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Metrological evaluation of Integrated Electronics Piezo-Electric Accelerometer measurement chains in industrial applications: Modelling and characterisation of noise

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Abstract

Integrated Electronics Piezo-Electric (IEPE) accelerometers are widely used for vibration monitoring in industrial manufacturing applications due to their linearity, dynamic range, and robustness. However, the accuracy of the vibration data using such sensors can be limited by noise sources within the measurement chain. This paper experimentally characterizes the noise parameters of IEPE accelerometers to improve measurement uncertainty. The metrological traceability of the IEPE sensor to a laser interferometer standard is established according to the ISO 16063-11. Sources of electronic, mechanical, and environmental noise, both internal and external to the accelerometer, are quantified through a series of static and dynamic tests. Noise modelling techniques are presented to optimize sensor configuration, cabling, and data acquisition parameters based on the target frequency range and environment. This work provides a rigorous metrology approach for industrial users for effective application of IEPE accelerometers considering a more robust approach towards their calibration, incorporating factors of noise. It is anticipated that the outcomes from this approach will further support traceable, and low-uncertainty vibration monitoring to enhance process control and machining accuracy.

Industrial Metrology, Measuring Instruments, Noise Estimation, Accelerometers, Calibration

1. Introduction

Mechanical error sources in precision engineering can have an impact on the machined part, the machine itself, or the manufacturing process [1]. Such errors in machine tools must be prevented or mitigated in order to ensure machine tool accuracy. Unwanted vibration is one of the major sources of dynamic errors in machine tools. Therefore, in order to ensure the accuracy of the machine tool, the vibrations must be measured, classified, and minimised in order to prevent their undesirable effect on the manufactured part [1].

Transformation driven by Industry 4.0 in the area of machine tool metrology, emphasizes the need for the optimization of manufacturing processes while focusing on high-end manufacturing [2]. To accomplish this, it is necessary to monitor vibration parameters, tool cutting speeds, high spindle rotation frequencies, and feed rates. As a result, vibration sensors are widely used in industry to monitor vibrations, such as to monitor and protect CNC machines throughout the manufacturing process. This is made possible through correlation of observed vibration and common wear-out mechanisms such bearings, gears, chains, belts, brushes, shafts, coils, and machine tools [3-5]. Such sensing mechanisms also permit recognition of chatter or self-excited vibrations in machine tools, which can be detrimental to the manufacturing process as it can lead to undesirable outcomes such as dimensional errors, poor surface finish, tool wear, and, if not immediately identified, potential machine damage [6].

Accelerometers are one of the most commonly used vibration sensors to make quantifiable measurements of vibration and shock [7]. Other sensors employed for vibration include velocity transducers, non-contact displacement transducers (NCDT), and laser doppler vibrometers (LDV). Incorporation of such vibration sensors, especially in the case of precision manufacturing, requires a high level of engineering confidence in the ability of the sensor to reliably detect and process excitation characteristics.

Integrated Electronics Piezo-Electric (IEPE) are the most popular class of accelerometers that have been traditionally employed for high-precision industrial manufacturing applications. Their response is characterised by a wide dynamic bandwidth and sharp frequency response, which provides an accurate time domain and spectral analysis. However, they have IEPE, has inherent technical limitations [8] such as source impedance and noise issues [9] which requires placement of sensors close to source of vibration, in addition to their high cost and setup requirements (data acquisition systems and cabling). They also suffer from frequency dependent noise performance and response saturation when subjected to shock or impact vibrations.

Therefore, in order to accurately sense vibrations on machine tools, an objective evaluation of errors and noise in vibration sensors should enable the development of a control model for reducing residual uncertainty. According to ISO 2954:2012 [10] which stipulates the requirements measuring vibration on machinery , sensors require evaluation of sensor parameters including sensitivity, frequency range , bandwidth, resolution of complete vibration measurement system (transducer, acquisition system and cabling) along with compliance with specified uncertainty limits.

Previous work has been performed for the characterization of baseline errors [11] and uncertainties in vibration sensors [12]. It was demonstrated that all sensor measurements have an associated level of uncertainty and noise [13], which can be attributed to systematic and random errors.

This paper experimentally characterizes the noise parameters of IEPE accelerometer measurement chains. The metrological traceability of the IEPE sensor to a laser interferometer standard is established according to the ISO 16063-11 [14]. Sources of electronic, mechanical, and environmental noise, both internal and external to the accelerometer, are quantified through a series of tests. Noise modelling techniques are presented to optimize sensor configuration, cabling, and data acquisition parameters based on the target frequency range and environment. This work provides a rigorous metrology approach for industrial users for effective application of IEPE accelerometers considering a more robust approach towards their calibration, incorporating factors of noise.

2. Noise in IEPE Accelerometer Measurement Chains

IEPE accelerometers are often considered the state of the art for usage in most industrial and engineering applications due to their ease of use, tri-axial capabilities, high precision, excellent linearity over their dynamic range, and wide frequency range (<10 Hz to 10000 Hz) [15]. The internal signal conditioning unit of the IEPE accelerometer enables for the use of regular co-axial cable over extended distances with negligible deterioration for any acquisition equipment. Few drawbacks which may limit their application includes maximum operating temperature due to internal circuitry, poor DC response due to low frequency roll-off, amplification at resonance, and saturation of the internal charge amplifier [16].

In instrumentation and sensors, noise, comprising intrinsic and extrinsic elements, remains a challenging and expanding area requiring ongoing research. In measurements, it is defined as any undesired signal in the sensor output (Figure 1).

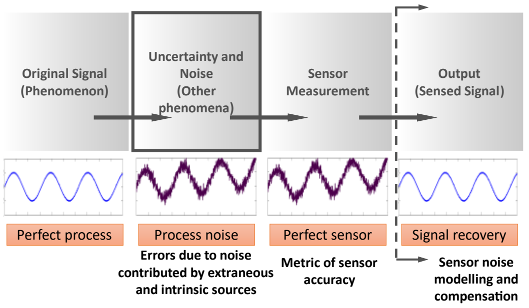

Figure 1. Vibration signal measurements subject to noise

While sensor calibration minimizes systematic errors, intrinsic noise persists post-calibration due to the complex nature of measurement systems. Comprising components such a sensing elements, pre-amplifiers, cabling, and a data acquisition systems, in the sensor measurement chain also exhibit an inherent noise. Mathematically it can also be shown that for the accelerometer output ($x_{meas}(t)$) is actually sum of actual signal of vibration ($a_{true}(t)$) and noise ($n(t)$), as shown in equation below

$$x_{meas}(t) = a_{true}(t) + n(t) \quad (1)$$

This emphasizes the necessity for probing into the noise within IEPE measurement chains utilized in precision manufacturing setups, as it plays a crucial role in maintaining stringent tolerances of machine product. The study identifies and models noise in industrial vibration sensors, specifically focusing on fundamental noise sources intrinsic to IEPE measurement chains, which are pivotal for expected instrument performance in metrological applications.

2.1. Characterisation of Noise in Accelerometer Measurements

Noise in accelerometer measurements $x_{meas}(t)$ or simply $x(t)$ can be characterised by modelling it as a stochastic process and analysing it using techniques like Power Spectral Density (PSD), Auto-Correlation Function (ACF) and so on. Within the scope of this work, noise is assumed to be additive (Equation 1). In such cases, noise in vibration sensors is often modelled as white noise to aid analysis, representing additive noise in sensor readings. The resultant sum of all noise sources represented by the noise (stochastic) model is denoted by $n(t)$.

The auto-correlation function of vibration signal $x(t)$ commonly used to assess self-similarity, serves as a valuable tool for noise analysis, representing the correlation of the signal with a time-delayed or noise-corrupted version of itself, $x(t-\tau)$. Assuming stationary ergodic noise affects the vibration sensor readings, the autocorrelation of $x(t)$ mathematically is expressed as Equation 2, where T is the time duration of sensor measurements for $x(t)$ and $\tau = t_1 - t_2$, the time delay between measurements taken at time instance t_1 and t_2.

$$\phi_{xx}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} x(t+\tau)x(t)dt \quad (2)$$

The Power Spectral Density (PSD) $S_x(f)$ of a vibration signal $x(t)$ can be defined as Fourier transform of its Auto-correlation Function (ACF) $\phi_{xx}(\tau)$. Mathematically the PSD [17, 18] can be shown be as. Where f is the frequency in Hz and $i = \sqrt{-1}$.

$$S_x(f) = \int_{-\infty}^{+\infty} \phi_{xx}(\tau)e^{-2\pi i f\tau}d\tau, -\infty < f < \infty \quad (3)$$

In vibration measurements PSD has units of $g/\sqrt{Hz}$. For noise estimation it signifies the spread of noise over the frequency bandwidth f_{BW} of the signal. Thereby by definition mathematically Equation 3, can be manipulated to estimate the total and average noise power (Equation 3) in sensor measurements recorded over time T.

$$S_x(f) = \frac{1}{2T}|X(f)|^2 \quad (4)$$

Where $X(f)$ is the Fourier transform of accelerometer measurements represented by $x(t)$. The RMS noise in sensors with bandwidth $f_{BW} = f_2 - f_1$ is more practical to compute using Equation 5 and has units of μg.

$$RMS\ noise\ f_1 to\ f_2 = \sqrt{\int_{f_1}^{f_2} PSD(f)df}\ \mu g \quad (5)$$

2.2. Sources of Noise in IEPE Measurement Chains

During the design of an accelerometer, trade-offs must be considered between small size and weight in comparison to low-noise and output sensitivity [19]. For IEPE accelerometers,multiple noise sources exist within the acceleration chain. However, this discussion would be limited to noise generated by the sensor's electrical and mechanical components, the amplifier, and cables, excluding sources such as ground loops, etc. [20]. This section provides a concise overview of noise sources and contributions in IEPE accelerometer measurement chains [21] to educate the reader.

The sources of noise in an IEPE accelerometer measurement chains can be broken down in terms of mechanical-thermal noise (a_{nm}) and electrical-thermal noise (a_{ne}). Noise estimates are typically presented in terms of the Power Spectral Density (PSD) of a sensor whose units are ($g/\sqrt{Hz}$). The noise spectral density P_{sD} for IEPE can be represented by Equation 6 [19].

$$P_{sD} = \sqrt{a_{nm}^2 + a_{ne}^2} \quad (6)$$

Previous experimental findings reveal that mechanical-thermal noise (a_{nm}) is significantly less than the electrical-thermal noise (a_{ne}) contribution across the entire frequency range [19]. However, it is crucial to note that mechanical-thermal noise dominates electrical-thermal noise above 10 kHz [9, 21]. To mitigate mechanical-thermal noise in a sensor due to mass-spring constant and mechanical resistance, steps include increasing mass and quality factor or decreasing resonant frequency during sensor fabrication. Effect of contributions from 1/f or pink noise and gate circuit shot noise are considered insignificant in IEPE sensors.

Electrical-thermal noise is an additional noise component from internal or external electronics in the measurement chain [21]. The accelerometer's noise source is influenced by the sensor material, where selecting materials with fewer defects and impurities can mitigate noise. Introducing capacitance to the system can lead to increased losses and subsequent electrical noise, predominantly noticeable at frequencies below 10 kHz [9, 19]. Modern accelerometers, designed with integrated electronics, strategically reduce the distance between the sensor and the charge amplifier, minimizing capacitance in the chain—a significant noise source—thus enhancing the Signal-to-Noise Ratio (SNR) [20].

3. Methodology

In this study, a mathematical analysis of sensor readings from the IEPE measurement chain is conducted to determine the contributions of various types of noise and random effects to sensor measurements. The noise parameters are modeled during measurements at a location with low vibration levels and minimal background noise influence. Prior to data collection, measures are taken to minimize temperature variations during tests, as these can impact the stochastic characteristics of noise parameters in vibration sensors.

To estimate and characterize noise in accelerometers, tests are conducted in accordance with the ISO 16063-11:1999 standard [14], ensuring traceability by comparing results to a reference laser interferometer in static conditions. A continuous long-term static test lasting approximately 60 hours is performed in a vibration-isolated and temperature-controlled environment to characterize and quantify different noise error terms in the sensor. The subsequent section details the experimental setup for metrological noise estimation.

3.1. Experimental Setup

An industrial grade tri-axial IEPE accelerometer (PCB 356A02) [22] was chosen to model noise parameters in industrial measurement chains. A Renishaw XL-80 laser interferometer [23] served as a traceable reference in acceleration measurement for setup benchmarking. The sensors were mounted on a 110 mm x 80 mm x 5 mm aluminum plate using bolts, and adhesive clamps secured the sensor cables to minimize unwanted vibrations. Digital temperature sensors (Maxim DS18B20) on the sensor plate and at a 25 cm distance recorded temperature variations throughout the test duration.

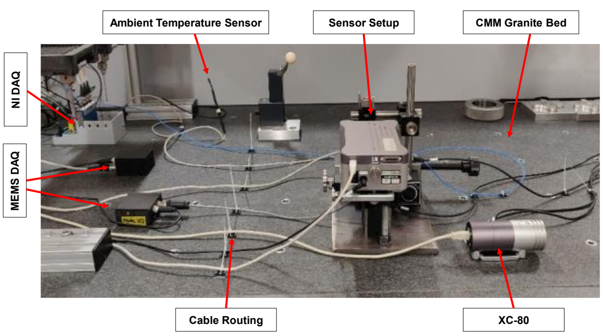

Figure 2. Experimental Setup for IEPE Noise Estimation on CMM Bed

The experimental setup, depicted in Figure 2, prioritized characterizing and modeling the noise parameters of vibration sensors within a vibration-isolated and thermally stable environment. Therefore, the test was conducted in a temperature-controlled environment of $\pm 1\ °C$ on a vibration-isolated, stable granite bed of the Zeiss Prismo Coordinate Measuring Machine (CMM). Furthermore, to minimize background noise contribution to the sensor from external sources such as opening and closing doors, movement of people, and so on, the tests were conducted over the weekend.

For accurate noise floor modelling,the IEPE sensor operated within its nominal operating range of $50\ g$. with a sampling rate set at $2000\ Hz$. The setup's vibrational stability, benchmarked at $0.316\ \mu g$ using the laser interferometer, was maintained in a temperature-controlled room to prevent environmental-induced bias in process noise characterization. Recorded temperatures indicated a stable sensor setup temperature of $18.83\ °C \pm 0.36\ °C$, with the ambient room temperature at $18.46\ °C \pm 0.85\ °C$.

4. Result and discussion

In the current research project, the noise contribution from various sources within the equipment and measurement chain of IEPE accelerometers was estimated. The measurement chain consists of a tri-axial PCB356A02 IEPE accelerometer [22] with a nominal sensitivity of $S = 10\ mV/g$, a 10 feet long low-noise coaxial cable, National Instruments NI-9234 Sound and Vibration module [24] and NI cDAQ-9174 four slot chassis [25]. While operating the equipment with a sampling rate of 2000 Hz the NI-9234 acquisition module contributes noise of $25\ \mu V_{rms}$ or a noise density of $780 nV/\sqrt{Hz}$ to sensor outputs. This converts to a contribution of $2.5\ mg$ noise contribution to sensor readings over the bandwidth due to acquisition module.

Similarly, the vendor for IEPE has specified the noise density values for the sensor in its datasheet. A comparison of theoretical versus experimental values for IEPE sensor was conducted. The noise density values were computed using Power Spectral Density (PSD) as visualized in Figure 3. The results are tabulated in Table 1. Using values in Table 1, the noise contribution to sensor measurements can be computed based on the bandwidth of sensor. For example, for a bandwidth $P_f = 100\ Hz$, the noise contribution in Z-axis can be computed as $30\ \mu g/\sqrt{Hz} \times \sqrt{100\ Hz}\ \ = 0.3\ mg$. Where $P_f = f_2 - f_1$ and f_2 and f_1 are upper and lower frequency limits for vibration measurement. Similarly, the values can be computed for any specified bandwidths from the PSD plots (Figure 3) of sensor as well.

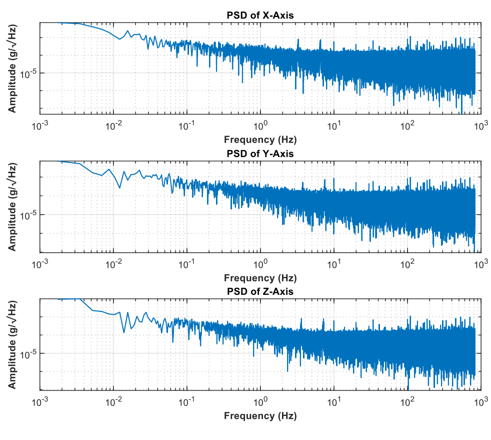

Figure 3. IEPE Measurement Chain Noise Density Estimation via PSD

3.1. Reducing Noise in IEPE Measurement Chains

The discussion on noise in IEPE measurements has predominantly focused on manufacturing and design aspects within controlled testing setups. However, users of the equipment play a crucial role in ensuring a noise-free sensor output, particularly in industrial setups.

Table 1 IEPE Measurement Chain Noise Density Estimation Results

S No	Frequency Bandwidth (Hz)	Experimentally Estimated Noise ($\mu g/\sqrt{Hz}$)			Theoretical [22]
		X-Axis	Y-Axis	Z-Axis	
1	1	211	112	167	150
2	10	112	62	45	25
3	100	16	76	30	10
4	825.80	39	62	72	4.12
5	1000	32	57	52	$5\ \mu g$

Reducing the noise floor involves key considerations such as minimizing sensor cable length to mitigate noise addition, as cables act like capacitors and longer lengths contribute to increased noise for example an AWG 24 will typically have a nominal capacitance of 35 pF/ft. While IEPE accelerometers typically use low-impedance co-axial cables to minimize noise pick-up, longer co-axial cables can inadvertently function as antennas, introducing higher noise levels. The choice of cabling fixtures is vital to prevent cable motion-induced self-generated noise (Triboelectric effect), and shielded, clean, and dry cable connectors are essential for precision measurements.

Another critical aspect is the selection of amplifiers, data acquisition, and power sources for lower noise acceleration signals. Experimental evaluations highlight the potential contribution of noise from these components to the vibration measurement chain. Users must be mindful of the equipment characteristics, as any noise generated can impact the accelerometer's output signal [21].

5. Conclusion

This paper presented a metrological approach for characterizing and modeling the noise parameters of IEPE accelerometers used in industrial vibration monitoring applications. Through experimental testing, the noise floor of a representative tri-axial IEPE accelerometer was quantified and sources of electronic, mechanical, and environmental noise were identified.

The metrological traceability of the IEPE sensor to a laser interferometer standard was established per ISO 16063-11 to benchmark the test setup. The result signify that noise density values computed from the power spectral density of the sensor outputs aligned closely with theoretical values from the sensor datasheet. For example the 100 Hz bandwidth, noise contribution was estimated to be 0.3 mg in the Z-axis. From the presented results specific values for designated bandwidths can also be computed as demonstrated.

In addition to quantifying the intrinsic sensor noise, techniques were presented to optimize the sensor configuration, cabling, and data acquisition parameters based on target frequency range and ambient conditions. This enables industrial users to make informed sensor deployment choices to minimize extrinsic noise pickup.

The rigorous noise characterization and modelling methodology provides improved understanding of uncertainty contributors in IEPE accelerometer measurements. By considering both intrinsic and extrinsic noise factors, the metrological reliability of vibration monitoring systems can be enhanced. This will in turn support precision manufacturing through traceable, low-uncertainty measurements for predictive maintenance and process control.

As Industry 4.0 brings tighter manufacturing tolerances and increased reliance on sensor feedback, the measurement uncertainty insights from this work will be key to unlocking the value of vibrational signatures. Further research can expand the noise model to additional sensor types leveraged in smart factory initiatives. Wider adoption of this metrological approach will aid in leveraging IEPE accelerometers and other integrated vibration sensors for preventive maintenance and optimized machining accuracy. Overall, the quantitative noise insights obtained will aid industrial adoption of next-generation sensing for quality and productivity gains.

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