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Influences of Geometric Configuration on the Analysis of Uncertainties Affecting a Novel Configuration of Self-Tracking LDV

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Abstract- The main purpose of the paper is to assess the reliability of particular configuration of Laser Doppler Vibrometry intended to be suitable for the analysis of vibrations affecting rotating components of machines. In the paper an analysis of uncertainty has been carried out due to the possible static misalignments of the mirrors utilized in the experimental apparatus set up for the estimation of the *out of plane* vibrations of moving (rotating) objects. Those misalignments have to be distinguished from the so called *dynamic* ones due instead to dynamic effects induced by the movement of the object itself. That is in order to give a better characterization of the self-tracking technique employed with the use of a 1D LDV and of the measurements done by means of it, whose uncertainties are mostly linked to the interaction between environment and instrumentation.

I. Introduction

The accurate evaluation and determination of the dynamic stresses due to vibrations is of considerable interest in the design, testing and running of turbo-machinery mostly. The measurements of these stresses become critical in the case of moving organs, especially rotating ones. Reason of that is the difficulty in providing a suitable set-up capable of acquiring data from sensors placed in the same environment and transferring them to the processing unit. In order to obtain more precise measurements, some innovative nonintrusive techniques (based on the use of appropriately installed noncontact sensors) have been developed.
Nowadays, in industrial ambit, optical or electromagnetic sensors are used to characterize the vibrational state of the rotating parts of the machines, ensuring nonintrusive measurements [1].
One of the most important techniques is based on the use of Laser Doppler Vibrometer (LDV): a laser beam, characterized by spatial and temporal coherence and also by a given frequency and wave length, impacts on a vibrating surface; the reflected light wave impinging the laser receiver, undergoes a frequency shift (Doppler effect) from which it is possible to evaluate the vibrational velocity of the object or structure under examination.
This technique allows to detect vibration frequencies up to 30 MHz with quasi-linear phase response and with spatial accuracy of a nanometre order, depending on the diameter of the laser beam. From the analysis of the vibration modes of a structure or object, it is possible to assess some parameters, defined modal parameters, related to inertial, elastic and viscous properties.
The embedded difficulties in the LDV technique for the measurement of moving and vibrating organs, as turbine blades, consist in the apparent impossibility of tracking the object, which the data required to assess the nature and the entity of vibrations have to be extracted from. This is why both industrial and academic researchers focus their efforts to develop new tracking systems based on laser technology.
There is a vast literature on this subject suggesting different techniques for tracking moving objects by adding optics to the laser equipment, [1], [3], [4]. More specifically, there have been several solution involving the adoption of Scanning Laser Doppler Vibrometer [5], [6], [7].
The analysis of the errors on the measurement of vibrations by these configurations is very complex. This paper deals with the study of errors caused by the employment of the additional external optics to better evaluate the relative uncertainty of the measurement. In order to pursue this aim, a simple 1D tracking configuration is considered and the possible errors due to a misalignment of the optics or the components of the experimental set-up are estimated.

II. Experimental setup

The *self-tracking* configuration suggested by Lomezo et al. [4] consists in a flat mirrors set: the *vertex-mirror* is rigidly placed upon the rotor axis and the *fold-mirror,* a stationary truncated cone, disposed in front of the rotor itself.

The here proposed configuration consists of four stationary fold-mirrors, right angle ones, (Figure 1.), placed at the end of two perpendicular arms and mounted on four precision oscillating goniometers that can slide over binaries, Fig. 2. Further, the support is free to rotate around its axis so that the mirror's angular position can vary.

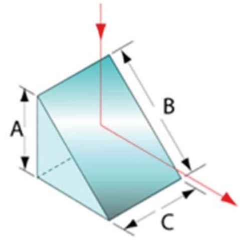

Figure 1. Technical image of the right angle mirror used in the proposed configuration (fold mirror)

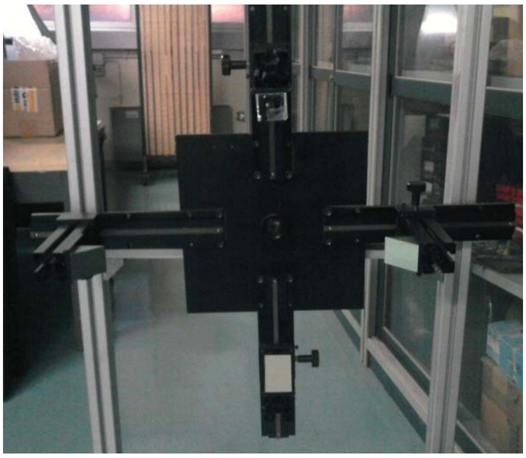

Figure 2. Support for the fold mirrors

The *vertex-mirror* placed on the rotor is a 45° rod mirror (Figure 3.).

Figure 3. Zoom of the 45° rod mirror (vertex mirror) embedded in the rotor

The use of oscillating goniometers has the purpose of varying the angular position of each fold mirror, so allowing to track different points along the longitudinal axis of the object (e.g. blade) simulating a scanning procedure in such a way.
It has been considered only a two flat blade rotor (governed by a DC motor), symmetrically placed for balancing problems, as shown in Figure 4.

Figure 4. Vertex mirror and blades

The four fold mirrors so located allow to catch the vibrations of the same point in four different angular positions. Then, vibration can be measured for each position with period of $2\pi/\omega$ (ω is the angular velocity of the rotor), Figure 5.

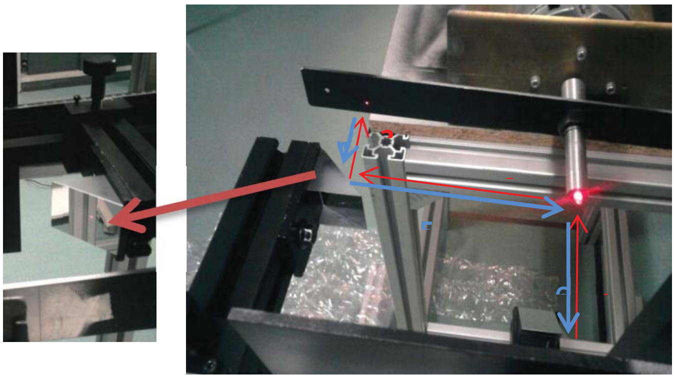

Figure 5. Laser beam paths.

Figure 6. shows the mutual position between LDV (PDV 100 Polytec) and the support of the fold mirrors.

Figure 6. Mutual position between LDV and fold mirrors.

III. Uncertainty Sources Analysis: Misalignment Errors

The LDV technique (in the self-tracking configuration) allows the measure of vibrations at every angular velocity in principle. Nevertheless the system is particularly sensitive to possible static misalignments among the laser beam, the vertex mirror axis, the axis of the fold mirrors support and the rotor axis, Fig 7.

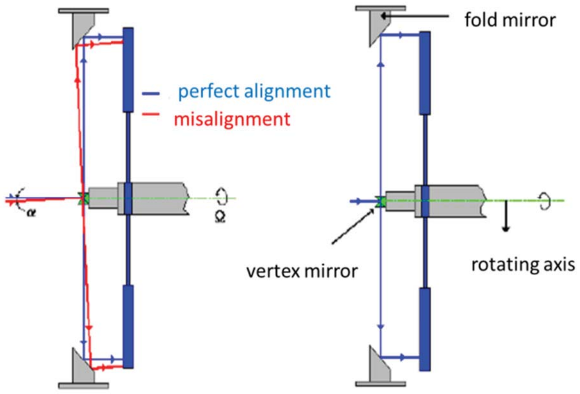

Figure 7. Scheme of possible static misalignments between rotor axis and laser beam axis and rotor axis and cross support of the stationary optics

It appears clear that those static misalignments provoke a displacement of the measurement point on the rotating blade. Since the purpose of the arranged set-up is to make the tracking of a pre-set blade point, a perfect alignment between each pair of the set-up components is required. If the alignment is not achieved in all the four angular positions of the blade, the measurement point (where the laser spot hits) changes and thus the measurement relative to the four angular positions are not representative of the vibration of the same blade point under analysis.
The measurement uncertainties are mainly due to the fact that those misalignments provoke laser beam reflections not orthogonal to the incident surface. Thus, the vibration sensed is not the desired out-of-plane one and this circumstance causes additional spectral components which are superimposed to the expected measurement spectrum, causing the presence of harmonic components non representative of the original vibration velocity signal.
These complications, then, are exacerbated by dynamic effects due to the revolution, to dynamic imbalances and so on.
Although the contact absence between the blade and the sensor is an advantage (with no persistent and systematic loading effects which would influence the dynamic behaviour of the rotating structure), another source of uncertainty has to be mentioned: the vibrometer would also sense the rigid body motion of the rotating structure (linked to the structural imperfections of the governor) as vibrational motion which is superimposed to the effective and real vibration motion of the rotating object due to the fluid dynamic phenomena affecting it.
Other sources of uncertainty are due to the optical components included into the core of the LDV head and to the output analogical signal treatment operations.

IV. II. Uncertainty Sources Analysis: Evaluation Procedure

The description of the frequency shift due to Doppler effect, which affect the laser beam incident onto diffusive and reflective surfaces follows.

A. Diffusive Surface

Several tests on diffusive surfaces have been performed in order to evaluate the amount of the errors affecting the measurements of the vibration velocity when misalignments between laser beam and surface under analysis are forced. These impositions have the main purpose of simulating misalignments which could occur in practice and due to not proper installations of the components of the experimental set-up.
By theoretical considerations, these misalignments influence the frequency shift affecting the laser beam (once it is refracted by the incident surface), by a specific and fixed amount. Thus, these static misalignments (due to not so precise installation of the components of the experimental arrangement) can be treated as systematic errors.
The frequency shift of laser beam reflected by a diffusive surface is expressed by the following equation:

$$\Delta f \cong \frac{2}{\lambda} v_m(t) \tag{1}$$

where, λ is the wavelength of the laser beam and $v_m(t)$ is the component of the vibration velocity vector (time dependent) along the direction of the incident laser beam.

From the (1), it is clear that misalignments or not proper installation of the components of the experimental arrangement, influence the vibration velocity of surface under analysis.

In order to characterize in an unequivocal way these uncertainties, an exciter (piezo-accelerometer) has been installed upon the rotating blade. The accelerometer behaviour is governed by a function generator which is able to produce a sinusoidal signal by given characteristics (amplitude and frequency), so causing the vibration of the blade. The position of the accelerometer has been changed for each test carried out in such a way several reciprocal positions between blade and accelerometer have been studied. At each angular configuration, the angles between the laser beam and the vibration velocity vector of the diffusive surface are forced. At each angle, the vibration velocity has been measured.

On Figure 8. the measured velocity is the component of vibration velocity vector along the laser beam direction. The velocity signals have been adequately filtered and purged in order to eliminate noise components and other spurious effects not easily identifiable.

In the case (a) the vibration velocity of the blade (impressed by the exciter) is directed along the direction of the incident laser beam, so the velocity of vibration is directly given by the (1). In the cases (b), (c) and (d), the angle between the velocity vector and the laser beam is 45°.

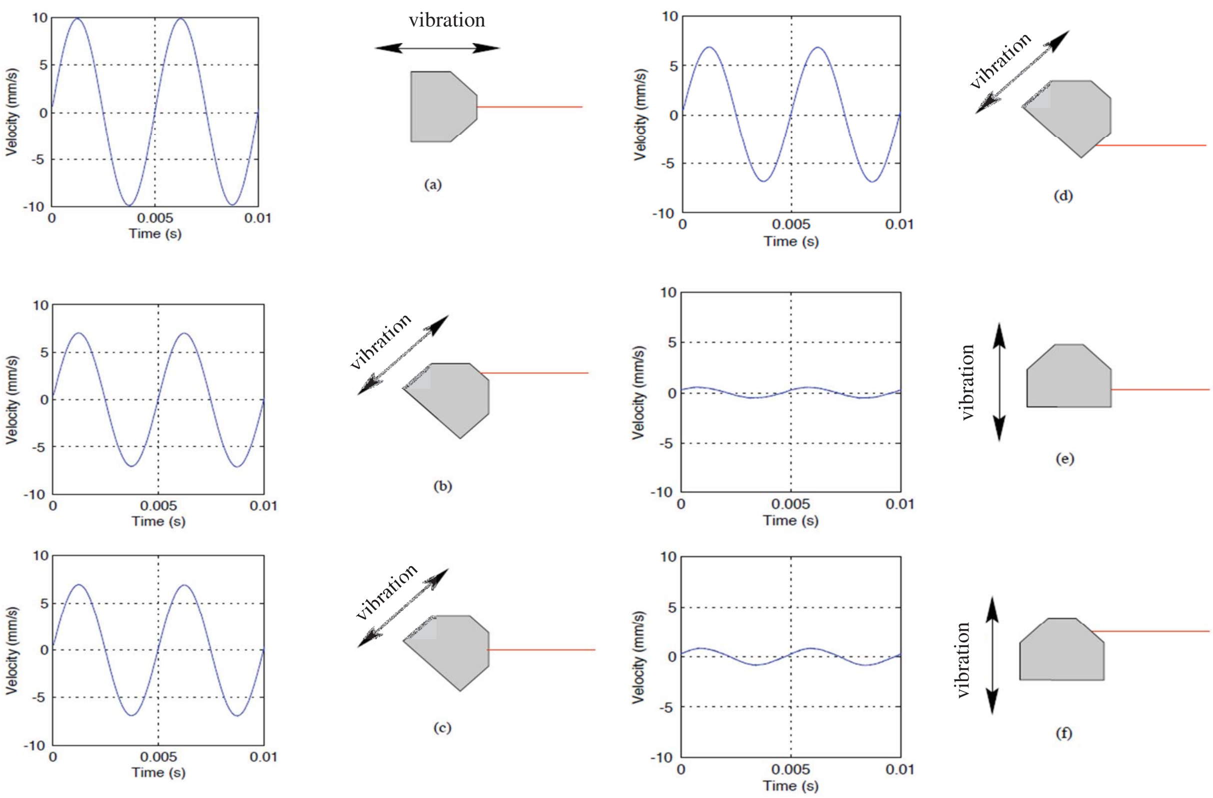

Figure 8. The sequence of figures reports the performed tests.

In addition, in all the three cases the measured velocity is independent from the angle between the normal vector to the vibrating surface and the laser beam. The cases (e) and (f) instead are characterized by no component of velocity vector along the laser beam direction. Nevertheless the output returns a not null signal, though very small, because of noise floor, speckle noise and so many other causes, mainly given by interfering phenomena.

By the performed tests on diffusive surfaces, it is possible to infer the following deductions:

- only vibration with velocity component along laser beam direction give significant output signal;
- vibrations orthogonal to the laser beam produce output which is characterized only by noise, speckle noise and other interfering effects of difficult characterization.

B. Reflecting Surface

Since the experimental set-up includes optical components (stationary fold mirror system and the rotating vertex mirror), an analysis of how reflection surfaces influence the frequency shift (due to Doppler effect) experienced by laser beam is required.
The fold mirrors do not induce frequency shift, since they are stationary. On the contrary, a moving mirror induces frequency shift expressed by the following formula:

$$\Delta f = \frac{4}{\lambda}(\vec{v} \cdot \vec{n})(\vec{r} \cdot \vec{n}) \qquad (2)$$

The vectors reported in the (2) are inferable by Fig (9)

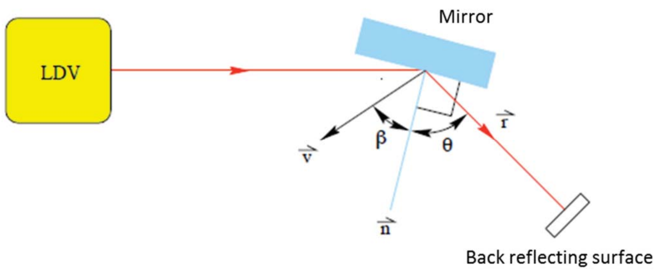

Figure 9. Frequency shift due to mouving mirrors

In the arrangement of self-tracking LDV, the only component giving frequency shift is the vertex mirror, whose reflecting surface is inclined of 45°. It is installed on the centre of the hub supporting the blades. All the points on the reflective surface have the same angular velocity (equal to the angular velocity of the rotor). In addition each point on the reflective surface has a velocity vector which is tangential to the circular trajectory described by each of them. The point on the reflecting surface which is illuminated by the light spot resulting in the intersection between the laser beam and the incident surface, has a velocity vector which results to be constant in time (if the angular velocity of the rotor is constant and the laser beam is stationary, which is the case since the incident laser beam previously reflected by the stationary fold mirrors is fixed in space). Since the reflecting surface is inclined, its normal vector will not be stationary but will rotate at the same angular velocity of the rotor and will describe a cone or a truncated cone, depending on the particular point chosen on the reflecting surface. These consideration have to be taken into account in order to quantify the frequency shift induced by the vertex mirror.

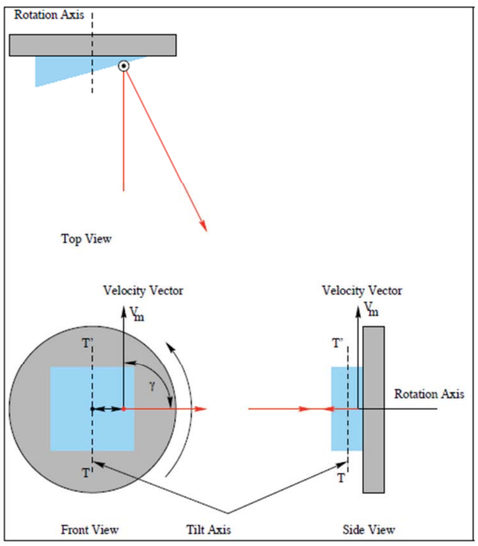

Figure 10. Geometry related to the vertex mirror

On Fig.10 the surface containing the incident and the reflected laser beams is considered. This plane has the same angular velocity of the rotor and is parallel to the rotation axis. The projection of the point of the reflective surface illuminated by the laser spot and the surface of both incident and reflected laser beams vary with a sinusoidal law as the following equation states:

$$v_l = v_m cos\gamma \quad (3)$$

where, v_m is the velocity vector of the point illuminated by the laser spot, v_l its projection on the rotating surface and γ the angle between the velocity vector, v_m and the surface.
Since the incident laser beam lies on a non-stationary point, it is affected by a frequency shift.
In order to avoid the frequency shift affecting the laser beam incident on the vertex mirror, a perfect alignment between laser beam, the vertex mirror and the rotor axis is required. In this way the point illuminated by the laser spot coincides with the centre of rotation of the entire system and thus, it results stationary. No frequency shifting is then generated if the alignment is guaranteed.

V. Conclusions

If the proper alignment among laser beam, rotor axis, vertex mirror axis and fold mirrors support axis is guaranteed, the laser beam generated by the LDV head experience a frequency shift only due to out-of-plane vibrations of the plane blade under analysis. The sources of uncertainties due to static misalignments are as much more reduced as the alignments are much more taken under control so obtaining an output signal from the LDV more representative of the vibration velocity of the moving object. The considerations made in this paper are effective in the case of only static misalignments. The rotation of the blades and other dynamic phenomena, such as dynamic unbalances of the rotor, might introduce misalignments which affect the overall frequency shift experienced by the laser beam. These so-called dynamic phenomena introduce random effects, which aren't predictable and highly difficult to quantify. Another phenomenon which influence the measurements made by LDV and the efficacy of the described self-tracking LDV arrangement is the speckle noise. This phenomenon occurs when a relative motion is between the laser beam spot and the surface under test. The phenomenon, due to the micro reflections and refractions locally distributed on the surface due to its roughness, results in a noise floor which is superimposed on the vibration velocity signal .

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