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Title: Substrate layer thickness effects on piezoelectric vibration energy harvesting with a bimorph type cantilever

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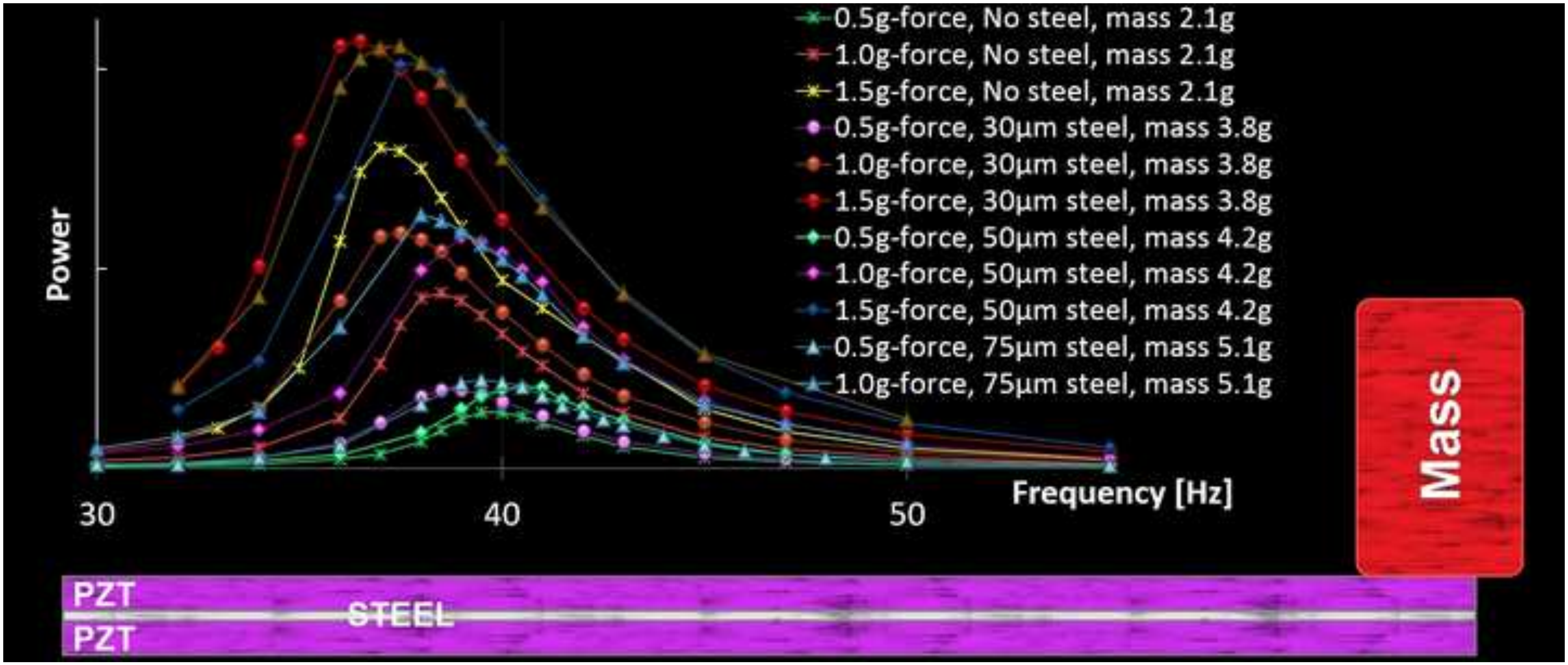
Graphical Abstract (for review)



Highlights

- Four piezoelectric bimorph type cantilevers for vibration energy harvesting were manufactured.
- The cantilevers had the same dimensions, but had different thicknesses of the steel substrate (no steel, 30 µm, 50 µm and 75 µm). and were tuned to the same resonance frequency with different sizes of tip mass (2.13 g, 3.84 g, 4.17 g and 5.08 g).
- The results showed that the harvested energy was similar between the samples except for the one with no passive steel layer
- 30 µm steel layer bimorph was the most efficient and required less ambient mechanical energy to produce the same harvested electrical energy.
- The highest average power of 8.74 mW was recorded under 2.5 g-force at a resonance frequency of 35 Hz from the cantilever with the 30 µm steel.

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The effects of substrate layer thickness on piezoelectric vibration energy harvesting with a bimorph type cantilever

In this research four piezoelectric bimorph type cantilevers for energy harvesting were manufactured, measured and analyzed to study the effects of substrate layer thickness on energy harvesting efficiency and durability under different accelerations. The cantilevers had the same dimensions of the piezoelectric ceramic components, but had different thicknesses of the steel substrate (no steel, 30 µm, 50 µm and 75 µm). The cantilevers were tuned to the same resonance frequency with different sizes of tip mass (2.13 g, 3.84 g, 4.17 g and 5.08 g). The energy harvester voltage outputs were then measured across an electrical load near to the resonance frequency (~40 Hz) with sinusoidal vibrations under different accelerations. The stress exhibited by the four cantilevers was compared and analyzed and their durability was tested with accelerations up to 2.5 g-forces.

Keywords: Piezoelectric, Energy harvest, Vibration, Cantilever

Introduction

As the power consumption of electronics becomes smaller while at the same time energy harvesting techniques and materials are being enhanced, interest is growing towards self-sufficient sensors [1-3]. Via piezoelectric material mechanical energy can be harvested and transformed to electrical energy. This technique requires accurate analysis of the kinetic energy experienced by the piezoelectric material so that the mechanics can be appropriately designed. Simultaneously the mechanical design has to safeguard the piezoelectric material from extreme forces that might cause cracks, while still transferring the kinetic energy efficiently. These requirements typically mean an exact energy harvest scheme for each ambient energy source at hand.

Many piezoelectric energy harvesting techniques have been developed for vibrations, including cymbal, diaphragm and cantilever type solutions [4-12]. The quantity of harvested energy outside the natural frequency of the device is still quite small and requires the optimization of the harvester dynamics to match the external vibration frequency in order to achieve usable power levels [13-15]. Not only does the harvester need to match the ambient vibrations, but also the input energy should be transmitted to the piezoelectric material as efficiently as possible. This is especially the case where the ambient vibration energy is limited and the harvesting mechanism could potentially have a major influence on the vibration source itself [16, 17]. This situation demands a high efficiency of transformation of the mechanical vibration energy into electrical energy.

It is well known that piezoelectric cantilever type actuators can be optimized to convert an electrical input to mechanical vibration amplitude. This can be done by the choice of material but also by adjusting the passive-to-active material thickness ratio, for example in unimorph type cantilevers [18]. With a unimorph cantilever the tip displacement varies with the passive layer thickness and determines the electromechanical coupling factor. This study was made to highlight the importance of optimization of the passive layer thickness in piezoelectric energy harvesting from ambient vibrations.

Materials and methods

Four bimorph type cantilevers with identical outer diameters were manufactured. Piezoelectric ceramic layers (PSI-5A4E) with a thickness of 200µm (191 µm without electrodes) were bonded using a conductive epoxy on both sides of a steel substrate layer with thicknesses of 30 µm, 50 µm and 75 µm. One bimorph structure was bonded without the passive steel layer. All parts were laser machined (ProtoLaser U3, LPKF Laser & Electronics AG, Germany) which provided the cantilevers with precise and identical dimensions for better comparison. The cantilevers were tuned to the same resonance frequency (~40 Hz) with different sized masses of 2.13 g, 3.84 g, 4.17 g and 5.08 g for the 0 μm, 30 μm, 50 μm and 75 μm passive steel layers respectively. Brass masses were glued on the tip of the cantilever free ends and fine-tuned to the correct weight with a blue-green sticker. The masses were glued at 2.0 mm distance from the tip. The shape of the cantilevers was slightly tapered from 9.0 mm clamping width to a free end width of 4.0 mm. The tapering will distribute the stresses more evenly across the length of the cantilever although highest stresses point will be at the clamping point. The total length of the cantilevers was 37.15 mm and the length of the clamping region was 2.28 mm. All the dimensions can be seen in Figure 1.

A shaker was used to accelerate the cantilevers with a sinusoidal displacement near to the resonance frequency. The movement was measured on top of the clamping point with a fiber optic laser vibrometer (OFV-5000, Polytec GmbH, Germany) to calculate the acceleration applied to the harvesters. Tip displacement was also measured from the tuning mass. The energy harvester output voltage was measured across an electrical load under different accelerations as a function of frequency. Average raw power curves were then calculated from the voltage measurements using Equation 1 where U is the root mean square (RMS) voltage and R is electrical load resistance.

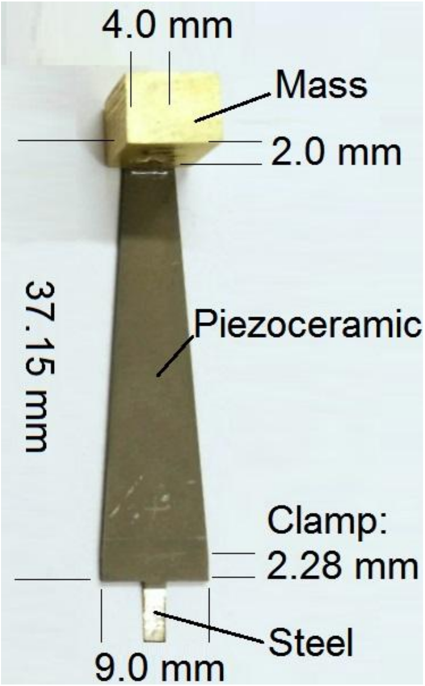

Figure 1. Cantilever dimensions

$$P = \frac{U^2}{R} \quad (1)$$

A 2D model was created with Comsol Multiphysiscs 5.2 simulation software and was used to analyze and compare the stress patterns of the cantilevers with different passive layer thicknesses. Simulations were carried out as transient simulations with the clamp point boundary set to sinusoidal acceleration. All the other boundaries were free. The 2D-model was tapered using the out-of-plane dimension as a variable to create the tapered width. The meshing was done with the automatic meshing tool of the software, which created triangular elements. The piezoelectric electrode boundaries were connected to a SPICE-circuit containing the load resistor. This is also facilitated by the Comsol software. The stresses were recorded as the maxima of the stress waveforms at the top of the piezolayer at the clamp point as shown in Figure 3.

Results

Firstly, the voltage (RMS) was measured with sinusoidal accelerations of 0.5 g-force (gravitational), 1.0 g-force and 1.5 g-force. The average raw power was then calculated from the measured voltage across an electrical load of 100 kΩ. Figure 2 shows the power curves as a function of frequency for each cantilever. The power levels were quite similar between cantilevers for every acceleration amplitude except in the case of the bimorph with no steel layer. For example, at 1.5 g-force the harvested average powers were all within 4.2 %, peaking at 4.28 mW with the 30 μm steel layer bimorph but the bimorph with no steel produced only an average power of 3.21 mW. Although the harvested electrical outputs were quite similar between cantilevers, the ambient mechanical energy for each cantilever was different. As the tip displacements and dimensions were quite similar between cantilevers which had a steel passive layer, required mechanical input energy difference was mainly determined by the tip mass weight. Due to this reason the cantilever with the smallest mass in the 30 μm steel layer bimorph was the most efficient and required less ambient mechanical energy to produce the same harvested electrical energy. The measured tip displacements of the harvesters under 1.0 g-force can be seen in table 1.

The large difference in power gain between the cantilever with no steel compared to cantilevers with steel could be that the no steel version had a shorter distance from the neutral stress axis to the surface. In other words, the thinner bimorph had a shorter leverage from the bonding layer to the piezoelectric material surface, therefore creating a smaller stress in the piezoelectric material. The lack of a steel layer, which has a higher Young's modulus than the ceramic material, could also be affecting the lower stress values inside the piezoelectric material because the ceramic-to-ceramic bonding layer could be more "flexible" than the ceramic to steel bonding layer. [19]

The resonance frequencies were all similar between the cantilevers and within ~1.5 Hz of each other. The small deviation in harvester voltage output could be a result of many small adjustable parameters such as slight differences in positioning of the mass, the size and shape of the mass, the clamping angle of the cantilever or the bonding layer thickness. All of these parameters were considered during the measurements, but were their effects were impossible to rule out completely.

The minor resonance frequency shift with higher accelerations was most likely due to the damping effect created by air resistance and/or due to slack in the clamping system. A higher acceleration creates a larger tip displacement and therefore a greater damping effect on the cantilever due to the fact that the air resistance increases exponentially with increasing velocity. For example, the cantilever with the 75 µm steel layer had a resonance frequency of ~39.5 hz at 0.5 g-force and ~38.0 Hz at 1.0 g-force as the tip displacements were 1.03 mm and 1.74 mm respectively. Very similar tip displacements and frequency shifts were also measured for the other two cantilevers with steel. The tip displacement of the cantilever with no steel was 2.62 mm under 1.0 g-force acceleration. As mentioned above, a small amount of slack in the cantilever clamping region could also affect this harmonic oscillator and decrease the resonance frequency slightly because higher accelerations created higher forces in the clamping region and as a result forced a little more free moving space for the cantilever. [20]

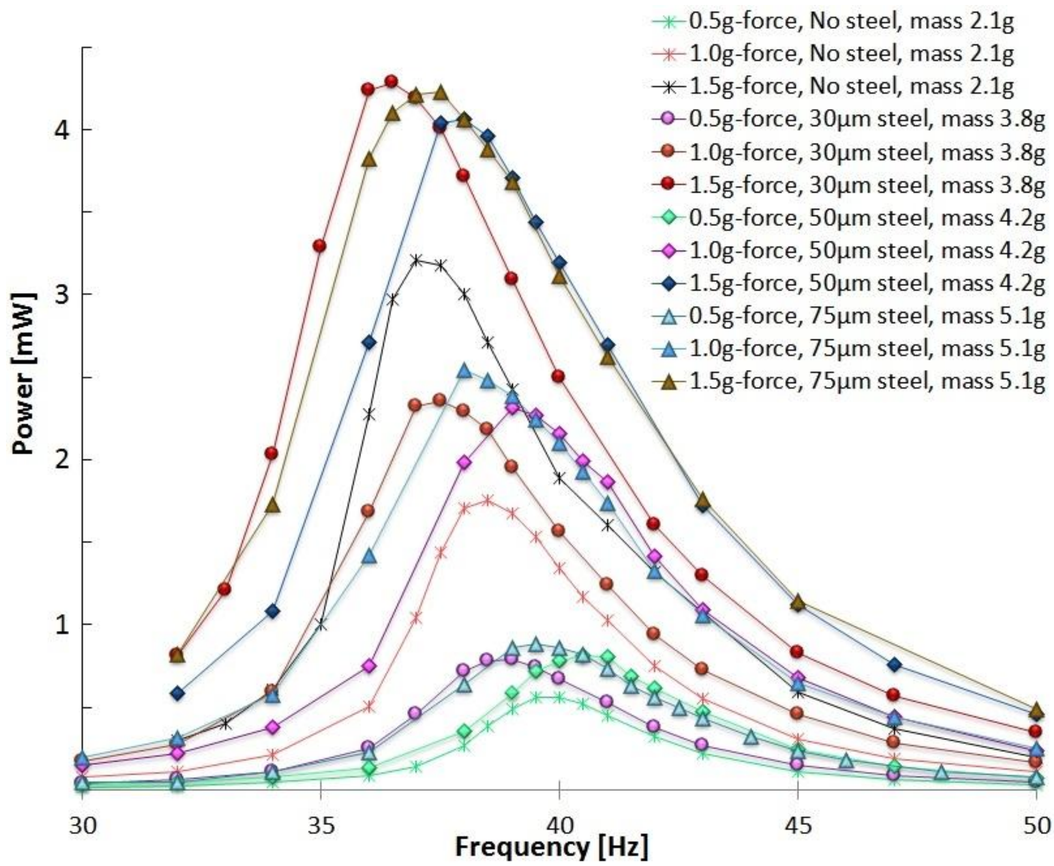

Figure 2. Average raw power as function of frequency measured under 0.5, 1.0 and 1.5 g-force accelerations from the cantilevers with different passive layer thickness of 0 µm (no steel), 30 µm, 50 µm and 75 µm and with tip masses of 2.1 g, 3.8 g, 4.2 g and 5.1 g respectively.

Simulation analyses were performed for the cantilever harvesters to compare their maximum stresses. The highest stresses were found to be near the clamping point and on the ceramic surface, as illustrated in Figure 3. The bimorph cantilever with a 50 µm passive steel layer experienced the lowest stress of 38.5 MPa force under 1 g-force acceleration and that with 75 µm steel was under the highest stress of 47.8 MPa. The bimorph with 30 µm steel experienced a slightly smaller stress than the 75 µm steel version and exhibited 43.2 MPa of stress in the piezoelectric ceramic. The bimorph with no steel experienced only 26.0 MPa under 1-gforce according to the simulations. The 75 µm steel version also delivered the highest voltage output and calculated average raw power of 2.55 mW under a 1.0 g-force. The 30µm steel and the 50 µm steel bimorphs delivered average powers of 2.36 mW and 2.31 mW respectively, as shown in Table 1. The lower stress level in the harvester without the passive steel layer was the reason for its measured lower voltage output and calculated average power compared to those with a steel layer.

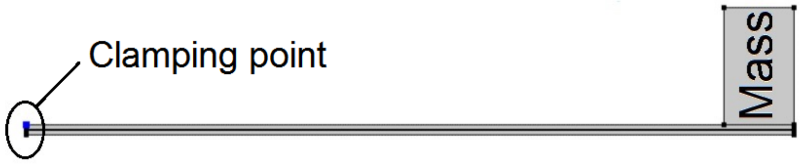

Figure 3. Illustration of maximum stress point in cantilever harvester.

Table 1. Simulation and measurement results for each energy harvester under 1 g-force acceleration at resonance frequency.

Passive layer thickness [µm]	Total thickness [µm]	Analysis clamping point stress [MPa]	Tuning mass [g]	Resonance frequency [Hz]	Harvested average raw power [mW]	Tip displacement [µm]
0	425	26.0	2.13	38.5	1.76	2615
30	466	43.2	3.84	37.5	2.36	1797
50	496	38.5	4.17	39	2.31	1652
75	529	47.8	5.08	38.5	2.55	1735

Figure 4 illustrates the measurements taken under maximum acceleration before the ceramic layers cracked. The cantilever with a 50 µm steel passive layer cracked at the beginning of the 2.0 g-force measurements. Those with the 75 µm steel layer and with no steel remained intact after the 2.0 g-force acceleration, but cracked under 2.5 g-force acceleration before the resonance frequency was reached. The cantilever with the 30 µm steel remained undamaged after 2.5 g-force and delivered a maximum average raw power of 8.74 mW at a resonance frequency of 35 Hz. This power computes to 0.25 mJ per cycle and a power-to-volume ratio of 92.5 mW/cm^3 for the piezoelectric material. In a real application the necessary housing would occupy a volume of 40 mm x 10 mm x 15 mm around the harvester. This space would result in a power-to-volume ratio of 1.46 mW/cm^3 for a practical device.

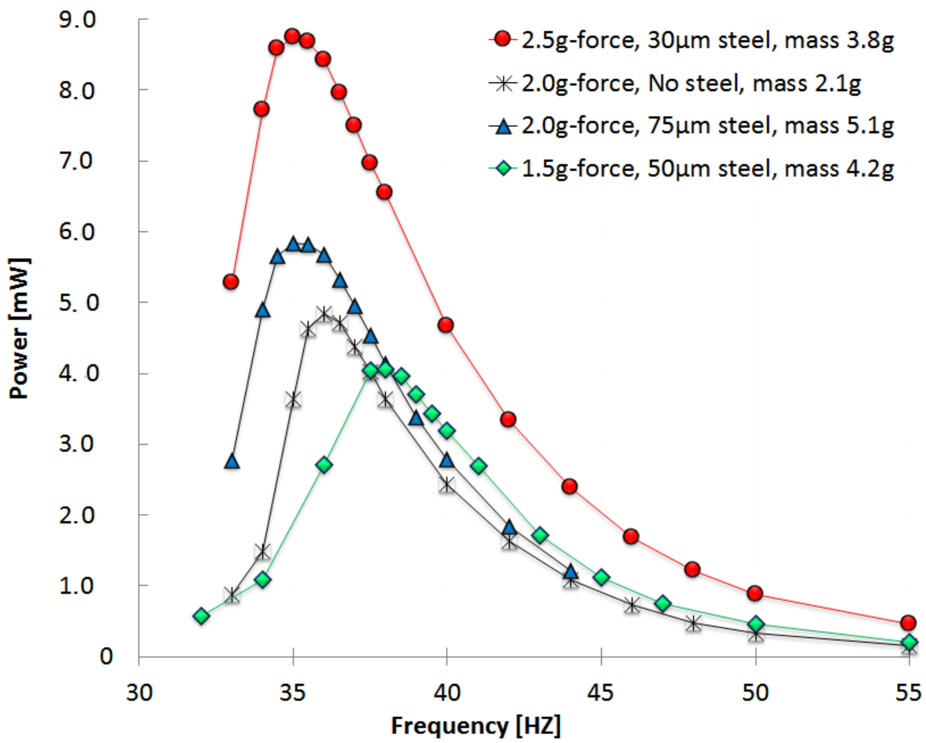

Figure 4. Harvester average raw power as a function of frequency measured under different accelerations before terminal damage.

Conclusion

Four piezoelectric bimorph type cantilevers with identical outer dimensions were manufactured for energy harvesting from ambient vibrations. The passive steel layer thickness was varied between 0 µm, 30 µm, 50 µm and 75 µm for the four harvesters and different weight tip masses were used to tune the cantilevers close to same resonance frequency (~40 Hz). Average raw powers were measured as a function of frequency under different accelerations. Simulations were performed to compare the maximum stress points between the samples. Results showed that the harvested energy was similar between the samples except for the one with no passive steel layer. For example, the harvested average raw power values measured under 1.5 g-force for all samples were within 4.2 % of each other and the highest output was 4.28 mW measured from the cantilever with a 30 µm thick passive steel layer. The harvester without the passive middle layer produced only 3.21 mW under the same conditions. Resonance frequencies were tuned within ~1.5 Hz for all samples. The highest average power recorded overall was 8.74 mW under 2.5 g-force at a resonance frequency of 35 Hz. This computes to a power to volume ratio of 92.5 mW/cm^3 for the piezoelectric material. The biggest benefit to use a thinner internal passive steel layer in bimorph cantilever is the higher efficiency as it requires less ambient mechanical energy to produce the same harvested electrical energy due to smaller mass. In addition, advantage is provided by a smaller physical size of needed mass. Results also show that insertion of an internal passive layer is essential to achieve maximum energy harvesting potential of the bimorph type cantilever. Further enhancement of the power-to-volume ratio could be achieved by optimizing the shape of the cantilever and gradient thickness of the piezoelectric ceramic.

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Table

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Figure 1.
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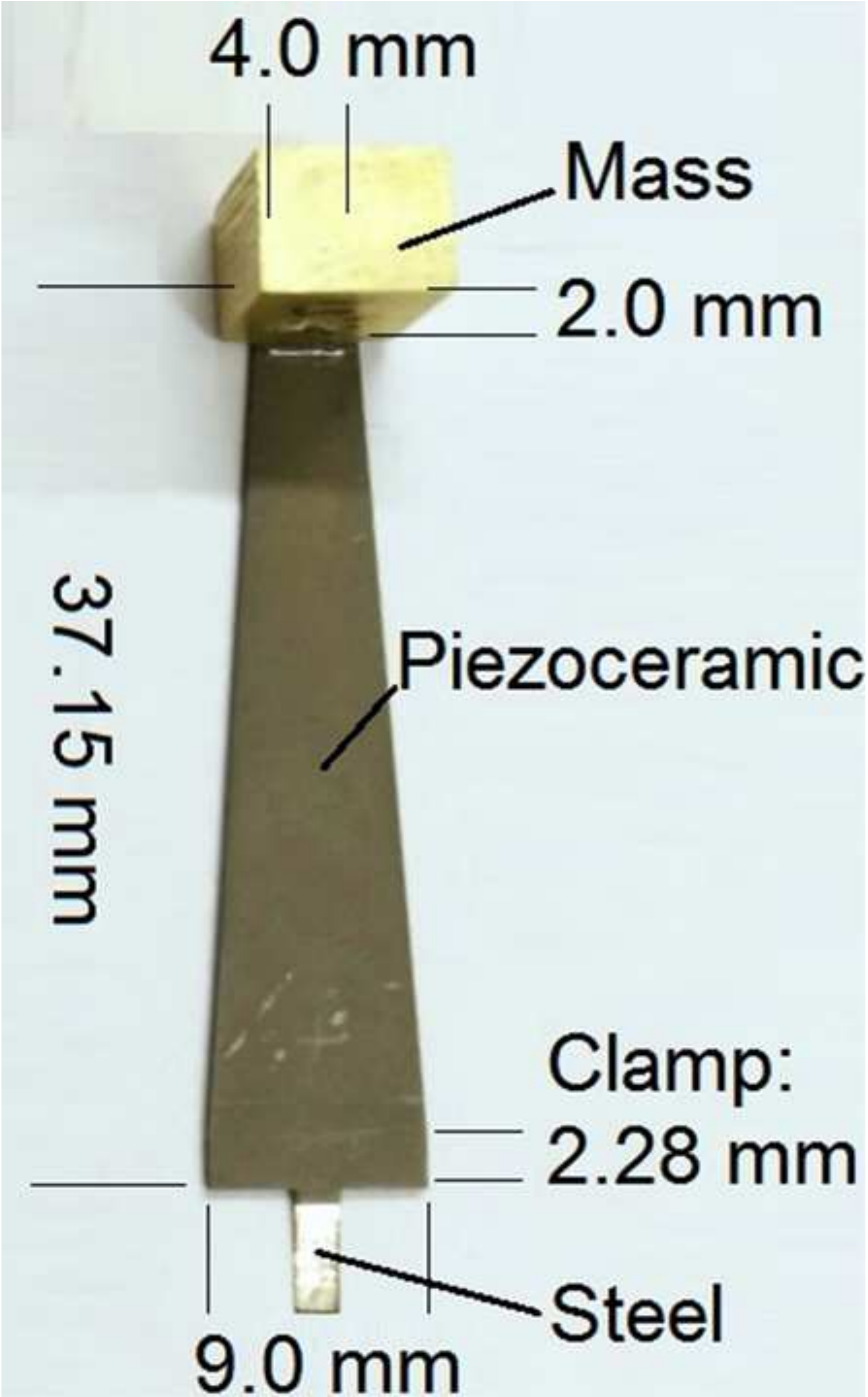

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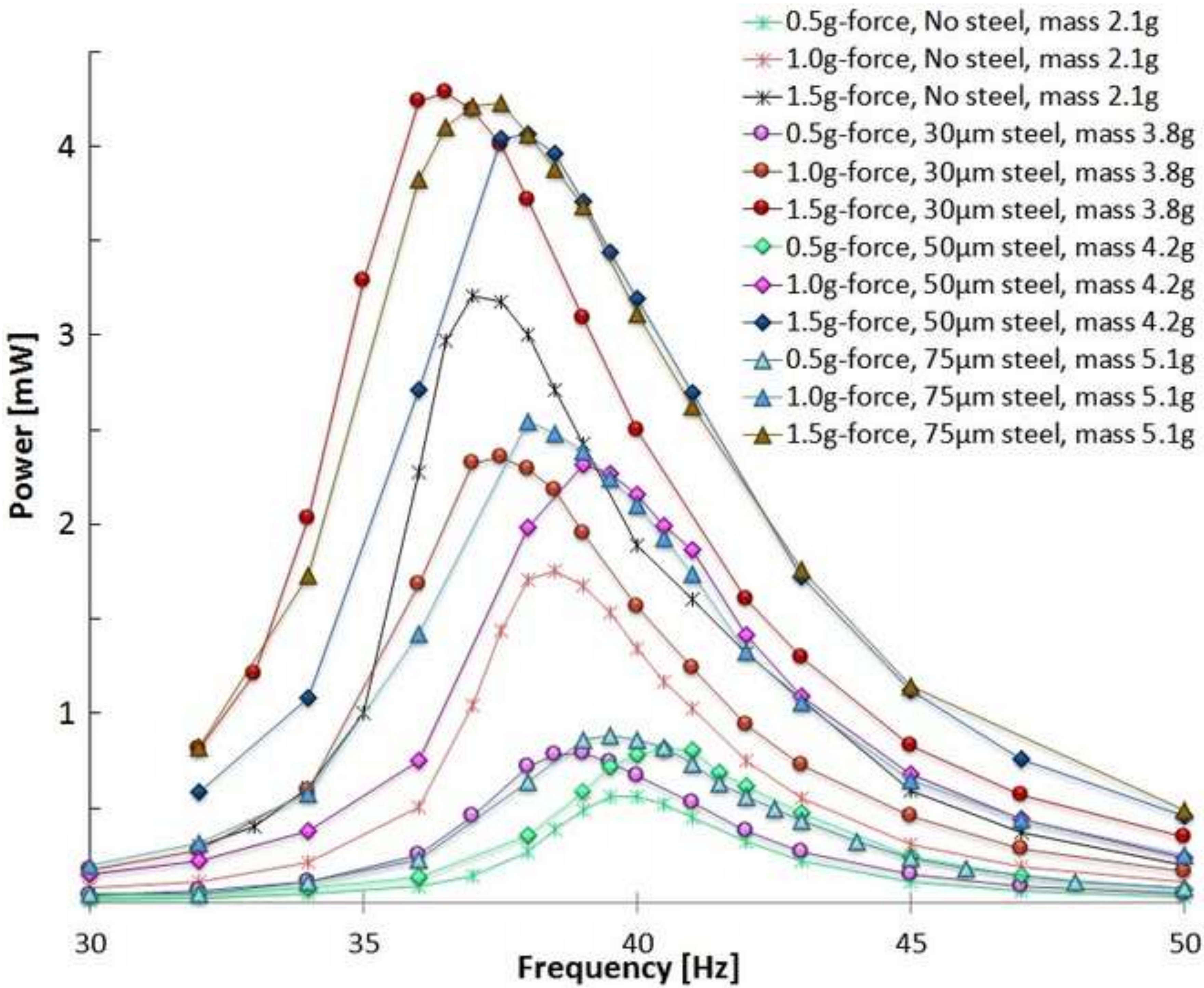

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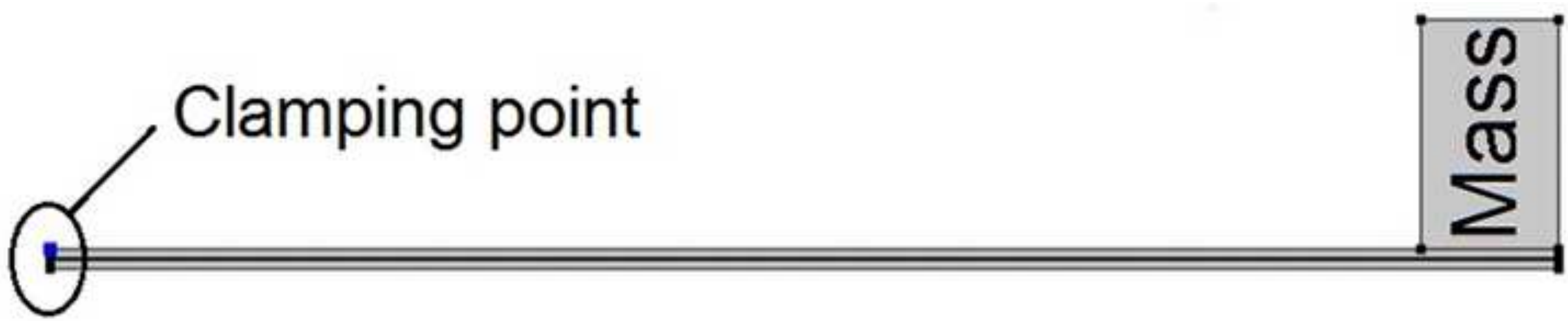

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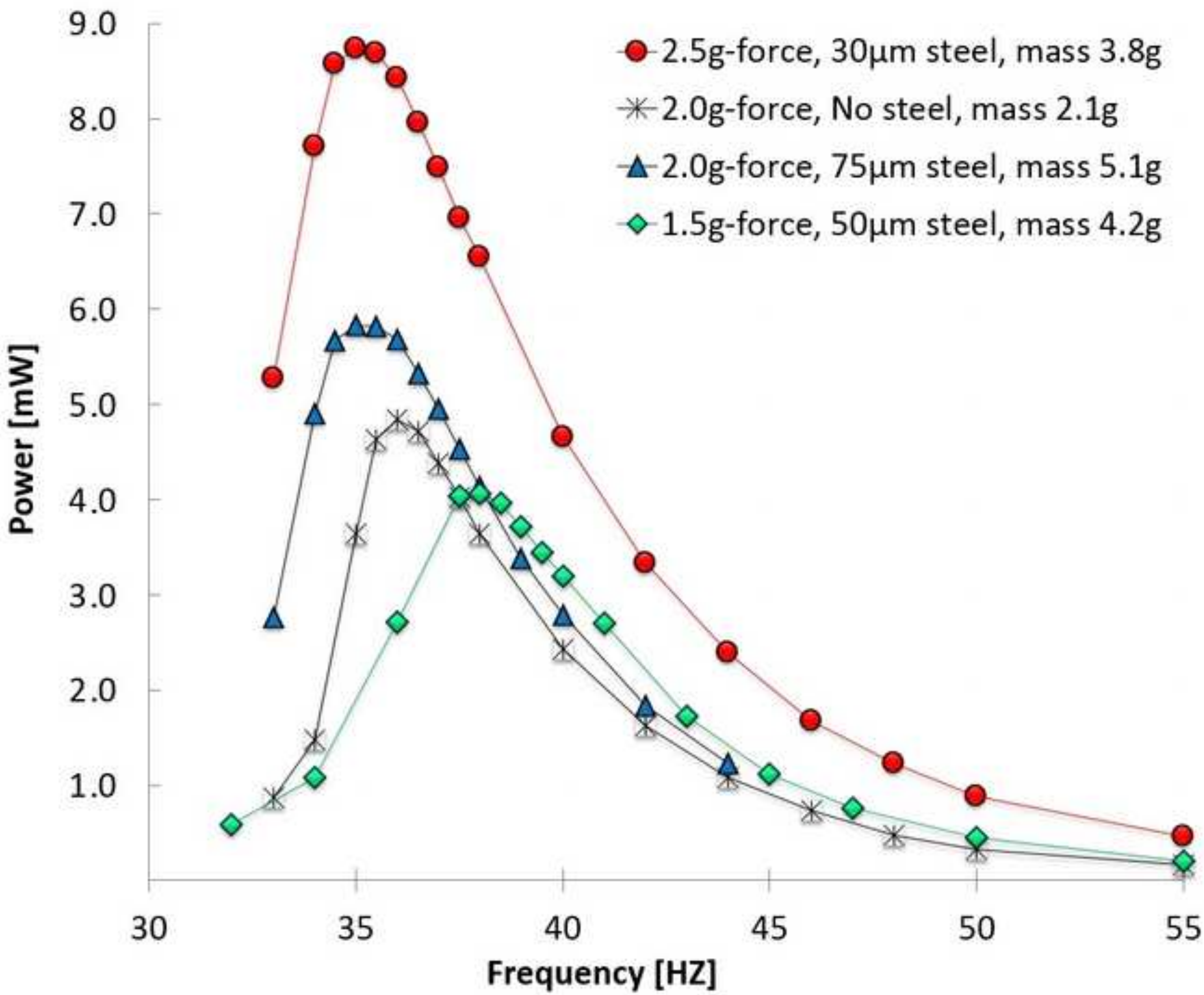

Supplementary Material Fig1.
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Supplementary Material Fig2.

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