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Magnet induced losses in LIGO large optics

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1 ABSTRACT

There is already considerable evidence that attaching magnets to the small test-masses used in the 40-m prototype causes a significant degradation of the mechanical Q's of the test-mass internal modes. A similar degradation in Q's has been observed when magnet/standoff assemblies were attached to the proposed LIGO large optic (25cm dia x 9.5cm thick). This report presents evidence that the effect of these magnets on thermal noise in the LIGO interferometer might not be as serious as formerly believed, due to the strong frequency dependence of the mechanical loss induced into the test-mass by a magnet/spacer combination. Experimental data from measurements on the Pathfinder large optic supporting this hypothetical frequency dependence is presented here for the first time.

2 KEYWORDS

LIGO, thermal noise, mechanical loss, pathfinder

3 INTRODUCTION

The data presented here are based on measurements on one of the Pathfinder optics, a test-mass of the dimensions (25cm diameter by 9cm thick) proposed for initial LIGO. The optic used has no mirror coating, but has a polished finish on all its surfaces. In order to characterize the optic, the Q's of several of its internal modes were measured in the Q-measurement apparatus located in the West Bridge Optics lab, with and without various attachments such as wire standoffs and magnet/spacer assemblies.

4 MEASURED LOSSES

Table 1 shows the measured mechanical losses (defined as Q^{-1} where Q is the quality factor of the mode) of seven axisymmetric internal modes of the optic lying between 9 KHz and 50 KHz :

Table 1: Measured Mechanical Losses in Pathfinder Optic

Mode Freq (KHz)	ϕ_1 (no magnets, quartz standoffs)	ϕ_2 (no magnets, grooved Al standoffs)	φ_3 (with magnets)
9.477	14.1×10^{-7}	42.9×10^{-7}	1.88×10^{-6}
22.424	3.88×10^{-7}	1.43×10^{-7}	0.54×10^{-6}
25.637	6.29×10^{-7}	7.94×10^{-7}	1.66×10^{-6}
29.489	1.90×10^{-7}	1.06×10^{-7}	1.78×10^{-6}
29.871	1.66×10^{-7}	0.98×10^{-7}	1.37×10^{-6}
42.765	2.38×10^{-7}		1.43×10^{-6}
47.341	4.76×10^{-7}		5.83×10^{-6}

The numbers in the second column (ϕ_1) were obtained using 3/4” long 3mm dia quartz wire standoffs and no magnets. The numbers in the third column (ϕ_2) were obtained using 3/8” long grooved aluminum wire standoffs and no magnets. At the present time I have only partial data for this configuration.

The data in the third column are typically within a factor of two of the 3/4” quartz wire standoff data in the second column except for the lowest frequency data point which shows excessive loss.[1]

The numbers in the fourth column (φ_3) were obtained using the same aluminum wire standoffs and three magnet/spacer assemblies glued to the optic. There were originally supposed to be four magnet/spacer assemblies, but one fell off during test-mass installation and pumpdown.[2] As can be seen from the table, the measured losses with these magnet/spacer assemblies attached are substantially higher than the losses with no magnets attached, in some cases by as much as an order of magnitude. Mechanical losses induced by the magnet/spacer attachments are seen to dominate the total mechanical losses in the suspended test-mass.

5 FREQUENCY DEPENDENCE OF LOSSES

The magnet/spacer glued to the face of the test-mass undergoes acceleration when the test-mass vibrates in one or more of its internal modes (driven by thermal energy). At the high frequencies involved the magnet and spacer are no longer rigid objects but instead can be treated as a spring/mass system driven by the test-mass (Fig. 1).

There is considerable evidence that the vast majority of solids exhibit mechanical losses that are independent of frequency, sometimes referred to as structural damping [1], [2]. Modeling the magnet/spacer assembly as a lossy spring/mass system and assuming

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[1] A look at the numbers in column 2 of table 1 shows that the 9.477 KHz mode has more than twice the mechanical losses of the next worst mode. This is hypothesized to be due to the fact that this mode has considerable axial motion at the optics edge, along the line of contact with the suspension wire and in a direction where the wire is poorly constrained. Any rubbing or friction with the suspension wire will cause additional mechanical losses for the mode.

[2] In the proposed initial LIGO configuration there will be a total of six such magnet/spacer attachments to the test-mass, four on the flat face and two on the cylindrical surfaces for actuation respectively along and perpendicular to the incident laser beam.

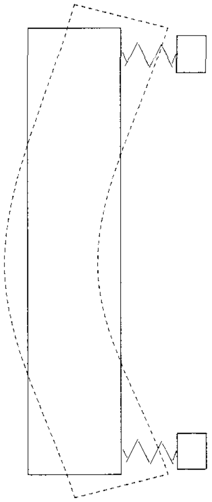

Figure 1. Magnet/spacer as a lossy mass/spring system

that the mechanical loss in the “spring” is independent of frequency results in a predicted effective mechanical loss for the system that has an f^4 frequency dependence at low frequencies, and a flat, frequency-independent behavior at frequencies above the longitudinal compressional resonance frequency of the magnet/spacer assembly (Fig. 2). The model also predicts that the amount of energy lost to the magnet/spacer assembly is proportional to the square of the amplitude of vibration at the magnet location. This model is discussed in Aaron Gillespie’s thesis [3]. However there was limited experimental data to back this up, because the high resonant frequencies of the small 10-cm diameter test-mass then being measured placed most if not all of the mirror internal mode resonant frequencies above the magnet/spacer longitudinal spacer resonance, in the frequency independent loss regime. Consequently it was not possible to get any good data on the f^4 frequency dependence. On the other hand the currently used magnet/spacer assemblies have a much higher longitudinal resonance frequency, close to 100 KHz (this has been estimated analytically as well as confirmed by finite-element analysis performed by Janeen Hazel), and at the same time the LIGO large optics have internal resonant modes down to 10 KHz. As a result most of the data from measurements on the large optic should lie in the f^4 frequency dependence regime.

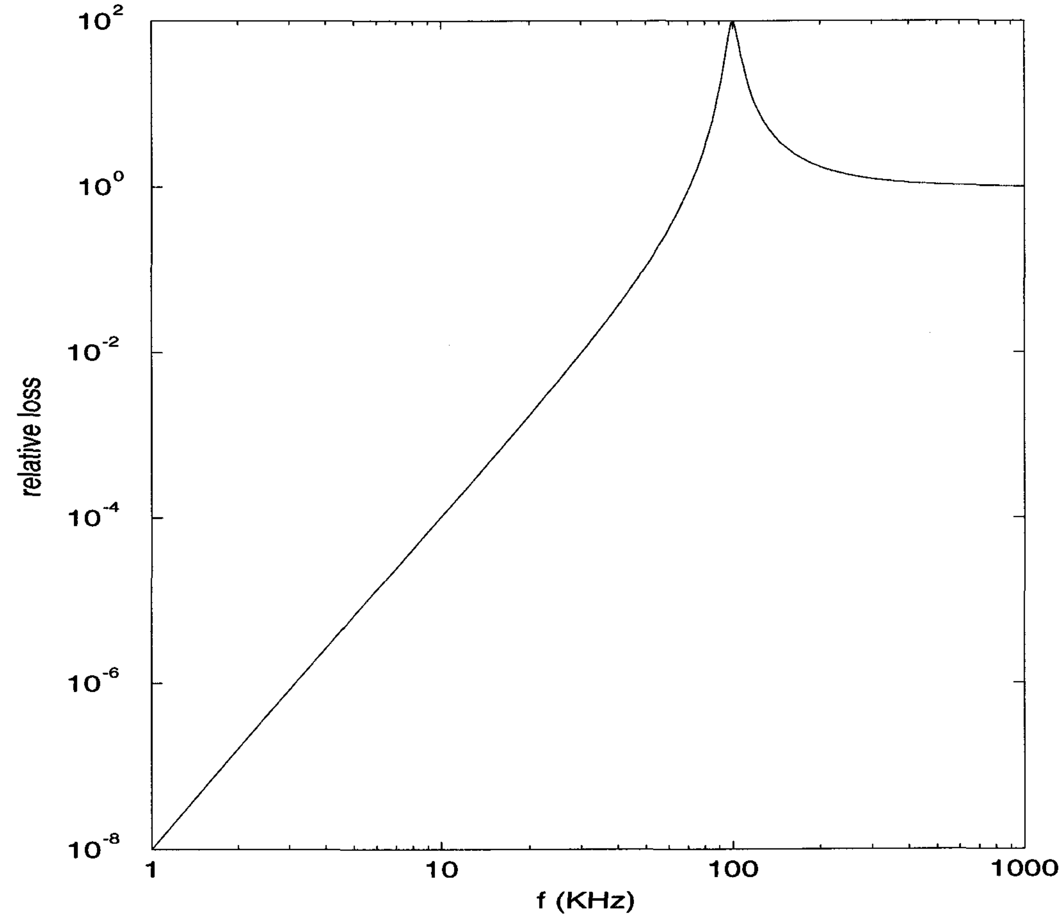

Figure 2. Theoretical frequency dependence of magnet/spacer induced loss.

Clearly a lossy magnet/spacer attachment will remove more energy from a test-mass - i.e. induce higher mechanical loss - if it is subjected to a larger amplitude of vibration than if it is not. The mechanical loss induced by the magnet/spacer is proportional to the square of the amplitude of vibration of the test-mass at the location of the magnet, as mentioned earlier. For a given amount of vibrational energy per mode, different internal modes of the test-mass have different amplitudes of vibration at the magnet locations and consequently suffer different amounts of mechanical loss due to the magnet/spacer attachments. In order to account for this Kent Blackburn's "effmass.c" program was modified and extended to calculate the test-mass internal-mode modeshapes.[1] The amplitude of vibration (namely axial displacement of the test-mass face from the undeformed position) at the magnet attachment location was calculated for the same, arbitrary, amount of energy in each internal mode in turn, and this was used to weight the loss data with magnets attached. Fig. 3 shows one such modeshape, for the 9.477 KHz mode, which happens to be the one having the largest vibrational amplitude at the magnet. The magnet is located at $r/r_{rmax} = 0.96$, near the right-hand edge of the plot.

For the currently used magnet/spacer assemblies the longitudinal mass/stiffness resonance is close to 100 KHz, as mentioned previously. At frequencies well below this resonance the magnet-induced losses are predicted to be of the form :

$$\phi_{eff} = Af^4x^2{}_{mag} \qquad 1$$

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[1] This "effmass.c" program has eliminated significant numerical instabilities and convergence problems displayed by Aaron Gillespie's "effmass.3.1.f" program and its derivative "shape.f" program which made them unsuitable for this purpose as they sometimes generated unphysical modeshapes, though they generated fairly accurate resonant frequencies.

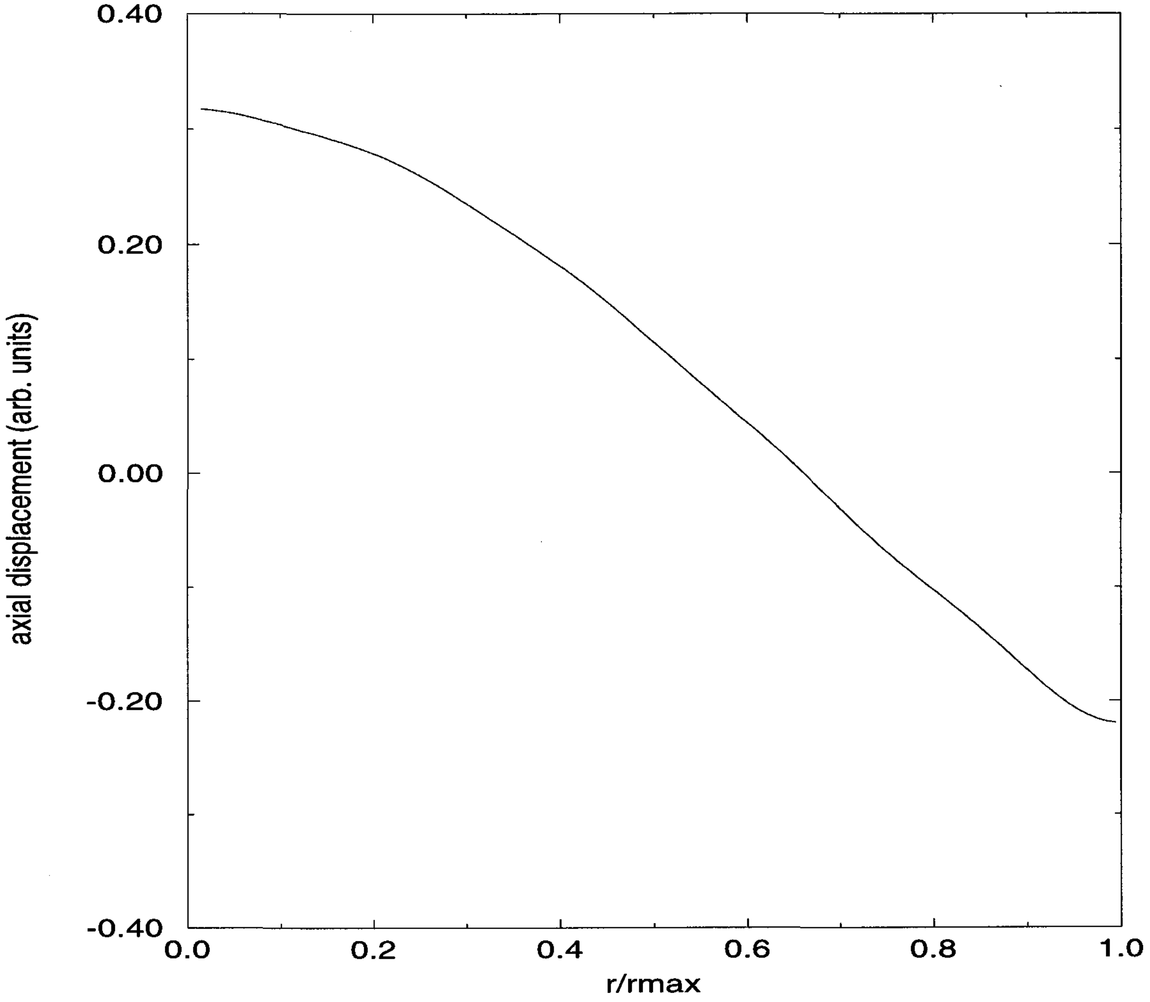

Figure 3. A modeshape of the Pathfinder optic (9.477KHz mode)

Consequently,

$$\phi_{eff}/x_{mag}^2 = Af^4 \qquad 2$$

Shown below in table 2 is a list of mode frequencies, ϕ_3 (same as column 4 of table 1), calculated x_{mag} , and ϕ_3/x_{mag}^2.

Table 2: Modeshape-corrected magnet loss data

Mode Freq (KHz)	φ_3	x_{mag} (arb units)	$\phi_4 = \phi_3/x_{mag}^2$ (arb. units)
9.477	1.88×10^{-6}	−0.2197	3.88×10^{-5}
22.424	0.54×10^{-6}	0.0280	6.82×10^{-4}
25.637	1.66×10^{-6}	−0.1224	1.12×10^{-4}
29.489	1.78×10^{-6}	−0.0763	3.06×10^{-4}
29.871	1.37×10^{-6}	0.0704	2.76×10^{-4}
42.765	1.43×10^{-6}	0.0433	7.73×10^{-4}
47.341	5.83×10^{-6}	0.0605	1.59×10^{-3}

Fig. 4 shows a plot of this data. The lower trace (square markers) show ϕ_3 vs mode frequency, the upper trace (triangles) shows ϕ_4 vs mode frequency. Also shown are least-square fits of the functional form $\phi = A_0 f^4$ to the two data sets.

6 GOODNESS OF FIT

As can be seen six of the seven data points in the upper trace (ϕ_4) fit very well to the f^4 line, while the lower trace data (ϕ_3) do not fit at all well. The seventh data point belongs to a mode at 9.477 KHz which is suspected to have additional mechanical losses induced by the test-mass suspension wire (discussed earlier in the footnote on page 6). Data points for this 9.477 KHz mode were omitted from the goodness of fit estimates discussed below.

In order to estimate the goodness of fit the quantity $\xi = \sqrt{1/(N-1)\sum_i^N((\phi_i^{\mathrm{expt}} - \phi_i^{fit})/\phi_i^{\mathrm{expt}})^2}$ was calculated for ϕ_3 and ϕ_4 fitted to their respective least-square fitted $A_i f^4$ polynomials. As can be seen from the formula, ξ is the rms fractional deviation from the fit.

For comparison both ϕ_3 and ϕ_4 were also fitted to a constant, as in the absence of any other information the simplest hypothesis would be that ϕ_3 was a constant, independent of frequency.

The results are summarized in the table below :

Table 3:

data	fit function	ξ
ϕ_3	$\phi_3 = A_3 f^4$	0.786
ϕ_3	$\phi_3 = B_3$	1.384
ϕ_4	$\phi_4 = A_4 f^4$	0.200
ϕ_4	$\phi_4 = B_4$	3.442

As table 3 shows, ϕ_4 fits the f^4 model with an rms fractional deviation of 20%; the three other fits are all significantly worse.

7 CONCLUSION

The magnet/spacer induced losses in the Pathfinder optic fit the predicted f^4 frequency dependence well over the range from 20 KHz to 50 KHz. If this frequency dependence holds down to below 1 KHz (the nominal bandwidth of initial LIGO) then the extrapolated mechanical losses induced by the magnets for the worst internal mode at 1 KHz is still less than 3×10^{-10}, which is far lower than the measured mechanical loss of the best mode of the bare optic (about 1×10^{-7}). Consequently if this extrapolation is valid the magnet/spacer assemblies will not add significant loss to the mechanical loss of the bare optics at frequencies below a few KHz and consequently not worsen the thermal-noise performance of the bare optics, which is currently sufficient to meet the goals of initial LIGO.

It should be noted that there are other hypothetical magnet-induced loss mechanisms which have a flat frequency response, such as loss due to transverse strain coupled through the spacer into the magnet. Some such mechanism might put a "floor" on how low the magnet-induced losses can get, limiting the range of validity of the f^4 frequency dependence at the low-frequency end.

8 FUTURE WORK

Attempts are currently being made to estimate the loss contribution of transverse strain coupled to the magnet through the spacer using data from the Pathfinder optic. However this is limited by the fact that the lowest internal mode of this optic is at 9.5 KHz, far above the 1 KHz region where we need information about mechanical losses. A possible solution would be to perform measurements on a dummy optic of the same diameter (25cm) as the Pathfinder optic, but much thinner. If the thickness is chosen to be 3 millimeters there will be internal modes at 733 Hz, 2.45 KHz, 5.13 KHz and 8.76 KHz, all of which lie below the Pathfinder optics lowest mode of 9.5 KHz. This will enable direct measurements of magnet-induced loss down to below 1 KHz.

9 ACKNOWLEDGMENTS

I thank Kent Blackburn for granting me access to the “effmass.c” code he wrote, and for helping me to understand it. The program that calculates test-mass internal mode-shapes, “modeshape.c”, is based on Kent’s program.

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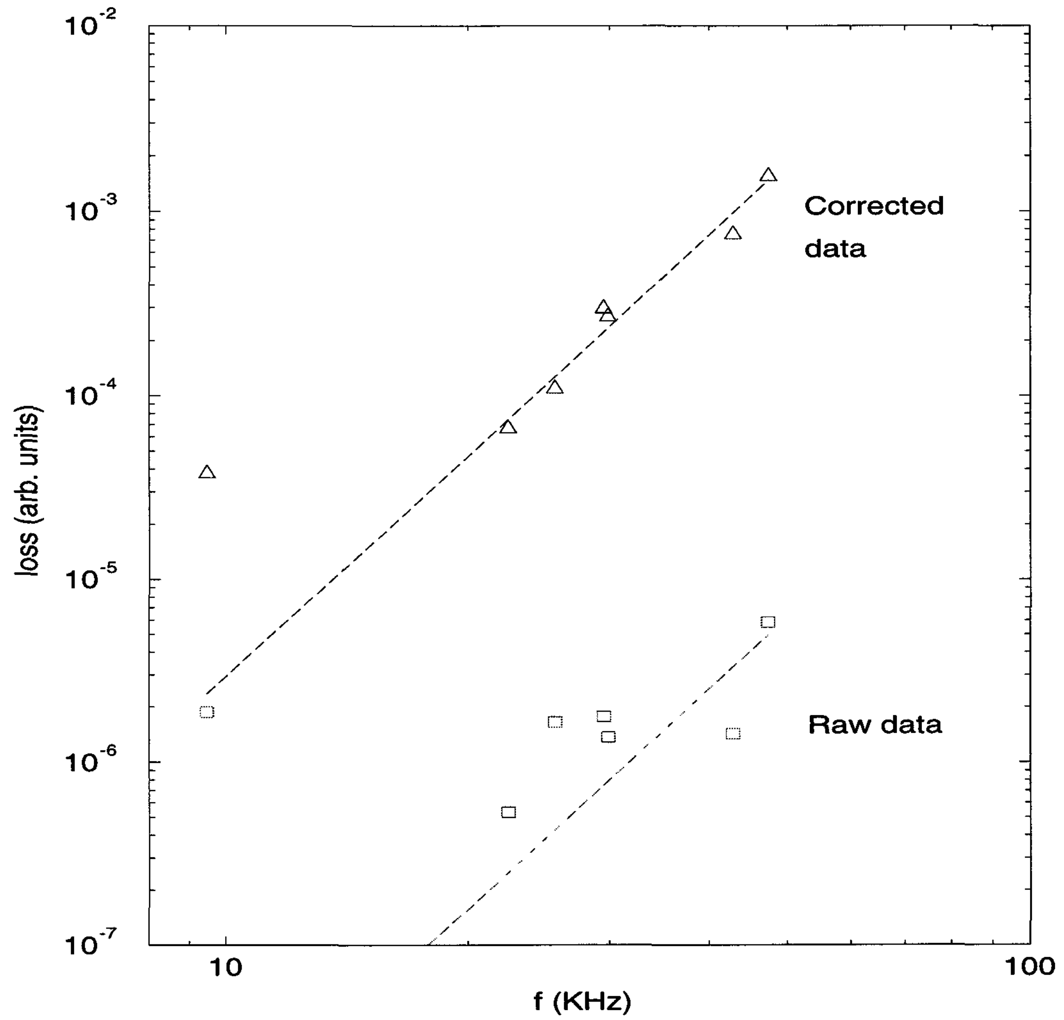

Figure 3: Mechanical loss vs frequency

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