Development of a Vibration Measurement Device based on a MEMS Accelerometer

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Abstract: This paper proposes a portable and low cost vibration detection device. Enhanced vibration calculation, reduction of error and low storage memory are complementary accomplishments of this research. The device consists of a MEMS capacitive accelerometer sensor and microcontroller unit, which operates based on a novel algorithm designed to obtained vibration velocity, bypassing the usual time-based integration process. The proposed algorithm can detect vibrations within 15Hz - 1000Hz frequencies. Vibration in this frequency range cannot be easily and accurately evaluated with conventional low cost digital sensors. The proposed technique is assessed and validated by comparing results with an industrial grade vibration meter.

1 INTRODUCTION

Advancement and Development of technology and smart devices increases the demand for comfort and safety, especially in transportation, where more emphasis is placed on ride comfort and safety by vehicle manufacturers. The ability to measure lower frequency vibration with high precision can cooperate in this regard. Human and environmental safety (Kuntiyawichai and Burdekin, 2003), vehicle comfort (Barone et al. 2016), engine performance (Dayyani et al., 2016), road profiling (Abulizi et al., 2016) and many more, necessitate vibration measurement for their analysis and evaluations.

Numerous types of vibration sensors are available, but the most common and advantageous way of detection is based on accelerometer. They can sense changes in velocity while oscillating in particular frequency ranges; although, the orientation of the sensor in this case is important and must be considered (Stein et al., 2007). Depending on the application, different types of accelerometer may be used, for instance, Piezo-electric accelerometers are well known for their precise measurement, however, these are expensive (Jamil et al., 2014). On the other hand, MEMS (Micro Electromechanical Systems) accelerometers have better dynamic specification and due to their small sizes, may be easily integrated in different environments; however, they present noisy outputs (Helal et al., 2015). (Jamil et al., 2014), presents a vibration device based on an accelerometer, and uses a microcontroller and computer to visualize the vibration graphically. Their device measure vibrations below 5KHz with applications aimed towards medium range vibration analysis.

This paper presents a low-cost vibration device, which is based on a novel algorithm. The proposed system optimizes the evaluation process for velocity calculation, while using less memory by bypassing the time-based integration process that requires an extra buffer to be stored, and prevents potential integration error, imposed in the computation. Obtaining velocity and displacement information is certainly possible by integration and double integration (respectively) of the acceleration data in the time domain. However, small DC offsets, or low frequency signals present in the input samples (acceleration data), will result in large cumulative error, post integration.

2 SYSTEM SET UP AND DESIGN

Vibration can be measured as either acceleration (which is the rate of change of speed in mm/s/s or G), velocity (the distance moved per time in mm/s), or displacement (inches or mm) in the x, y, z plane of a 3-dimensional space. The method described in this paper evaluates vibration in terms of velocity. As

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shown in equations (1) and (2), there is a relationship between acceleration, velocity and displacement, although, velocity has the most direct relationship between how much a body is displaced per unit of time (which is ideal, as the severity of vibration is a factor of moved distance and frequency of the movement). Hence, vibration measurement based on velocity is the most common and preferred method in monitoring vibration related to mechanical problems such as unbalance, misalignment, etc.

$$v = u + a\Delta t \tag{1}$$

$$s = u\Delta t + \frac{1}{2}a(\Delta t)^2 \tag{2}$$

Where $\boldsymbol{v}$ is velocity, $\boldsymbol{u}$ is previous velocity, $\boldsymbol{a}$ is acceleration, and $\Delta\boldsymbol{t}$ is the change in time.

The device developed for this research consists of a MEMS accelerometer (ADXL345) and a Microcontroller Unit (MCU) (dspic33EP256MC202), where the MCU is used to sample and process acceleration data at a rate dependent on the expected maximum vibration frequency. Considering the ADXL345 has a maximum sampling rate of 3200Hz, the theoretical maximum frequency for vibration that can be measured is 1600Hz, which is determined based on Nyquist theorem in Equation (3). For this experiment, the frequency range is between 15 – 100 Hz, therefore the minimum sampling rate must be 200Hz.

$$f_s \geq 2f_{max} \tag{3}$$

Where f_s is frequency of sampling and f_{max} is the maximum frequency level for detection.

Note that the frequency range considered for this experiment is not due to a limitation in the method described, but on the memory constraints of the selected MCU. The amount of memory required to perform a Fast Fourier Transform (FFT) analysis on the signal is a factor of the measurement sampling rate, and the number of samples required.

The industrial grade vibration meter (HS-620) manufactured by Hansford Sensors was used to verify all test results in this experiment.

Figure 1 displays the setup used to verify the results of this experiment. The image shows the HS-620 vibration meter, the custom MEMS meter (designed for this research) and vibration test rig developed to simulate various vibration levels.

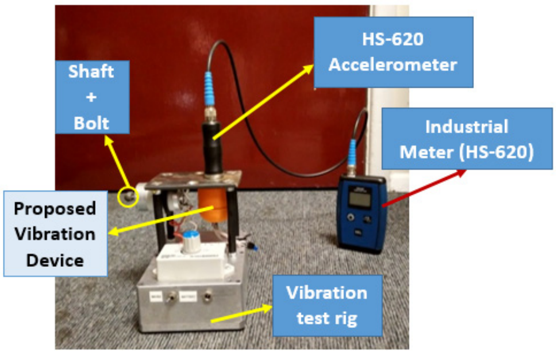

Figure 1: Experiment setup.

The test rig is battery operated (12v input) which consists of a DC motor (to generate the vibration) and a potentiometer (to vary the speed of the motor, increasing the frequency and magnitude of vibration). The motor is fitted to a metal plate, which is connected to the base of the unit using rubber stands (allowing pronounced vibration magnitudes to be sensed on the plate). To vary the intensity of vibration at specific frequencies, bolts of different sizes and weights were connected to the shaft of the motor, which creates the force needed to generate the required vibration level.

The HS-620 and MEMS meter were mounted at the same point, on opposite sides of the plate to ensure the sensed vibration is consistent. The results obtained during the tests confirms that this configuration lets both meters receive similar vibration levels, allowing accurate verification. Other configurations, like, mounting both meters side by side, on different areas of the plate, resulted in false data, since the vibration sensed across the plate is uneven. It is also important to ensure there are no moving parts in the MEMS unit during measurement, as this will reflect false vibrations. The experimental unit was potted with epoxy to guarantee this.

3 IMPLEMENTATION

Common practice integrates the acceleration samples, deriving a velocity waveform. This waveform is then passed through number of filters to minimize the effect of the error obtained from the integration process, before any vibration analysis is carried out.

The method described in this paper attempts to improve the accuracy of MEMS based vibration systems, by bypasses the effect of integration error on the results, calculating the velocity of the signal directly from the acceleration's frequency domain.

This process obtains the acceleration samples from the sensor, performs an FFT analysis on the acceleration, and evaluates the velocity based on this analysis.

3.1 Acceleration Measurement

The first step is obtaining the samples from the accelerometer. A common source of error is having uneven period between each sample. It is vital to ensure consistency in the time difference between each sample that make up the signal to be processed, because irregularities will result in false frequency domain representations. For example, using Equation (4), for a sampling rate of 250Hz, the period between each sample is expected to be 4ms. The aim here is to measure vibration irrespective of the orientation of the accelerometer, to achieve this, each sample from the x, y, and z plane was consolidated using vector summation (5), to obtain a single value that represents the acceleration in a 3-dimensional space.

$$f = \frac{1}{t} \tag{4}$$

$$A = \sqrt{X^2 + Y^2 + Z^2} \tag{5}$$

Where $\boldsymbol{f}$ is the frequency of the signal, $\boldsymbol{t}$ is the period, $\boldsymbol{X}$ is the acceleration on the x axis, $\boldsymbol{Y}$ is the acceleration on the y axis, $\boldsymbol{Z}$ is the acceleration on the z axis, and $\boldsymbol{A}$ is the equivalent acceleration of all axis.

After obtaining data from the accelerometer, the next step is to run the acceleration signal through a band-pass filter (consisting of a high-pass and low-pass filter). The filter cut-off frequencies are selected based on the required measurement frequencies as indicated in equation (6). In this experiment, the frequency range explored is between 10Hz – 100Hz.

$$f_{min} \leq fc_{high-pass} < fc_{low-pass} \leq f_{max} \tag{6}$$

Since MEMS accelerometers are good at detecting the earth's gravitational pull, this produces an offset equivalent to the gravity's magnitude (approximately 9.81(m/s^2)) to the axis acting against this force. This causes the resulting signal to contain a DC offset even when static, hence the high-pass filter is needed to eliminate this offset.

3.2 Fast Fourier Transform (FFT) Analysis

Up until this point, the acceleration samples measured has been visualized in the time domain. A big part of vibration analysis is investigating the signal in the frequency domain (Figure 2) which is done using a Fast Fourier Transform (FFT) algorithm (Rao et al., 2011). The purpose of this is to determine the magnitude and frequency of the various signals that produce the waveform, making it easier to identify the nature and source of vibration.

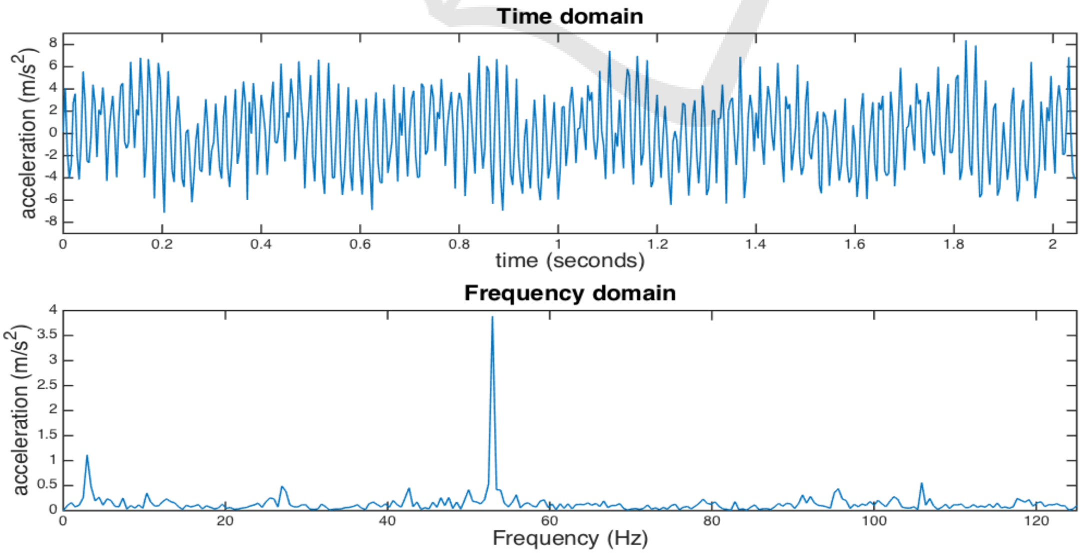

Figure 2: Vibration signal in time and frequency domain.

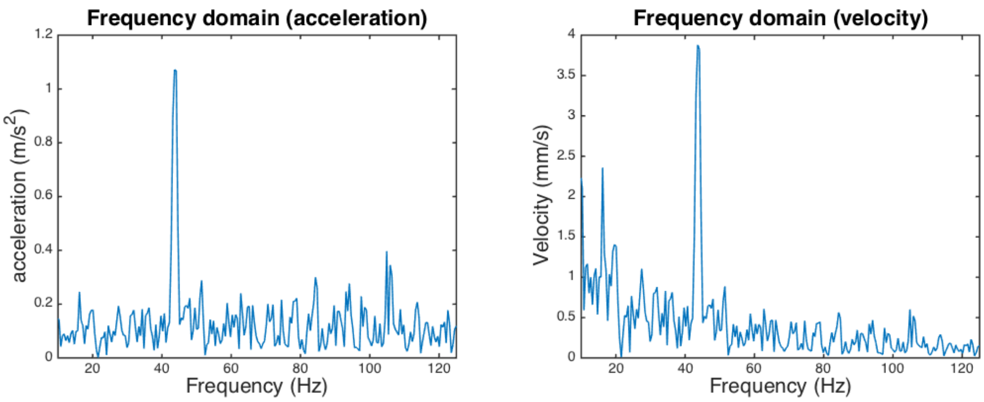

Figure 3: Velocity FFT derived from acceleration FFT.

Before performing an FFT analysis on the original signal, the sampling rate, and number of samples should be decided. This decision is based on the length of time, and expected frequency range which needs to be analysed. In vibration measurement, for accuracy and consistency, analysing short time intervals (i.e. < 3 seconds) is preferred, especially in a vehicular environment where the speed of travel determines the length of the road scanned per time. For example, surface irregularities (which may cause increased vibration) present in small sections of the road will be overshadowed, if a much larger portion of the road is scanned as a single waveform.

In common FFT algorithms, the number of samples (FFT size) evaluated are in powers of two (i.e. 64, 128, 256, 512 etc.), otherwise, zeros are added to the end of the signal to generate the desired length. This is a common source of error that can easily be avoided by acquiring the right number of samples.

The FFT size defines the number of bins (amount of samples in the frequency domain), and the sampling rate determines the maximum frequency that can be identified. According to equation (7), the number of bins is half the FFT size, where each bin has a resolution (frequency difference per bin) calculated using equation (8). For this experiment, a sampling rate of 250Hz and FFT size of 512 was chosen. This was preferred based on several factors, including, required measurement frequencies, resolution, and memory capabilities of the selected MCU.

$$n_{bins} = \frac{N}{2} \quad (7)$$

$$FFT\ resolution\ (\Delta f) = \frac{f_s}{N} \quad (8)$$

Where $\boldsymbol{n_{bins}}$ is the number of bins, $\boldsymbol{N}$ is the total number of samples (FFT size), $\boldsymbol{\Delta f}$ is the FFT resolution, and $\boldsymbol{f_s}$ is the sampling rate.

3.3 Conversion of Acceleration FFT to Velocity

When the FFT for the acceleration samples is calculated, the next phase is to evaluate the velocity (in mm/s) of each frequency bin using equation (9). The samples obtained for acceleration are in the unit of metres per second squared (m/s^2), hence, the derived velocity is multiplied by 1000 to evaluate its value in millimetre per second (mm/s). Figure 3 shows the derived velocity's frequency domain.

$$v(n) = \frac{a(n)}{2 * \pi * \Delta f * n} * 1000 \quad (9)$$

Where $\boldsymbol{v}$ is the velocity, $\boldsymbol{a}$ is the acceleration, $\boldsymbol{\Delta f}$ is the FFT resolution, and $\boldsymbol{n}$ is the index of the sample

3.4 Root Sum Squared (RSS) Moving Average

After calculating the equivalent velocity for each frequency, due to the resolution of the FFT bins, and irregularity of the vibration signals, in some cases, the magnitude of the vibration (after the FFT analysis) spans across neighbouring frequencies. This causes a reduced amplitude to be reflected on the frequency domain as shown in Figure 4a. Running an RSS moving average (equations (10) and (11)) on the samples corrects this problem as illustrated in Figure 4b, producing accurate and consistent results.

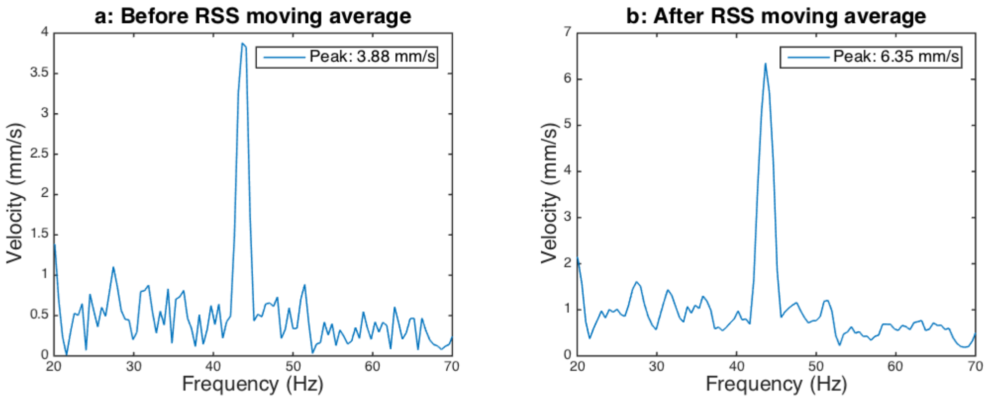

Figure 4: Derived velocity FFT showing the effect of RSS moving average (signal vibration = 6.32 mm/s).

The moving average requires a window length, which indicates the number of samples to evaluate when computing the average. In this application, it is advisable to select an even number for the window length; this is to maintain uniformity on either side of $\boldsymbol{v(n)}$ in equation (11). For this experiment, a window length of two was chosen, as tests taken proved more accurate.

$$RSS = \sqrt{b1^2 + b2^2 + \cdots + bn^2} \tag{10}$$

$$a(n) = \sqrt{v\left(n - \frac{l}{2}\right)^2 + \cdots + v(n-1)^2 + v(n)^2 + v(n+1)^2 + \cdots + v\left(n + \frac{l}{2}\right)^2} \tag{11}$$

Where $\boldsymbol{b}$ is the number of values to be averaged, $\boldsymbol{a}$ is the calculated RSS average, $\boldsymbol{v}$ is the velocity, $\boldsymbol{l}$ is the moving average's window length, and$\{n \in \mathbb{R} \mid 1 \leq n \leq N\}$.

The equivalent vibration (in mm/s) and frequency of the measured samples is then evaluated based on the maximum value detected across the different frequencies i.e. the vibration calculated for Figure 4 is 6.35 mm/s at 44Hz.

4 RESULTS

Figures 5 – 10, show the results obtained while taking measurements for different vibration levels at varying frequencies. Using the HS-620 Hansford meter as the benchmark for the error analysis, Table 1 compares both results obtained from the MEMS meter and the HS-620, showing the percentage error in each case.

Table 1: Experimental results with percentage error.

HS-620	MEMS meter	% Error
1.08 mm/s	0.91 mm/s	**15.7%**
3.42 mm/s	3.61 mm/s	**5.6%**
5.02 mm/s	5.06 mm/s	**0.8%**
7.72 mm/s	7.75 mm/s	**0.4%**
8.3 mm/s	8.3 mm/s	**0%**
11.7 mm/s	11.8 mm/s	**0.9%**
17.9 mm/s	17.9 mm/s	**0%**

The images below show the peak amplitudes obtained after the RSS averaging, and these amplitudes define the vibration levels in velocity. As shown in Figure 5, there are instances where the frequency analysis produces multiple peaks at various frequencies, and this indicates the presence of vibration from different sources. In this instance, the RMS velocity is calculated (based on Parseval's theorem) on all the peaks.

Currently, the consistency of the algorithm is between ±1 mm/s, which is based on the accuracy and sensitivity of the accelerometer. Other filtering and processing methods are been considered to improve this consistency. One of these include using an exponentially weighted moving average on the raw samples to reduce the effect of sudden peaks and high frequencies. Another method considered, is applying a window to the samples used for the FFT analysis, to help with signal discontinuity, comparing the various windowing techniques, with and without overlapping.

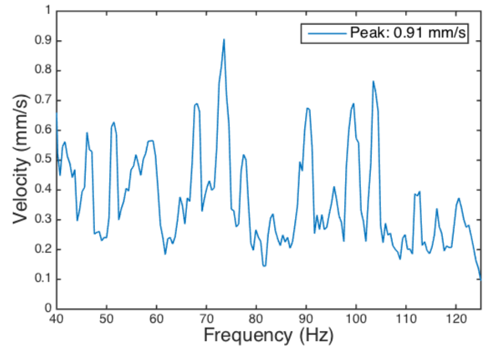

Figure 5: Vibration signal (1.08 mm/s @75Hz).

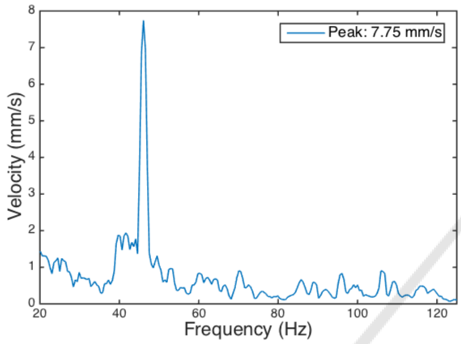

Figure 6: Vibration signal (7.72 mm/s @46Hz).

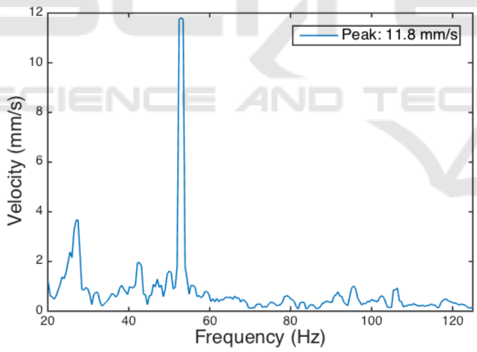

Figure 7: Vibration signal (11.7 mm/s @53Hz).

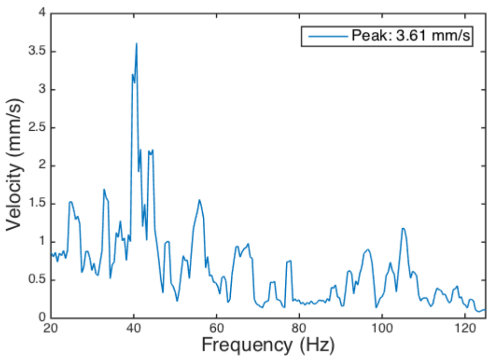

Figure 8: Vibration signal (3.42 mm/s @42Hz).

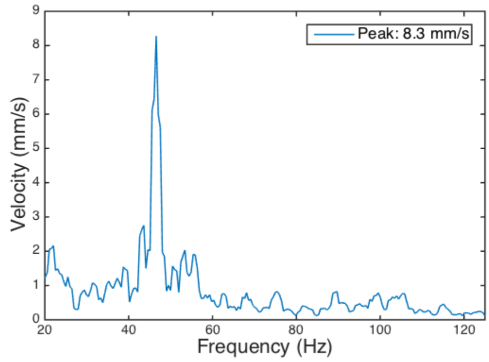

Figure 9: Vibration signal (8.3 mm/s @46Hz).

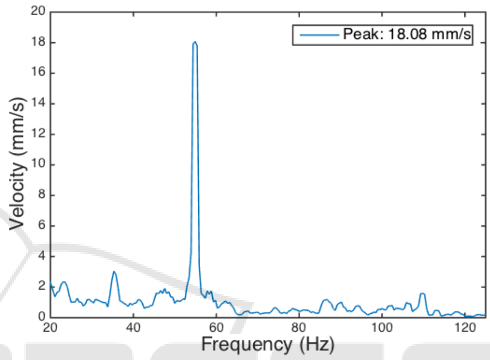

Figure 10: Vibration signal (17.9 mm/s @56Hz).

5 CONCLUSIONS

Vibration monitoring has a wide range of applications in machine mentoring, ranging from industrial to domestic use cases. This paper proposes a novel process of achieving accurate and precise vibration measurement using MEMS accelerometers. Results show an error rate of <1% for vibrations greater than 5 mm/s. While error rates of up to 15% was achieved for vibrations less than 1 mm/s, which according to the International Organization for Standardization (ISO), is insignificant in machine based monitoring, since unsatisfactory conditions begin at ~3 mm/s.

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