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Investigation of Violin Mode *Q* for Wires of Various Materials

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Investigation of violin mode *Q* for wires of various materials

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ABSTRACT

The *Q* factors of violin modes for wires of various materials have been measured in order to determine which would be most suitable for use in the suspension of test masses in the initial Laser Interferometer Gravitational-wave Observatory (LIGO) interferometers. A “guitar” type apparatus was employed to measure violin mode *Q*s, and losses due to clamping and other practical sources were successfully suppressed below the level of intrinsic wire losses. Steel music wire was found to give the highest extrapolated *Q* factors under LIGO conditions among the wires we tested. This extrapolated *Q* sets a target for the LIGO suspension which can be attained if all the losses other than the intrinsic wire loss are successfully suppressed. The measured *Q*s for the steel, tungsten, and titanium wire, which were approximately frequency independent for the first two to three modes, were found to be roughly proportional to the square root of the tension in the wire. This is consistent with the theory of violin mode losses due to frequency-independent intrinsic wire losses.

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I. INTRODUCTION

The LIGO project [1] [2] will use laser interferometry between test masses to detect gravitational waves of strain amplitudes $h \sim 2\times10^{-22}$ over the 4 km baseline of the interferometers, equivalent to measuring a change in length of $\sim10^{-18}$ meters. At such a level of sensitivity, the reduction of noise becomes an urgent priority if it is not to overwhelm the gravitational wave signal. The test masses are suspended as pendulums by fine wires as the final stage of the seismic isolation system: such pendulums will have a resonant frequency of approximately 1 Hz, and at the frequencies of interest to LIGO (≥ 10 Hz) this will allow the test masses to behave as essentially free masses.

Such a system will have inherent thermal noise, due to the inescapable equipartition of thermal energy between the normal modes of oscillation of the system. A simple calculation shows the rms thermal noise displacement of the LIGO test mass (10.7 kg) due to its pendulum motion at room temperature is of the order 10^{-12} m, which would drown any gravitational wave signal. However, application of the fluctuation-dissipation theorem [3] to find the expected spectrum of the thermal noise shows that within the LIGO gravitational wave bandwidth, thermal noise displacement of the test mass can be reduced to the required levels by using pendulums of a sufficiently low loss; such a pendulum will have the great majority of its thermal energy concentrated at its resonant frequency with very little in the ‘tails’ of the thermal noise spectrum in the frequency band of interest to LIGO [4]. This is why development of ultralow loss suspensions is essential to LIGO.

Several groups [5] [6] [7] have shown that there exists a simple relationship between the loss of the pendulum modes of the suspension and the violin modes. The violin mode Qs are generally easier to measure than the pendulum mode *Q*. This is because the violin modes are less subject to recoil losses due to the lighter mass of the wire, and also because the violin mode *Q* measurement can be done within a reasonable period of time due to its higher resonance frequencies. It also allows some frequency dependence of the loss to be studied by measuring the *Q* for different modes of the violin resonances. Therefore we have measured violin mode *Q*s for various wire materials instead of the pendulum mode *Q*.

The major goal of the tests carried out was to select from a range of candidate wire materials the one which would have the highest *Q* factor when used in the LIGO suspension. In this investigation we concentrated only on metal wires. Although much higher violin mode *Q*s have been obtained for fused silica fibers [8], their use would require significant changes in the suspension design and is not planned for the initial LIGO suspension.

II. VIOLIN MODE LOSS

According to theory [5] [6] [7], the violin mode losses $\varphi_V(\omega)$ due to intrinsic wire losses have a dependence upon the length *L* and diameter *d* of the wire used (for circular wires) and upon the tension on the wire *T* of the form

$$\varphi_v(\omega) = \frac{\sqrt{\pi}}{4} \cdot \sqrt{E} \cdot \frac{d^2}{L\sqrt{T}} \cdot \varphi_w(\omega), \qquad (1)$$

where $\varphi_W(\omega)$ is the intrinsic loss function of the wire material, which may exhibit some frequency dependence, and *E* is the Young's modulus. $\varphi(\omega)$ is equal to $1/Q$ on resonance. Eq. (1) holds when the losses are concentrated near sharp bends at the ends of the wire, and losses due to the bending along the length of the wire is negligible. This is true for the first several harmonics of the wire for our application.

One well-established mechanism for internal friction in materials, proposed by Zener [9], is that of thermoelastic damping. The loss function given by the thermoelastic damping model exhibits a Debye peak, the frequency of which is determined by the relaxation time of the thermoelastic effect. When the thermoelastic damping is the strongest dissipation mechanism in the system, then its Debye peak will be seen; when other mechanisms dominate, then their frequency dependence is what is observed. *Q*s of tension-free wires were measured to be consistent with thermoelastic models for some materials [10]. On the other hand several experiments have shown that violin mode losses of loaded wires are largely frequency independent over a limited range [5] [11] [12], which indicates that some other mechanisms dominated the thermoelastic damping.

Recently Huang [11] demonstrated that the largely frequency-independent *Q*s of steel wire could be explained by the thermoelastic model with the conjecture of heat flow along the longitudinal axis of the wire and also into the clamp. (Conventional models were based on the assumption that heat flow is strictly transverse and not into clamps.) This results in the Debye peak being stretched out to higher frequencies; measurements taken near the peak will then appear to be frequency independent over a limited range. On the other hand Huang found that tungsten exhibited internal friction at a level much higher than can be explained by thermoelastic damping.

Losses due to clamping at the ends of the wires are one of the causes for excess losses. Slippage at the clamp will result in additional energy dissipation, and under some circumstances may significantly increase the loss [13]. In any experiment to determine wire *Q*s, care must be taken to ensure that clamping losses do not overshadow losses intrinsic to the material.

III. MEASUREMENT OF VIOLIN MODE *Q*

We chose to test wires made of aluminum, molybdenum, niobium, tantalum, titanium, tungsten, beryllium copper, invar, and steel music wire, for various reasons, including a high intrinsic *Q* where known, high tensile strength, and low thermal expansion ratio. All the wires used were fully annealed except steel music wire. All the wires had a diameter of 0.25 mm except for the steel music wire, whose diameter (0.30 mm) was the same as that which would be used in the initial LIGO interferometer.

Each wire was stretched across an aluminum block, and clamped at each end using two planar clamping pieces secured with screws (Fig. 1). The distance between the clamps was 10 cm. The heavy block (5 cm × 12 cm × 15 cm; ~2 kg), machined from a single piece of aluminum, was designed to suppress energy transfer from the wire to the block due to the high resonant frequencies of its internal modes and high ratio of block mass to wire mass. The wire was loaded at various tensions below its yield stress (except Titanium). This “guitar” type apparatus was used inside a vacuum chamber ($\sim 10^{-2}$ Torr) to avoid air damping; this pressure was calculated to be low enough to cause negligible damping. Piezoelectric transducers were placed between the aluminum block and the bottom plate of the chamber to excite violin modes, instead of between the clamp and the aluminum block to avoid any mechanical wobbliness that might impair the measurement. A HeNe laser focused on the wire was used to cast a shadow upon a split photodiode to monitor the motion of the wire. To measure the *Q* of the mode, the photodiode output was compared with a reference frequency ~ 1 Hz greater (or smaller) than that of the mode under study using a lock-in amplifier and function generator. The resulting beat signal was fed to a chart recorder. The *Q* factor was obtained by measuring the 1/e amplitude decay time of the beat envelope from the trace.

It was a concern that losses in the clamping could hide those intrinsic to the wire. In order to overcome this problem, the following experimental precautions were taken:

1. A plate-sandwich clamp was used instead of a spacer at the wire ends [14]. It had been reported [11] that the spacer exhibits more excess loss than the plate-sandwich clamp.
2. The distance between the clamps was chosen to be relatively short. By this measure we aimed to reduce the effect of clamping losses so we could clearly distinguish material effects. A short length of wire emphasizes intrinsic wire losses [See Eq. (1)], whereas losses due to clamping do not seem to be affected by changes in wire length.
3. We tested clamps made from a variety of materials (aluminum, titanium, stainless steel and heat-treated hardened steel, in order of increasing material hardness) to verify that losses due to clamping were negligible compared with those intrinsic to the wire.

Table I shows the results of the measurements. It was observed that *Q*s were an order of magnitude lower with the aluminum clamps for the molybdenum wire. We believe the reason for the poor performance of the aluminum clamps is that the metal is too soft to allow effective clamping. Large grooves were left in the aluminum surfaces where the molybdenum wire had been clamped; this suggests that the wire could also slip and hence lose energy via friction. Supporting this conclusion is the fact that, using aluminum clamps, it was not possible to attain high tension in the wires once they were clamped. We must attribute this to slippage since the other alternative, yielding of the wire, would also have happened with other clamps; this was not observed.

Steel music, invar, and tungsten wire, in this order, were found to have the best Q factors when the measurements were extrapolated to wires whose dimensions are appropriate for the initial LIGO suspension assuming the dependence of Eq. (1) with frequency-independent intrinsic wire losses. For these three wires and the titanium wire, we measured the Q factors of the first two to three modes at six to eleven different tensions with various clamps. For each tension a different piece of wire was used, and for each piece of wire one to three ringdown times were measured. Fig. 2 shows the violin mode Qs of those wires plotted as a function of $\sqrt{T}$, where T is the tension on the wire. The Q values plotted are mean values of Q factors for the first two to three modes measured at that tension. This averaging was meaningful because the Qs for the first two to three modes were found to be independent of frequency. The error bars indicate the combined statistical variation of Qs for different measurements and for different modes, but for the same piece of wire. The tension on the wire was calculated from the frequency of the fundamental violin resonance.

The data show that the Qs for the steel, tungsten, and titanium wire have roughly a dependence of $\sqrt{T}$ with slopes that depend on the type of wire [15]. This is consistent with the dependence in Eq. (1) together with the observation that the loss is roughly frequency independent around the frequency of the measurement. It can also be seen that for these wires, the different clamps give broadly comparable results. We have interpreted this as indicating that we had successfully reduced clamping losses to below the level of internal damping.

IV. DISCUSSION

Table II shows comparison of our results with Qs obtained by other measurements. The measured Qs are “extrapolated” to the LIGO wire dimensions using Eq. (1) assuming that the measured losses are dominated by frequency-independent intrinsic wire losses. This “extrapolation” does not completely account for all possible losses. Additional losses may have been present in some measurements, especially when measured Qs are very high, and other intrinsic losses (such as thermoelastic losses) may become important at the extrapolated dimensions. Unfortunately it is difficult to properly estimate these effects, which can depend on the details of each experimental setup for the different experiments compared in Table II. Generally the higher the “extrapolated” Qs are, the less likely it is that additional losses were present in the measurement. Our results for steel and tungsten are among the highest “extrapolated” Qs derived from measurements for each wire, whereas the Qs we measured are among the lowest. This supports our interpretation that our measured Qs were not dominated by losses other than the intrinsic wire losses. Therefore, if all sources of excess loss are successfully suppressed, the maximum Q achievable for each wire in the LIGO suspension is indicated by the values extrapolated from our measured Qs. Careful evaluation of the wire clamping configuration and materials will be required to achieve this goal.

ACKNOWLEDGMENTS

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[14] Cylindrical or wedge spacers are frequently used as wire standoffs for test mass suspension system.

[15] The data for the invar wire show that there is larger scatter for different pieces of wire than variation for different measurements and modes, and the hardened steel clamps tend to give higher *Q*s than the stainless steel clamps. This could indicate existence of clamp losses which depend on a material of the clamp and a subtle condition of clamping. Since invar has much higher measured *Q*s than the other wires, any variation in *Q* due to subtle clamping effects will be more apparent than with the other wires.

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TABLE I. Measured *Q* and extrapolated *Q* for the LIGO wire dimensions.

Wire[a]	Clamp[b]	Tension (N)	Measured *Q*	Yield Tension of Wire (N)	Extrapolated *Q* for LIGO Wire Dimensions[c]
Steel Music Wire[d]	H, S	10 - 34	17,000 - 40,000	90	200,000 (± 17%)
Invar	H, S	3.5 - 11	28,000 - 91,000	21	140,000 (± 21%)
Tungsten	H, S, T	13 - 32	10,000 - 40,000	100	130,000 (± 11%)
Niobium	S	3.6	25,000 - 31,000	10	65,000
Molybdenum	S	6 - 14	14,000 - 14,500	30	59,000
	A	1	900 - 1,600	N/A	N/A
Tantalum	S	1.3	15,000	8	46,000
Titanium	H, T	4 - 10	20,000 - 43,000	8	22,000 (± 6%)
Beryllium Copper	S	4 - 5	1,000 - 11,000	12	20,000
Aluminum	Too weak to test			3	N/A

[a] l = 10 cm, ϕ = 0.25 mm except steel music wire (ϕ = 0.30 mm)

[b] H: Hardened steel, S: Stainless steel, T: Titanium, A: Aluminum

[c] Diameter of each wire is chosen to give half yield tension for the LIGO test mass (10.7 kg). We assumed the dependence of Eq. (1) with frequency-independent intrinsic wire losses.

[d] C 1085 (Carbon: 0.66 - 1.04%, Manganese: 0.17 - 0.63%, Phosphorus: 0.033% max, Sulphur: 0.038% max, Silicon: 0.08 - 0.32%), procured from Precision Brand Products, Inc., Downers Grove, IL 60515

TABLE II. Comparison of violin mode Qs measured in various measurements and its “extrapolated”[a] Q for the LIGO wire dimensions.

Wire		Reference	Clamp Type[b]	Diameter (mm)	Length (cm)	Tension[c] (N)	Measured Q[d]	“Extrapolated” Q for LIGO Wire Dimensions[e]
Steel	Music Wire	Dawid and Kawamura (this report)	P-P	0.30	10.0	21.6	29,000	200,000
	Stainless Steel	Huang [11]	P-P	0.125	30.3	7.4	250,000	170,000
	Music Wire	Gillespie and Raab [12]	P-S	0.075	35.0	3.9	430,000	130,000
	Music Wire	Killbourn and Robertson [16]	P-S	0.178	25.0	6.93	42,000	74,000
	C85 Harmonic Steel	Kovalik [17]	P-P	0.20	71.6	50.2	240,000	69,000
Tungsten		Dawid and Kawamura (this report)	P-P	0.25	10.0	23	20,000	130,000
		Huang [11]	P-S	0.175	37.0	36	180,000	90,000

a. See IV. DISCUSSION for detail.
b. P: plate-sandwich clamp, S: spacer
c. Typical tension used
d. Average Q for the first one to three modes
e. Diameter: 0.30 mm (steel) and 0.25 mm (tungsten), Length: 45.5 cm, Tension: 52.4 N. Note that the diameter of 0.30 mm gives half yield stress for the steel music wire we used; for different kind of steel wire, the diameter may be slightly different.

FIGURE CAPTIONS

FIG. 1. Experimental apparatus for measuring violin mode *Q*s of the wire clamped at both ends.

FIG. 2. Violin mode *Q*s of invar, titanium, steel, and tungsten with the clamps made of hardened steel, stainless steel, and titanium, measured as a function of $\sqrt{T}$. The dotted lines indicate best fit to data with the assumption of zero-crossing linear dependence to $\sqrt{T}$.

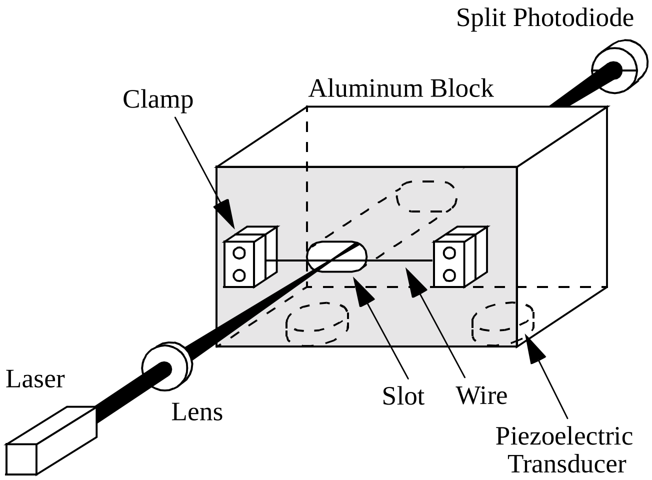
Split Photodiode
Clamp
Aluminum Block
Laser
Lens
Slot
Wire
Piezoelectric Transducer

Fig. 1

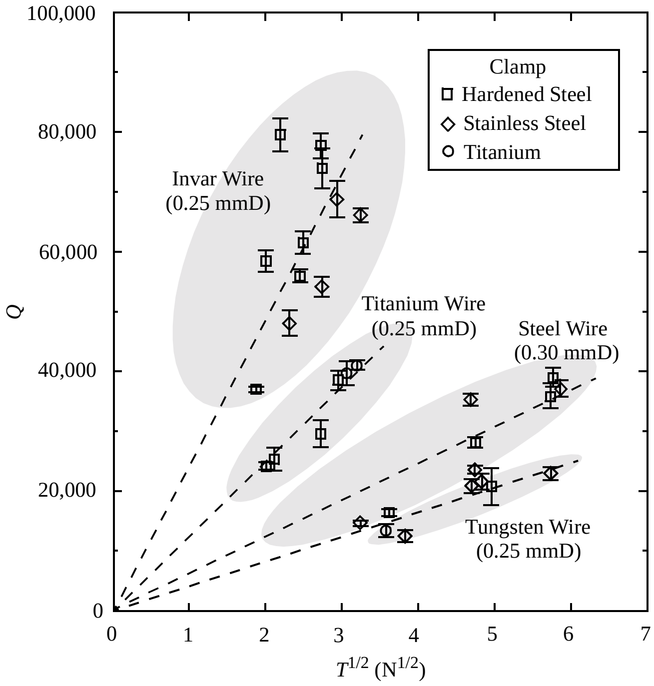
100,000
80,000
60,000
40,000
20,000
0
Q
0
1
2
3
4
5
6
7
$T^{1/2}$ ($N^{1/2}$)
Clamp
□ Hardened Steel
◇ Stainless Steel
○ Titanium
Invar Wire
(0.25 mmD)
Titanium Wire
(0.25 mmD)
Steel Wire
(0.30 mmD)
Tungsten Wire
(0.25 mmD)

Fig. 2

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2. The distance between the clamps was chosen to be relatively short. By this measure we aimed to reduce the effect of clamping losses so we could clearly distinguish material effects. A short length of wire emphasizes intrinsic wire losses [See Eq. (1)], whereas losses due to clamping do not seem to be affected by changes in wire length.
3. We tested clamps made from a variety of materials (aluminum, titanium, stainless steel and heat-treated hardened steel, in order of increasing material hardness) to verify that losses due to clamping were negligible compared with those intrinsic to the wire.

Table I shows the results of the measurements. It was observed that *Q*s were an order of magnitude lower with the aluminum clamps for the molybdenum wire. We believe the reason for the poor performance of the aluminum clamps is that the metal is too soft to allow effective clamping. Large grooves were left in the aluminum surfaces where the molybdenum wire had been clamped; this suggests that the wire could also slip and hence lose energy via friction. Supporting this conclusion is the fact that, using aluminum clamps, it was not possible to attain high tension in the wires once they were clamped. We must attribute this to slippage since the other alternative, yielding of the wire, would also have happened with other clamps; this was not observed.

Steel music, invar, and tungsten wire, in this order, were found to have the best Q factors when the measurements were extrapolated to wires whose dimensions are appropriate for the initial LIGO suspension assuming the dependence of Eq. (1) with frequency-independent intrinsic wire losses. For these three wires and the titanium wire, we measured the Q factors of the first two to three modes at six to eleven different tensions with various clamps. For each tension a different piece of wire was used, and for each piece of wire one to three ringdown times were measured. Fig. 2 shows the violin mode Qs of those wires plotted as a function of $\sqrt{T}$, where T is the tension on the wire. The Q values plotted are mean values of Q factors for the first two to three modes measured at that tension. This averaging was meaningful because the Qs for the first two to three modes were found to be independent of frequency. The error bars indicate the combined statistical variation of Qs for different measurements and for different modes, but for the same piece of wire. The tension on the wire was calculated from the frequency of the fundamental violin resonance.

The data show that the Qs for the steel, tungsten, and titanium wire have roughly a dependence of $\sqrt{T}$ with slopes that depend on the type of wire [15]. This is consistent with the dependence in Eq. (1) together with the observation that the loss is roughly frequency independent around the frequency of the measurement. It can also be seen that for these wires, the different clamps give broadly comparable results. We have interpreted this as indicating that we had successfully reduced clamping losses to below the level of internal damping.

IV. DISCUSSION

Table II shows comparison of our results with *Q*s obtained by other measurements. The measured *Q*s are “extrapolated” to the LIGO wire dimensions using Eq. (1) assuming that the measured losses are dominated by frequency-independent intrinsic wire losses. This “extrapolation” does not completely account for all possible losses. Additional losses may have been present in some measurements, especially when measured *Q*s are very high, and other intrinsic losses (such as thermoelastic losses) may become important at the extrapolated dimensions. Unfortunately it is difficult to properly estimate these effects, which can depend on the details of each experimental setup for the different experiments compared in Table II. Generally the higher the “extrapolated” *Q*s are, the less likely it is that additional losses were present in the measurement. Our results for steel and tungsten are among the highest “extrapolated” *Q*s derived from measurements for each wire, whereas the *Q*s we measured are among the lowest. This supports our interpretation that our measured *Q*s were not dominated by losses other than the intrinsic wire losses. Therefore, if all sources of excess loss are successfully suppressed, the maximum *Q* achievable for each wire in the LIGO suspension is indicated by the values extrapolated from our measured *Q*s. Careful evaluation of the wire clamping configuration and materials will be required to achieve this goal.

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[15] The data for the invar wire show that there is larger scatter for different pieces of wire than variation for different measurements and modes, and the hardened steel clamps tend to give higher *Q*s than the stainless steel clamps. This could indicate existence of clamp losses which depend on a material of the clamp and a subtle condition of clamping. Since invar has much higher measured *Q*s than the other wires, any variation in *Q* due to subtle clamping effects will be more apparent than with the other wires.

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TABLE I. Measured *Q* and extrapolated *Q* for the LIGO wire dimensions.

Wire[a]	Clamp[b]	Tension (N)	Measured Q	Yield Tension of Wire (N)	Extrapolated Q for LIGO Wire Dimensions[c]
Steel Music Wire[d]	H, S	10 - 34	17,000 - 40,000	90	200,000 (± 17%)
Invar	H, S	3.5 - 11	28,000 - 91,000	21	140,000 (± 21%)
Tungsten	H, S, T	13 - 32	10,000 - 40,000	100	130,000 (± 11%)
Niobium	S	3.6	25,000 - 31,000	10	65,000
Molybdenum	S	6 - 14	14,000 - 14,500	30	59,000
	A	1	900 - 1,600	N/A	N/A
Tantalum	S	1.3	15,000	8	46,000
Titanium	H, T	4 - 10	20,000 - 43,000	8	22,000 (± 6%)
Beryllium Copper	S	4 - 5	1,000 - 11,000	12	20,000
Aluminum	Too weak to test			3	N/A

[a] $l = 10$ cm, $\phi = 0.25$ mm except steel music wire ($\phi = 0.30$ mm)

[b] H: Hardened steel, S: Stainless steel, T: Titanium, A: Aluminum

[c] Diameter of each wire is chosen to give half yield tension for the LIGO test mass (10.7 kg). We assumed the dependence of Eq. (1) with frequency-independent intrinsic wire losses.

[d] C 1085 (Carbon: 0.66 - 1.04%, Manganese: 0.17 - 0.63%, Phosphorus: 0.033% max, Sulphur: 0.038% max, Silicon: 0.08 - 0.32%), procured from Precision Brand Products, Inc., Downers Grove, IL 60515

TABLE II. Comparison of violin mode Qs measured in various measurements and its “extrapolated”[a] Q for the LIGO wire dimensions.

Wire		Reference	Clamp Type[b]	Diameter (mm)	Length (cm)	Tension[c] (N)	Measured Q[d]	“Extrapolated” Q for LIGO Wire Dimensions[e]
Steel	Music Wire	Dawid and Kawamura (this report)	P-P	0.30	10.0	21.6	29,000	200,000
	Stainless Steel	Huang [11]	P-P	0.125	30.3	7.4	250,000	170,000
	Music Wire	Gillespie and Raab [12]	P-S	0.075	35.0	3.9	430,000	130,000
	Music Wire	Killbourn and Robertson [16]	P-S	0.178	25.0	6.93	42,000	74,000
	C85 Harmonic Steel	Kovalik [17]	P-P	0.20	71.6	50.2	240,000	69,000
Tungsten		Dawid and Kawamura (this report)	P-P	0.25	10.0	23	20,000	130,000
		Huang [11]	P-S	0.175	37.0	36	180,000	90,000

a. See IV. DISCUSSION for detail.
b. P: plate-sandwich clamp, S: spacer
c. Typical tension used
d. Average Q for the first one to three modes
e. Diameter: 0.30 mm (steel) and 0.25 mm (tungsten), Length: 45.5 cm, Tension: 52.4 N. Note that the diameter of 0.30 mm gives half yield stress for the steel music wire we used; for different kind of steel wire, the diameter may be slightly different.

FIGURE CAPTIONS

FIG. 1. Experimental apparatus for measuring violin mode *Q*s of the wire clamped at both ends.

FIG. 2. Violin mode *Q*s of invar, titanium, steel, and tungsten with the clamps made of hardened steel, stainless steel, and titanium, measured as a function of $\sqrt{T}$. The dotted lines indicate best fit to data with the assumption of zero-crossing linear dependence to $\sqrt{T}$.

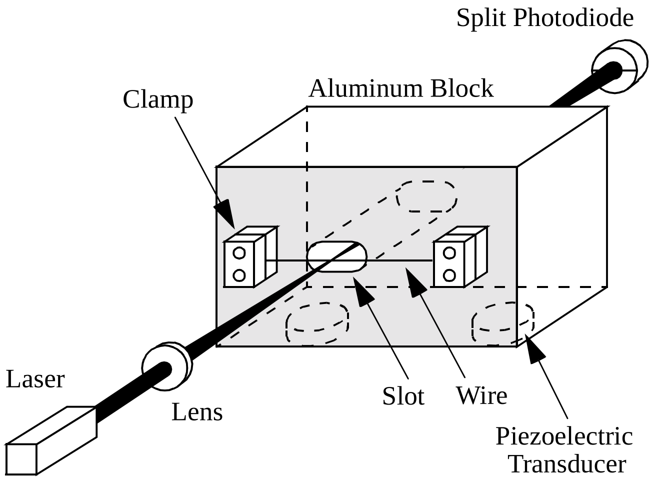
Split Photodiode
Clamp
Aluminum Block
Laser
Lens
Slot
Wire
Piezoelectric Transducer

Fig. 1

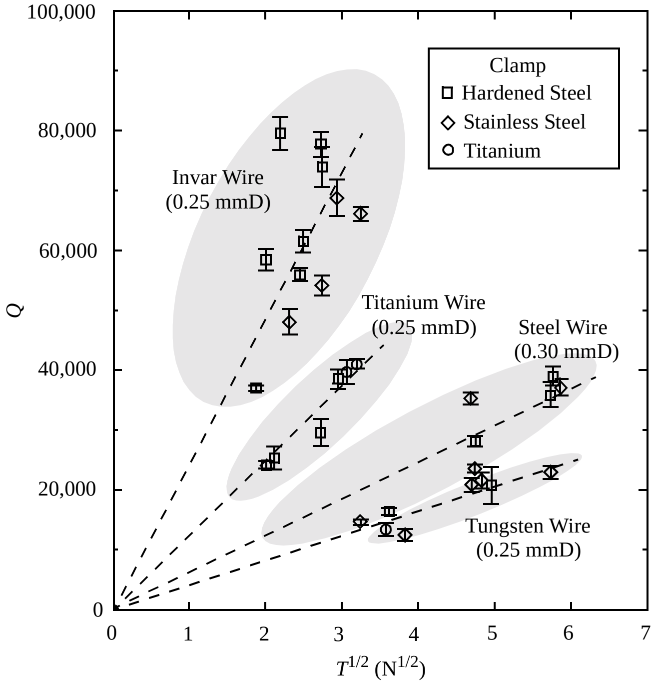
100,000
80,000
60,000
40,000
20,000
0
Q
0
1
2
3
4
5
6
7
$T^{1/2}$ ($N^{1/2}$)
Clamp
□ Hardened Steel
◇ Stainless Steel
○ Titanium
Invar Wire
(0.25 mmD)
Titanium Wire
(0.25 mmD)
Steel Wire
(0.30 mmD)
Tungsten Wire
(0.25 mmD)

Fig. 2