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Calibration of a multicomponent MEMS sensor for vibration monitoring of rolling bearings: broad-band and amplitude traceability up to 20 kHz

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Abstract— **In the field of vibration monitoring and control, the use of low-cost multicomponent accelerometer sensors is nowadays increasingly widespread. Low-cost multicomponent sensors allow implementing monitoring systems and networks (even very extensive ones) supported by a very large number of sensors, with low management costs, low power consumption, light weight and small size. In many advanced engineering applications, such as defects prevention and malfunctioning of systems, smart industries development, automation and machine learning managing, it is often necessary to "densify" the spatial resolution of the surveys, to detect more in detail the occurring dynamic phenomena, under investigation. However, for the monitoring systems to provide trustworthy and actually meaningful data, the reliability of sensors is an essential requirement. As a consequence, traceable calibration methods for multicomponent accelerometer sensors, including the appropriate uncertainty evaluation, are necessary to guarantee the reliability in the frequency domain of data provided. Proper metrological characterizations and calibration of these sensors allows to define the reliability in terms of sensitivity, with respect to mechanical reference standards, traceable to SI units. At present, the sensitivity parameters provided by the manufacturers are not traceable and often referred to static conditions only: dynamic response, as a function of frequency, is often barely known or completely disregarded. In this paper, a dynamic calibration procedure is applied to provide the sensitivity parameters of a low-cost multicomponent accelerometer sensor prototype, designed, developed and realized at the University of Siena, conceived for rolling-bearings vibration monitoring, in a broad frequency domain, from 10 Hz up to 20 kHz. The calibration procedure is performed by comparison to a reference transducer (in analogy to ISO Standard 16063-21).**

Keywords— Multicomponent MEMS sensor, low-cost, traceability, broad-frequency band

I. INTRODUCTION

A reliable and traceable vibration monitoring system, based on calibrated multicomponent MEMS sensors, beyond its proper suitability in terms of low-cost, low power consumption and small pervasiveness, will provide trustworthy data of dynamic phenomena under investigation, with quantitative information of actual amplitude and frequency of involved oscillatory motions [1-9]. The determination of the sensors' sensitivity and the associated uncertainties, from metrological calibration methods against reference standards traceable to SI, allow to properly identify the precision (in terms of width of data dispersion, around the measured value) and the accuracy (in terms of closeness between the measured value and the actual physical magnitude of investigated phenomenon) of data provided in working conditions and survey [10-15], beyond to be a metrological need highlighted by BIPM [16].

The low-cost multicomponent MEMS accelerometer sensor investigated in this work, is conceived for vibration monitoring of rolling-bearings, over a broad frequency range, from 10 Hz up to 20 kHz. Nevertheless, as observed in previous works, the responsiveness of MEMS sensors is particularly effective and reliable in static conditions or in low/medium-frequency ranges [17,18]; at high frequency ranges, generally beyond 500 Hz, the sensitivity of the MEMS accelerometer sensor dramatically decreases [19]. Moreover, in 3-axis MEMS accelerometer sensors, the transverse sensitivities significantly increase as a function of frequency, showing values close to main sensitivities values, making detections inapplicable, beyond 1 or 2 kHz.

In order to monitor the functioning of rolling bearings in working conditions, it is necessary to accurately quantify vibrational fields in very high frequency ranges, namely beyond 1 kHz, up to 10 or 20 kHz. To achieve this performance by using a low-cost multicomponent accelerometer sensor, 3 separated uniaxial analogue sensing elements are orthogonally embedded in a resin case. The sensing elements are commercially available low-noise, high frequency uniaxial MEMS accelerometer, provided by Analogue Device Inc. (ADXL1005Z) [20]. The 3 sensing elements independently provide the response of the vibration, along 3 orthogonal axes, without cross-talk effects and transverse overlap. Although an accurate calibration statement of the ADXL1005Z individual MEMS sensor accelerometer was made available by the manufacturer, in this work the calibration of the whole assembled multicomponent MEMS accelerometer (realized by embedment of 3 sensing elements) is performed. The 3 main sensitivities, and related uncertainties, are referred to the so-built whole device.

II. THE MULTICOMPONENT MEMS SENSOR

The multicomponent MEMS sensor, realized at the University of Siena, and the individual low-noise, high frequency uniaxial MEMS accelerometer, provided by Analog Device Inc. (ADXL1005Z), embedded in the multicomponent MEMS sensor, are shown in Fig. 1.

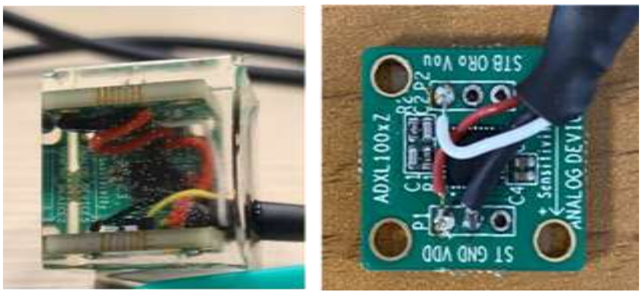

Fig. 1. The multicomponent MEMS sensor and the individual sensing element.

The multicomponent MEMS sensor is realized by orthogonally embedding the 3 sensing elements in a resin case. The sensing element (ADXL 1005Z), according to the manufacturer information, has a linear frequency response from DC (0 Hz) to 23 kHz, with resonant frequency at 42 kHz. The linearity is within ±0.1% of full-scale range, with a cross axis sensitivity of ±1% along perpendicular axes. Low-noise density is 30 μg/√Hz, and low-power consumption is 1.0 mA, with low power and single-supply operation from 3.3 V to 5.25 V.

The three sensing elements are mounted on three specific demo boards, mounted by orienting the sensing axes in order to have triaxial responses. The boards were initially fixed together with cyanoacrylate glue then they were coated with epoxy resin.

III. CALIBRATION METHOD

As a first step, the sensing element ADXL 1005Z is individually calibrated, to evaluate the intrinsic responsiveness as a function of mechanical vibration. Calibration is carried out by gluing (Loctite®) the sensing element on a hexagonal prism mass, and the assembling is screwed on the vertical vibrating table, as shown in Fig.2.

Fig. 2. The individual sensing element ADXL 1005Z on the vertical vibration table.

The reference acceleration, along vertical z'-axis a_{ref}, is measured by a single axis reference transducer (PCB model 080A199/482A23), calibrated according to ISO 16063-11:1999 [21], against INRiM primary standard, integrated within the stroke of the shaker. Calibration is carried out according ISO 16063-21:2003 [22]. The reference acceleration is acquired by an acquisition board NI 4431 (sampling rate of 50 kHz) integrated in the PC and processed through LabVIEW® software to provide the RMS reference value in ms^{-2}. Actually, the calibration of the individual sensing element, by using the set-up shown in Fig. 2, is affected by some systematic errors induced by the vibrational modes of the hexagonal prism mass, and by the small (but not negligible) damping of the glue. The errors depend on both frequency and amplitude and cannot be experimentally evaluated with this calibration setup, thus it needs to be considered in the evaluation of the overall uncertainty.

Once the sensitivity of the individual sensing element is known, the calibration of the multicomponent MEMS sensor is carried out. Calibration is performed with a specific system suitable for the simultaneous amplitude calibration of multicomponent MEMS sensors. The calibration set-up allows to generate a projection of the reference acceleration along three axes simultaneously, by means of inclined planes. Main sensitivities are provided for each sensitive axis from 10 Hz up to 20 kHz, at nearly-constant peak amplitude of 10 m/s².

The calibration method and the experimental set-up, shown in Fig. 3, are described in details in [11].

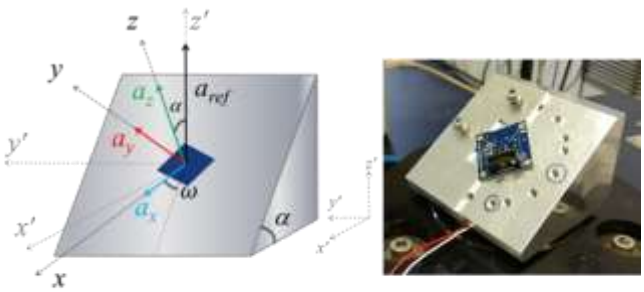

Fig. 3. The multicomponent calibration system: inclined plane allows to generate a projection of the vertical reference acceleration along three axes simultaneously.

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IV. CALIBRATION RESULTS: SENSITIVITY AND UNCERTAINTIES

Calibration is carried out from 10 Hz up to 25 kHz and the sensitivity values are determined with different values of power supply, namely 3.5 V, 4 V, 4.5 V and 5 V. Since the standard deviation of calibration at different values of power supply is negligible (< 1%), the overall average values are considered representative of the actual sensitivity of the individual sensing element under investigation. In the graph of Fig. 4 the sensitivity of the individual sensing element ADXL 1005Z is shown. Data are expressed in dB referred to the sensitivity at 10 Hz, which is 1.98982 mV/(ms^{-2}).

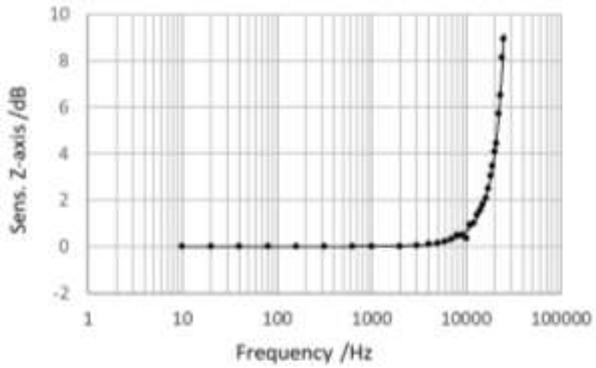

Fig. 4. Sensitivity in dB of the individual sensing element ADXL 1005Z.

From calibration it can be seen that the 10% accuracy bandwidth is 12 kHz.

[N.d.A.: Experimental result and analysis from calibration of the embedded multicomponent sensor are not available, since still *in course*, sensitive data and related uncertainty budget will be provided in the full conference paper version].

V. Example of Application

The suitability of the developed device to applications typical of condition monitoring of rotating machinery is demonstrated, by comparing the signals obtained through the multicomponent MEMS with those obtained using a much more expensive large band piezoelectric accelerometer (4326A Bruel&Kjaer).

The piezoelectric accelerometer is characterized by 10% accuracy bandwidths of 9 kHz, 8 kHz and 16 kHz along the x, y, and z axes respectively.

The two devices were used to gather typical vibration signatures of rolling bearing faults. The test bench for the comparison has the structure shown in Fig. 5 and allows for emulating the vibration signals and to acquire the signals from the three axes of the MEMS and of the piezoelectric accelerometers synchronously.

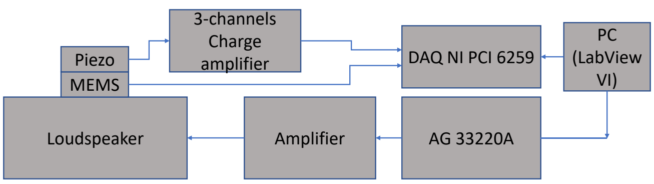

Fig. 5. Test bench.

The vibration signatures were derived from the data stored in a public database [23], which provides access to ball bearing test data for normal and faulty bearings. The signals were emulated by means of an arbitrary signal generator, operating at 48 kHz of sampling frequency, and an amplifier, driving a loudspeaker. An acceleration nominally aligned with the symmetry axis of the cone was generated. The accelerometers were fixed to an aluminum support solidly mounted on the voice coil with the z-axis parallel to the displacement of the cone. The setup was described in detail in [24, 25].

The 6 signals provided by the two devices were acquired with an acquisition board (DAQ PCI 6259 1.2 MS/s, 16 channels, 16 bits) with a sampling frequency of 160 kHz. Exploiting the three axes information, the obtained acceleration data were compensated for possible misalignments and vibrations accounting also for the small acceleration components lying in the x-y plane. Figs. 6 and 7 show the comparison of vibration signals for the two devices in the two cases of an outer race fault and ball fault respectively. From this test, it is confirmed what found with the calibration procedure: the quality of the information provided by reference piezoelectric sensor, which can be considered as an upper-level standard for industrial condition monitoring systems, coincides with (or is better than) the one obtained using the proposed multicomponent low-cost device. In fact it can be seen that the deviation between the two signals is due to the larger bandwidth of the MEMS device along the x and y directions. For signals with spectral components lying in the bandwidth of the two sensors the deviation between the measured acceleration value is in accordance with the calibration data.

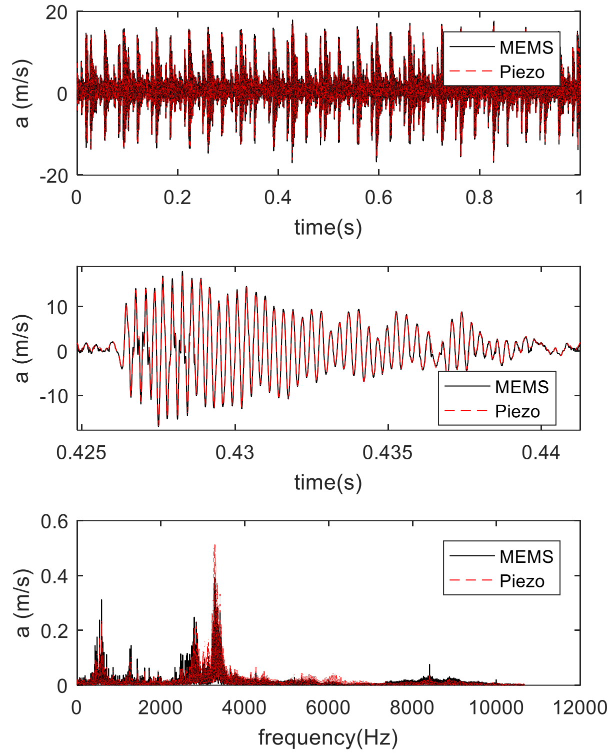

Fig. 6. Outer race fault (base signal: OR021@6_0 in [22]). ‘a’ indicates the acceleration value along a vector parallel to the acceleration itself but always maintaining the same direction with respect to the z-axis.

VI. Conclusions

[N.d.A.: Not yet available, this section will be added in the full conference paper version].

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