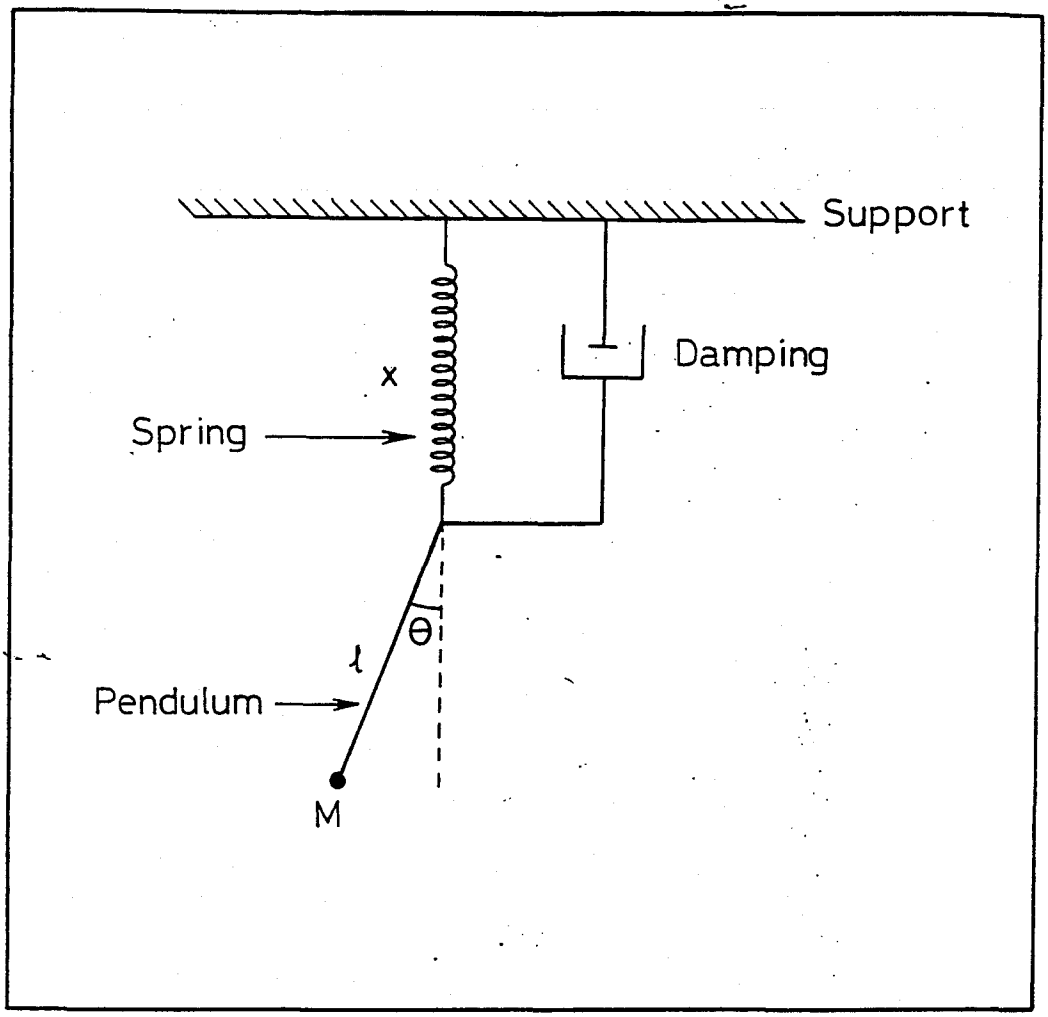
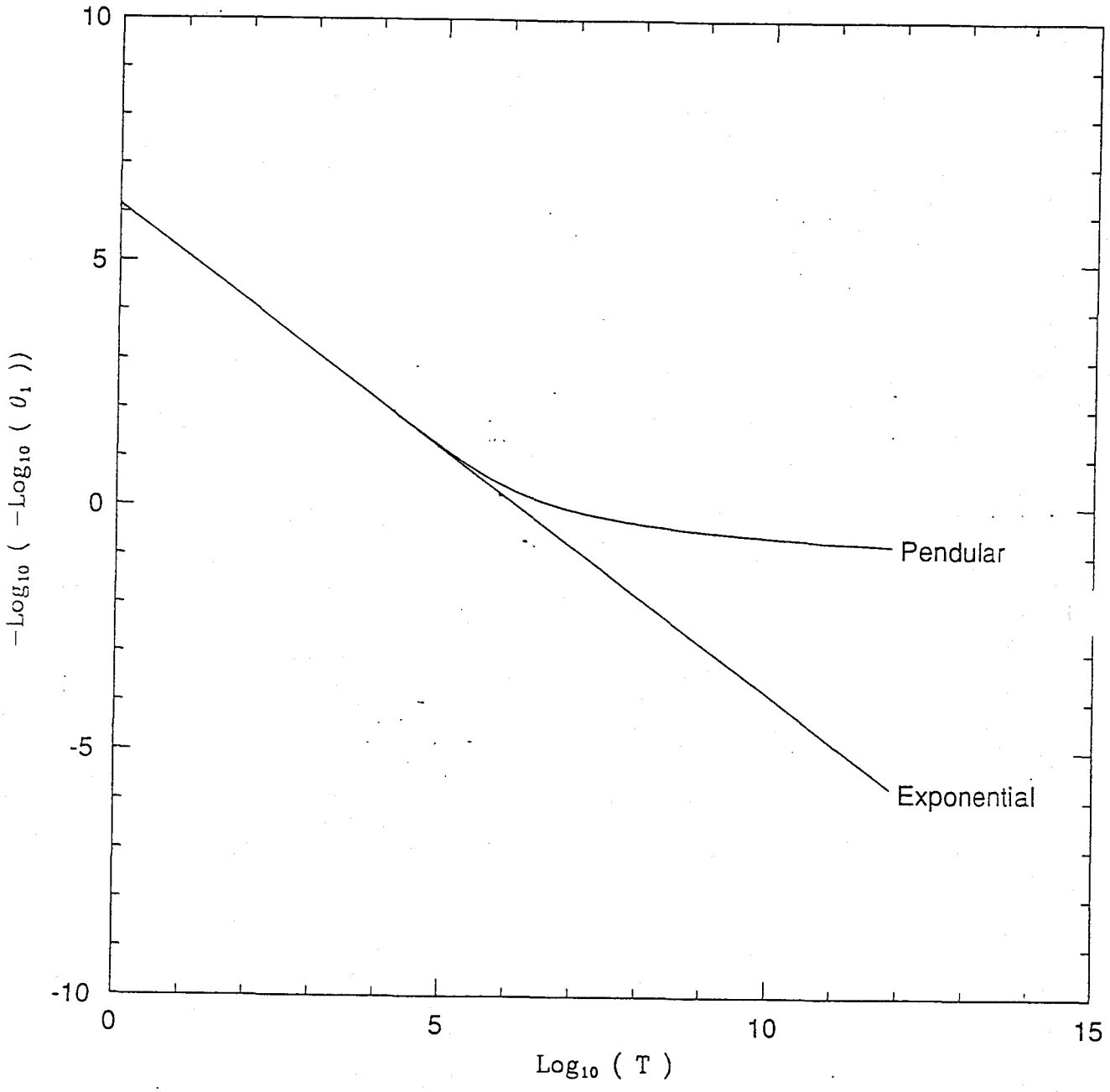


Figure - 2


10
5
0
-5
-10
0
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15
$-\mathrm{Log}_{10}\ (\ -\mathrm{Log}_{10}\ (\ \theta_1\ )\ )$
$\mathrm{Log}_{10}\ (\ T\ )$
Pendular
Exponential

Figure-3

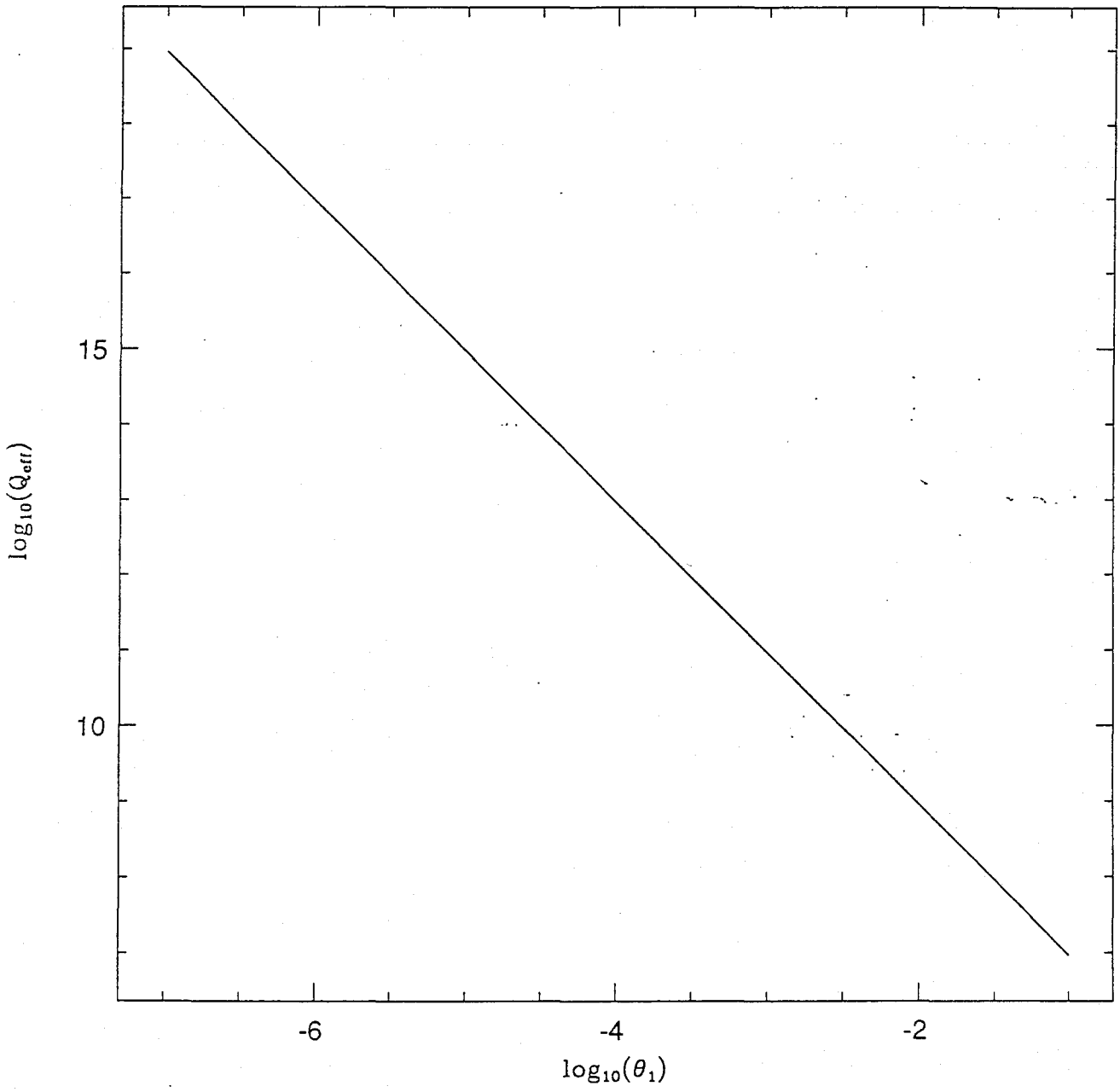

Figure - 4