MINIATURE VIBRATION SHAKER FOR MEMS-SCALE VIBRATION-BASED ENERGY HARVESTERS APPLICATION

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ABSTRACT

This paper describes the design and fabrication of miniature electromagnetic-type vibration shaker for generating sinusoidal vibrations. Conventional machining is used to produce different parts of the vibration shaker. The shaker's table is supported by zig-zag planar beams and a copper wound coil is contained at the lower portion of the shaker's table. Alternating magnetic field of the wound coil and the magnetic field of the permanent magnet generates a sinusoidal force that causes the shaker's table to vibrate at the frequency of input electrical signal to the shaker. Modal analysis of the suspension system performed in COMSOL Multiphysics®, indicates that in the first mode of the vibration the shaker's table is perfectly moving up and down. The developed vibration shaker is characterized for sinusoidal electrical input signal. At different gain levels of the power amplifier, the shaker is subjected to a frequency sweep from 1 Hz to 1 kHz. At resonant frequency of 60 Hz, acceleration amplitudes of 5, 10, 18, 20 g are produced at gain levels of -60, -55, -50 and -48 dB respectively. Beyond 200 Hz almost constant acceleration levels of 1.8, 1.3, 0.9 and 0.7 g are obtained at -48, -50, -55 and -60 dB respectively. Current drawn and power delivered are maximum, when the shaker is operated at the resonant frequency. Operating on the resonant frequency of 60 Hz, a maximum power of 0.6 W is delivered to the shaker at -48 dB gain level.

KEYWORDS: *Electromagnetic; Linear system; Miniature; Sinusoidal; Vibration shaker*

INTRODUCTION

A wide application of Micro accelerometers[1] and recent development of vibration-based energy harvesters[2] leads to the requirement of in-lab characterization of these MEMS scale devices under sinusoidal and random vibration[3]. Miniature vibration shakers are utilized to determine the performance of accelerometers and vibration-based energy harvesters during prototyping. Moreover, these are widely used for accelerometer calibration, vibration testing of medical devices, electronic circuits and shock testing of mechanical systems[4,5,6]. Vibration shaker is capable of generating mechanical vibration of different frequencies and acceleration levels depending on the input electrical signal. Sinusoidal as well as random vibrations are produced when a sinusoidal or a random input electrical signal is subjected into the shaker.

Several types of vibration shakers have been developed and are available, such as, mechanical shakers, electro-hydraulic shakers, piezoelectric shakers and electrodynamics shakers[7]. Mechanical shakers use crank and slider mechanism. These are simple, reliable and inexpensive shakers, however, they generate only sinusoidal vibration over a frequency range from 10 Hz to 60 Hz only[8]. Piezoelectric shakers use piezoelectric material that converts an electrical signal (energy) into a desired mechanical motion. Piezoelectric shakers are very robust and can produce vibrations with low acceleration levels as well as excitation with very high acceleration levels up to 1000 g and forces up to tens of kN. The frequency of operation ranges from audio to 100 kHz. However, the amplitude of generated vibration in piezoelectric shakers is very small (in μm range)[9]. Piezoelectric shakers are available in both large, medium and miniature scale. Electro-hydraulic shakers comprises of pump, valves, plunger and cylinder. In Electro-hydraulic shaker[8] there is an electromagnetically activated pilot valve which operates by the electrical signal. The oil flowing through the pilot valve is proportional to the electrical signal. Plunger (shaker table) oscillates to and fro due to high and low pressures in the cylinder. Electro-hydraulic shakers can produce high forces and normally are designed for high payload capacity. Moreover, they can oscillate with low frequency (20 to 800 Hz) with the amplitude of vibration being on large side (2 mm or above). Electro-hydraulic shakers are available in large sizes and not available in small and miniature size.

In Electrodynamic shakers[10] vibration is produced by passing alternating electrical signal in a coil that is placed in a magnetic field of permanent magnet. Electrodynamics

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shakers are used for generating sinusoidal as well as random vibrations. These shakers produce vibration in audio range (20 Hz to 20 kHz. Electrodynamics shakers are available in large, medium and miniature scale.

ARCHETECTURE AND WORKIING MECHANISM OF PROTOTYPE VIBRATION SHAKER

Figure 1 shows the cross-sectional view of the miniature vibration shaker. The prototype vibration shaker comprises of iron core connected to a permanent magnet and a wound coil. A copper wire is wound around a Teflon cylinder which is suspended through planar springs. The top end of the Teflon cylinder is attached to the vibration shaker table. The iron cylinder is used to support the fixed ends of the planar springs as well as to enclose the coil-Teflon cylinder and magnet-core assemblies. A rubber membrane at the top of the polycarbonate shaker casing safeguards the vibration shaker from the environment. However, thick rubber pads located at the bottom of the polycarbonate casing serves as vibration isolators for the miniature shaker. The solid model of the miniature vibration shaker is shown in Figure 2.

The working mechanism of the shaker is based on the principle of electrodynamics. Interaction between the field of permanent magnet and alternating magnetic field of the wound coil generate an alternating excitation force that causes the armature to oscillate. The planar springs work as stiffness members and store strain (potential) energy during vibration. The frequency of the force of

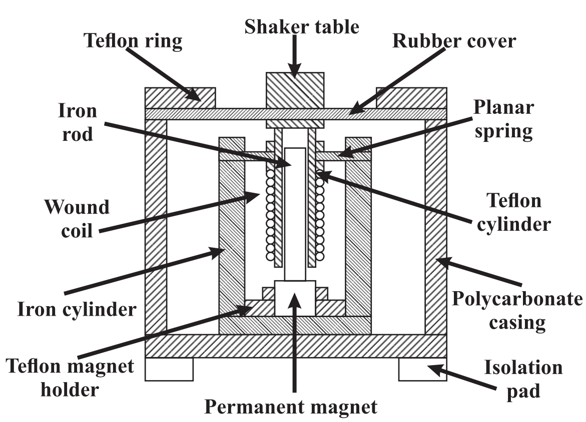

Figure 1: Cross-sectional view of a miniature vibration shaker.

excitation is drive by the alternating current flowing in the wound coil.

PROTOTYPE VIBRATION SHAKER FABRICATION

The fabrication of different main parts, sub-assemblies and the assembled vibration shaker is shown in Figure 3. Conventional machining is used to produce several parts of the vibration shaker. The shaker cylinder base (6.5 cm in diameter and 2 cm high) is fabricated from an iron rod. A permanent NdFeB magnet (K & J Magnetics, Inc., Jamison, Pennsylvania, United States of America) with 1 Tesla, residual magnetic flux density is attached to the cylinder base, Figure 3(a).

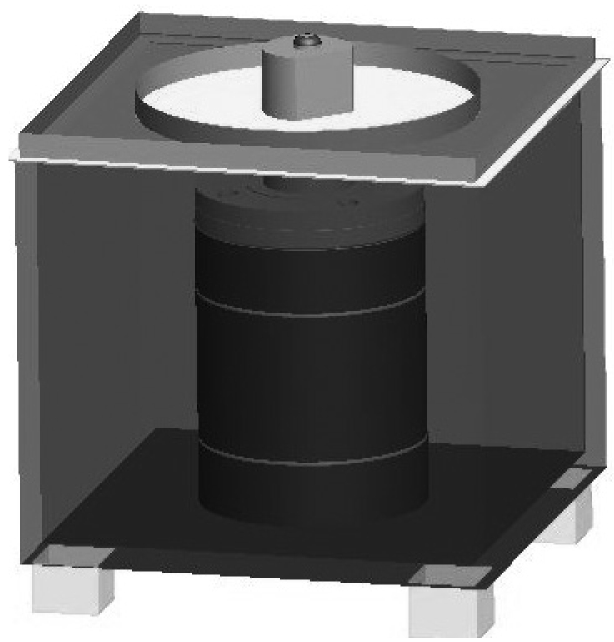

Figure 2: Solid model of a miniature vibration shaker.

A magnet holder, Figure 3(b), fabricated from Teflon (Professional Plastics, inc., Fullerton, California, United States of America) is used to keep the magnet at the centre of cylinder base, Figure 3(c). An iron rod (1 cm diameter and 4 cm high), Figure 3(d), is attached to the top side of the permanent magnet to enhance the magnetic field strength. The iron cylinder, Figure 3(e), is connected to cylinder base with screws and iron ring, Figure 3(f), and Teflon rings, Figure 3(g), are used to attach the suspended armature assembly to the iron cylinder. The armature assembly of the shaker is shown

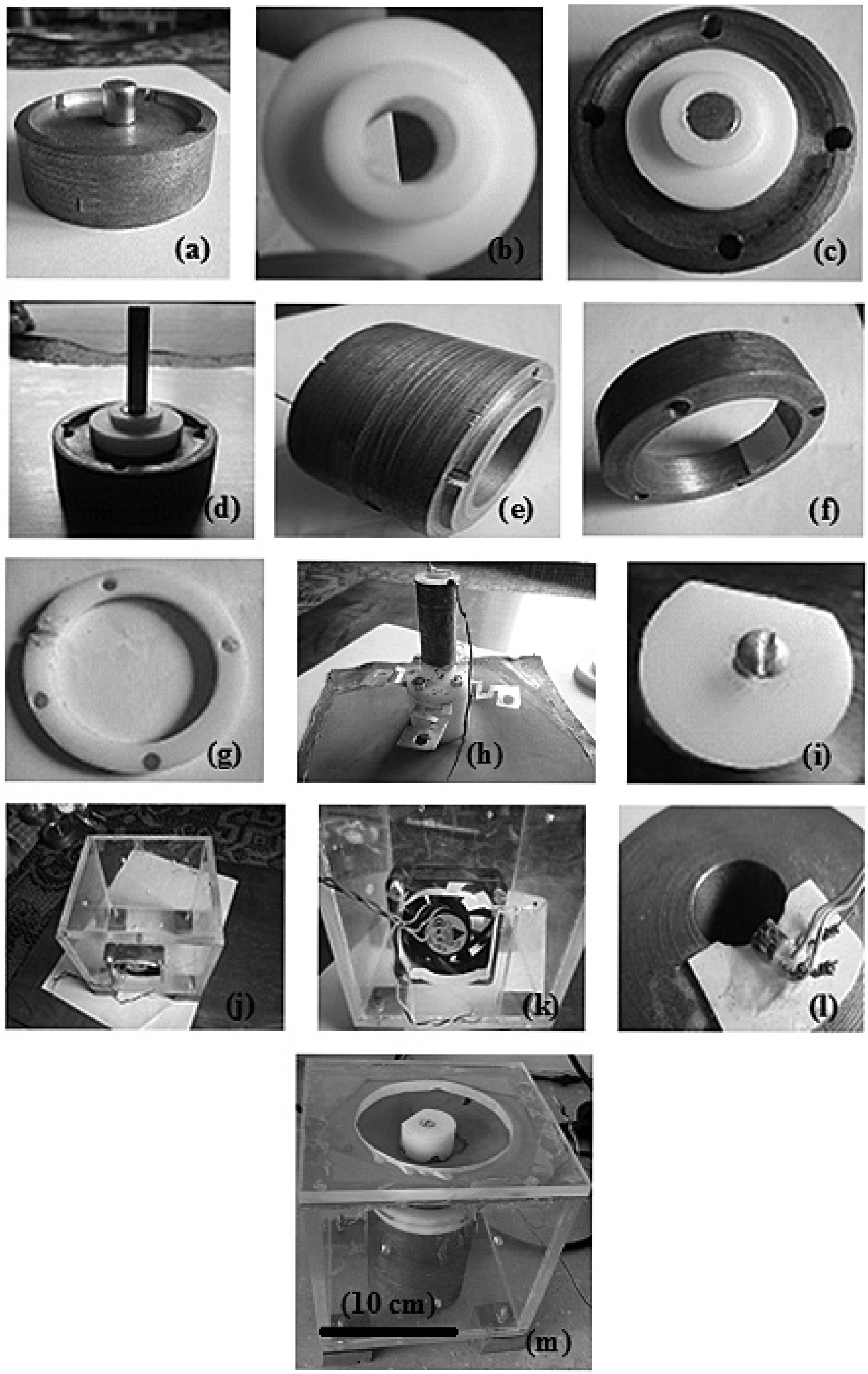

Figure 3: Photographic images of vibration shaker during fabrication and assembling: (a) Iron cylinder base with magnet, (b) Teflon magnet holder, (c) Cylinder base, magnet holder and magnet, (d) Iron core attached to magnet, (e) Iron cylinder, (f) Iron ring, (g) Teflon ring, (h) Shaker table, (i) Planar beam, shaker table, Teflon and wound coil sub assembly, (j) Polycarbonate vibration shaker case, (k) Fan attached to polycarbonate casing, (l) Temperature sensor bonded to iron cylinder top cover, (m) Assembled miniature vibration shaker.

in Figure 3(h). A copper wire (0.5 mm diameter) is wound around the Teflon cylinder to produce a 60 turns wound coil. Zig-zag shaped planar beams are attached to the top side of the coil wound Teflon cylinder using a Teflon block and small size nut and bolts. A vibration shaker table is then screwed to the coil wound Teflon cylinder, sandwiching the rubber cover, Figure 3(i). A casing for the vibration shaker has been fabricated from a transparent, 1 cm thick, polycarbonate (Sheffield Plastics Inc., Sheffield, Massachusetts, United States of America) sheet, Figure 3(j). For cooling purpose a fan is mounted in one of the side of the casing, Figure 3(k), to refresh the inside air and safe guard the shaker from overheating. Moreover, for overheating protection a temperature sensor is connected to the top cover of the shaker cylinder, Figure 3(l), and a micro controller is used to automatically switch-off the power, whenever the temperature of the air near the wound coil exceeds 90^{o} C (well below the safe temperature (120^{o} C) for the coil. The assembled, prototype miniature vibration shaker is shown in Figure 3(m). Table 1 presents the summary of dimensions and main parameters for the fabricated vibration shaker.

MODAL ANALYSIS OF THE VBRATION SHAKER

For the vibration shaker, the modal analysis is performed in COMSOL Multiphysics® in order to find the first few resonant frequencies and the corresponding mode shapes of the suspension system of the vibration shaker. The simulation results of the modal analysis are shown in Figure 4 and Table 2. The first mode, Figure 4(a), is the normal mode during which the shaker's table oscillates perpendicular to the plane of the spring. However, in the second mode, Figure 4(b) and third mode, Figure 4(c), the shaker's table appeared to rotate about an axis parallel to the plane of the springs. The first mode is the desired mode for the application to produce perfectly up and down vibrations. Mode 2 and Mode 3 are the rotational modes and keeping in view the tolerance between the coil-Teflon cylinder and iron rod mounted on magnet, the vibration shaker need not to be operated near the second and third resonant frequencies.

CHARACTERIZATION AND DISCUSSION

The block diagram (Figure 5) and photographic image

Table 1: Dimensions and parameters of developed prototype miniature vibration shaker

Description	Value/Type
Magnet type	NdFeB, Grade: N52
Magnet size	1 cm dia. x 1 cm thick
Magnet residual flux density	1 Tesla
Coil type	Wound
Coil material	Copper
Coil wire diameter	0.5 mm
No. of turns in coil	60
Shaker dimensions	6.5 cm dia. x 14 cm height
Casing dimensions	14 cm x 14 cm x 14 cm
Overall vibration shaker size	14 cm x 14 cm x 16 cm

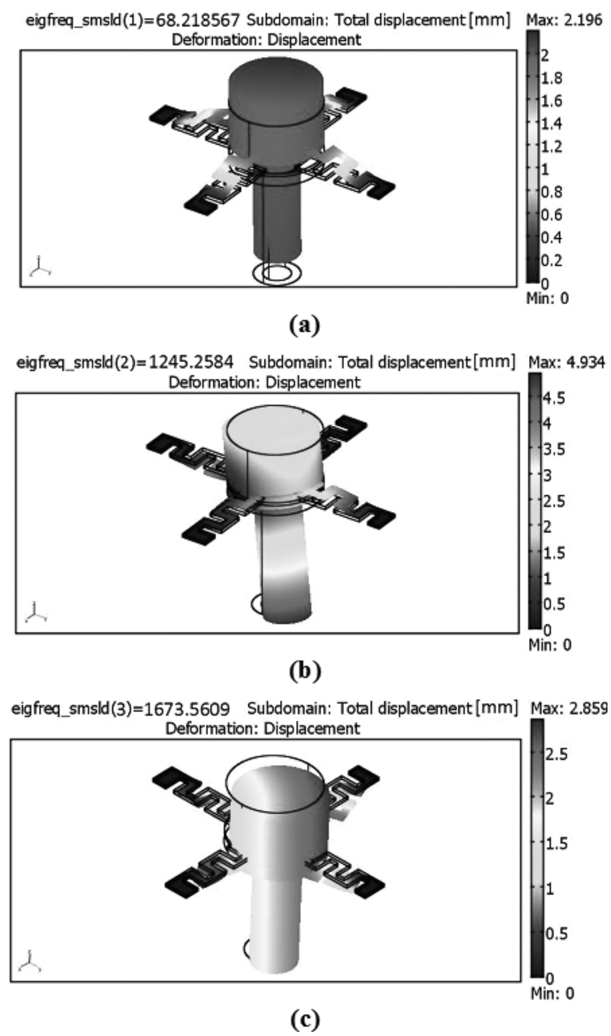

Figure 4: Modal analysis of the device: (a) first mode shape, (b) second mode shape, (c) third mode shape.

Table 2: Simulated resonant frequencies of the vibration shaker

Mode	Natural frequency (Hz)
First Mode	68.2
Second Mode	1245.2
Third Mode	1673.5

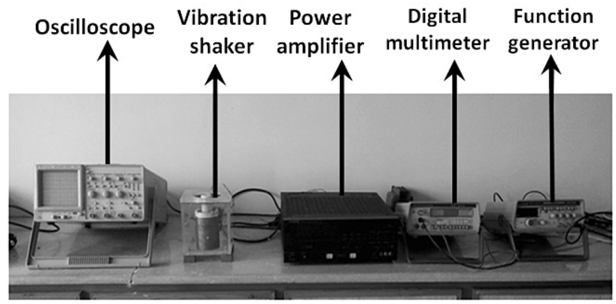

Figure 6: Experimental setup for characterization of the vibration shaker.

(Figure 6) of the experimental setup used for the characterization of the vibration shaker is shown in Figure 5. The Experimental setup consists of a function generator, power amplifier, vibration shaker, digital multimeter, accelerometer and oscilloscope.

The function generator produces a sinusoidal signal and power amplifier amplifies the power of the sinusoidal signal. The amplified sinusoidal signal is applied to the wound coil of the vibration shaker. Accelerometer is mounted on the shaker table to measure the acceleration levels generated by the vibration shaker. Oscilloscope reads the output signal from the accelerometer and digital multimeter is used to measure the current drawn and voltage applied across the wound coil of the shaker. The vibration shaker is characterized for the gain levels of -48 dB, -50 dB, -55 dB and -60 dB. The vibration shaker is subjected to a forward frequency sweep from 1 Hz to 1 KHz and current drawn, voltage across coil and power consumed by the shaker are measured.

Figure 7 shows the acceleration levels developed by the vibration shaker at -48 dB, -50 dB, -55 dB and -60 dB gain levels of the power amplifier. The shaker is subjected to sinusoidal signal from 1 Hz to 1 KHz. The frequency response curve of the shaker seems symmetric and no tilting of the response curve to the high or low frequency side is observed which shows linear behaviour. The linear behaviour of the shaker is attributed the linear stiffness of the planar springs at these vibration levels. In the frequency response a peak is obtained at 60 Hz, which corresponds to the resonant frequency of the shaker. Under resonance and at gain levels of -60 dB, -55 dB, -50 dB and -48 dB the shaker produced acceleration amplitudes of 5, 10, 18, 20 g respectively. Beyond 200 Hz the acceleration levels produced by the shaker are almost constant. Almost a constant acceleration of 1.8, 1.3, 0.9 and 0.7 g are obtained at -48 dB, -50 dB, -55 dB and -60 dB respectively.

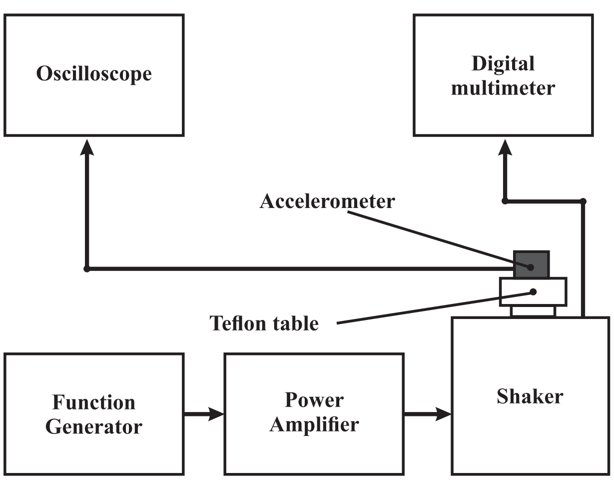

Figure 5: Block diagram of the experiment setup.

In the input amplified signal, the voltage (rms) applied to the wound coil of the as a function of frequency at different gain levels of the amplifier is shown in Figure 8. As the gain level is increased the voltage applied to the coil is also increased. Moreover, maximum voltage is subjected to the wound coil at the resonant frequency of the shaker.

Figure 9 shows current (rms) drawn by the wound coil of the shaker as the function of frequency at different gain levels of the amplifier. With increasing the gain of the input amplified signal, the current drawn by the shaker increases. The increasing current causes a strong alternating magnetic field in the coil and generating an increased excitation force. The current drawn by the shaker is maximum at the resonant frequency of the vibration shaker. At high operation frequencies, beyond 600 Hz, the current drawn by the shaker becomes almost constant at different gain levels.

The power delivered to the vibration shaker as the function of the frequency at -48 dB, -50 dB, -55 dB and -60 dB gain levels is shown in Figure 10. At increasing gain more power is delivered to the shaker which in turn produced high acceleration level vibration. The shaker consumes more power at the resonant frequency. Operating on the resonant frequency, a power of 0.6, 0.52, 0.18 and 0.06 W is delivered to the shaker at -48 dB, -50 dB, -55 dB and -60 dB gain levels respectively.

Figure 11 shows the comparison of acceleration level of bare shaker's table and acceleration levels when different masses are mounted to the shaker's table. The shaker is subjected to frequency sweep at -48 dB gain. For small mass (10 grams), the change in acceleration level and resonant frequency of the shaker is negligible, however, for a mass of 500 grams, there is

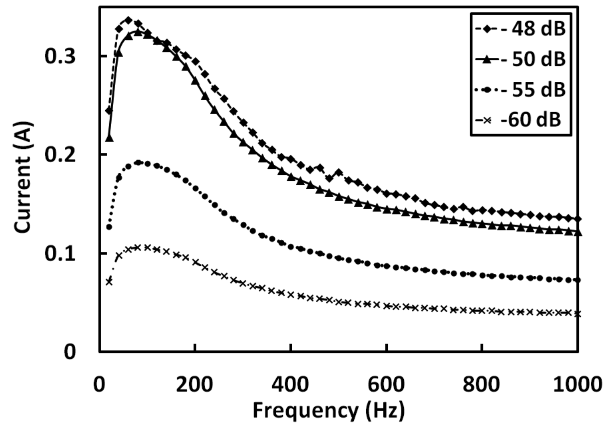

Figure 9: Current through wound coil as function of frequency at different power amplifier gains.

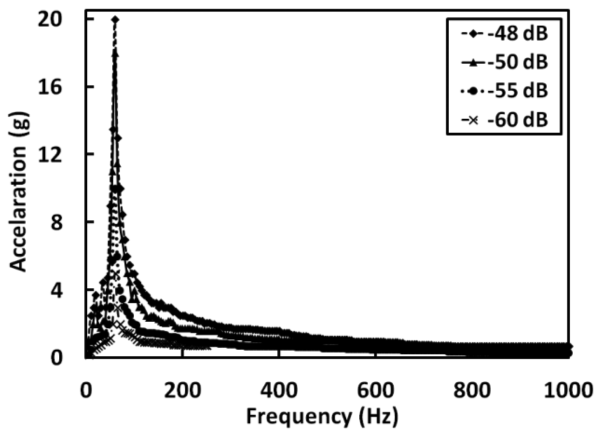

Figure 7: shaker table acceleration as function of frequency at different power amplifier gain levels.

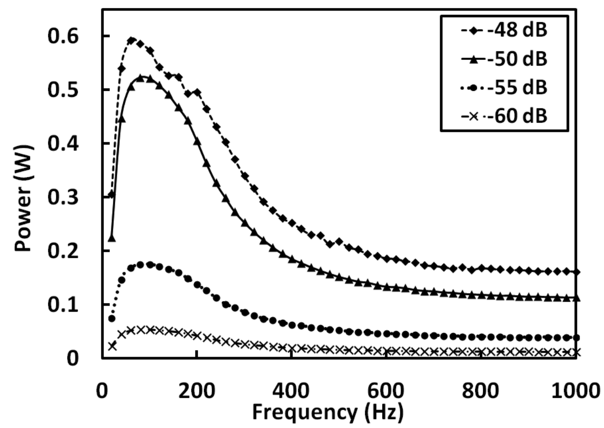

Figure 10: Power delivered to wound coil as function of frequency at different power amplifier gains.

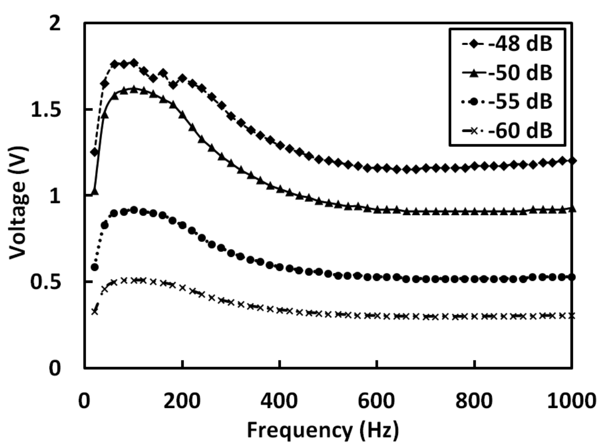

Figure 8: Voltage across wound coil as function of frequency at different power amplifier gains.

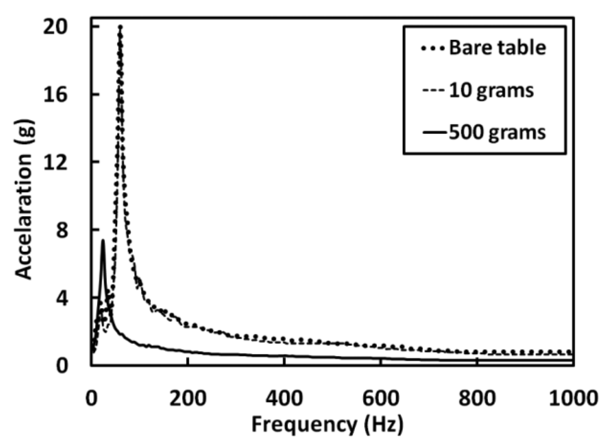

Figure 11: Force as function of frequency at different power amplifier gains.

considerable decrease in the acceleration of the shaker's table. Moreover, a shift in the resonant frequency of the harvester is also significant.

Table 3: Summary of experimental results of developed prototype vibration shaker

Description	measurement
Max. acceleration generated	20 g
Operational range	1 Hz to 1 kHz
Frequency range for constant acceleration	200 to 1 kHz
Shaker's resonant frequency	60 Hz
Max. current drawn	0.34 A
Max. power consumption	0.6 W

CONCLUSIONS

A miniature vibration shaker is developed for the characterization of MEMS accelerometers and vibration-based micro energy harvesters. The working mechanism of the developed vibration shaker is based on the principle of electromagnetism. The interaction between the magnetic field of the current passing through the wound coil and magnetic field of the permanent magnet causes the shaker's table to vibrate. The operational range for the shaker is from 1 Hz to 1 kHz. The resonant frequency of the shaker is on the lower side and is only 60 Hz. At resonant frequency of 60 Hz, acceleration amplitudes of 5, 10, 18, 20 g are produced at gain levels of -60, -55, -50 and -48 dB respectively. Beyond 200 Hz the response of the vibration shaker is almost constant, which is beneficial for testing the micro devices under constant acceleration sweep. For high acceleration testing the shaker must be operated near the resonant frequency (60 Hz), however, for low acceleration testing the shaker need off frequency operation at lower gain levels (Table 3).

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