J. Engg. and Appl. Sci. Vol. 35 No. 2 July - December 2016 ISSN 1023-862X - eISSN 2518-4571

DEVELOPMENT OF A TESTING RIG FOR VIBRATION AND WIND BASED ENERGY HARVESTERS

Farid Ullah Khan[1], Muhammad Iqbal[1]

ABSTRACT

This article describes the fabrication and characterization of a medium scale vibration shaker and a wind tunnel for testing of micro and meso scale vibration based, wind based and hybrid (using combined vibration and wind) energy harvesters. The mechanical shakers used for vibration and shock testing are the most versatile, inexpensive and easy to operate, however, due to their fixed displacement, single frequency and sinusoidal behavior, usage of these shakers is limited. The less known electro-hydraulic shakers are more robust, but due to their high forces and high velocities, these are usually utilized to characterize heavy samples. Electromagnetic shakers are the most reliable and accurate and are increasingly used for accelerometers calibration and aerospace applications. Unlike mechanical shakers, electromagnetic shakers can produce random vibrations and can also be used for shock tests. The reported vibration shaker is electrodynamic type. Different parts of the vibration shaker and wind tunnel are fabricated by conventional machining. For vibration shaker, a 1000 W speaker is fitted in a wooden box. The wooden box is made adjustable and through the railing mechanism it can move vertically as well as horizontally. Moreover, a wooden block containing a fixture for a device is glued to the center of the speaker. A power amplifier and a function generator are utilized to provide the desired signal for the operation of the shaker. The wind generating portion of the testing rig comprised of a variable speed fan, a duct pipe and an anemometer. The vibration and wind producing units of the testing rig are assembled on the same base, such that, these can operate separately as well as simultaneously. In the testing rig the vibration shaker is characterized for sinusoidal input signals from the function generator. With the vibration shaker base acceleration levels from 0.01 g to 2.0 g are produce during a frequency sweep from 1 to 200 Hz. Beyond, 200 Hz, the excitation levels obtained from the shaker are constant. Moreover, the shaker is also characterized by placing different weights on the shaker's table. The excitation levels for bare table test decreases down from 0.54 g to 0.30 g and 0.22 g by adding a weight of 500 grams and 1000 grams respectively. In the developed testing rig, the wind tunnel is capable of producing an air velocity from 0.4 to 11 m/s at the corresponding fan speed of 1000 rpm to 10000 rpm respectively. Furthermore, the reported wind tunnel is quite able to producing a maximum mass flow rate of 0.170 kg/s.

INTRODUCTION

In order to avoid catastrophic failure and insure human safety, wireless micro acceleration sensors are usually utilized for structural health monitoring, condition monitoring of machines and critical civil infra-structures[1]. The wireless micro acceleration sensors offer several advantages over the existing wired monitoring systems, especially in remote and embedded applications, such as, wind turbines[2]. Moreover, recent research and progress in small-scale vibration type energy harvesters[3-9] and micro wireless accelerometers[10], and due to the rapid advancements of the novel technologies, such as, hybrid energy harvesting, there is a need to test and analyze these vibration energy harvesters and micro accelerometers under different conditions of vibration inside the lab. Miniature and small scale vibration shakers can be used to characterize devices, such as gyroscopes, accelerometers and vibration based energy harvesters. Furthermore, shock testing of mechanical systems, medical equipment, electronic gadgets and navigation devices, and calibration of accelerometers are also performed on these vibration shakers[11]. In response to the electrical input signal from equipments, such as, signal generators, data acquisition cards and power amplifiers, a vibration shaker, actually produce vibration excitations of desired amplitudes and frequency.

On the basis of architecture, working mechanism and practical applications, different types of vibration shakers are developed and commercially available, as listed in table 1. The vibration shakers commercially produced includes, electro-hydraulic shakers, mechanical shakers, piezoelectric shakers and electromagnetic shakers. Among

1 Institute of Mechatronics Engineering University of Engineering and Technology Peshawar, Pakistan

all the developed vibration shakers, mechanical shakers have shown high reliability and efficiency. Mechanical shakers is composed of a slider and crank mechanism and are capable of generating sinusoidal vibrations in the frequency range of 10-60 Hz. In electromagnetic shaker, the coil (attached to the shaker's table) is suspended in a strong magnetic field of a cylindrical permanent magnet, and when current passes through the coil, due to the interaction of the alternating magnetic field of the coil and the field of the permanent magnet causes the shaker's table to oscillate[12]. Piezoelectric vibration shakers are superior to the electromagnetic shakers because these offer high specific forces, broadband of frequency, high energy densities and can be produced with high device's stiffness and compact design. Moreover, very high mechanical force (up to few kN) and pressure intensity can be generated with piezoelectric shakers. Furthermore, with the help of piezoelectric vibration shakers, broadband frequencies (from 20 Hz to 100 kHz) and high base acceleration levels can be easily produced. However, small vibration amplitudes (range nm-µm) can only be produced with piezoelectric a shaker which is the main disadvantage of these shakers. Piezoelectric shakers are available in small, medium and large sizes. Furthermore, piezoelectric shakers can also be utilized for vibration analysis and to examine noise in machine components[13]. Electro-hydraulic vibration shakers are known to be the most robust and it consists of valves, plunger, cylinder and an oil pump. An electrodynamic (solenoid) valves operated by input electrical signal are used to allow entry (high pressure oil) and exit (low pressure oil) of pumping oil. The pressure of oil inside the cylinder produces motion of the plunger, which is attached to the shaker's table. Due to the hydraulic mechanism of operation very powerful vibrations can be produced by the electro-hydraulic shakers. Large sized electro-hydraulic shakers usually generate high amplitude and low frequency (that may range from 20 to 80 Hz) vibrations. These shakers can produce high forces[12] and can be used for the characterization of large structures, systems and devices.

Table 1. Commercially produced vibration shakers

Type of vibration shaker	Frequency range (Hz)	Acceleration levels (g)	Operating voltage (V)	Shaker's displacement amplitude	Modulation force	Shaker's size	Ref
Electromag-netic	20–20000	0-40	90	mm range	Moderate	Miniature, medium and large	[12]
Piezoelectric	20- 100000	10-1000	150-1000	nm-µm	Up to tens of kN	Miniature, small and medium	[13]
Mechanical	10-60		230	mm to cm	Greater	Medium & large	
Electro-hy-draulic	20-80	-	-	≤ 2 mm	Greater	Large scale	[14]

Likewise, vibration-based energy harvesters, wind-driven energy harvesters have recently gained a lot of interest. Air flow-driven harvesting approach is increasingly adopted in meso and micro-scale energy harvesters by the researchers. The shrouded meso-scale wind turbine (blade chord of 3 mm diameter) developed by Howey et al.[15], produced a maximum electrical power of 80 µW to 2.5 mW at an applied wind velocity of 3 to 7 m/s in a wind tunnel of diameter 2 cm. Moreover, the reported turbine can be operated at an air speed less than 3 m/s. To operate wireless sensors, an airflow miniature turbine has been reported by[16]. The turbine blades are fabricated from Thorgren plastic and with a turbine a DC brushless motor is coupled for electricity generation. The turbine was tested for an input air speed from 3 to 4.5 m/s, moreover, during characterization different load resistances from 5 to 500 Ω were also connected across the generator terminals. Power harvesting from wind flow to make a wireless sensor an autonomous system is reported[17]. A miniature wind turbine with a blade size of 10 cm is developed in this work. A DC three phase brushless, servomotor (as an electrical generator) is driven by this small-scale wind turbine. Moreover, to rectify the AC output voltage into DC voltage for sensor's use, a three phase analog to digital (ADC) bridge circuit, containing six diodes is also produced. The developed wind turbine was operated at air velocities of 2.54, 4 and 5 m/s. At a wind velocity of 5 m/s, the

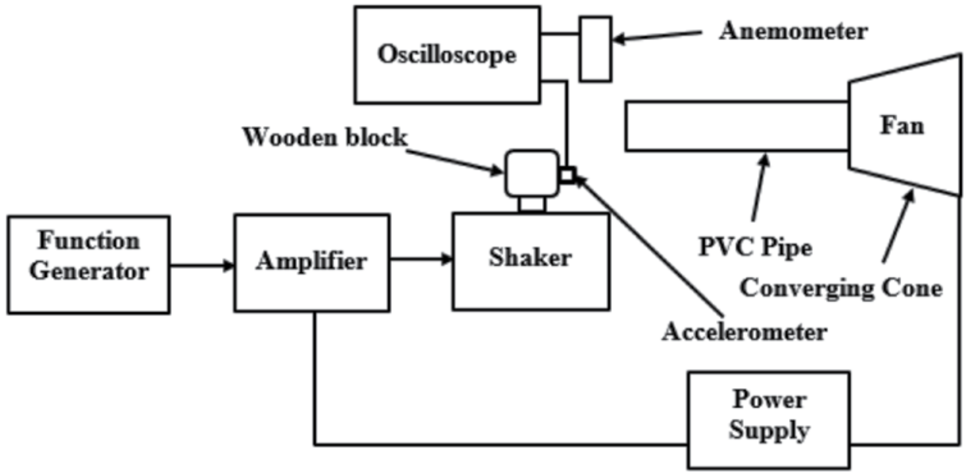

Figure 1: Schematic diagram of the developed testing rig.

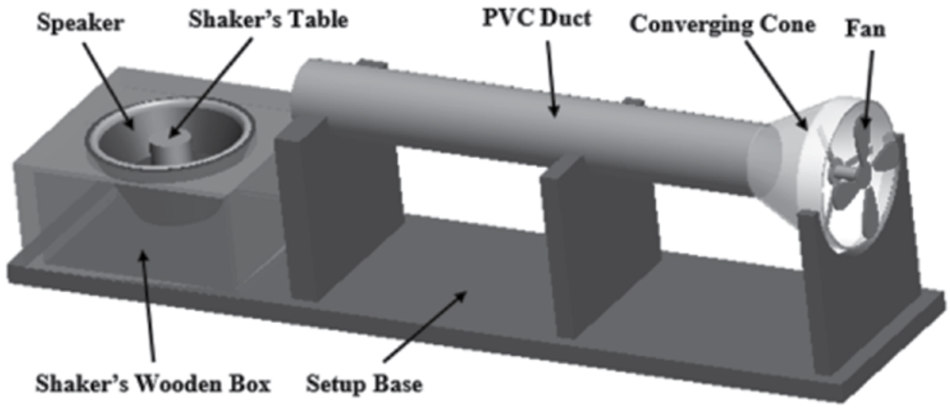

Figure 2: 3-D model of the developed vibration and wind testing rig.

turbine produced an output power of 28 mW, when a 100 Ω load resistance was connected across the generator. Furthermore, it reported that the developed turbine is capable of operating a wireless sensor even at a very low air speed of only 0.76 m/s. An airfoil based, wind-type, electromagnetic energy harvester is developed and tested inside the wind tunnel[18]. The developed harvester comprised of airfoil, cantilever beam, bluff body, permanent magnet and a wound coil. A centrifugal fan, producing high speed wind of about 10 m/s in wind tunnel is used to characterize the energy harvester inside the tunnel. The wind duct has an opening of 30 cm × 22.5 cm. At 2.5 m/s wind velocity, the harvester generated a power level of 470 μW. However, a peak power of 1.6 mW is reported for the harvester at a wind velocity of 5 m/s. A meso-scale wind turbine is developed [19] to operate wireless sensors for condition monitoring of air quality in ventilation ducts. The diameter of the turbine's rotor is only 4.2 cm and is composed of four blades. The reported miniature wind turbine is characterized in a wind tunnel. Three prototypes are fabricated and tested. Prototype-1 produced the maximum power of 2.4 mW and 130 mW at the wind speeds of 5.5 m/s and 11.83 m/s respectively. The maximum energy transduction efficiency of the turbine varies from 53 % to 19 % for a supplied air speed of 11.8 m/s to 5.5 m/s respectively.

Development of a novel testing rig for the analysis and characterization of accelerometers, vibration-based, wind-based and hybrid energy harvesters is reported in this research work. The fabricated testing rig is multi-purpose and is provided with a vibration shaker and a wind tunnel developed by traditional machining. An electrical circuit managing power to vibration shaker as well as to wind generation setup is established. The apparatus is designed in such a way that, vibration based as well as wind based energy harvesters can be tested separately. Moreover, hybrid wind-vibration based energy harvesters that harvest both wind and vibration energies simultaneously can also be characterized in the developed testing rig.

Architecture and working principle of electromagnetic shaker and wind testing rig

The schematic of the developed testing rig is shown in figure 1. The testing rig is composed of two portions, the vibration generation portion and the air blowing portion. The vibration generation portion of the setup comprised of a vibration shaker, power supply (Universal electronics, Pakistan), signal generator (GFG 8020H, GW Instek, New Taipei, Taiwan) , an amplifier (RM–AT2900, Rock Mars, United Arab Emirates), digital multimeter (UT81A/B, Uni-Trend Technology (Dongguan), China), oscilloscope (GOS 6112, GW Instek, New Taipei, Taiwan) and an accelerometer (EVAL-ADXL335Z, Norwood U.S.A). However, the air blowing portion of the setup consisted of a variable speed fan, PVC (PIT uPVC, Pakistan) duct pipe and anemometer (AR-856, Intell Instruments™ Plus, China).

The solid model of the testing rig is shown in figure 2. It is composed of a power amplifier, a speaker, a wooden cylindrical block (shaker's table, on which for the device is to be mounted), power supply and an accelerometer. A 1000 W speaker is contained in a close box made up of hardboard material. A power amplifier is connected to the speaker which step-up the input sinusoidal voltage signal of the signal generator. A cylindrical wooden block is pasted over the shaker's base and the object to be tested can be placed over this block. An accelerometer (EVAL-ADXL335Z, Norwood U.S.A) is bonded to the shaker's table for the measurement of the acceleration levels of the shaker. A DC power source (12/24 V, 20 Amp) is utilized to operate the vibration shaker and air fan of a wind tunnel.

The wind generation setup is composed of a 12.7 cm diameter, polyvinyl chloride (PVC) pipe (PIT uPVC, Pakistan), a fan with a blade diameter of 25.4 cm and an electrical motor (maximum speed = 10000 rpm) for driving the fan. To assure that optimum wind flow is available to the tested device, the fan's air is directed into the PVC duct with a converging pipe-section. Moreover, the blades of fan are safeguarded with a steel safety cage in order to avoid any unpleasant accidents during testing. The fan's speed is variable, and its speed is regulated to the desired rpm with a speed regulator. Moreover, an anemometer (AR-856, Intell Instruments™ Plus, China) is utilized to measure the air speed in the PVC duct.

Fabrication of the testing rig

Figure 4 shows various parts of the testing rig during production, and assembling. The vibration shaker is electrodynamic type. The cross-section of the vibration shaker is shown in figure 2. In order to produce the vibration shaker, a 1000 W speaker (Model KFC-W3010, Kenwood, Japan), figure 4(b), is fitted in a rectangular box (figure 4(a)) made from the hard plywood. To safeguard the devices (to be tested) from the electromagnetic field of the speaker, a wooden block is bonded to the central portion of the speaker, figure 4(b). A fixture is mounted on the wooden block to hold the devices, figure 4(c). An accelerometer (Model EVAL-ADXL335Z, Norwood U.S.A) is also attached to the wooden block (figure 4(d)). The power amplifier is then placed onto the wooden base of the rig with wood screws, figure 4(e).

To develop the blowing air portion (wind tunnel) of the testing rig, a fan rotor is mounted on the shaft of the variable speed motor, figure 4(f). The fan-motor assembly is then fitted into a protected cage, figure 4 (g). One end of the PVC pipe is attached to the cone made from the galvanized steel sheet, figure 4 (j). The pipe-cone assembly is then put over the vertical supports provided on the setup base (figure 4 (k)) in such a way that the conical part fits in the casing of the fan, as shown in figure 4 (l).

In order that the vibrating prototypes during testing are also aligned with the center of the air blowing pipe, for the vibration shaker box, railings (figure 4 (m)) are provided for the horizontal (figure 4 (h)) and vertical (figure 4 (i)) movements of the shaker.

In the testing rig the electrical wiring system consisting of electrical cable, connectors and switches (on-off), is established to manage electricity to both fan's motor and vibration shaker. The power coming from the main power supply is distributed to the vibration shaker and the fan separately, and there are separate electrical wiring,

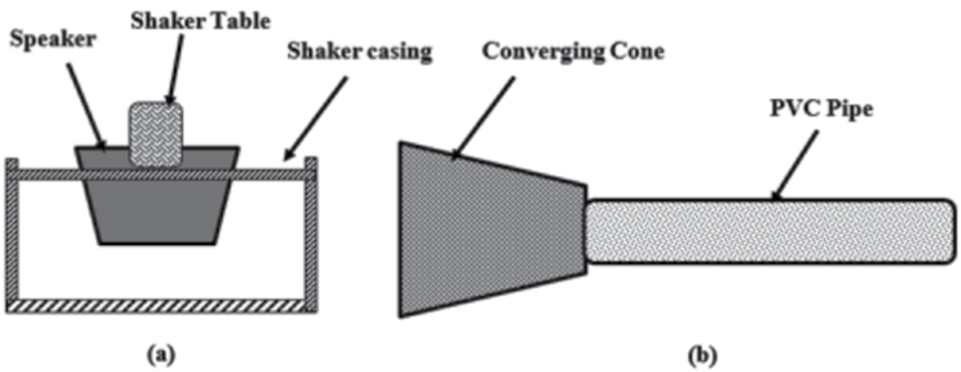

Figure 3: Cross-sectional view: (a) Vibration shaker, and (b) Wind tunnel.

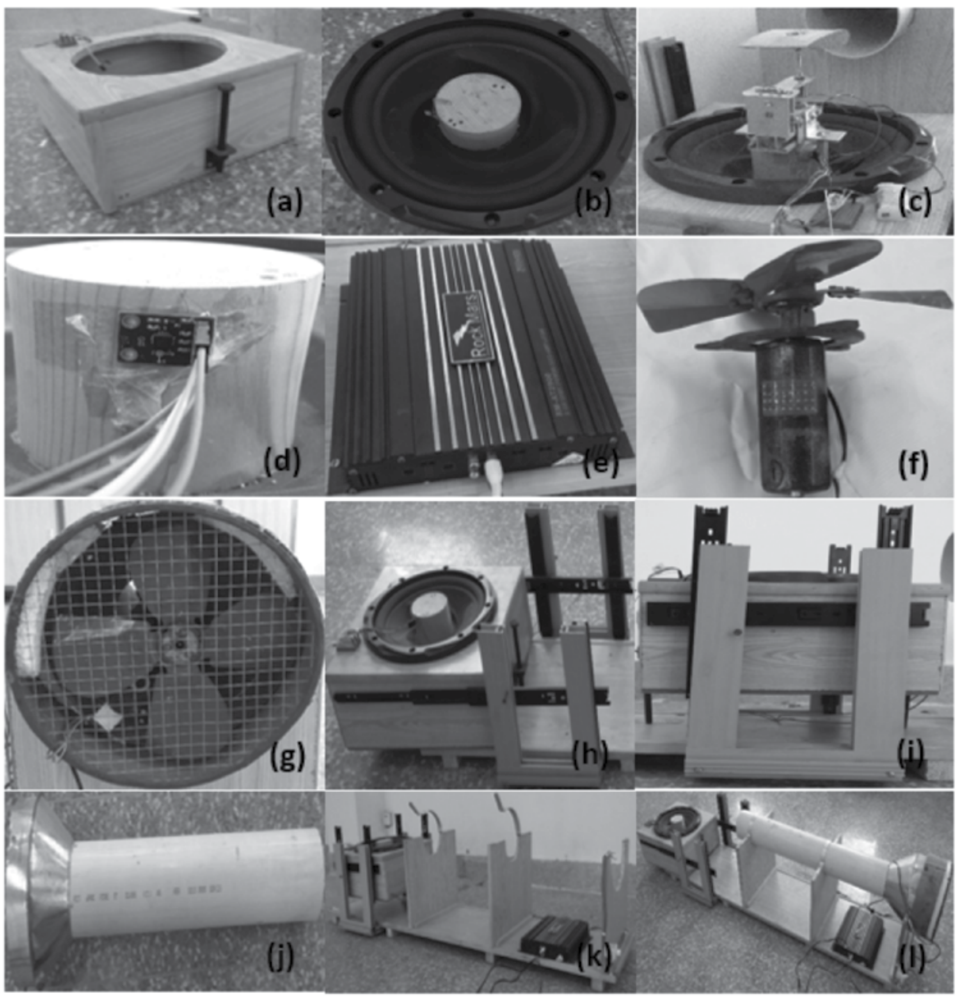

Figure 4: Images of testing rig during production and assembly: (a) Shaker's wooden box with Long bolt; shaker stand, (b) Speaker with the wooden block, (c) Speaker fitted in the wooden box, (d) Accelerometer mounted on the shaker's table, (e) Amplifier screwed to the base, (f) Fan attached to the electric motor, (g) Safety cage for fan blades, (h) Shaker's, horizontal movement mechanism, (i) Shaker's vertical movement mechanism, (j) PVC pipe with converging cone, (k) Assembled shaker with base, (l) Assembled testing rig.

Table 2. Dimensions and parameters of various components of the testing rig.

Component	Value/Dimensions	Unit
Speaker's max power	1000	W
Speaker's rated power	200	W
Speaker coil's resistance	4	Ω
Speaker size	12 × 6 × 6	cm
Shaker's size	15 × 15 × 8	cm
Power supply	12/24	V
Supply current	20	A
Accelerometer	3-axis	g
Anemometer wind speed range	0.3-45	m/s
Air velocity resolution	0.001	m/s
Temperature accuracy	±3%+0.1 digit	m/s
Air temperature resolution	0.1	oC
Channel's dimensions	13 × 12 × 9.5	cm
PVC pipe diameter	12.7	cm
PVC pipe length	91.4	cm
Fan blades diameter	25.4	cm
Motor max speed	10,000	RPM
Motor power	180	W
Motor current	0.9	A
Motor voltage	220	V
Cone size	11 × 9 × 4.9	cm
Cone net size	11.2 × 2	cm
Setup overall size	66 ×13 × 13	cm

terminals and switches for both the vibration shaker and fan. Power supply could be switched ON and OFF with these the switches accordingly. Moreover, circuit breaker and emergency shut-off system is also provided in the testing rig.

Operation of the testing rig

Operational principle of the developed vibration shaker is based on electromagnetism. When an input voltage signal from the signal generator is supplied to the power amplifier, it is magnified by the amplifier and is supplied to the wound coil of the vibration shaker. Due to the interaction between the magnetic field of a permanent magnet and the magnetic field produced when the current flows in the shaker's coil, the shaker's table starts vibrating. The amplitude of vibrations can be regulated from the gain levels provided at the power amplifier as well as from the amplitude knob of the input signal available at the function generator. The frequency of the vibration can be regulated with the frequency range selected push buttons and the frequency knob of the function generators. The output of the analog accelerometer which is used to monitor the acceleration levels of the shaker's table is a voltage signal which is the supplied to the oscilloscope. The amplitude or rms value of the output voltage signal of the accelerometer is then converted into the corresponding acceleration level with the help of the sensitivity value provided in the accelerometer operation manual. However, for the wind testing, the speed of the fan is controlled with a speed regulator and anemometer records the wind speed just in front of the mounted energy harvester.

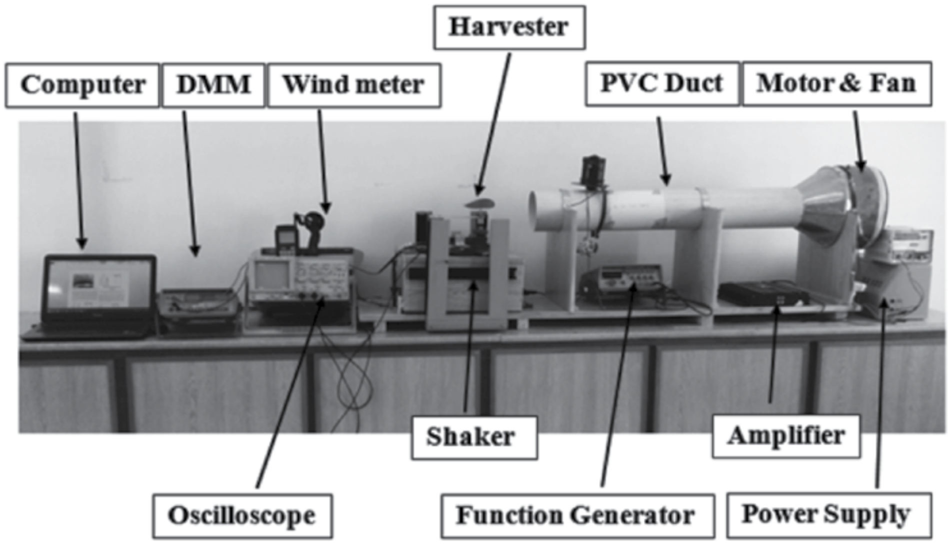

Figure 5: Developed testing rig during characterization of energy harvesters.

EXPERIMENTATION AND DISCUSSION

After fabrication the behavior of the testing rig is analyzed. Both time and frequency response of the vibration shaker is measured at several base acceleration levels. However, for the blowing air portion of the testing rig the air velocity is measured with respect to the variable speed of the fan. During experimentation, the vibration shaker of the testing rig is characterized for acceleration levels of 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, 1.0, and 2.0 g, and for an increasing frequency sweep from 0.2 Hz to 200 Hz. However, the air blowing setup is characterized for an air speed that ranges from 0.1 m/s to 11 m/s.

Figure 6, shows the frequency response of vibration shaker when different weights are placed on the shaker's table. It is clear during this experiment that as weight on the shaker's table is increased, the acceleration level produced by the shaker is dropped. During this experimentation the acceleration amplitude is not kept constant, however, the input frequency of the excitation is gradually increased. The vibration shaker is characterized for bare table and for a load mass of 500 gram and 1000 gram on the shaker's table. As indicated in the figure, at bare table, two peaks are observed, first peak is at 30 Hz (0.54 g base excitation), however, the second peak occurs at 70 Hz. However, as mass on the shaker's table is placed, the excitation levels decrease down and the resonance peaks shift to the left. The shift in the resonant frequencies is attributed to the increased mass of the shaker table. At a dead mass of 500 gram, the acceleration level recorded is 0.3 g at the shaker's resonant frequency of 19.5 Hz. However, at a mass of 1000 gram, the excitation level further dropped down to 0.22 g, and the resonant frequency is shifted to 13 Hz.

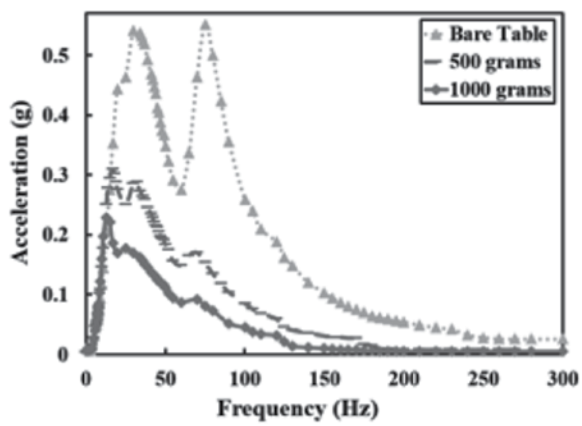

Figure 6. Frequency response of the vibration shaker at different weights during forward frequency sweep.

The frequency response of the vibration shaker under different dead weight is depicted in figure 7. In this experiment, after the shaker's table vibrations reached to the maximum acceleration during the resonance, the amplitude of the base acceleration is kept constant by regulation the amplitude knob at the function generator. As shown in the figure, at bare table, when the acceleration level reached to 0.54 g (at 30 Hz), the amplitude of the acceleration is manually adjusted and kept constant at the same acceleration level during the remaining frequency sweep from 30 Hz to 300 Hz. When the dead weight is place onto the shaker's table, the acceleration level reduces down depending on the weight level. While keeping 500 grams dead mass on the shaker's table, when the excitation level is reached to 0.3 g at 17 Hz frequency, the acceleration is kept constant during the further frequency sweep. By adding 1000 grams weight on the shaker's table at a resonance of 13 Hz, when the acceleration level is 0.22 g, the vibration shaker is operated under the constant acceleration for the remaining forward frequency sweep. The significance of this experimentation of the vibration shaker would be very helpful during the testing of the vibration-based energy harvesters when these are required to be characterized under constant acceleration forward frequency sweeps.

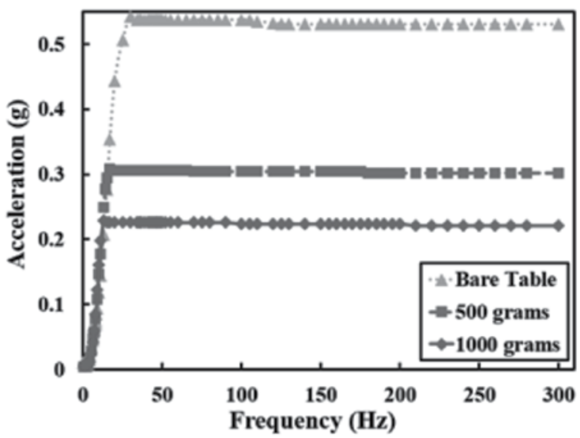

Figure 7. Frequency response of the vibration shaker at bare table and at different dead weights, during constant forward frequency sweeps

Figure 8, shows the experimental results of air blowing portion of the testing rig. Air mass flow rate is plotted against the air speed in figure 8. The plot is a straight line which indicates a linear behavior (direct relation) of air mass flow rate and air speed. At 2 m/s air speed, a mass flow rate of 0.031 kg/s is passing through the PVC duct. The mass flow rate in the duct increases linearly with increasing air speed, and an optimum flow of 0.170 kg/s was observed at a maximum air speed of 11 m/s.

The air speed in the wind tunnel as a function of the fan rotor speed is plotted in figure 9. An optical tachometer (Model-DT 6234 B, Sinometer Instruments Co. Ltd, China) is used to record the rpm of the fan

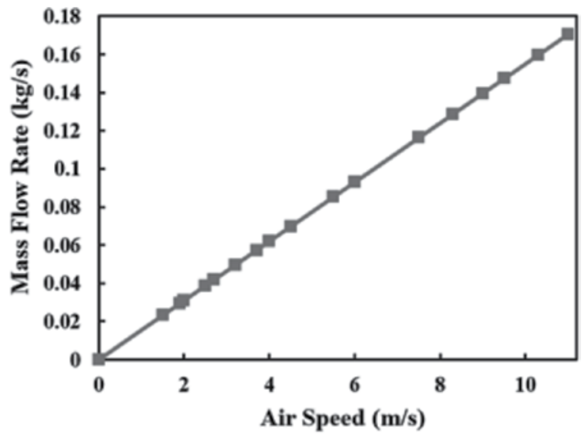

Figure 8. Air mass flow rate as a function of air's speed in the wind tunnel

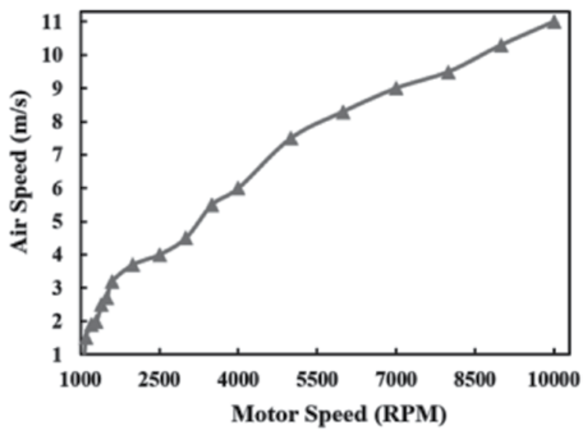

Figure 9. Air speed as a function of fan speed (RPM) in wind portion of the testing rig

shaft. During this experiment the fan motor speed is gradually increased from 1000 rpm to 10,000 rpm (the maximum motor speed) and at the outlet of the pipe the air velocity is measure with the anemometer. As shown in the figure, as the fan rpm is increased the air speed at the outlet of the pipe also increases. At maximum motor speed, the anemometer recorded an air velocity of 11 m/s.

CONCLUSION

For testing of micro-scale accelerometers and characterization vibration based and wind based energy harvesters a testing rig has been developed. In the rig provision is provided to test vibration and wind energy harvesters separately as well as the vibration portion and the wind portion of the rig can be operated simultaneously to test the hybrid (vibration and wind based) energy harvesters. Micro as well meso scale devices can be characterized in the developed testing rig. In the testing rig, the operational frequency range of the vibration shaker is from 0.2 Hz to 10 kHz. Moreover, in the frequency range from 1 to 200 Hz, the shaker showed the capability of producing acceleration levels from 0.01 g to 2.0 g. In the shaker beyond 200 Hz, the excitation levels obtained from the shaker are constant. However, at payload testing it generated maximum acceleration levels of 0.54 g, 0.30 g and 0.22 g at bare table, 500 grams and 1000 grams weight respectively. Furthermore, the wind portion of the rig is quite capable of producing variable velocity air surges. Air speed from 0.4 m/s to 11 m/s can easily be produced with the setup and is has shown the ability to handle a maximum air flow rate of 0.170 kg/s.

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