Low-cost and Low-Size Interferometer for Accelerometers Replacement

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Abstract — This paper presents the development and characterization of a self-mixing interferometer, especially designed to replace normal accelerometers, used for measuring vibrations to detect defects or malfunctions. The sensor's design emphasizes minimal footprint with a straightforward baseband signal decoding enabled by the intrinsic distortion in the SMI waveform, resulting in vibration measurement of the target, with a resolution better than 10 nm. Experimental validation on the ISE OneX test bench, equipped with a commercial axial accelerometer and fault-simulated bearings, demonstrates that the SMI system delivers a signal-to-noise ratio and sensitivity at least two orders of magnitude higher than the accelerometer, particularly in the low-frequency range. These results confirm the potential of the proposed interferometer as a high-performance, contactless solution for industrial condition monitoring and its suitability for integration into advanced diagnostic platforms.

***Keywords*:** Interferometry, Vibration Measurement, Fault Detection, Measurement and Diagnostic, Contactless Sensor.

1. INTRODUCTION

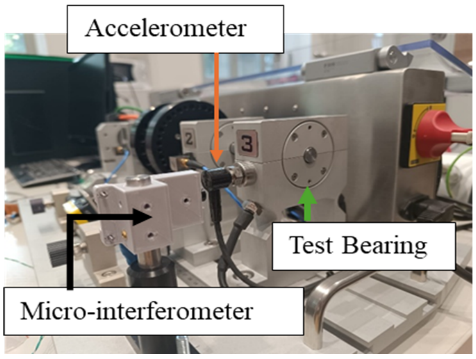
Condition monitoring in rotating machinery often relies on vibration measurement for fault diagnosis [1]. The most widely adopted sensors in industrial practice are piezoelectric accelerometers. They are low-cost, compact, and offer high bandwidth, good sensitivity, and ease of integration into various monitoring systems. The main limitation of the accelerometer is its requirement for stable contact with the surface under inspection. Another limitation is its response at low frequencies, which is very restricted since the sensors provide a signal proportional to the acceleration, which increases quadratically with the frequency for the same vibration amplitude. In contrast, the self-mixing interferometer (SMI) directly measures displacement, maintaining high sensitivity and a superior signal-to-noise ratio in the low-frequency range. Such enhanced performance is crucial for early fault detection, where weak vibrational signatures often precede major failures. This capability is particularly valuable in applications requiring high reliability and uptime, such as CNC machining and tool wear monitoring in smart manufacturing, as well as structural vibration analysis in precision robotics [2-4]. This paper presents the development and characterization of a self-mixing interferometer specifically designed to replace standard accelerometers used for measuring vibrations to detect defects or malfunctions. Following its customized and compact design, the SMI signal is considered also in presence of sharp phase transitions, corresponding to displacement steps of $\lambda/2$. By detecting and compensating for these positive and negative steps, the signal is unwrapped into a continuous displacement trace [5].

2. Methods and Procedures

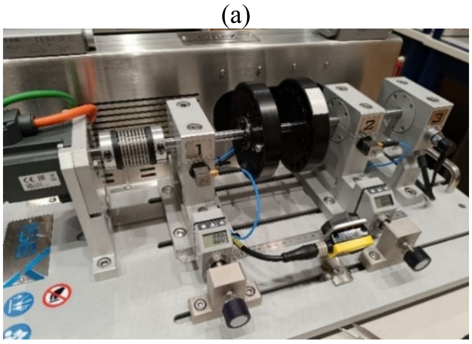
The self-mixing interferometry (SMI) technique is based on the small amplitude modulation that a laser source undergoes when subjected to optical back-reflection [6]. A laser diode (LD) focused through a low-cost plastic lens (typically with a focus length of about 6-8 mm and diameter M9x0.5) on a metallic target, placed at a few centimeters of distance, induces a back-reflection of about 10^{-4}-10^{-5} of the emitter power. This amount of back reflection is enough for a very good SMI signal, proportional to the back-injected field, therefore about 1% of the emitted power. With a careful design of the low-noise current generator to supply the LD, and of a dedicated trans-impedance amplifier, it is easy to reach a detection regime where the shot noise is the main limit. It corresponds to a Noise-Equivalent-Displacement (NED) of 5-10 pm/$\sqrt{\text{Hz}}$ [7] (about 1 nm on some tens of kilohertz). This limit can be further improved by a sort of optical balanced detection [8], by using the difference between the monitor photodiode and an external photodiode. The mechanical test bench is designed for analyzing different bearing faults and monitoring vibration signatures, for example, arising from a distributed outer ring defect. Considering that the accelerometer provides a signal proportional to the acceleration, while the interferometer measures the displacement, for the frequency range of interest, the interferometer sensitivity and, above all, its signal-to-noise ratio, are at least two orders of magnitude higher than those of the accelerometer. Indeed, the frequency range of interest for mechanical inspection and fault detection is normally below 1 kHz and, in any case, is always limited to a few kHz.

3. Results and Discussion

The measurement performances of the realized prototype are compared with the ones of a standard accelerometer: an axial sensor from PCB PIEZOELECTRONICS. The measurement campaign is taken using the ISE OneX test bench, which is equipped with different sensors such as thermometer and tachometer. Figure 1 shows an assembly of the prototype sensor mounted in front of the test bearing, equipped with the accelerometer in addition to the test bench. Figure 2 shows a direct comparison of the signals measured by the accelerometer and the micro-interferometer, in the two cases of healthy and faulty bearing (the test bearing is replaced with one damaged). As it is evident from the measurements, the accelerometer is limited in sensitivity and cannot detect properly the fault, while the interferometer shows an incomparable signal-to-noise ratio. To better explain the system, the signal in figure 2b is the native SMI signal and it does not include the unwrap elaboration: every sudden transition amplitude in the signal corresponds to half a wavelength. The transition amplitude is about 470 mV and corresponds to $\lambda/2$= 655 nm, therefore the sensor sensitivity is about 0.7 mV/nm.



(a)



(b)

Figure 1. Micro-interferometer setup (a), ISE OneX test bench platform for evaluating the performance of rotating machines under different conditions (b): the test bearing is damaged.

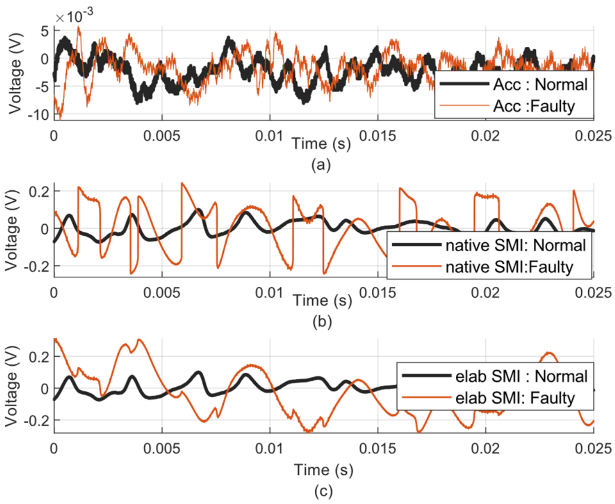


Figure 2. The comparison between the measurement system response for healthy and faulty test bearing, (a) accelerometer with sensitivity of 100 mV/g, (b) micro-interferometer with sensitivity of 0.7 mV/nm, (c) unwrapped SMI signal.

The developed prototype includes a self-calibration algorithm, elaborating further on the jumps in the signal and uses it to directly provide the measurement in nm. Figure 2c shows an example of an unwrapped SMI signal as pre-calibration step. As expected, fault-induced vibrations are clearly distinguishable from a healthy bearing behavior. The main limit in accuracy is the non-linearity of the interferometric fringes, inducing a distortion in the order of 10 nm on vibration with an amplitude higher than 655 nm.

4. CONCLUSIONS

Compared to traditional interferometers, SMI allows minimizing the optical components and not carrying out any mechanical or optical alignment procedure. Additionally, particular distortion of the SMI modulation signal allows a simple processing of the baseband signal, which provides the vibration measurement of the target, with a resolution better than 10 nm. On simulated bearing faults in a dedicated test bench, the developed micro-interferometer achieves significantly higher sensitivity and signal-to-noise ratio then standard accelerometers. These results substantiate the sensor’s capability to serve as a compact and low-cost optical alternative to conventional contact-based sensors, offering even better accuracy in vibration diagnostics, with also the advantages of contactless operation. The developed solution is adaptable for a number of cases of industrial inspection and can be integrated into more complex diagnostic systems.

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