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Uncertainty evaluation of low-cost vibration sensors in precision manufacturing applications

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Abstract

Vibration monitoring is one of the key areas of interest in precision manufacturing setups to ensure high level of engineering confidence in manufactured products and associated machinery. Traditionally, high-cost vibration sensors have been employed in industrial manufacturing scenarios. The recent development of industrial grade MEMS based vibration sensors has shown promise in viability offered by such low-cost sensors in metrological applications enabling Industry 4.0. Previous work was conducted to characterize the performance and background noise of measurements from low cost triaxial accelerometers in terms of identifying the parameters that induce uncertainties and baseline errors in measured data. This work expands the study by evaluating uncertainty in measured data of such low-cost vibration sensors according to stochastic (JCGM 100:2008) and Monte Carlo methods (JCGM 101:2008). The recorded data was captured after conducting static and dynamic tests on a calibration test bench using a range of frequencies while establishing traceability according to the ISO 16063-11:1999, ISO 16063-21:2003 and the IEEE 1293-2018 standards. The work investigates uncertainty in measurement by installing the sensors on machine tools and conducting traceability tests. The work also identifies the main aspects which contribute to measurement uncertainty and proposes an improved setup to mitigate effects of uncertainty of such low-cost vibration sensors offering a viable implementation for smart condition monitoring and smart machining purposes.

Precision Manufacturing, Measuring Instruments, Performance Evaluation, Uncertainty, Accelerometers, Calibration, MEMS

1. Introduction

Vibration monitoring is one of the key areas of interest in precision manufacturing setups to ensure high level of engineering confidence in manufactured products and associated machinery [2]. Traditionally, high-cost vibration sensors such as Integrated Electronic Piezoelectric (IEPE) have been employed in industrial manufacturing scenarios. The recent development of industrial grade Micro-Electro-Mechanical Systems (MEMS) based vibration sensors has shown promise in viability offered by such low-cost sensors in metrological applications enabling Industry 4.0. MEMS sensors are already in wide usage for a variety of vibration sensing applications such as seismology, wind turbines, oil rigs, bridges etc. [3, 4]. However, metrology aspects related to the accuracy, uncertainty, repeatability, and traceability of such MEMS sensors [2] have not been explored in detail. Previous work was conducted to characterize the performance [5] and estimate background noise arising from measurements of low cost triaxial accelerometers. This work expands the study by evaluating uncertainty in measured data of such low-cost digital MEMS vibration sensors according to classical probabilistic (JCGM 100:2008) and Monte Carlo methods (JCGM 101:2008).

The outcomes of this research is an example application of applying a metrological approach when selecting sensors in Industry 4.0 [6].

2. Methodology

The uncertainty assessment and evaluation for digital MEMS accelerometers was conducted by establishing traceability according to the ISO 16063-21 [7] and ISO 16063-11 [8] standards. These standards define procedures for calibration of vibration sensors by comparing their results to a reference transducer and laser interferometer [9]. These methods are typically suitable for traditional vibration sensors, so had to be adapted for the MEMS sensors using IEEE-STD-1293-2018 [10].

A series of static and dynamic traceability tests were performed based on the aforementioned standards. To perform the tests sensors were mounted on an electrodynamic shaker in a temperature-controlled environment. The static tests were performed when the sensor was subject 'zero excitation' conditions. While the dynamic testing was performed, when the sensors were subject to sinusoidal excitation at discrete frequency points in the range of 5 Hz to 1 kHz. This frequency range was selected to cover most structural resonance frequencies for the majority of machine tools in industry. This range would also cover frequencies of interest for most rotary components on a machine tool, such as bearing rotational speeds, ball-pass, and ball-spin frequencies, excluding high-speed spindles in industrial setups for condition monitoring and prognostics [11]. To ensure repeatability according to the industry practice, each set of readings was repeated five times.

The recorded data from the sensors was then evaluated for quantification of uncertainties in accordance with "The Guide to the Expression of Uncertainty in Measurement (GUM)" by means of GUM Uncertainty Framework [12] and Monte Carlo Methods (MCM) [13]. The JCGM 100:2008 guide [12] provides guidelines for estimation of uncertainty in measurements based on the Law of Propagation of Uncertainties (LPU). While GUM Supplement 1 or JCGM 101:2008 [14] provides basic guidelines for using the Monte Carlo Methods (MCM) for the propagation of distributions in metrology for evaluating measurement uncertainty.

2.1. Experimental Setup

An industrial grade tri-axial digital MEMS sensor (ADXL355) [15] was selected as a low-cost vibration sensor for evaluation of uncertainty. While several MEMS sensors at further lower costs are also available, the selected MEMS sensor provides high resolution (20 bit) ADC on chip to give the required sensitivity that may be expected from traditional accelerometers while also providing a digital communication option (I2C/SPI) for convenient data acquisition. A tri-axial IEPE accelerometer (PCB 356A02) [16] was employed as the primary reference transducer in the experiment. While a Renishaw XL-80 [17] laser interferometer was also used to establish metrological traceability in acceleration measurement mode in accordance with ISO 16063-11 [8].

The sensors were mounted on a 5 mm aluminium plate and secured using bolts, while the sensor cables were secured using adhesive clamps. Finite Element Analysis (FEA) was conducted during the design and installation of sensors on the plate to ensure uniform vibration pickup is enabled across all sensors. This would also ensure that the sensor setup is not affected by a systematic cosine error due to the arising vibrating modes.

Digital temperature sensors (Maxim DS18B20) were used to monitor environmental temperature variations as well temperature variations on the plate which may induce uncertainties in the vibration sensors. All three sensors (MEMS, laser and IEPE accelerometer) had separate Data Acquisition Systems (DAQs) which recorded to a single computer to aid synchronisation and to ensure correct timing information for the recorded data.

The data from the MEMS sensor was recorded and transmitted wirelessly to a PC through a Raspberry Pi 3 Model A+ processor. Laser measurements were recorded via a USB interface to the PC. While the data from the IEPE accelerometer was acquired using a National Instruments DAQ (NI 9234). The nominal range of the MEMS sensor was set to be ±2.048 g (where g=9.81 m/s^2) to ensure high sensitivity operation, while the IEPE sensor was used in its nominal operating range of ±50 g. The sampling rate was set to be 2 kHz across all sensor acquisition systems to ensure to ensure fulfilment of Nyquist criterion for dynamic test frequencies in current application and to aid comparability of uncertainty results.

2.2. Calibration Test Rig

The calibration test rig was setup to characterize the uncertainty parameters of the MEMS sensor in comparison to the chosen transfer standard (laser interferometer) or reference transducer (IEPE). The test was conducted in a temperature-controlled environment of ±1 °C, in accordance with ISO 17025:2017 standard which sets the general requirements for testing and calibration setups. Moreover, the setup was allowed to stabilize after installation for a duration of 24 hrs to minimize the environmental and self-heating effects on sensors, which may cause sensitivity drift. For example, nominal sensitivity of 100 mV/g of the IEPE based sensor in the experiment could vary up to ±1 % due to variation of temperature in operating range of -54 °C to +121 °C [16], while the MEMS vibration sensor's output can vary up to 0.15 mg/°C or ±0.01 %/°C [15]. The average temperature during the tests was recorded to be 19.25 °C and 19.5 °C for the sensor setup and the installation environment, respectively.

The calibration setup was created to perform static tests at DC (0 Hz) or 'zero excitation' and dynamic tests using sinusoidal excitation, as shown in Figure 1 and Figure 2. The setup consists of the aluminium plate which was mounted securely on an electrodynamic shaker system (TIRA 500). In this experiment, the sensors were excited in only one axis of movement (Z-Axis), as a proof of concept. However, similar concept can be extended to excite the sensor in specified direction i.e., X and Y axis as well. Future work would include slight redesign of the current rig for simultaneous excitation of sensor for determination of tri-axial uncertainty in a single experimental configuration [18]. The input to the shaker is from a Data Physics signal generator via an amplifier and only the frequency of generated waveform is modified, whilst keeping the signal amplitude and amplifier power constant. The shaker is capable of providing a power output of up to 300 W. However, to prevent overloads in sensing, especially in the case of the MEMS sensor the power output from shaker was limited to 20 mW. The fifteen frequencies on which the sine testing was conducted within the 5 Hz to 1 kHz range were selected in accordance with ISO 266:1997 [19]. Five tests were conducted in order to determine the static uncertainties. Similarly, for each frequency, the test was conducted five times for repeatability as well. Therefore, in total eighty (five static plus seventy-five dynamic) readings of 20 s duration each were recorded by the sensors.

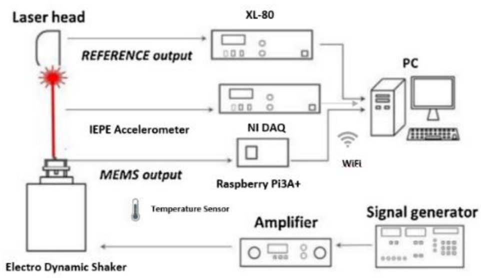

Figure 2 Calibration Test Rig

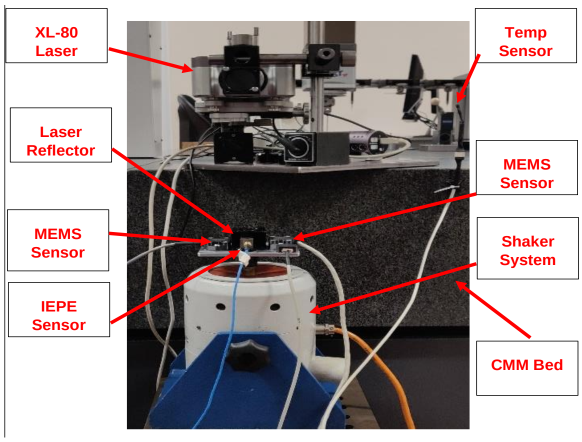

Figure 1 Calibration Test Rig

3. Uncertainty assessment and evaluation

The error in any measurement can be defined as the difference between the true value and the observed value of the measurand [20]. An estimate of the 'error' is often referred to as associated uncertainty. Therefore, measurement uncertainty can be understood as the quantitative indicator of the quality or accuracy of reported measurement. Without the knowledge of associated uncertainty of a sensor measurement, the metrological characterization cannot be carried while comparing to specified reference values or a standard. The Guide to the Expression of Uncertainty in Measurement (GUM) provides standard methods and techniques for evaluation of measurement uncertainty in metrology [21].

Table 1 Uncertainty Budget for ADXL355 Digital MEMS Accelerometer (Confidence Interval = 95 %)

S No	$u(x_i)$	Source of Uncertainty	Probability Distribution	Factor	Value (g) $u(x_i)_{MEMS}$	$u^2(x_i)_{MEMS}$	Relative Standard Uncertainty (%)
1	$u(x_i)_r$	Repeatability	Normal	1	6.49E-04	4.21E-07	0.016
2	$u(x_i)_{nl}$	Nonlinearity	Uniform	$\frac{1}{\sqrt{3}}$	2.36E-03	5.59E-06	0.058
3	$u(x_i)_{cs}$	Cross Axis Sensitivity	Uniform	$\frac{1}{\sqrt{3}}$	2.36E-02	5.59E-04	0.577
4	$u(x_i)_{sv}$	Senstivity Variation ADC	Uniform	$\frac{1}{\sqrt{3}}$	1.54E-02	2.37E-04	0.376
5	$u(x_i)_{tv}$	Temperature Effect Senstivity	Uniform	$\frac{1}{\sqrt{3}}$	1.46E-04	2.14E-08	0.004
6	$u(x_i)_{zo}$	Zero-g Offset	Uniform	$\frac{1}{\sqrt{3}}$	1.44E-02	2.08E-04	0.352
7	$u(x_i)_{to}$	Temperature Offset	Uniform	$\frac{1}{\sqrt{3}}$	5.77E-05	3.33E-09	0.001
Variance		u^2_{MEMS}	1.01E-03	**Standard Uncertainty (g)**		u_{MEMS}	3.18E-02
Confidence Interval		**95 %**	k=2	**Expanded Uncertainty (g)**		U_{MEMS}	6.36E-02

The GUM allows evaluation of the uncertainty in measurement by application of GUM Uncertainty Framework (GUF) and Monte Carlo Methods. The GUF evaluates the output uncertainty through propagation of input uncertainties, while MCM involves the propagation of the distributions of the input sources of uncertainty. The comparison of both methods is illustrated in Figure 3 [1].

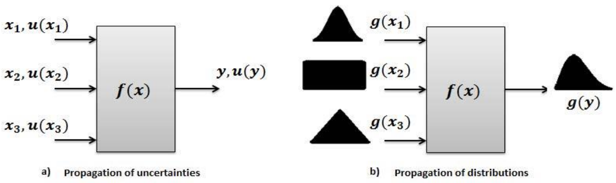

Figure 3 Comparison of GUF vs MCM [1]

The measurement uncertainty for digital MEMS accelerometer was evaluated by applying both methods as contained in GUM for a confidence interval of 95 %. For traceability traditional IEPE or laser based sensors can be used for determining relative uncertainty based on the current experimental configuration. However, for simplification the current work chooses IEPE sensor as the reference transducer for evaluating the static and dynamic uncertainty of MEMS sensor and the work can be expanded in the future to include laser interferometer results.

3.1. Uncertainty sources and measurement model

The uncertainty value associated with a measurement is an estimate of residual error in that sensor after all the systematic corrections have been applied [20]. The list of factors that can be included as possible sources of uncertainty for any measurement are those which induce residual errors in true value of measurand [18]. If such a list is drawn it is often non-exhaustive in nature. However, according to GUM the

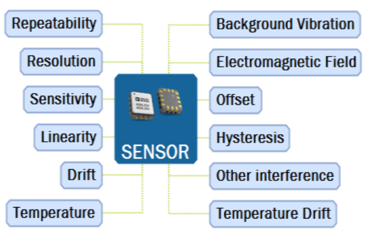

Figure 4 Uncertainty Factors

uncertainty components worth evaluating can always vary according to the experimental requirements. The factors that can typically affect the measurement uncertainty in a MEMS sensor are shown in Figure 4. While the sources of uncertainty $u(x_i)$ investigated and evaluated as part of this work are shown in Table 1.

Assuming that the sources of uncertainty of the MEMS vibration sensors are independent of each other and random in nature, the mathematical model of the sensor's measurement uncertainty can be represented as: -

$$U_{MEMS} = U_R + U_{NL} + U_{CS} + U_{SV} + U_{TV} + U_{ZO} + U_{TO}$$

Where, U_{MEMS} represents the uncertainty as the sum of individual contributions by the components, represented by their relevant subscripts. For example, U_R , represents the uncertainty value due to repeatability.

3.2. Measurement uncertainty based on GUF

Based on the classical statistical methods as outlined in GUF an estimate of uncertainty from randomly varying input quantities of the sensor's mathematical model can be calculated. By applying the principles of GUF the uncertainty budget as shown in Table 1, was calculated for static sensor measurements, as an example. The Type 'A' uncertainty parameters were evaluated from the MEMS sensor's measurements, while Type 'B' uncertainties were evaluated based on information provided by the manufacturer for the MEMS sensor. For a set of n measurements from the sensor an output y based on inputs $x_1; x_2 ; \ldots; x_n$, where $y = f(x_1; x_2 ; \ldots; x_n)$, the mean of measured values, $\bar{x}$ and standard deviation, $s(\bar{x})$, of a randomly varying input quantity, x can be shown as:-

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \; ; \; s(\bar{x}) = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2} \; ; \; u(x) = \frac{s(\bar{x})}{\sqrt{n}}$$

Where estimate of uncertainty according to GUM is $u(x)$. From Table 1, a baseline expanded uncertainty of U_{MEMS} = ±6.36E-02 g or 1.55 % was computed for a confidence interval of 95 % (k=2), when the MEMS sensor operated in a nominal range of ±2.048 g.

3.3. Measurement uncertainty based on MCM

Alternatively, the evaluation of measurement uncertainty for MEMS sensor was also done by applying MCM through propagating probability distributions $g(x_1; x_2 ; \ldots; x_n)$. The estimate of sensor output uncertainty $g(y)$ was obtained according to mathematical model outlined in Section 3.1. A key factor for correctly estimating the uncertainty through MCM is setting the value of M, the number of Monte Carlo trials. For this work $M = 10^6$ was chosen in MATLAB for numerical implementation of MCM. Based on the Monte Carlo Method (MCM) the uncertainty in MEMS sensor was estimated to be ±6.07E-02 g or 1.48 %. for a confidence interval of 95 %. The results from the GUM and MCM are shown in Figure 5. The results from both evaluation methods are in agreement with each other, while it can be seen that GUM overestimates the measurement uncertainty by 0.07 % as compared to MCM.

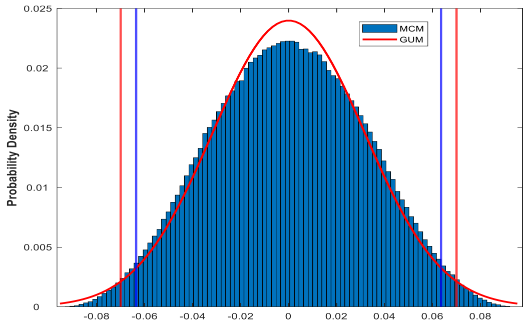

Figure 5 Probability Distribution of Uncertainty: GUM vs MCM

4. Results and discussion

The determination of measurement uncertainty in static conditions for MEMS sensor has been explained in detail in sections 3.2 and 3.3 of the paper and the results are reported in Table 1 and Figure 5. These methods for uncertainty evaluation for MEMS vibration sensor were extended to evaluate the dynamic uncertainty as well. The summary of results for expanded dynamic uncertainty in the range 5 Hz to 1 kHz for a confidence interval of 95 % are tabulated in Table 2 along with actual vibration measurement amplitudes for the IEPE and MEMS sensors. Obtaining the repeatability for dynamic tests of MEMS in comparison to the traditional IEPE sensor was not trivial in nature. The issue was resolved by computing the difference between root mean square error (RMSE) of the sinusoidal variations in accelerations sensed by the two sensors. As any sensing errors should result in dynamic variability of recorded sine waves while comparing the results from IEPE and MEMS sensors. The uncertainty values for MEMS sensors range from 1.55 % to 19.83 %. Upon investigation the high value uncertainty at 900 Hz and 1000 Hz was attributed to sampling limitations of MEMS sensor-setup limiting its performance to 855 Hz. Therefore, the effective expanded uncertainty for MEMS sensor ranges from 1.55 % to 11.38 % at dynamic test conditions for a confidence interval of 95 %.

5. Conclusion

This work focuses on uncertainty evaluation of low-cost MEMS sensors for use in industrial manufacturing scenarios. The uncertainty evaluation was done in accordance with JGCM 100:2008 and JGCM 101:2008 through performing static and dynamic traceability tests through comparison to a reference transducer (IEPE). The expanded uncertainty for digital MEMS accelerometers was evaluated to be 1.48 % at static test conditions while it was evaluated to be in the range of 1.55 % to 11.38 % for dynamic test conditions for a confidence interval of 95 %. The work also identifies the main aspects which contribute to measurement uncertainty and proposes an improved setup to the mitigate its effects in such low-cost vibration sensors offering a viable implementation for precision manufacturing applications. Future work requires validation of MEMS sensors through applications on machine tools and comparison of results from laser Interferometry. Such tri-axial MEMS vibration sensors provide exciting opportunities in application areas of Industry 4.0 due to their low-cost and digitalization aspects. The knowledge of residual errors in MEMS can lead to building an on-line self-calibration setup in sensor-nets. Such advantages further widen the scope of the applications of MEMS sensors in industries in applications such as Servitization, condition monitoring, prognostics, and smart machining.

Table 2 Summary of Dynamic Uncertainty Budgets

S No	Excitation Frequency (Hz)	Vib Amp IEPE (g)	Vib Amp MEMS (g)	Expanded Uncertainty (g) U_{MEMS}	Relative Uncertainty (%)
1	5	0.072	0.071	6.44E-02	1.57
2	10	0.229	0.227	1.02E-01	2.49
3	25	0.765	0.741	6.98E-02	1.70
4	50	1.143	0.973	6.36E-02	1.55
5	75	1.556	1.355	6.59E-02	1.61
6	100	1.503	1.067	6.46E-02	1.58
7	200	1.220	0.808	9.40E-02	2.29
8	300	1.183	0.690	7.25E-02	1.77
9	400	1.543	0.724	1.64E-01	4.02
10	500	1.086	0.757	4.66E-01	11.38
11	600	1.168	0.613	3.57E-01	8.72
12	700	1.258	0.490	1.58E-01	3.87
13	800	1.450	0.323	9.88E-02	2.41
14	900	1.304	0.433	4.11E-01	10.03
15	1000	1.432	0.407	8.12E-01	19.83

Acknowledgements

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