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An optical instrument based on defocusing for dynamic response model testing in water or wind tunnels

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ABSTRACT

The design and performance of an optical measurement system that can be used for studying the three-dimensional dynamic response of flexibly mounted rigid or elastic bodies in laboratory facilities is presented. The photogrammetric technique implemented on the instrument is based on the defocusing principle, which was first introduced for three-dimensional (3D) robotic vision applications. The technique was later on applied for the measurement of seeded 3D flow velocity fields. The emphasis of this work is given to the design of the tool itself as well as to its validation by using an application that involves the dynamics of a spar floater in a water tank. The final purpose of this work is to produce a non-intrusive and accurate instrument for measuring the fluid-induced responses or deformations of bodies in laboratory facilities. The result is an optical tool that provides an accurate and better alternative to other traditional dynamic response measurement techniques used to study vortex-induced vibrations (VIV), wave-induced motions (WIM), etc. in water or wind tunnels.

1. Introduction

Experimental set-ups and scale models used for fluid–structure interaction (FSI) research in laboratory facilities can be very complex because of the instrumentation needed to measure the dynamic response and the motions excited by the action of fluid flows in bluff bodies. Examples of how complex the design of the models can get and the complicated set-ups generated can be found in many topics related to FSI. Examples of set-ups and models designed for measuring the vortex-induced vibrations (VIV) of elastic bodies can be seen in the research by Grant (1977), Vandiver (1983), King (1995), Hong and Choi (2002), Vandiver and Marcollo (2003), Chaplin et al. (2005a), Trim et al. (2005), and Huera-Huarte and Bearman (2009a,b, 2011). Experimental campaigns to study the dynamics of spar platforms for oil rigs or for supporting wind turbines are also a typical example of FSI research carried out in water tanks (Carpenter et al., 1995; Montasir and Kurian, 2011; Sethuraman and Venugopal, 2013). Novel ways of generating energy from the currents or other concepts in renewable energy require as well test and validation campaigns that involve complex experimental set-ups (Bernitsas et al., 2008; Lee and Bernitsas, 2011). Studies of the wind effects on slender and light structures in wind tunnels are not an exception (Bartoli et al., 2006).

For this reason, a non-intrusive measurement technique with high accuracy, high spatial resolution and high speed sampling capabilities would be ideal to experimentally investigate all these FSI problems. Also, it would be very interesting to be able to produce models inexpensively and easily by not having to embed instrumentation and sensors in the model itself. For example, if the effect of structural mass on the VIV of a cable in cross-flow wants to be investigated, it would be ideal not having to design and construct several instrumented models with different masses, as it could be very expensive and a tedious work.

Some work in this direction has been done in the past, such as the moored buoy research carried out by Jenkins et al. (1995), in which the authors measured the dynamics of the model using four video cameras. Benetazzo (2011) described a system to obtain the six degrees of freedom motions of generic small-scale models in flume facilities by using a single camera. Another example of research with the purpose of measuring different experimental variables in water tanks is that by Wang et al. (2012). All these techniques use targets that tend to be large in comparison to the model size and that can modify the dynamics of the experiment itself. The work presented here describes a completely non-intrusive optical instrument that allows us to measure accurately, with high temporal and spatial resolution, the dynamics and the motions of objects in laboratory facilities, by imaging with the optical system illuminated particles or point sources of light attached to the model. The tool is especially designed for its use in standard water or wind tunnels, and it is therefore of extreme interest for researchers working in the field.

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2. The measurement technique

The photogrammetric measurement technique is based on the concept of range-measurement, first described for robotic vision applications by Rioux and Blais (1986). They imaged a solid surface after projecting a dot pattern on it by means of a laser source. By using a specially designed aperture mask on the lenses, they were able to reconstruct the three-dimensional positions of the projected dots, therefore the surface of the solid. These types of measurements are possible by considering the amount of blurriness of a particle in the sensor, or what is the same, the degree of defocusing. The concept is simple, a particle out of focus will appear to be blurred on the sensor and the size of the blurred particle can be related to the depth position of the particle. This defocusing principle implies a very low depth of field that can be increased if a mask with at least two off centre apertures are used (Rioux and Blais, 1986). By doing this, the imaged points become sharp and the separation between the points becomes the equivalent to the degree of blurriness. So, if a two aperture mask was used, the image of each particle in the sensor plane is a couple of sharp points, if an annular aperture mask was used, sharp circles resulted in the image plane. Therefore, range-measurement allows the recovery of the *x*, *y* and *z* coordinates of a point in space, after acquiring a two-dimensional representation of it on a sensor, through a lens with a special aperture design.

Willert and Gharib (1992) used the same idea to measure the 3D trajectories of illuminated seeding particles in a flow. They used an aperture mask with three pinholes on it distributed in a triangular shape, so each illuminated particle in the measurement volume, appeared as a triangle in the image sensor. The centre of the triangle gave the *x* and *y* position of the particle in space, and the *z* coordinate was related to the size of the triangle. The triangle was used to overcome the problem of non-uniqueness in the *z* coordinate, pointed out by Rioux and Blais (1986), when two apertures or an annular aperture masks were used. In Pereira et al. (2000), Pereira and Gharib (2002), Jeon et al. (2003), and Pereira and Gharib (2004) the authors further developed this advanced optical measurement tool for fluid flows, and called it Defocusing Digital Particle Velocimetry (DDPIV) or three-component three-dimensions (3C-3D) Digital Particle Image Velocimetry (DPIV). They used several sensors, each one with a single pinhole mask, instead of using a single sensor with multiple pinholes in the mask, so the performance of the system was increased. At the moment, DDPIV has become a true alternative to other previous three-dimensional optical measurement techniques in fluid mechanics such as stereo DPIV, Holographic DPIV and tomographic DPIV. Once the positions of the particles in space are known, the velocity field is obtained by 3D cross-correlation or 3D particle tracking velocimetry.

The concept of range-measurement or defocusing is easily understood by looking to Fig. 1 taken from Pereira and Gharib (2002). The figure represents a simplified optical system, with the focal plane (the reference plane in the figure), the aperture plane (considered to be the same as the lens plane) and the image plane (the sensor plane). In the upper part of Fig. 1(a) the aperture plane is made of a single pinhole, coaxial with the optical axis of the system (dotted horizontal line). With this optical arrangement, all points or illuminated particles in the camera-lens field of view (FOV), such as point A in the focal plane, will be imaged in the sensor as defocusing sharp points, as shown in the image with A′. On the contrary, all points outside the focal plane such as point B, will appear blurred or defocusing in the image, as B′ shows. If instead one centred aperture two apertures, equally spaced with respect to the optical axis, are used, the light scattered by points such as B in Fig. 1(b), will result in 2 images B′ and B″ in the sensor. The vertical distance between these, defined as *b*, measured in the image plane can be related to the depth of B in space.

For the measurement of the positions of seeding particles in fluid dynamics, three pinholes are required to overcome the fact that two points with the same *x* and *y* and a *z* symmetrical with

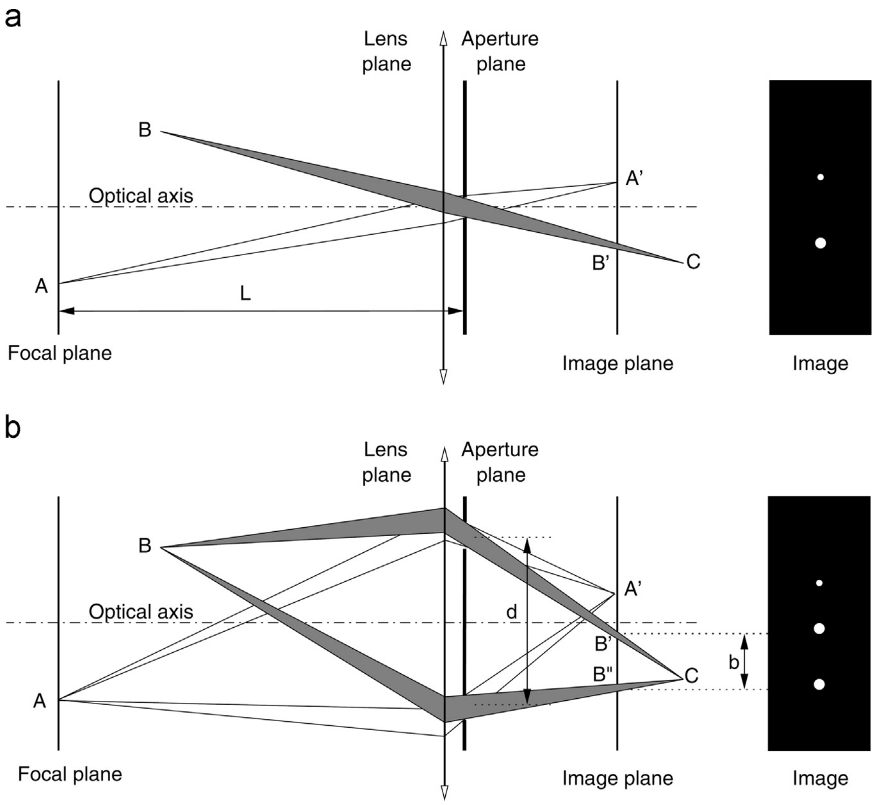

Fig. 1. Defocussing concept. Planar simplification of the DDPIV technique based on pinhole optics taken from Pereira and Gharib (2002).