An Electro-Dynamic 3-Dimensional Vibration Test Bed for Engineering Testing

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Abstract
Primary objective of the work is to design, fabrication and testing of a 3-dimensional Mechanical vibration test bed. Vibration testing of engineering prototype devices in mechanical and industrial laboratories is essential to understand the response of the envisioned model under physical excitation conditions. Typically, two sorts of vibration sources are available in physical environment, acoustical and mechanical. Traditionally, test bed to simulate unidirectional acoustic or mechanical vibration is used in engineering laboratories. However, a device may encounter multiple uncoupled and/or coupled loading conditions. Hence, a comprehensive test bed in essential that can simulate all possible sorts of vibration conditions. In this article, an electrodynamic vibration exciter is presented which is capable of simulating 3-dimensional uncoupled (unidirectional) and coupled excitation, in mechanical environments. The proposed model consists of three electromagnetic shakers (for mechanical excitation). A robust electrical control circuit is designed to regulate the components of the test bed through a self-developed Graphical User Interface. Finally, performance of the test bed is tested and validated using commercially available piezoelectric sensors.

Keywords: Vibration Exciter, 3-Dimensional Vibration, Mechanical Excitation, Energy Harvester.

Introduction
With the advancement of scientific and technological advancement, all kinds of machinery products and apparatus have progressed in many aspects of engineering such as higher speed, high-performance, accuracy, low power consumption and mechanization. Hence, structural dynamics, specially, vibration analysis of the devices has found tremendous in recent days. Vibration refers to a phenomenon generally happened in mechanical structural upon harmonic excitation \cite{1}. Vibration can have various aspects in engineering domain. In most cases, vibration analysis is crucial to predict the structure response under dynamic loading. Resonance is a key phenomenon in vibration analysis, which takes place when the excitation frequency of the mechanical structure comes close to its natural frequency \cite{2}. While structural resonance can be very devastating for the mechanical structure, same phenomenon is used in energy harvesting domain to scavenge electric energy from mechanical vibration. Thus, influences of vibration are getting increasingly more prominent in designing mechanical structures, and vibration testing has become a fundamental means of the experimental science which has widely been applied in many fields of modern industry, such as vibration test for the rockets and satellites, vibration test caused by the roughness of the road for the vehicles, mobile machinery and test of fatigue strength of the engineering materials under high-frequency circulated force, endurance test, dynamic behavior and instrument calibration by exerting simple harmonic output forces or displacements\cite{3}, and it is necessary in aircraft and ship manufacturing, machining, bridging and building\cite{4}. These tests are commonly conducted under an artificial vibrating environment provided by vibration exciters in laboratories\cite{5}. Vibration exciter is defined as kind of transducer which converts electrical energy in to reciprocating mechanical movement \cite{1}. According to mechanical structures and operating principles, vibration exciters are divided in to three most common different types of mechanical, electro-hydraulic and electrodynamic vibration exciters \cite{6}. The mechanical vibration exciter operates on the principle of vibration excitation by means of centrifugal force or driven directly by the cam-shaft mechanism \cite{7}. Due to the restrictions of the mechanical structure fabrications and strength of materials, both the high frequency bandwidth and the output force range are limited. In the electrohydraulic vibration exciter, the exciting force from high frequency servo valve controlled hydraulic cylinder piston drives the working table periodic sinusoidal movements or random vibration. By supplying a sinusoidal current to the electrical-to-mechanical transformer of the servo valve, the spool will make a reciprocating motion to switch pressurized flow rate to chambers of the cylinder or motor alternatively and thus a vibration is created to the piston of the cylinder and connected load \cite{4}. The electro-hydraulic exciter is characterized by the larger output force and amplitude. But its frequency domain highly depends on the responding speed of the servo valve, which cannot be enhanced to a very high level and accordingly a frequency bandwidth of some several hundred is a much as can reasonably be expected \cite{2, 5, 6}. The Electrodynamical vibration is excited by Lorenz
force through supplying the coil a sinusoidal wave current. Electrodynamic exciters used in laboratories are ordered in specific configuration and must have specific operating parameters [5, 8]. These are generally operating along a single axis. However, there has been an increasing demand for laboratory stands in which the examined object is impacted by forcing signals along two or even three axes. Compared to the mechanical exciter, the electrodynamic exciter has a wider bandwidth. But because of the limitation of magnetic saturation, it is incapable to output large force without sacrificing bandwidth.

Sources of ambient vibrations which can be found in motors, pumps, fans, pipes and ducts can be separated into three main categories as seismic (ground) vibrations, acoustic vibrations, and forces applied directly to the load on the working surface [9]. Seismic vibrations refer to all sources that make the floor under the experimental setup vibrate such as vehicle engines, wind blowing the building, and ventilation fans [10, 11]. Many of the sources that generate seismic vibrations also generate acoustic vibrations. The difference is that acoustic vibrations are a measure of the effects of air pressure variations on the experiment [12]. The fact is all these ambient vibrations are directly coupled in a 3-dimensional mechanically to any structure connecting to these sources of vibrations or any experimental setup. When a wind is blowing to a bridge, or when an earthquake happens, the mechanical structure shakes the bridge in all directions so structure test study must be done in all Cartesian directions. Similarly, isolation test study between road and vehicle dampers or energy harvesting study between shakers and energy harvesters can be performed in all directions.

2. DESIGN AND FABRICATION OF ELECTRO-DYNAMIC VIBRATION EXCITER WITH 3-D EXCITATION SYSTEM

2.1 Mechanical structure

Mechanical structure of an operating unit of the 3-D exciter is discussed here. The half inch thick acrylic sheet frame of the structure was cut by laser cutter and then whole structure is screwed on a heavy laboratory test bench, which provides appropriate stability of the construction. In the proposed design, ball in socket joints are used to provide us a 2-dimensional movement perpendicular to its body axis, like in y and z direction [10]. The ball in socket joint can provide us a rotational movement around its ball bearing center inside its structure as in Fig.1. This rotational movement happens in y-z plane which is considered as 2-dimensional movement.

![Ball Bearing](image)

Figure 1. Movement of ball and socket joint in x-y plane.

2.1 Main control unit

In the structure, all shakers and speakers are connected in three X, Y, and Z directions. At this point, a sinusoidal signal from the signal generator can be amplified and fed to all 6 exciters. In this method, all the exciters stimulate the specimen with the same frequency in all directions as a coupled excitation motion. In this section, the coupled excitation motion means that the EVE device vibrates the specimen mounted on top of the movable platform in all directions of X, Y, and Z simultaneously with the same vibration frequency as all the exciters and speakers are activated with the same signal. Upon testing and validation of the mechanical unit coupled with the shakers and speakers, in order to provide a decoupled motion of vibration for the end effector on top of the moveable platform, a separate electrical unit is designed including a 6-channel signal generator and 6-channel amplifier. A desktop application is also designed by which the user can set the frequency of each individual excitation channel on a graphical user interface (GUI). The desktop application communicates with the 6-channel signal generator through a USB port using serial communication. With this augmented system, we can achieve three decoupled 1-D vibrations.
by separately stimulating each shaker and its corresponding speaker. For example, 1-D vibration in the X direction may be achieved by sole stimulation of the shaker and speaker dedicated for the X axis. Similarly, stimulating the shakers and vibrators in the X and Y axes result in a planar vibration in X-Y plane. The same scenario is also true for the creation of 3-D vibrations. Since the oscillation frequency and amplitude of the sinusoidal signals fed to the speakers and shakers can be set individually and differently, this methodology provides nicely customizable 1-D, 2-D, and 3-D vibrations in EVE machine. The 6-channel signal generator is developed using three Arduino Due microcontrollers. Arduino Due which is based on a 32-bit ARM core microcontroller was selected as it has two programmable digital-to-analogue converters (DAC). We programmed each microcontroller to generate two sinusoidal signals with adjustable frequency using the two DACs. Each microcontroller is dedicated to the shaker and its corresponding speaker for each of the X, Y, and Z axes hence we had three Arduino Dues onboard. The desktop application, developed using MATLAB programming language, receives the desired frequencies from the user and then communicates with the three microcontrollers through three USB ports. The user first clicks a button in order to initiate the communication between the GUI and the microcontrollers, and then enters the desired oscillation frequency for the shakers and speakers. After pressing the “Set” button, the GUI transmits the inserted numbers to the microcontrollers using serial communication. Upon receipt of the frequencies, each microcontroller produces two sinusoidal signals with the set frequencies using its internal clock and math library. The internal clock of Arduino Due keeps tracks of the number of microseconds elapsed since the microcontroller comes on. Using this clock, the desired frequencies, and the math library, Arduino Due computes and outputs two sine waveforms on its DACs.

3. EXPERIMENTS, RESULTS AND DISCUSSION

In order to validate the proposed 3-D vibration exciter, a new arrangement of three cantilever energy harvesters is used as the testing sample. In this structure, Fig.2. 3 of a kind cantilever energy harvesters are being connected together in a shape of a tree style and mounted on top of the moveable platform. Then the EVE device is used as the test bench for vibrating the tree style energy harvester structure in different directions in coupled or decoupled modes. The output voltage of each cantilever is measured while the test bench is running in a coupled mode so that all the 3 cantilevers shake in X, Y and Z direction. And then the measured output voltage of each cantilever is compared with the vibration of each cantilever in its individual excitation.

![Tree style CAD design and the fabricated 3D energy harvester mounted in EVE device](image)

In this experiment, three same commercialized cantilever energy harvesters with a natural frequency of 130Hz in a shape of a three style harvester were excited in each excitation direction of X, Y and Z directions separately and the output voltage of each cantilever was measured. For example, in the first experiment, the EVE vibrates the three style harvester only in X-direction while the other two Y and Z directions has no excitation. So Fig.3 shows that harvester number 1 which is perpendicular to X-direction, has the highest output voltage and the other two harvesters which have no perpendicular surface to excitation direction, have minimum output voltage. It was seen that the maximum output voltage happens at the resonance frequency of the cantilever harvester which is 130Hz in this case.
Figure 3. Output voltage of cantilever energy harvester number 1 in comparison with cantilever number 2 and 3 during 1-D X-direction excitation.

Figure 4. Output voltage of cantilever energy harvester number 2 in comparison with cantilever number 1 and 3 during 1-D Y-direction excitation.
Figure. 5. Output voltage of cantilever energy harvester number 3 in comparison with cantilever number 1 and 2 during 1-D Z-direction excitation.

Another experimental results of decoupled individual excitation in only Y-direction and after that in only Z-direction are being shown in Fig.4 and Fig.5. In the second experiment, the three style harvester is being vibrated only in Y-direction and the output voltage of each single harvester is measured again like in first experiment. Fig.4 shows that the harvester number 2 which has the perpendicular surface to Y-axis, has the highest output voltage at its resonance frequency and the other two harvesters which are perpendicular to X-axis and Z-axis have very little output voltage. Same thing happened in the third experiment when the three style harvester was excited in Z-direction. Fig.5 shows that harvester number 3 which has the perpendicular surface to Z-axis has again the highest output voltage and the other two harvesters which are perpendicular to X-axis and Y-axis have very low output voltage. Fig.6 shows the output voltage of each perpendicular energy harvester in three style model while they are being excited in the perpendicular direction to their surfaces. A same pattern is observed in all harvesters and the measured output voltage was the highest in the natural frequency of each harvester.

![Graph showing output voltage vs frequency](image)

Figure. 6. Output voltage of each cantilever energy harvester in 1-D different individual excitation direction of X,Y and Z.

In the 4th experiment, the three style energy harvester is being excited in a coupled mode so that model is being vibrated in X, Y and Z directions simultaneously. And the output voltage of each cantilever beam is being measured at the same time. Fig.7 shows that all the harvesters are following the same pattern and each cantilever beam has its highest output voltage at its natural frequency. The important point this experiment is that, the measured output voltage of each cantilever beam in coupled excitation mode is at least 1.23% higher than the measured output voltage of each cantilever beam in individual decoupled excitation mode. It has been observed that the output voltage of each cantilever beam is in the frequency range of 120 (Hz) to 140 (Hz). And if we define a frequency range from 120 to 140 (Hz), the average output voltage of each cantilever beam in X-direction in decoupled mode is 978.5 (mV) while in the coupled mode is 1101 (mV), which shows the 1.23% improvement in output voltage in coupled vibration. The same thing is happening for Y and Z direction which we have 1.36% and 1.67% improvement.
Conclusion

The presented tri-axial Acoustic Electro-Dynamic Vibration Exciter of the horizontal working platform was constructed in this paper including three main parts of Operator Panel, Control System and Testing Section. The usefulness of the EVE device for so far conducted laboratory research in application of Cantilever harvesting energy was proved by comparing the output voltage of an energy harvester cantilever in a three-style structure in coupled and Decoupled modes. Comparisons showed that the cantilevers in 3-dimensional vibration (coupled) have the same behavior with the individual excitation of a single cantilever in decoupled excitation mode. Furthermore, experimental results show that the cantilever harvesters have at least 1.23% improvement in their output voltage in the 3-D coupled excitation. In the other side, the experimental results of acoustic section of EVE machine show that the fabricated cantilever beam have a same pattern in all X, Y and Z acoustic excitations. And they have the highest output voltage at 140(HZ) which is very near to simulation results.

References: