On the robustness of microflown probe for the assessment of the vibro-acoustic signature: methodological and experimental aspects in a modal test environment

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Abstract. Potentialities of merging contact and noncontact measurement techniques for structural analyses are studied in this paper, to explore limits and advantages of classical and innovative techniques (accelerometers, Laser Doppler Vibrometer and microflown pressure-velocity probes). The analysis refers to a previous experimental campaign, devoted to a specific test case in a modal analysis environment; this appears as a suitable and representative field of application for the goal of highlighting possible correlations to the benefit of a robust comparison among resulting indications coming from different transducers. Methodological suggestions, addressing future and more focused measurement campaign, post-processing algorithms and optimization procedures are provided in this paper. They will be used also for defining a more systematic experimental campaign to be carried in order to identify possible guidelines for both fusion of sensor indication and more complex structural characterization.

1. Introduction

The vibro-acoustic signature of assets is of fundamental importance in many operating scenarios, from civil to military, [1], [2], [3], [4]. Vibrating source localization and quantification is widely used for diagnostics purposes or for quality control end-of-line testing, e.g. in the automotive audio assessment of the vehicle cabin, [5], [6]. Nowadays, advances in technology offer several solutions for the characterization of the sound field, [7], [8], [9]; among these, microflown (p-u) probes are used in applications where complex acoustic field are generated, [10], [11], [12], [13], [14]. In very short terms, a pressure-velocity sound intensity probe (or a 'p-u intensity probe') is a device that combines a pressure microphone with an acoustic particle velocity transducer (RDT).

The air flow resulting from a pressure gradient induced by a source of noise present in the surrounding environment and investing the two hot-wires determines a first cooling of the first wire, which will release part of its thermal energy by convective exchange with the particles investing it and so heating them, and a second cooling of the second wire, invested by the same particles at a slightly higher temperature, thus determining a temperature gap between the two wires which is directly dependent on the acoustic speed of the particles. Heating the wires requires only about 70mW of power.
From 1994 to 2004, an intense research activity conducted around the world by Universities and Industries made it possible to explore a great variety of measurement techniques with these devices, which have been approved and accepted in the industrial world, especially in the automotive sector (as well as the military one). This "acoustic multimeter", as some researchers have defined it, has provided great potential in acoustic problems for identifying not only the amount of noise caused by a source but also its geolocation through the use of multiple devices at the same time, [15], [16].

Such kind of probes provide useful information in all those applications ranging from noise reduction to the identification of sound sources up to condition monitoring applications for maintenance procedure streamlining.

Nevertheless, especially in the most challenging field of operation, like in the very near field (VNF), making the measurements compatible is not a trivial task, [12], [13], [17], [18]. The benefits deriving from the possibility of interchanging non-contact techniques to obtain the vibro-acoustic signature of a general asset are many: just to name one above all, there is the possibility of cost-reduction for carrying out Operational Modal Analysis, with comparable results in terms of measurement accuracy with reference, for example, to multipoint Laser Vibrometers [19].

Standard procedures for microflown calibration may be found in the literature, [19]: far field methods exist which require an anechoic room, near field methods involving sound emitted from a small hole in a plane baffle, and a near field method in which the sound is emitted from a hole in a spherical baffle. Starting from these stringent methodologies, requiring special laboratory conditions, devices and careful procedures, a simplified and optimized in situ calibration procedure appears useful for those applications whose unavoidable uncontrolled operating conditions may increase the measurement uncertainty and thus affecting the overall results.

In the present paper the signals acquired from a first campaign of measurements on a PolyMethylMethAcrylate (PMMA) plate (length = 500 mm, height = 320 mm, width = 23 mm) excited by a shaker are investigated in order to metrologically validate the comparisons among results come out from microflown probes - positioned in different sensor locations on the plate and at different distances from it, LDV and accelerometer respectively, taking into account the vibrational modes of the plate.

Aim of this activity is the individuation of the metrological criteria to optimize the use of microflows for the modal analysis referred to a simple test case by means of the discussion of the main uncertainty causes.

2. Experimental background

A previous work, [12], highlighted the outcomes obtained in measuring the surface velocity by means of a scanning laser Doppler vibrometer, a piezoelectric accelerometer and a microflown p-u probe, with reference to modal tests carried out considering both the vibration of a single speaker belonging to a loudspeaker panel and the one of a PMMA plate suspended in free-free conditions.

In this work a design of experiments is proposed to evaluate the metrological quality of these sensor. In particular, the main effects under investigations are summarized in the following:

- Relative distance between microflown and vibrating plate
- Relative positioning of the sensor head on the vibrating plate
- Choice of the reference point for characterization purposes
- Preliminary calibration parameter set-up

2.1. Experimental set-up

The microflown p-u probe is capable of measuring the acoustic velocity (u) of a fluid particle and pressure (p). Its specificity is having assembled in the same device two sensors, one real acoustic, the microphone, and an anemometric one, consisting of two wires (RTD) arranged parallel next to each other and heated to 200 ° C above the ambient temperature when in use, figure 1.

A complete modal test has been performed by suspending the plate, adopting the so-called free-free boundary conditions. To this aim, two rubber cords have been used, whose distance from the edges was 110 mm. The excitation of the plate has been achieved by the usage of a electro-dynamic shaker,
connected to the structure by a stinger and a impedance head, reported in figure 2, able to measure both the acceleration of the driving point (DP) and the corresponding injected force.

![Figure 1. Microflown detail of anemometer component (adopted from [13], [21])](image1)

![Figure 2. Detail of experimental setup: p-u mini probe (right side), and impedance head (left side)](image2)

The vibration in each sensor location have been measured by using (i) a set of 8 monoaxial piezoelectric accelerometers, of which 4 supplied by Kistler and the remaining by PCB Piezotronics, all having sensitivity 100 mV/g, (ii) a scanning laser Doppler single point vibrometer (LDV) comprising a Polytec OFV-505 sensor head and a OFV-5000 controller and (iii) a set of 2 microflown 1/2"p-u mini 1-D sound intensity probes, able to measure the sound pressure p and the air particle velocity u. A LMS SCADAS front end connected to a laptop pc has been used for all the acquisitions, driven by the LMS Test.Lab analysis suite. With regards to microflown measurements, we specify that the acquired signals have been treated according to the calibration documents provided by the manufacturer.

The sensor locations have been distributed on a point grid consisting of 32 positions. In the case of the accelerometer-based campaign, the whole measurement collection has been divided into 4 different runs, with the 8 sensors that have been made migrating, adopting the impedance head measurement as the reference for subsequent merging of modal vectors’ components. Similarly, microflown-based campaign has been split into 16 different runs, with the 2 sensors migrating, while, in the LDV case, only a limited number of 4 locations out of 32 have been considered, besides the DP, measured with all the available sensor types.

Mobility functions have been estimated in all the cases and compared, to analyze the influence of the effect of normal distance from the plate. To this aim, several p-u probe measurements have been performed at different distances from the plate.

We comment that the added mass effect, related to the usage of accelerometers, can be considered negligible, owing to (i) the small mass of each sensor involved, (ii) the limited number of sensors used in each run, and, in turn, (iii) with respect to the mass of the plate.

3. Data processing

Data processing aims at identify the main uncertainty causes, starting from the manufacturer specifications and calibration certificates. In order to provide some validated techniques to integrate the informative content coming from accelerometers, laser vibrometer and microflown, it appears essential focusing on some synthetic indication to make the comparison, which can be easily recognized, transferred and used in field, i.e. for modal analysis purposes, like in the case here analyzed. For this reason, in this preliminary work attention is paid to the verification of the first vibration mode, which is expected to correspond to 133 Hz. The plate dynamic identification has been achieved by post-processing the acquired signals by using a Multi-Input-Multi-Output fitting procedure in the frequency
domain, available in the Test.Lab suite. Specifically, the modes’ identification have been performed by merging the information coming from the different runs. To find the first resonance peak, an algorithm developed in Matlab® for the automatic research of the most prominent local maxima has been used.

The following preliminary validation actions have been taken:
- Association between grid and available signals, for the purpose of effective and modular processing of the data available (figure 3);
- Verification of sampling parameters (aliasing, leakage)
- Verification of linearity and static sensitivity conditions (as a function of frequency)

Figure 3. Spatial distribution of points on the plate. Driving Point (DP) is referred as the 33rd point, in red.

4. Observations and conclusions
The results of the first measurement campaign done on the plate show that the microflown used returns signals, in terms of Bode diagrams, quite in line with those provided by the LDV, taken here as reference instrument, in the grid point DP, 12, 16, 21, representative of the most diversified positions in the grid (figures 4 and 5). In these grid points, the comparisons between first mode frequencies in the calibrated and uncalibrated configurations of the probe have been shown, by way of example. By neglecting the lower frequencies (where the instrument does not work in the linearity band) and the higher frequencies, closer to the cut frequency and beyond it (where the wave propagation speed becomes too high for the RDTs to well appreciate the temperature jump resulting from its passage), what can be noted at this early stage, is that the amplitude of the microflown signals, while providing well the frequencies of the vibrating modes of the plate, decreases with increasing positioning distance from the plate, giving rise to a bias due to the loss of acoustic energy of the propagating wave with the square of the distance, and therefore valuable in principle. Over 50 mm distances, there are other disturbances that affect the measurements of the instrument, presumably due to the interaction of acoustic waves coming from several surrounding points, while still identifying the first modes of vibration induced by the shaker in the DP. As regards the evolution of the phase of the returned signals, especially in correspondence with the modal frequencies, there are sometimes small uncertainties of measurement that need to be further investigated, from a purely metrological point of view, through a targeted procedure that guarantees the repeatability of the measurements, from which to infer more detailed and precise information, which is going to be done in the programmed experimental campaigns.
Figure 4. Mobility function referred to points 12, 16 and 21: comparison at different relative positions between microflown and plate.
Figure 5. Mobility function referred to points 12, 16 and 21, on a limited frequency range (100-200 Hz): comparison at different relative positions between microflown and plate.

In Table 1 below, with respect to the only points given by way of example, there are small, but to be assessed in the effects, frequency differences in the detection of the first mode relatively to the signal acquired by the microflown in calibrated and uncalibrated mode. Specifically, the former case refers to signals calibrated by following the software procedure suggested by the manufacturer; the latter one refers to the raw signals.
These differences, even taking into account the frequency resolution ($\delta_f = 0.25 \text{ Hz} \rightarrow u\_\delta_f = 0.07 \text{ Hz}$), must be once more investigated through a procedure of repeatability, in order to assess more correctly the uncertainties involved, in order to determine the significance of the results from the application point of view. In figure 6, then, such differences are reported for all the grid points of the plate and compared with the 1st mode frequencies returned by the LDV and the accelerometer. Even though the differences between calibrated and uncalibrated values seem negligible for most of the points analyzed, it is opinion of the authors that it would be interesting to assess more reliable answers supported by an intra-laboratory uncertainty evaluation, (e.g. through a repeatability procedure of the measurements). The effect of the application of the calibration function is a further aspect worth of a more refined analysis, if the differences in points 2, 9, 10, 19, 28, 30 of figure 6 are considered.

**Table 1.** Comparison among resulting frequencies of the first mode obtained using calibrated and uncalibrated data, at different relative distances between microflown and vibrating plate. The values are given in hertz.

| Mode 1 (133 Hz) | Uncalibrated Data | Calibrated Data |
|----------------|-------------------|-----------------|
| Relative distances microflown-plate |
| 10 mm | 30 mm | 50 mm | 100 mm | 10 mm | 30 mm | 50 mm | 100 mm |
| **DP** | 133,00 | 132,75 | 133,00 | 132,75 | 133,00 | 132,75 | 132,75 | 132,75 |
| 12 | 132,25 | 132,75 | 132,50 | 133,00 | 132,25 | 132,75 | 132,50 | 133,00 |
| 16 | 132,25 | 132,25 | 132,25 | 132,25 | 132,25 | 132,25 | 132,25 | 132,25 |
| 21 | 132,25 | 132,75 | 132,50 | 132,00 | 132,25 | 132,75 | 132,50 | 132,00 |

**Figure 6.** Comparison of the frequencies obtained from accelerometers, from vibrometers and from microflows (both calibrated and uncalibrated cases) at each point of the grid (1 to 33, being this latter the DP).
Moreover, looking at figure 6, differences in the comparison among transducers arise where the signal-to-noise ratio is less favorable (i.e. points 5, 9, 11, 14, 19, 22, 24 and 28), that is in the plate regions where the modal displacement is relatively small, being close to a so-called nodal line. To this regard, we specify that coherence values computed in all the cases resulted satisfactory not only for LDV and accelerometers as expected (being close to 1 and higher than 0.98, respectively), but also for microflowns (higher than 0.92), witnessing the goodness of the overall setup (figure 7).

Future work will be based on a procedure exploiting an analysis carried out on each vibration mode and on the points where the signal-to-noise ratio can be considered satisfactory for comparison and purposes and to verify an optimal layout that favors the points affected by the other modes. Further analyses will focus on more complex geometries, starting from a rigorous check of the calibration curve, taking the vibrometer as reference, finalizing it to the specific application. These actions are expected to return the possibility of deploying sensor fusion techniques merging the information deriving from different transducers, to study the limits to characterize the structural behavior.

![Figure 7. Coherence function computed for microflowns' measurements.](image)

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