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Vibration monitoring via nano-composite piezoelectric foam bushings

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Abstract

Most mechanical systems produce vibrations as an inherent side effect of operation. Though some vibrations are acceptable in operation, others can cause damage or signal a machine's imminent failure. These vibrations would optimally be monitored in real-time, without human supervision to prevent failure and excessive wear in machinery. This paper explores a new alternative to currently-used machine-monitoring equipment, namely a piezoelectric foam sensor system. These sensors are made of a silicone-based foam embedded with nano- and micro-scale conductive particles. Upon impact, they emit an electric response that is directly correlated with impact energy, with no electrical power input. In the present work, we investigated their utility as self-sensing bushings on machinery. These sensors were found to accurately detect both the amplitude and frequency of typical machine vibrations. The bushings could potentially save time and money over other vibration sensing mechanisms, while simultaneously providing a potential control input that could be utilized for correcting vibrational imbalance.

Keywords

Self-sensing, vibration, piezoelectric, foam, bushing, nano-composite, self-monitoring

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Introduction

Various types of mechanical systems inherently produce vibrations. These can oftentimes affect the machine's performance or degrade the surrounding environment [1, 2]. These vibrations can cause damage or even complete failure in the machines that create them [3]. Some may even signal the machine's imminent failure if no action is taken to address them [1]. Recent developments have focused on machine health monitoring through deciphering these vibration patterns. Currently-used vibration sensors include accelerometers, proximitors, strain gauges and other similar devices [1, 4-7].

This paper investigates an alternative approach that replaces compliant bushings and other damped mounting equipment with inexpensive self-sensing components. Such devices can be integrated into advanced sensing systems and readily retrofitted into existing machines. The proposed sensors may be advantageous in comparison to other control sensors due to their simple in situ installation, as well as low cost and power consumption. Currently-used sensors are typically mounted some distance away from the origin of vibrations, thus introducing measurement bias. Accelerometers also have an intrinsic bias, including drift in both zero point and scaling factor [8-10]. Accelerometers, strain gauges, and proximitors often require very accurate installation so that existing measurement bias approximations can be used and accounted for in post-signal processing [7]. For rotating machinery, the commonly accepted measurement system consists of a strategically-mounted triaxial accelerometer, which often requires skill and high cost [4, 6, 11, 12]. In situ installation of a single instrumented bushing at each support can remedy these issues because of its simple installation at the origin of

vibrations with minimal required placement accuracy. Because the proposed sensors are made of foam, they can replace existing bushings and dampen vibrations to create a still and quiet environment [13, 14]. Since foam bushings contain no electronic components, they can be produced cheaper and use less power than currently used vibration-sensing equipment.

The proposed vibration-sensing system utilizes the quasi-piezoelectric effect present in recently discovered nano-composite foam [15]. This foam material is embedded with nano- and micro-scale conductive particles, causing it to exhibit an electrical potential upon impact. Previous impact testing on the foam shows that the energy of impact is directly correlated to the foam's voltage response [15, 16]. Figure 1 shows that this response takes a monotonic, nonlinear form in the sensors used in this paper. This paper describes development of the foam for vibration-sensing and demonstrates the multifunctional capabilities of these sensing materials by providing both isolation damping and integral monitoring. The foam sensors are built into machine-mounting components and characterize the speed and amplitude of vibrating machinery.

Figure 1. Nano-composite silicone foam impact test characterization. Sensors used to gather this data were the same sensors used in reported tests.

Characterization of the nano-composite foam in vibration was initially undertaken using a purpose-built rig for applying deformation at a desired frequency and amplitude. The sensors were subjected to a wide range of frequencies and vibration levels typical of real-world machinery. Based upon the success of these trials, a practical demonstration of the sensing components was performed by retrofitting self-sensing feet to the base of a centrifugal mixer. Process cycles were monitored at various levels of unbalance. The frequency of vibration was found via a spectrogram approach and the precision of these measurements was determined.

Experimentation

Experimental method

Nano-composite foams made with several polymer matrix materials (including polyurethane, silicone and latex) have been shown to exhibit quasi-piezoelectric effects [15]. For the development of self-sensing components, a silicone-based foam (Platinum Silicone Foam, Factor II, Inc.) was selected due to its similarity in mechanical properties to commercially available machine vibration-isolating feet. Sensors were made by casting a low-density silicone foam in a custom aluminum mold shaped as a half-inch tall, two-inch diameter bushing (Figure 2) to match the size of such feet. To prepare the foam mixture, an optimal ratio of conductive particles (18% of the foam by weight) was incorporated into the 'B' component (catalyst) of the two-part foam base until the additives were well dispersed. The 'A' component (base) was then added to this mixture (at a ratio of 1:1 'A' to 'B'), quickly stirred in a centrifugal mixer and then poured into the 45° C mold. Once in the mold, the rising foam was covered and clamped on top to regulate sample size and density. After 15 minutes on a hot plate, the partially cured foam was blown out of the mold and left to sit at room temperature for 24 hours to finish the curing process.

Figure 2. A quasi-piezoelectric silicone foam mounting foot.

To characterize the foam's response to a vibrating environment, a cyclic compression testing apparatus was custom-built. This device features a small platform on which the sensor can sit and cycle up and down at frequencies from 5 to 60 Hz. For tests reported in this paper, the foam was brought into contact with a rigid plate above it while the movable plate was at bottom dead center, and cyclically compressed by a magnitude of 0.2 inches over the range of available frequencies. The frequency of the vibration stand was validated by measurements from a laser tachometer. Figure 3 shows the entire device, with the foam sample positioned on the platform between the two plates. The foam was electrically isolated from the vibration stand by covering both plates with vinyl (electrical) tape.

Figure 3. Cyclic compression testing machine, with the foam sensor positioned between the compression plates.

The sensor being tested was connected to a LabVIEW Data Acquisition (DAQ) system to log the voltage produced in the foam while the vibrating device was running. Multiple half-inch long spike leads were stabbed into opposite sides of the bushing to collect resultant voltages. Experimentation has shown that a sensor's output voltage is affected by its foam volume to lead surface area ratio up to a critical threshold, and lead length was selected to surpass this critical value. Data from each sensor was gathered at a sampling rate of 8.533 kHz for 5 seconds while being compressed at separate constant cyclic frequencies of 20, 30, 40 and 50 Hz.

Practical Application

After characterizing the response of the sensors on the vibration stand, a series of tests were performed to examine the capability of these sensors in detecting vibration characteristics of typical machinery. A planetary centrifugal mixer (Figure 4) was selected as the test machine due to its programmability and range of available frequencies (11-33 Hz) and magnitudes of vibration. This mixer is also typical of a machine that is often monitored by qualitative, rather than quantitative methods. An experience-based sight and sound test is generally performed by a technician to sense from its vibrations that the mixer is functioning properly [17]. Results from experimentation on this mixer were intended to validate whether an inexpensive self-sensing material could be used to replace triaxial accelerometers to monitor the operations of vibrating machinery.

Figure 4. Centrifugal mixer testing setup. All data was gathered from sensor in lower-left corner. Validation from triaxial accelerometer directly above it.

The mixer was set to spin for 10 seconds at 2000 rpm (33 Hz) for each trial run. This setting causes the machine to start from rest, speed up to 2000 rpm, hold the speed between 1900 and 2100 rpm, and then slow back down until stopped. Data was gathered from the same LabVIEW DAQ system utilized in cyclic compression testing. In some tests, the mixer was appropriately counterbalanced to match the mass of the cup inside and in others it was offset by 25 and 50 grams to create levels of increasingly forceful vibrations. This was done to simulate the same machine operating with both acceptable vibrations and typical problematic ones [18]. One sensor was placed under each foot of the mixer; data for these tests was collected from the sensor in the front-left foot position (Figure 4). A triaxial accelerometer (Vernier 3-Axis Accelerometer) was glue-mounted to the machine just above the active foam sensor.

Results and Discussion

Cyclic Test Stand

All data was uploaded into MATLAB for analysis and presentation. Raw data for the entire duration of one 30 Hz test is included in Figure 5, with a single zoomed-in cycle shown in Figure 6. The peak voltages generated in this testing averaged about 140 mV, corresponding to compressions of 0.16 inches (32% strain) for each cycle. This voltage signal is consistent with a cyclic pattern reflective of the stable 30 Hz vibrations imposed upon the sensor (Figure 5). A single cycle from this data (Figure 6) starts at the negative voltage peak at 1.367 seconds and ends at the next negative peak at 1.4 seconds. Thus, this particular cycle exhibits a period of vibration equal to 0.033 seconds (frequency of

30.3 Hz), which matches the tachometer reading (30 Hz with a precision of 1 Hz) used to set the speed originally.

Figure 5. Voltage signal (raw data) from sensor over 5-second test on cyclic test stand.

Figure 6. Voltage signal (raw data) from sensor during one compression cycle on cyclic test stand.

To examine the consistency of this vibrational frequency throughout the five second test, a spectrogram (Figure 7) was generated from the same raw voltage data presented in Figures 5 and 6. The spectrogram function calculates a series of short-time Fourier transforms, which maps the voltage-time signal to the frequency domain [19]. Using this data, the spectrogram maps the change in a signal's spectrum of frequencies over time. The shades of a spectrogram essentially show the power of certain harmonics in the voltage signal. In this case, the shades at the top of the scale reflect the times and frequencies where the sensor detected the strongest harmonic, which correspond to the frequency of the cyclic load. At any given instant, the width of the most powerful line (reflective of the cyclic load) in this spectrogram is 1 Hz. The resultant precision of this

spectral analysis method is better than 1 Hz (60 rpm), as is demonstrated by a closer analysis of the data.

Figure 7. Spectrogram generated from voltage data in Figure 5, which maps the power of harmonic frequencies registered in the sensors over the duration of the 5-second test on the cyclic test stand.

The fundamental frequency of the vibration stand was extracted by plotting the frequency of the strongest harmonic for each time interval. This measure of the dominant vibrational frequency can be resolved to a precision of significantly better than 1 Hz (Figures 8(a) and (b)). By considering the greatest difference in frequency between two consecutive points in Figure 8(b), this method can resolve frequencies to a precision of 0.09 Hz (5.4 rpm).

Figure 8(a). Plot of the strongest vibrational frequency registered in the sensor over the 5-second cyclic compression test.

Figure 8(b). Zoomed-in dot plot of data presented in Figure 8(a).

The spectrogram and frequency-time plots vary from 30-31 Hz for the length of the test, which matches the frequency measurement given by the laser tachometer. The resolution of the tachometer is 1 Hz. Hence, the voltage signal from the piezoelectric foam sensors accurately reflects the frequency of mechanical vibrations to within this resolution.

Another series of tests was performed to investigate the sensors' voltage response to cyclic compressions imposed upon them at different amplitudes. Though the vibration stand had a fixed stroke, multiple amplitudes were achieved by modifying the strain ranges imposed upon the sensor. To do this, the same sensor was cycled at nominally the same average frequency of 28.4 Hz (actual values are 28.73, 28.75 and 27.76 Hz) across different strain ranges of 15-45%, 22-52% and 29-59%. The upper and lower bounds of these ranges represent the strain in the foam when the vibration platform is at bottom and top dead center, respectively. The sensor produced higher voltages in response to greater strain levels (Figure 9). The average peak voltage amplitudes (evaluated for each compression cycle) for the three levels of increasing strain are 151, 174 and 181 mV, respectively. This suggests that increasing amplitudes of vibration trigger higher voltages in the sensors in a nonlinear relationship.

Figure 9. Plot of running average of sensor's voltage peaks (extracted from raw data) in response to cyclic impacts at three different levels of strain.

Planetary Mixer

Data retrieved from the planetary mixer tests is shown in Figures 10 and 11. These plots display the voltage signal over time for all three tests: 0, 25 and 50 grams over-counterbalanced, all with the mixer set to spin at 2000 rpm (33.3 Hz). Running the mixer at the 2000 rpm setting for 10 seconds causes it to start from rest, accelerate up to a range of 1900-2100 rpm, hold it there until 10 seconds passes and then finally decelerate back to rest. The more off-balanced runs of the mixer registered an overall higher voltage signal in the sensors compared to the properly counterbalanced runs (Figures 10 and 11). For each of the three tests, this mixer vibrated most forcefully at the 13.5 second mark (during deceleration of the machine; Figure 10). The signal also increases in magnitude

as the mixer accelerates and experiences harsher vibrations. During the time of most forceful turbulence (at 13.5 seconds), the 50 g over-balanced run registered a peak voltage of 10 mV in the foam, while the 25 g and 0 g over-balanced runs produced peak voltages of 3.5 and 0.6 mV, respectively.

Figure 10. Voltages registered in the sensor during the three separate 10-second 2000 rpm tests of the centrifugal mixer at varying levels of counterweight. This data was filtered with a 6th order low-pass Butterworth filter (cutoff frequency of 43 Hz).

Figure 11 shows the raw voltage data of the sensors during a single cycle of the mixer while it is spinning at 31 Hz (1860 rpm). Although the various counterweights registered different magnitudes of voltage in the bushings, sensors from each test show a similar period of oscillation (0.032 seconds) at this given time.

Figure 11. Voltages (raw data) in the sensors during a single compression cycle of the planetary mixer, counterweighted at three different levels.

The spectrograms corresponding to two of these three individual tests (Figures 12 and 13) show a powerful line that depicts the fundamental frequency of the mixer during a 10 second trial. The lines representing the frequencies of the strongest harmonic at each time are plotted directly over the spectrograms. These plots clearly show the path of the mixer's spinning frequencies for a ten second programmed mix cycle. When the mixer starts, the inner drum speeds up linearly to 35 Hz (2100 rpm) in about 4 seconds. Upon reaching this upper limit, it slows down to 32 Hz (1900 rpm) and repeats this motion two more times (until 10 seconds have passed), when it slows back down and stops. After validating the sensors' frequency-detecting accuracy via the tachometer in the cyclic

testing, we can assume that these mixer speed approximations are also valid. Note the sensor's precision in detecting the mixer's running speed, independent of the difference in magnitude of vibrations between the evenly-balanced and 50 g over-counterbalanced runs. Similar to the vibration stand tests, the sensors identified the mixer's vibrational frequency to a precision of 1 Hz (60 rpm) from the spectrogram alone and 0.1 Hz (6 rpm) from the strongest harmonic plot. It should also be noted that data from these tests were analyzed using smaller time increments than those utilized in the vibration device experiments, so these spectrograms have a noticeably higher resolution.

The 50 g over-counterbalanced test spectrogram (Figure 12) shows a few spots of high voltage at 6 and 14 seconds and 26 Hz. These correspond to the times seen in Figure 10 when the mixer experienced the highest turbulence as the motor revved up to 2000 rpm and back down to 0 rpm. These spots distinctly stand out above the rest on the mixer's path in the frequency-time map. Other lines and spots in the spectrogram (such as the weak line at 15-22 Hz from 6-14 seconds) represent the resonant frequencies of the mixer's system. Due to their lower magnitudes, these resonant signals are easily distinguishable from the mixer's path.

Figure 12. Spectrogram and corresponding strongest harmonic plot of 50 g over-counterbalanced, 10-second, 2000 rpm trial of centrifugal mixer. The data used to generate this spectrogram is the raw data from Figures 9 and 10.

The evenly counterbalanced spectrogram (Figure 13) shows a defined path which stretches all the way from 4 to 15 seconds, representing the duration of the mixer's spin cycle above about 12 Hz (700 rpm). Notice the absence of any powerful spots along this line such as were present in the over-counterbalanced run (Figure 12). The constant shade seen along this path shows that the strength of the foam's signal was nearly constant over the duration of the test. This is verified by the low amplitude of its voltage data (Figures 10 and 11).

Figure 13. Spectrogram and corresponding strongest harmonic plot (disregarding very low frequencies) of evenly-counterbalanced, 10-second, 2000 rpm trial of centrifugal mixer. This data (from Figures 10 and 11) was filtered with a 6th order low-pass Butterworth filter (cutoff frequency of 60 Hz) before generating this spectrogram.

Other testing has been done with the same sensors and mixer, with the mixer set to spin at different speeds in a continuous test. During a particular test (shown in Figure 14), the mixer was programmed to spin for five seconds at each step of 800, 1100, 1500, 1100 and 800 rpm. Results were similar to those of the 2000 rpm tests; the sensors could resolve the mixer's vibrating frequencies to a precision of 0.1 Hz (60 rpm). Each step of the mixer's spin cycle is distinctly visible in the spectrogram. The first and last steps of 800 rpm (13.33 Hz) are represented by the weak lines from 3-7 seconds and 26-29 seconds. The 1100 rpm (18.33 Hz) steps are stronger and more clearly depicted from 7-

12 and 20-24 seconds. The most violent oscillations happened at the 13-16 second interval during the 1500 rpm (25 Hz) step.

Figure 14. Spectrogram of evenly-counterbalanced, 15-second, 800-1100-1500-1100-800 rpm stepped run of the centrifugal mixer. This data was filtered with a 6th order low-pass Butterworth filter (cutoff frequency of 50 Hz).

Conclusions

A low-cost and combined vibration isolation and vibration monitoring system has been designed, characterized and tested. The self-sensing piezoelectric nano-composite foam system is capable of detecting a range of frequencies and amplitudes for typical machinery, in real-time. Characterization of the foam between two plates of a custom-built vibration stand yielded a voltage response capable of determining the machine's

vibrational frequency to a precision of 0.09 Hz and an accuracy of better than 1 Hz. The magnitude of response reflected different levels of vibrational amplitude imposed on the sensor in a nonlinear yet monotonic manner.

Practical application of the sensors was demonstrated on a real-world system by using the foam as mounting feet on a centrifugal mixer. Voltage response from the mounts reflected the level of load imbalance and mixing rotational speed.

The voltage output of the sensors could be utilized as a control input to fault detection, machine maintenance, and load-balancing systems. Possible applications for this self-sensing material include mounts and bushings for manufacturing equipment, washing machines, automatic doors, compressors, car engines, air conditioning units, remote systems and many other mechanisms used in both engineering facilities and the home.

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Conflict of interest

The authors declare that there is no conflict of interest in regards to the publication of this article.

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