Endoscopic PIV and holography applied to the study of opaque vessels mechanics

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Abstract In this work endoscopy and traditional fluid and solid mechanics measurement techniques have been combined for the study of opaque vessels characteristics. Techniques such as high speed PIV, for the flow velocity measurement, and digital holography, for the simultaneous velocity and wall deformation measurement, have been adapted to be used with endoscopes. Those have been used for illumination and/or recording of PIV images and digital holograms. The performance of three endoscopes in different vein models has been tested. Preliminary results of flow velocity and wall deformation are presented.

1. Introduction

More and more experiments are being carried out in vascular systems with the objective of studying cardio vascular diseases. The simultaneous measurement of the whole velocity field in a blood vessel together with the measurement of the internal wall deformation would allow the study of flow-structure interactions, which play an important role in the formation of some medical conditions like atherosclerosis and aneurysms.

The velocity fields of confined liquid flows in complex geometry configurations can be measured with optical non-intrusive techniques (Palero et al. (2010), Arévalo et al. (2012, 2013)). In those cases the liquid was enclosed in a transparent vessel, so the observation can be done through transparent windows. But, as veins are opaque, the blood flow visualization has to be done in a different way.

A different way of visualizing the blood flow can be done by using endoscopes, which are designed for inspection of places that cannot be easily accessed, like body cavities and biological tissues or some inner parts of machines or structures. Several authors have proposed the combination of optical metrology with endoscopes (Kemper et al. (2000), Schedin et al. (2001)). In those works, solid mechanics information is obtained through interferometric based techniques but no fluid mechanics is involved in the process.

In this work we propose the combination of well known measurement techniques such as high speed PIV and digital holography to obtain both fluid mechanics (flow velocity field) and solid mechanics (wall deformation) information in a model of a vein using commercial endoscopes. There are several possibilities which we are going to explore in this work. A priori, the simplest technique to be implemented with endoscopes is PIV: the flow velocity can be obtained using PIV illumination and endoscopic image recording. Even more, one or two endoscopes can be set in a stereoscopic configuration, to measure the velocity inside an opaque vessel. Digital holography can be implemented combining endoscopic illumination and imaging. The reconstructed phase should provide information on the wall deformation while the reconstructed intensity should allow calculating the velocity field. Thus, the main purpose of this work is to study the performance of three different endoscopes (an arthroscope, an otoscope and a laparoscope) with the techniques mentioned above and to show some preliminary measurements obtained in different vein models.

2. Endoscopes and vessels

Three commercial rigid endoscopes with a viewing direction of 0° (made by ST Endoscopy) have been used
to access inside the vessel. The laparoscope (figure 1) has a working length of 300 mm, a diameter of 10 mm, a field of view of 75° and a working distance from 10 mm to infinity. The otoscope, which is an optical diagnostic instrument used for the study of the internal ear, has smaller dimensions than the laparoscope (50 mm of working length and 4 mm of diameter) but has also a wide vision angle. The arthroscope (180 mm of working length and 4 mm of diameter), has been custom made with the same lenses as the laparoscope in order to have the same field of view and working distance, with a smaller working length.

Silicon tubes and small balloons were used as vein models. These materials are opaque and have different grades of flexibility. In these experiments no real veins were used. However from now on we will refer to the vessel models as ‘veins’. Due to the blood vessels opacity, the illumination and observation directions cannot be normal to the vein wall. On the other hand, the real flow velocity field is to be measured and the endoscope should not disturb it. Thus the endoscope has to be located outside the flow. For these reasons the vein is coupled with a transparent tube at both ends (Figure 2a), made of glass or PVC, which is transparent enough to allow illumination and observation through it. Figure 2b is a photograph of the setup used with the laparoscope.

A special mixture of glycerin and water is used to simulate the blood. This mixture has a viscosity similar to the blood one and the same refractive index as the silicone (1.4185). This liquid was pumped into the model with a diaphragm pump and a shock absorber was connected to the rubber pipes to remove the vibrations produced by the pump. The flow rate could be controlled by changing the voltage that feeds the pump, up to a value of 300 ml/min. The model was immersed in a rectangular glass cell filled with the same liquid that the veins in order to avoid reflections in the external model walls. For measuring the flow velocity the fluid was seeded with polypropylene particles (10 μm in diameter).

**Preliminary analysis of the endoscope performance**

Several are the advantages of using endoscopes. One of them is the illumination system which is included in the device. It consists of a bundle of fibers distributed around the lenses. The input light port is lateral (C, figure 1). The fibers output are in the distal end of the endoscopes (B) and are located in an external circle. Some preliminary studies were done with the otoscope in order to know the output light distribution and the extension of the visualized region. Figure 3a shows the light distribution just at the point B of the otoscope. The optical fiber distribution can be clearly seen. The light distribution at 15 mm from B is shown in Figure 3b. In that position the illuminated region is big enough to cover the whole vein diameter. Similar results were obtained for the laparoscope and the arthroscope.
velocity components in each point are obtained from correlating corresponding small regions on each

In PIV the fluid is illuminated with laser light and is seeded with particles that will act as tracers. Two

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An oblique observation produces a perspective distortion in the image as it is shown in figure 4. There, we
can see an image of a scale attached to the vein as it is produced with the laparoscope looking inside the
vein. There is an important difference in the area visualized when the vein is full with liquid. As the
visualized area is smaller, the perspective distortion affecting the image is also reduced. This distortion is
exclusively perspective distortion, that is, it is due to the fact that the vessel is not observed at 90º but at an
angle. As the endoscope end can be immersed in the liquid, the image is not affected by the
distortion/aberrations due to the change in the refractive index. Thus, the endoscopes can be used in a
stereoscopic configuration and no liquid or glass prisms have to be used as in other stereoscopic experiments
in liquid flows (Prasad and Adrian, (1993), Lawson et al. (2005)).

The perspective distortion can be corrected by using double systems, as in regular stereoscopic PIV, where
two similar endoscopes observe the same region from different points of view with a stereoscopic
configuration. Besides, this configuration will allow the application of stereoscopic PIV for the measurement
of the three velocity components (Arroyo and Greated (1991)). Figure 5a shows the results obtained when a
small scale was introduced inside the vein and was visualized using two otoscopes in a stereoscopic
configuration. The deformation was corrected (figure 5b) using both images and the commercial software
Davis 7.2 from LaVision. One important result of the stereoscopy correction is that it increases the spatial
resolution of the region further away from the endoscope end.

3. Endoscopic high speed PIV

In PIV the fluid is illuminated with laser light and is seeded with particles that will act as tracers. Two
velocity components in each point are obtained from correlating corresponding small regions on each

Fig. 3 Otoscope output light distribution a) close to its end; b) at 15 mm from the otoscope end.

Fig. 4 Perspective distortion obtained when the laparoscope is viewing inside the vein: a) without liquid; b) with liquid.

Fig. 5 Stereoscopic configuration: a) a scale is visualized from two directions with two otoscopes; b) resulting corrected
image
intensity distribution. A maximum in the correlation function is obtained, and its position indicates the particle displacement.

To combine PIV and endoscopy, an artroscope was used as the imaging system in a high speed PIV set-up. The central plane of the vein was illuminated with a laser sheet and the artroscope formed its image on a high speed camera sensor. The high speed system consists of a two-cavity New Wave Pegasus laser (λ = 527 nm, energy per pulse = 10 mJ at 1000 Hz), each cavity with maximum repetition rate of 10000 Hz. A Photron Fastcam SA2 camera was used for recording 12 bits PIV images at 1000 frames/s, (ΔT= 1 ms). The camera sensor has 2048x2048 pixels (10μm pixel size).

The set-up used for the high speed PIV measurements is shown in figure 6. The vein is illuminated from above, so the light is travelling from top to bottom. The angle between the endoscope and the illuminated plane (θ) can be changed easily from 90º as in a regular PIV experiment, to 10º as in a stereoscopic PIV configuration. The endoscope is also forming an angle γ with the xy plane. The lens L was chosen with a focal length f= 100mm, so the image filled the whole camera sensor. The mirror (figure 6a) allows the image adjustment on the sensor without moving the camera. In order to evaluate the artroscope performance as imaging system in a PIV experiment, the vein was a glass tube (inner diameter: 12 mm, external diameter: 16 mm) connected to the pump with rubber tubes. For these experiments, the flow rate was set at 230 ml/min.

Images were recorded with θ = 90º, where the image corresponds to a regular PIV image (vein longitudinal section) and with θ = 40º. Figure 7a shows the image provided by the endoscope for θ = 90º. A small section of the vein is imaged (image magnification, M=1.14). The velocity vector map was obtained with the software Davis 7.2 from LaVision. The final interrogation area was 32x32 pixels, with an overlapping of 50%. The velocity vector map can be observed in figure 7b. For clarity, only one out of four velocity vectors is plotted. The vector color represents the velocity magnitude. The velocity field shows the typical parabolic profile corresponding to a viscous liquid moving along a pipe. The maximum velocity magnitude was 75 mm/s, giving a flow rate of 252 ml/min, similar to the theoretical value.

Figure 8a shows the vein image for θ = 40º, where the perspective distortion can be appreciated. The image magnification is not constant, and changes along the image. Figure 8b shows the displacement in pixels. In order to obtain the displacement and velocity in mm, the image has to be corrected as in stereoscopic PIV. Then, a calibration scale inside the liquid is recorded (figure 9a) and corrected (figure 9b) using a commercial software which gives the appropriated conversion from pixels to mm.
Fig. 7 a) PIV image recorded with the artroscope at 90°; b) Velocity vector map.

Fig. 8 a) PIV image recorded with the artroscope at 40°; b) Displacement vector map in pixels.

Fig. 9 a) Calibration scale image; b) Corrected scale image.

The corrected PIV image and the corresponding velocity vector map are shown in figure 10a and b, respectively. Here, the measured area is bigger than in the case when the endoscope was at 90°. As the image is corrected, the spatial resolution in the image left side is increased. However, smaller values of the velocity...
magnitude are obtained. Now, the maximum velocity magnitude is 65 mm/s, which gives a flow rate of 220 ml/min, close to the theoretical value.

![Fig. 10 a) Corrected PIV image; b) Velocity vector map.](image)

#### 4. Digital image plane holography: Theory

In digital image plane holography an object is illuminated and its image (the object wave \( o(x,y) \)) is formed with a lens in a digital sensor, where it will interfere with a reference wave, \( r(x,y) \). These waves have a complex form that can be written as:

\[
o(x,y)=A_o(x,y) \exp\left[j\phi_o(x,y)\right] \quad r(x,y)=A_r(x,y) \exp\left[j\phi_r(x,y)\right]
\]

(1)

where \( A \) is the wave amplitude and \( \phi \) the phase. The hologram intensity is given by

\[
I(x,y)=A_o^2+r(x,y)^2+2A_oA_r\cos(\phi_o-\phi_r)
\]

(2)

This expression shows that the hologram preserves both, the amplitude and the phase of the waves. The equation (2) can also be written as

\[
I(x,y)=|r(x,y)|^2+|o(x,y)|^2+\ast(r(x,y))|o(x,y)+r(x,y)\ast(x,y)
\]

(3)

In the particular case where the reference beam is a divergent wave with its origin in the lens aperture plane, the recorded hologram is a lens-less Fourier hologram of the aperture (Schnars and Jueptner, 2005). The hologram Fourier transform will reconstruct the object wave at the reference source plane (Lobera et al, 2004), and can be expressed as,

\[
I\{I(x,y)\} = I\{R(\xi,\eta)\} = A_r^2\delta(0,0)+A_o^2S(\xi,\eta)+I\{r \ast\}+I\{o \ast\}
\]

(4)

The two first terms correspond to the object and reference wave spectrum, and lie in the image center. The third and the fourth terms are the virtual and the real images of the aperture respectively, which are completely separated. Any of them can be isolated and centered, its inverse transform calculated and the object obtained in the image plane (sensor plane).

When two holograms are recorded in different times, separated \( \Delta T \), the reconstructed intensity distributions can be taken as PIV images (Hinsch, 2002) while the phase distributions can be analyzed by an interferometric approach (Vest, 1979) The subtraction of the two phase distributions gives a map which is related to the displacement \( d \) in \( \kappa \) direction such that,
\[
\Delta \phi = K \cdot d = \frac{2\pi}{\lambda} \left( \vec{u}_0 - \vec{u}_i \right) \cdot \vec{d}
\]

where \( K \) is known as sensitivity vector and depends on the observation \( \vec{u}_o \) and illumination \( \vec{u}_i \) directions.

5. Endoscopic digital image holography: experimental results

Figure 11a shows a schematic of the experimental setup, which is based on off axis digital holography. A solid state laser of 532 nm is used for illumination. The laser beam is splitted in two beams with a wedge. Approximately, 5% of the original intensity forms the reference beam, while the rest is used to illuminate the vein. For an easy access to the system, both beams are guided by two monomode optical fibers. The vessel is illuminated through the endoscope. A 50 mm focal length lens has been used as an ocular lens in order to image the object into the CCD sensor (size 640 x 480 pixels, 6.7 µm x 6.7 µm per pixel). The reference beam is directly sent to the sensor through a beam splitter.

The first experiments were done using the otoscope for illumination and recording inside two vein models. These models consisted of a portion of flexible material attached to a glass tube. Visualization was done as it is shown in figure 11a. With the objective of avoiding the air-glass interface reflections and aberrations an auxiliary glass tube is attached to the model and filled with glycerin (which has the same refractive index as glass). The endoscope is inserted in this auxiliary tube (figure 11b).

![Fig. 11](image)

**Fig. 11** a) Sketch of the off-axis digital holography setup; b) sketch of the vessel visualization system; c) model A; d) model B

Figure 11c shows the so-called model A. The vessel consisted of a silicon tube, with both ends open so that it could be used in a closed circuit with a pump, and connected to the main glass tube. As the optimum visualization is obtained with the otoscope as parallel to the vein as possible, the auxiliary tube was at an angle \( \theta = 13^\circ \). This is the smaller angle that was possible to achieve by connecting both glass tubes. The results obtained in model A are shown in figure 12. The vessel diameter was 6 mm and the recorded area had a length of 20 mm. A volume was illuminated using the endoscope illumination system. Glycerin seeded with particles was falling freely inside the vertical tube. The big bright spots observed in figure 12a are some of the seeding particles. Curved particle traces can be observed if four consecutive images are superimposed (figure 12b). These traces are transformed into straight lines when the image is corrected of the perspective distortion (figure 12c). As the otoscope aperture is small, the whole illuminated volume is in focus. Therefore the velocity vector map can be calculated using a PIV algorithm (figure 12d).

Holograms were also recorded in order to analyze the vein deformation. However, the fringes in the phase maps had low contrast and there were doubts about which part of the model was being visualized.
Fig. 12 a) View of the liquid seed with particles that is flowing inside the vessel; b) four superimposed consecutive images of the glycerin flowing; c) corrected image; d) measured displacement map.

Then, model B (figure 11d) was used as it provides a better visualization direction. Model B was built to allow a complete visualization of the vessel (a small balloon in this case), by attaching the auxiliary tube at $\theta = 90^\circ$. Holograms were recorded while the balloon was deformed by blowing inside the model with a straw. Figure 13 shows the obtained phase maps. Looking at the fringe distribution we can conclude that the otoscope is recording information from the balloon bottom and from its wall.

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Using the otoscope presents an important drawback: the visualized area, even when the vein is full of liquid, is quite large. Due to the perspective distortion, the region further away from the otoscope end is compressed in the image. Thus, the spatial resolution decreases making difficult to resolve the fringes in the phase maps.

Then, the otoscope was changed by the laparoscope and new measurements were done. Experiments were done in a model that was a transparent rigid PVC tube with a balloon attached at its end (figure 14a). The first task was to analyse the influence of the liquid inside the vessels into the measurement of the wall deformation. The laparoscope was introduced in the tube and the balloon was deformed by introducing a straw and blowing softly trough it. Figure 14b shows an example of the phase maps obtained in such conditions. Good quality fringes were obtained.

In order to prevent any disturbance from the endoscope, in real measurements, the laparoscope has to be placed outside the vessel. Thus, the inner vein wall was visualized from the outside of the vessel (figure 15a and b). Both the balloon and the laparoscope were immersed in glycerin and the deformation of the balloon is achieved in the same way as before.
The deformation of the outer and inner wall of another vessel model were also measured using the set up shown in figure 2b. A piece of soft rubber (the vein) was attached at both ends to rigid PVC tubes. The vessel was immersed in a mixture of glycerine and water, with the same refractive index as the PVC and the whole system was connected to a pump in a closed circuit. The laparoscope end was also immersed in the mixture. Figure 16 (a,b) shows the phase maps obtained for the deformation of the external wall, while figure 16 (c,d) shows the phase maps for the internal wall deformation.

Fig. 16 Phase maps obtained from the external vein wall deformation (a, b) and the internal vein wall deformation (c, d).

6. Conclusions
The performance of three different commercial endoscopes combined with well established measurement techniques has been studied. A high speed PIV system has been adapted to be used with an arthroscope as its imaging system showing that it is possible measuring velocities with normal visualization (θ = 90º) or at a smaller angles (θ =40º). On the other hand, digital holography has been combined with endoscopy for the study of confined flows in configurations with a very limited optical access. Some preliminary results have been presented, showing that it is possible to obtain both the flow velocity inside the vein as well as the vein deformation.

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6. References