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Benchmarking of a Cost-effective Micro-Interferometer for Remote Vibration Monitoring

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Abstract. A low-cost and low-size interferometer, based on self-mixing interferometry, has been developed for replacing standard accelerometers. The structure of the micro-interferometer is described in detail, and its measurement performances are evaluated with particular reference to preventive diagnosis of mechanical systems. For this purpose, a test bench equipped with accelerometers was used, on which intact or damaged ball bearings can be mounted. In the experimental tests carried out, the micro-interferometer showed significantly superior performance to accelerometers in reporting faulty behaviour of the mechanical structure.

1. Introduction

Vibration-based fault diagnosis is fundamental to condition monitoring in rotating machinery and other mechanical systems. In industrial settings, piezoelectric accelerometers are the predominant vibration sensors because of their high accuracy, broad frequency bandwidth, and ease of integration into automated monitoring systems [1]. Their reliability and straightforward signal processing have enabled successful deployment across a spectrum of applications, from traditional subtractive manufacturing to modern additive manufacturing systems [2-5]. Vibration analysis using accelerometer data is effective for detecting faults such as imbalances, misalignments, bearing defects, and gear damage, establishing it as a key technique in predictive maintenance programs. Despite their widespread use, contact-based accelerometers have inherent limitations. Mounting an accelerometer is not always feasible due to restricted access, particularly in high-speed rotating or thermally sensitive components, or when the sensor's mass affects the dynamics of lightweight structures. Optical interferometry, and specifically self-mixing interferometry (SMI) as presented in this paper, addresses these challenges by retrieving vibration displacement signals with a compact and cost-effective approach. Unlike conventional laser Doppler vibrometers or Mach–Zehnder interferometers, SMI does not require external mirrors or beam splitters, as interferometric mixing occurs internally. This design minimizes the number of optical components and results in a highly compact sensor suitable for different applications ranging from displacement measurements [6-9], microscale-flow sensing [10-14], optical vibrometers and absolute distance sensors in addition to diagnosis applications [15-21]. Furthermore, SMI-based sensors are inherently non-invasive and can operate at substantial stand-off distances without special target preparation [22]. These characteristics make SMI particularly suitable for monitoring vibrating or enclosed parts where traditional accelerometers are impractical. In this paper, we introduce a cost-effective SMI micro-interferometer and benchmark its performance against a standard piezoelectric accelerometer in a fault diagnosis application. The sensor employs a semiconductor laser diode aimed at the vibrating target, with the self-mixing interference signal extracted via the laser's internal photodiode. The micro-interferometer is assembled from off-the-shelf components with minimal alignment, resulting in a device that is both inexpensive and compact compared to conventional laser vibrometers. We assess the micro-interferometer's capability for preventive fault detection by testing it on a rotating machine ISE OneX test bench. Due to its high displacement sensitivity and wide dynamic range, the SMI micro-interferometer detects characteristic vibration signatures of bearing defects more prominently than accelerometers under identical conditions. The experimental results demonstrate that the proposed low-cost SMI sensor achieves superior fault indication performance without requiring contact or precise mounting. The remainder of the paper is structured as follows: Section 2 details the design of the micro-interferometer, including its circuitry; Section 3 discusses its experimental performance in failure detection; and Section 4 presents the conclusion and outlines future work.

2. Self-Mixing Micro-Interferometer

Self-mixing interferometry is based on measuring the disturbance a laser diode experiences when a small fraction of the emitted power is back-reflected into the cavity [23][24]. This disturbance induces coherent modulation of the laser emission, resulting in amplitude (AM) and frequency (FM) modulation. Frequency modulation is much more sensitive than amplitude modulation [25-27], but requires a more complex optical structure, which cannot be achieved at very low cost. In contrast, AM modulation can be read by a simple monitor photodiode, or even directly by measuring the laser supply voltage, but with a worse signal-to-noise ratio [28]. Another possibility is to implement a sort of balanced detection to improve to SNR [29][30], but it also required a more complex structure. The basic structure of a self-mixing interferometer is shown in Figure 1: the power emitted by the laser is focused (or collimated) on the target and a small fraction reflected back is allowed to re-enter the laser cavity.

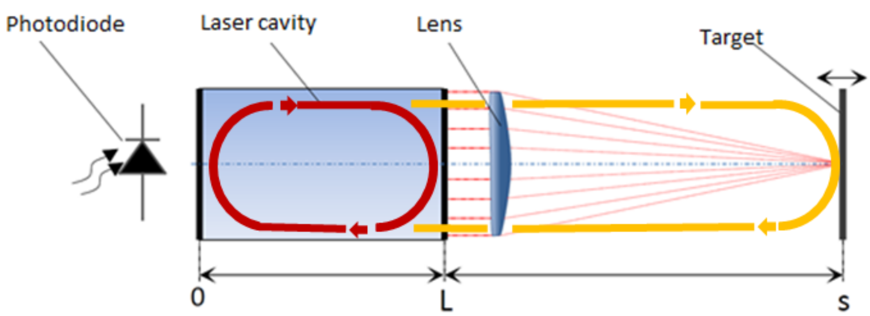

Figure 1. Structure of a simple self-mixing interferometer.

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Considering a small plastic lens (diameter and focal length of a few millimetres) that focuses the laser on a metal target a few centimetres away, a back-reflection of approximately 10^{-5}-10^{-6} in power is obtained [31]. This level of optical back-injection is sufficient to obtain a good self-mixing signal, measurable by the reflection coefficient C [28]. For C>1 the interferometric signal is distorted and takes on a sawtooth shape, periodic with a period of half a wavelength, and with good linearity with the displacement within the single fringe. This paper assesses the metrological performance of the proposed micro-interferometer using a distributed-feedback (DFB) laser diode ML720J11S with a wavelength (λ) of 1310nm and an output power of 5mW. Figure 2 shows the schematic of the laser's DC power supply circuit. The electronic circuitry for driving and reading the signal is kept to a minimum to reduce system size and cost. Figure 3 shows the schematic of the transimpedance circuit for reading the laser's monitor photodiode current. Note how the current is AC-coupled to best amplify the self-mixing signal, which consists of a small modulation of the emitted power (typically less than 1%).

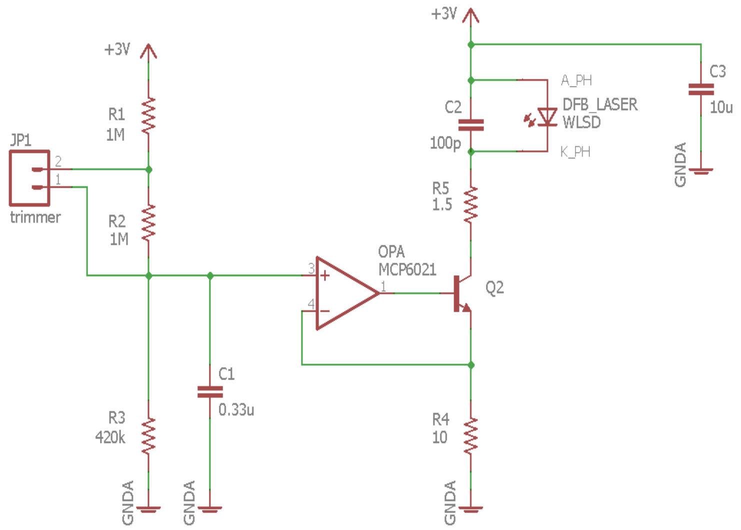

Figure 2. Schematic of the laser supply.

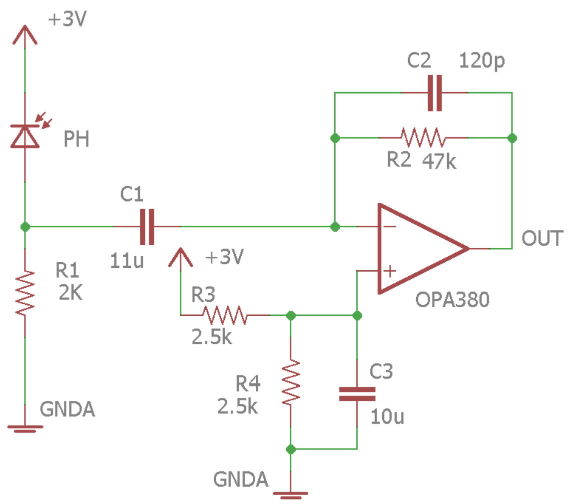

Figure 3. Schematic of the AC-coupled trans-impedance amplifier.

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3. Performance measurement in failure detection

The micro-interferometer is used to detect vibration of a rotating machine, together with an accelerometer. The two sensing systems are deployed simultaneously on a bearing fault simulation test bench to monitor vibration signatures arising from an outer ring defect. Figure 4 shows the experimental setup to measure the vibration using the proposed self-mixing vibrometer and accelerometer under a faulty bearing using the ISE OneX test bench. As shown in figure 4, the test bench is equipped with different sensors. For vibration analysis, an axial sensor from PCB PIEZOELECTRONICS with a sensitivity of 100 mV/g is used on the bearing's 3 housing.

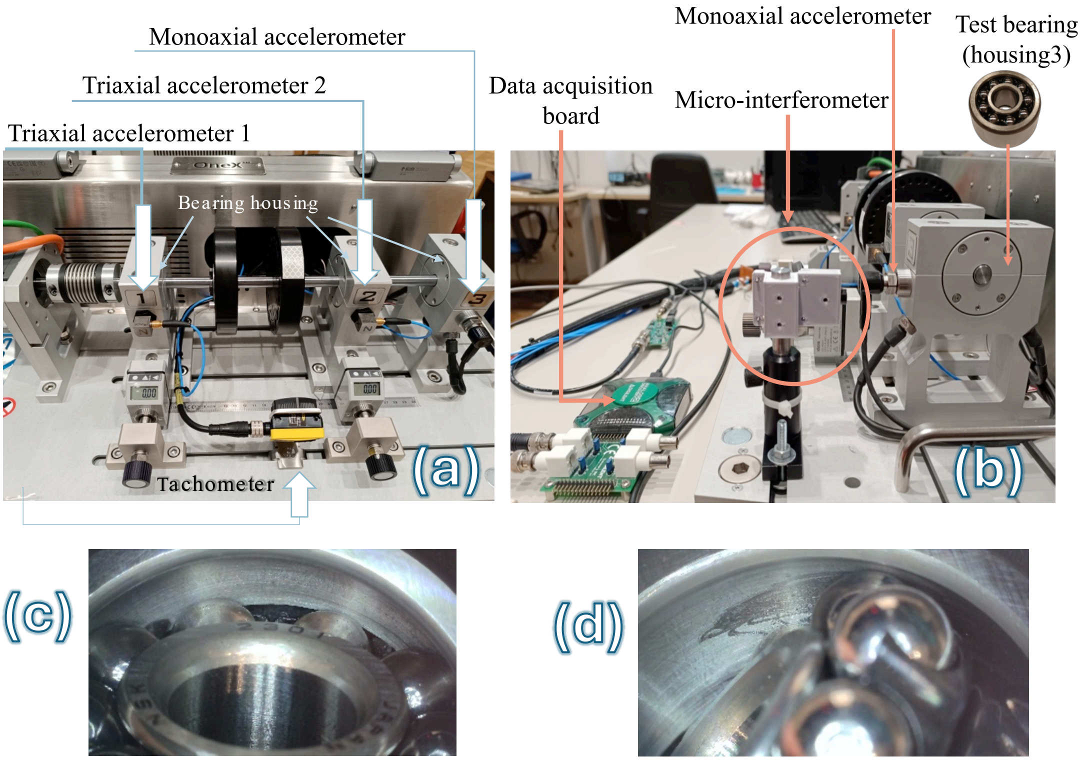

Figure 4. ISE OneX test bench platform for evaluating the performance of rotating machines under different conditions (a). Micro-interferometer setup (b), Example of healthy test bearing presented in housing 3(c), Example of faulty bearing with distributed fault on outer race presented in housing 3(d).

DIGILENT-Analog Discovery 2 (AD2) is utilized as a data acquisition (DAQ) board, as shown in Figure 4b, including two analog inputs capable of acquiring analog signals with an analog bandwidth of up to 30 MHz using two synchronous ADCs at 100 MSPS with 14-bit resolution.

Figure 5 shows the comparison between the output signal acquired at 500 kHz for 2s for healthy and faulty bearings with an outer ring defect. As expected, for early fault diagnosis and therefore less impulsive response and distributed faults, accelerometers may struggle to provide valuable insights as shown in figure 5a. In contrast, the micro-interferometer shows periodic behaviour with good enough sensitivity for a faulty bearing (figure 5b). The presented defect on the outer race causes the observed abrupt transitions in acquired interferometric signal, known as fringe jumps. These jumps occur when the amplitude of the displacement surpasses $\lambda/2$

considering high optical feedback (C >1). These results substantiate the sensor's capability to serve as a compact and low-cost optical alternative to conventional contact-based sensors,

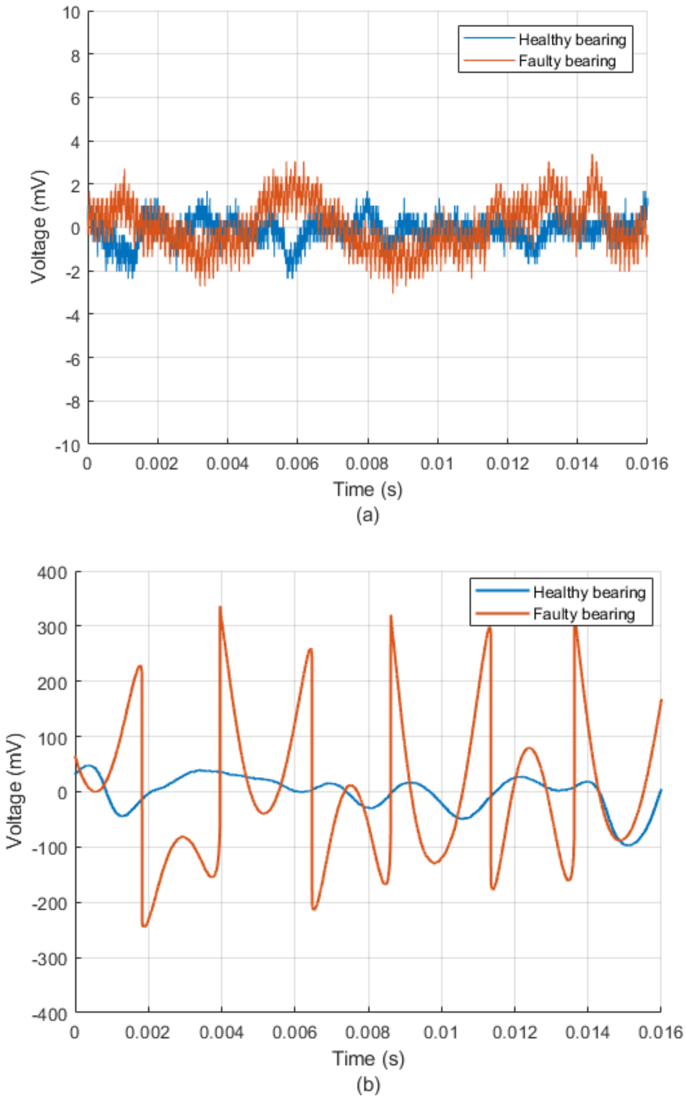

Figure 5. Comparison between the measurement system response for healthy and faulty test bearing, (a) accelerometer, (b) micro-interferometer.

offering comparable accuracy in vibration diagnostics while maintaining the advantages of non-contact operation and simplified instrumentation, including more advanced techniques.

4. Conclusion

This paper presents the benchmarking of a cost-effective micro-interferometer utilizing SMI for remote vibration monitoring and fault diagnosis in rotating machinery. The system, constructed from commercially available components, demonstrates that a minimal optical and electronic configuration can provide metrologically significant vibration measurements with high displacement sensitivity. The experimentally observed fringe jumps in the interferometric signal effectively captured the onset and periodicity of outer race defects, validating the sensor's capability to detect incipient faults non-invasively. Compared to conventional accelerometers, the SMI sensor offers distinct advantages, including non-contact operation, immunity to mass loading effects, simplified mounting, and suitability for measurements in restricted or low-speed environments.

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