A preliminary performance validation of a MEMS accelerometer for blade vibration monitoring

Andrea Rossi[1], Francesco Orsini[1], Andrea Scorza[1], Fabio Botta[1], Fabio Leccese[2], Enrico Silva[3], Kostiantyn Torokhtii[3], Ivan Bernabucci[3], Salvatore Andrea Sciuto[1]

[1] *Engineering Department – "Roma Tre" University, Via della Vasca Navale 79, 00146 Roma, Italy*
[2] *Science Department – "Roma Tre" University, Via della Vasca Navale 84, 00146 Roma, Italy*
[3] *Engineering Department – "Roma Tre" University, Via Vito Volterra 62, 00146 Roma, Italy*

***Abstract* – Nowadays a large number of studies are being carried out on active vibration control, especially in the aeronautical gas turbine industry. Indeed, uncontrolled vibration in aeronautical engine blades can lead to fatigue failure with catastrophic consequences. For this reason, many efforts are made to implement an embedded active vibration control on rotors. Furthermore in this particular kind of application a compact, integrated and robust system, controlled by a wireless remote system, is necessary. Before designing the vibration active control it is mandatory to characterize the vibration monitoring system of the blade in order to develop a feedback system for active damping. To this regard a MEMS accelerometer for mobile applications ($MEMS_{WMAA}$) may be considered a good choice, since the wireless features are relevant in a rotor vibration monitoring application, its cost is usually low and its size and weight allow to obtain a lower insertion effect. However, the metrological limits of this type of sensors are not well investigated. In this work a preliminary characterization of a $MEMS_{WMAA}$ for blade vibration monitoring application is proposed. In particular the authors evaluate the actual performance of $MEMS_{WMAA}$ by means of a direct and simultaneous comparison with a reference sensor. The frequency range of investigation (10 Hz up to 1080 Hz) includes the first three resonant frequencies of a cantilever beam that will be used in a future work to experimentally validate the vibration control algorithm.**

Keywords – acceleration, measurements, MEMS, vibration, frequency,

I. INTRODUCTION

Many aspects in gas turbine optimization have been studied in literature [1-4] nevertheless also in recent years the vibration of blades has been one of the most important topics: finding effective methods for vibration control is still a field in progress, and there are ambiguous results. Piezoelectric actuators and sensors are nowadays widely used to monitor and control vibrations of different structures [5-11], due to their ability to convert mechanical energy into electrical and vice versa. There are several types of active vibration damping. The active control allows to obtain consistent damping of structural vibrations over a wide frequency range, i.e. by means of piezoelectric elements that can be used both as sensors and as actuators; there are many works in the literature dealing with active control of vibration by means of piezoelectric, such as the active control of beams or plates [6,7,9,14-16]. The active control has some drawbacks: it requires appropriate amplifiers to drive piezo elements, electronic circuits to amplify and filter the signal from sensors and a real-time control of the system. It also may present instability effects due to an imperfect modelling of high-frequency vibration modes. In the application of our interest, active damping is required to control vibration in aeronautical gas turbine blades. To this regard a MEMS accelerometer for wireless and mobile applications ($MEMS_{WMAA}$) may be considered a good choice, since its wireless feature is relevant in a rotor vibration monitoring applications and its cost is usually low. However, performances of the above instrumentation are often not well known, therefore a series of validation tests are required [5,10]. In this paper a preliminary validation of a $MEMS_{WMAA}$ for blade vibration monitoring is conducted by means of a reference piezo accelerometer. In particular, after some theoretical considerations and a brief description of the measurement system, we describe our measurements of the first three experimental natural frequencies and of the corresponding maximum acceleration amplitudes in a simplified blade (thin rectangular plate). We then compare and discuss the data from the $MEMS_{WMAA}$ and from the reference transducer.

II. DESCRIPTION OF THE METHOD

The blade is a rectangular steel plate such that the length is much greater than the width. The dimensions of the blade are: 215 mm length, 36 mm width and 2 mm thickness. The blade can be coupled to a shaft by a key on one side, while a hole (diameter 2 mm) at its right end has been made to allow the screw coupling with the $MEMS_{WMAA}$. The blade mass is 147.72±0.03 g, measured by means of a precision balance *PCE* LS3000, while its density and flexural rigidity are ρ=7.8±0.4·10^3 kg/m^3 and E·I=7.9±0.2 Nm^2, respectively, where E is the Young modulus and I the second moment of area of the plate's cross section. A simplified blade geometry has been chosen in order to analytically and numerically calculate the first three resonance frequencies, providing the reference values for the transducer validation.

The analytical frequencies have been calculated with *Euler-Bernoulli* beam theory [17] and expressed in (1) in SI units:

$$f_j = \frac{k_j^2}{2\pi}\sqrt{\frac{EI}{\rho S}} \qquad (1)$$

Where j=1, 2, 3, 4 … and S is the cross section of the beam, the coefficient k_j can be obtained from the solutions of the following equation:

$$\cosh(k_j L) + \cos(k_j L) = -1 \qquad (2)$$

Where L is the beam length. Within the applicability of the model here adopted, from (1) and (2) the first three frequencies are estimated: f_1=61 Hz, f_2=384 Hz and f_3=1080 Hz with a relative uncertainty of about 6%. Furthermore a finite element simulation by means of the COMSOL Multiphysics software has been performed to verify the above frequencies: a difference up to 2% only, between the simulation results and the analytical values has been found, confirming the suitability of the cantilever beam model.

Measurement System

The measurement system for the validation of the $MEMS_{WMAA}$ is set in order to provide and measure the first three natural frequencies of the cantilever and it is made up of:

1. A mini uniaxial piezoelectric accelerometer (*PCB* 352A56) mounted on the free end by PCB wax. The accelerometer mass is 1.8 g so its influence on the blade vibration can be considered negligible. It is the reference transducer.
2. An analog triaxial MEMS (Analog Devices ADXL335) powered by a Data Acquisition Board (point 8). Since its mass is 2 g, the influence on the blade vibration can be considered negligible. It is the $MEMS_{WMAA}$ under validation and some of its features are reported in table I.
3. An I.C.P. accelerometer power supply (*Piezotronics* 482A05)
4. An electrodynamic shaker (*Data Physics Corporation* Signal Force GW-V20)
5. A power amplifier (*Data Physics Corporation* PA300E) for the amplification of the signal coming from the function generator, and for the drive of the electrodynamic shaker
6. A function generator (*Hewlett Packard* 33120A) to provide a sinusoidal waveform to the shaker
7. A digital oscilloscope (*Agilent Technologies* DSO3202A) to display the output signal from the accelerometers
8. A Data Acquisition System (*National Instruments* NI USB 6251) to acquire (DAQ system), process and store the measurement data. The DAQ system settings and the processing of the measurement signals from the two sensors are performed by means of an in-house software in a LabVIEW™ environment.

Table 1. $MEMS_{WMMA}$ specifications

Parameter	Min	Typical(1)	Max
Measurement Range	±3 g	±3.6 g	
Non linearity		±0.3 % FS	
Interaxis Alignment Error		±0.1 °	
Cross-Axis Sensitivity (2)		±1 %	
Sensitivity at each axis	270 mV/g	300 mV/g	330 mV/g
Bandwidth X, Y		1600 Hz	
Bandwidth Z		550 Hz	
Sensor resonant frequency		5.5 kHz	
Operating Voltage Range	1.8 V		3.6 V
Supply Current		350 µA	
Operating Temperature Range	-40 °C		+85 °C

(1) Typical specifications are not guaranteed
(2) Coupling between any two axes

A scheme of the whole measurement system is reported in Fig. 1. Each test on the blade has been conducted for 4s at 20kS/s sampling frequency. The frequency spectra of both the measurement signals have been obtained by software in a LabView environment. Only one direction has been considered for the acceleration, i.e. orthogonal to the blade longitudinal plane (Z-axis, Fig. 1).

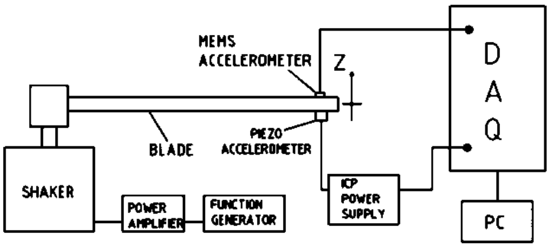

Fig. 1. Scheme of the measurement system. Both the accelerometers are placed at the free end of the blade (on opposite faces) by using PCB wax.

III. RESULTS AND DISCUSSIONS

In a future work, the authors intend to evaluate the blade vibrations in a rotating system, which properly simulates the application of our interest. For this purpose the MEMS$_{WMAA}$ becomes a good candidate with the wireless data transmission feature [18,20-21]. Nevertheless, a preliminary test has been carried out by means of the system in Figure 1, in order to verify the measurement uncertainty related to the use of the MEMS$_{WMAA}$ and to confirm its suitability for our application. Moreover, the same system is used to estimate the goodness of matching between analytical/numerical and experimental frequencies of the first three modal shapes. In particular the MEMS$_{WMAA}$ performance are verified in terms of frequency and acceleration measurement uncertainty by means of a comparison with a reference measurement system [5,19] as done in other dynamic applications [22-26].

In Table II the measurement results for the two sensors are reported: for the first three modal shapes, the first three columns are the analytical and experimental frequency values respectively, while the last two columns are the corresponding peak-to-peak accelerations a_{pp}. No significant differences have been found in the experimental modal frequencies between the two transducers. On the other hand, for increasing frequency, the magnitude of the acceleration differs significantly between the transducers. Uncertainties are expressed in terms of repeatability as standard deviation of the measurement data collected over 4s at 20 kS/s.

Table 2. measurement results by means of the MEMS$_{WMAA}$ and the reference accelerometer.

Mode	Analytical freq. [Hz]	Ref. acc. Freq. [Hz]	MEMS$_{WMAA}$ freq. [Hz]	Ref. acc. a_{pp} [m/s^2]	MEMS$_{WMAA}$ a_{pp} [m/s^2]
I	61	59.5±0.3	59.5±0.3	53±5	35.3±0.5
II	384	356.3±0.3	356.3±0.3	27±5	4.3±0.5
III	1080	887.5±0.3	Range exceeded	156±5	Range exceeded

As it can be seen from Table 2, MEMS$_{WMAA}$ outcomes are very poor in regards to the evaluation of the peak-to-peak acceleration, if compared to the reference accelerometer. Furthermore, its error is not linear and its frequency response is similar to a low pass filter. In particular a spectral analysis of data has shown that MEMS$_{WMAA}$ accelerometer filters high-frequency harmonic components so that some of them may be attenuated or even not detected. Moreover it has been found that the largest harmonic component detected by the MEMS$_{WMAA}$ is at 119.3 Hz, while the largest harmonic measured by the reference accelerometer is at 357.5 Hz: this is likely due to the bandwidth limit of the MEMS$_{WMAA}$, since in other tests the MEMS$_{WMAA}$ fails to detect higher frequency components. In fact, although the measurement signal from the reference accelerometer confirms that the blade has not been subjected to a perfect sinusoidal vibration, the signal provided by MEMS$_{WMAA}$ seems to be a perfect sinusoidal signal. The vibration spectra at the third resonance frequency are not reported since for the MEMS$_{WMAA}$ the signal app exceeds the measurement range. This preliminary study on acceleration and spectrum measurements substantially confirms the analytical frequencies obtained from the cantilever beam model. The percentage difference between analytical and experimental frequencies can be considered acceptable in regard to approximations introduced with the physical model. The absolute percentage differences Δ% can be expressed as

$$\Delta\% = \frac{\left|f_{experimental} - f_{analytical}\right|}{f_{analytical}} \cdot 100 \qquad (3)$$

From Table 2 Δ% is 2.8 % at the first resonance frequency, 7.3 % at the second and 17.5 % at the third: these differences Δ% are identical both for the MEMS$_{WMAA}$ and the reference transducer, except at the third frequency where the MEMS$_{WMAA}$ signal is not available because the test exceeded its bandwidth and measurement range limit. It comes out that the MEMS$_{WMAA}$ accelerometer cannot accurately measure the amplitude of acceleration, in particular at the higher frequencies (300-500 Hz): differences with the reference transducer up to 83% of the reference value are measured. Furthermore, the error of MEMS$_{WMAA}$ in amplitude evaluation is frequency dependent.

IV. CONCLUSIONS

The use of MEMS accelerometer for mobile applications (MEMS$_{WMAA}$ for the monitoring of vibrations in rotors is a potentially very promising field. Taking into account the lack of information on this topic, we have performed a preliminary validation of a MEMS$_{WMAA}$ for blade vibration control and monitoring. A test system has been set and the first three natural frequencies have been calculated and measured: no significant discrepancy has been found between the measured natural frequencies and the calculations. After that the acceleration amplitude of the $MEMS_{WMAA}$ under study has been compared with a reference piezoelectric transducer: the $MEMS_{WMAA}$ can detect the first two resonant frequencies with good approximation, nevertheless its metrological characteristics are not suitable to collect measurements of the blade acceleration with an acceptable uncertainty for the application requested.

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