COMBINED HIGH SPEED STEREOSCOPIC P.I.V MEASUREMENTS AND UNSTEADY PRESSURE MEASUREMENTS IN THE VANELESS DIFFUSER OF A CENTRIFUGAL PUMP.

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ABSTRACT

The paper refers to the behavior of the flow in a vaneless diffuser of a radial flow pump operating at partial flow rates or in transient conditions. Some new experimental data have been obtained using 2D/3C High repetition rate PIV within the diffuser, in various operating conditions. These tests have been performed on a test rig with the so-called SHF impeller, using air. Pressure measurements on the shroud wall of the vaneless diffuser and on the suction pipe of the pump have also been used in order to characterize the unsteady flow especially when rotating instability appears, at partial flow rates.

Introduction.

Rotating instability in the vaneless diffuser of a centrifugal pump or compressor is a low frequency and high amplitude phenomenon which can cause damage and noise. It also affects the performance of the pump or the compressor.

The behavior of vaneless diffusers of radial flow pumps, fans and compressors has been widely studied theoretically, experimentally and numerically (Jansen 1964, Senoo et al 1977, Nishida et al 1988, Kobayashi et al 1990, Ferrara et al 2004). Tsujimoto et al (1996) have used a two-dimensionnal inviscid and incompressible flow analysis to study the rotating stall of vaneless diffuser. They suggest the existence of a two-dimensionnal core flow instability at the onset of rotating stall in vaneless diffusers. There is still a need for a better knowledge of the complex flow fields that can be encountered during the development of rotating instabilities. The development of PIV allows for such a better understanding (Hayashi et al 2000).

Levjar et al (2006a) have conducted numerical calculations using a two dimensional viscous incompressible flow model to decide if 2D instabilities in the diffuser can contribute to rotating stall. They have compared their results to already published (Wuibaut et al 2000, 2001a, b, c) PIV measurements performed in the vaneless diffuser of a centrifugal pump (Levjar et al 2006b). In order to make better comparison between experiments and calculations and to improve the knowledge of the flow, new experiments, associating PIV and unsteady pressure measurements, have been conducted on the same test-rig. The diffuser has a larger outlet radius compared with the one used in the previous experiments, in order to obtain operating conditions with well established rotating instability. Preliminary results of these experiments are presented here.

Beside, space launcher turbopumps are characterized by fast start-ups: actually, the time delay between the inception of the shaft rotation and the nominal flow conditions is usually close to one second. It means that the rotation speed increases from zero up to several tens of thousands of rotations per minute during a single second. Such a fast start-up results in severe transient effects. Several studies have aimed at understanding the phenomena occurring during fast transients ((Tsukamoto & Ohashi 1982, Saito 1982, Picavet & Barrand 1996, Tanaka & Tsukamoto 1999, Bolpaire et al 2002). Theoretical models predicting the behaviour of the pump characteristics during the start-up have been proposed (Tsukamoto & Ohashi 1982, Saito 1982, Dazin 2007). The precision of these models is limited by the limited knowledge of the pump internal flows during transient operations.

It is clear that the study of such complex and unsteady flows that the ones encountered in turbomachines operating in unstable or transient conditions is strongly limited by the standard experimental techniques : these ones are either resolved in time (LDV, hot wire, unsteady pressure measurements) or in space (Particle Image Velocimetry, Particle Tracking Velocimetry). The recent development of high repetition rate Particle Image

Velocimetry allows obtaining velocity measurements resolved both in time and space. This paper reports some results of a measurement campaign of high repetition rate PIV coupled with unsteady pressure measurements realised in the vaneless diffuser of a centrifugal pump in transient or steady operations at partial flow rates. Some specifics problems encountered during these experiments are also described.

Test Rig

The tests refer to the so-called SHF impeller matched with a vaneless diffuser. They have been made in air, on a test rig (Fig. 1) well adapted for studies on interactions between impeller and diffuser, as there is no volute downstream of the diffuser. The test rig is also well adapted for the use of optical methods and especially Particle Image Velocimetry (PIV). It has been used for a lot of studies with the same impeller:

- Studies with a short vaneless diffuser (Wuibaut et al 2001a, b, c)
- Studies with two different vaned diffusers (Wuibaut et al 2002a, Dupont et al 2005)

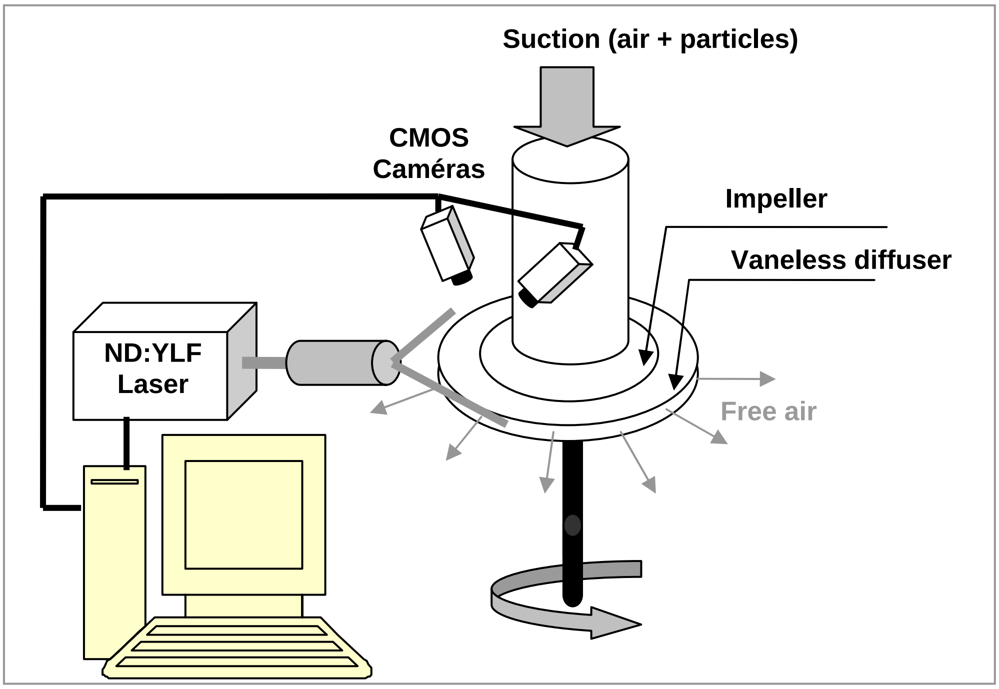


Fig. 1 : Experimental set-up.

The present study refers to new experiments combining pressure measurements and 2D/3C High Speed PIV at partial flow rates within a new vaneless diffuser with a large outlet radius, in order to obtain conditions with well established rotating instabilities.

The main characteristics of the so called “SHF” (Fig. 2) pump impeller used for tests in air are:

Outlet radius: R_2=256.6 mm
Tip inlet diameter: R_1 = 141.1 mm
Number of blades: Z_1=7
Outlet width: b_2 = 38.5 mm
Outlet blade angle measured from the peripheral direction: 22.5°
Mean blade thickness: 9 mm
Nominal speed of rotation: N=2500 rpm
Design flow rate : Q_d=0.336 m^3/s (at 1710 rpm)
Reynolds number : Re=7.86 10^5

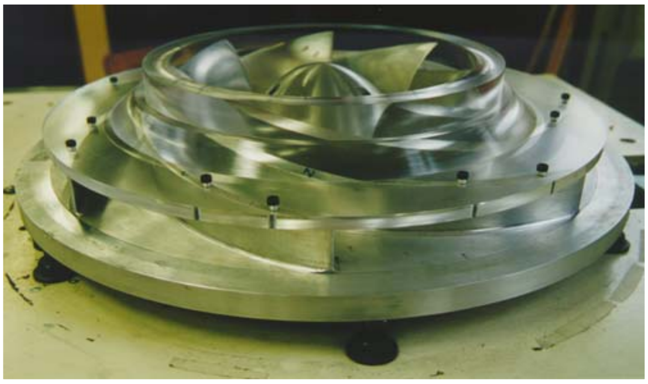


Fig.2: SHF Impeller.

The main characteristics of the new vaneless diffuser are:

Inlet radius: R_3 = 257.1 mm
Outlet radius: R_4 = 390 mm
Constant width: b_3=40 mm

The rotation speed of the impeller during these experiments was 1200 rpm.

Measurements.

Four Brüel & Kjaer condenser microphones (Type 4135) are used for the unsteady pressure measurements. Two of them were flush mounted on the shroud side of the diffuser wall (Fig 3). The two other microphones were flush mounted on the suction pipe of the pump at 150 mm from the impeller inlet. The data are acquired by a LMS Difa-Scadas system. The sampling frequency was 2048 Hz.

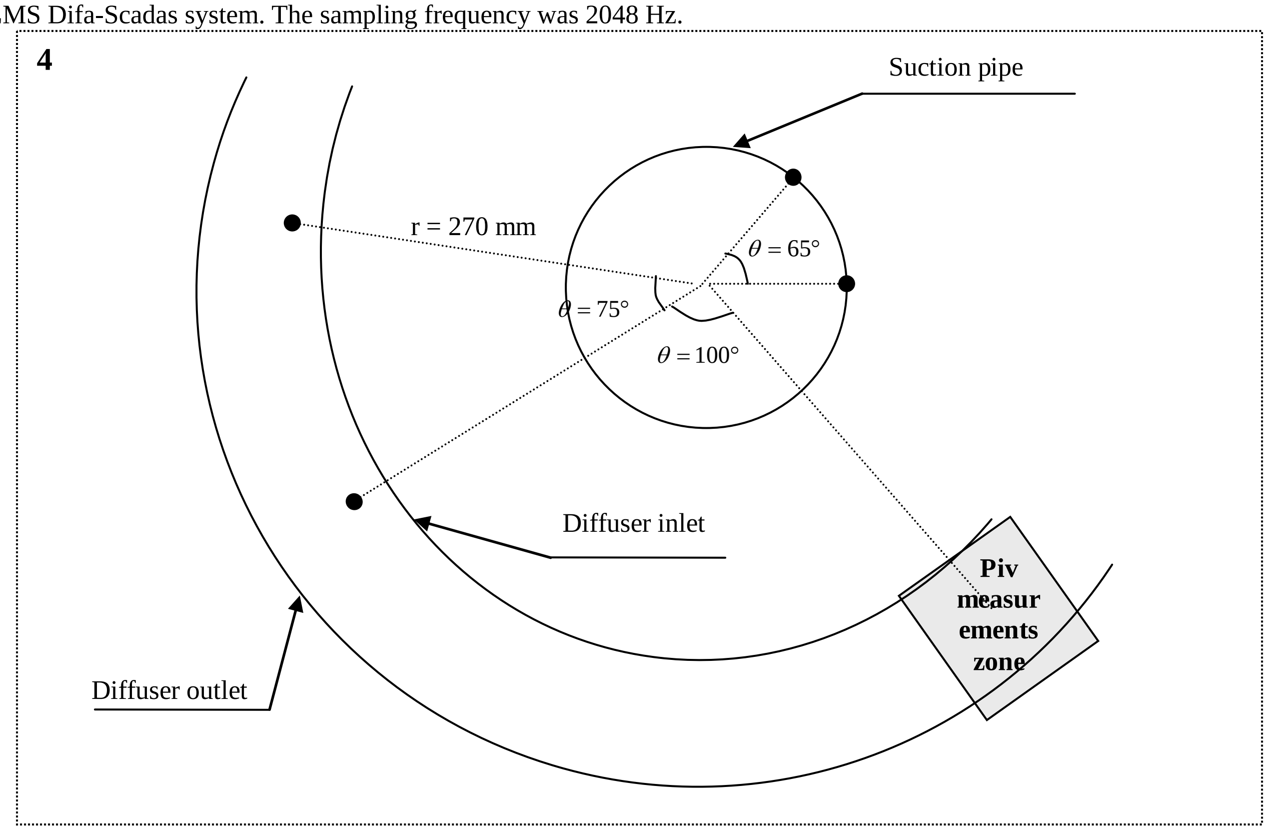


Fig 3 : Location of the pressures sensors.

For PIV measurements, the laser sheet is generated by a Darwin PIV ND:YLF Laser (20 mJ/pulse) at quarter, mid or three-quarter-height of the vaneless diffuser. The frequency of both cavities of the Laser was 980 Hz. The time delay between the pulses of the two cavities was set to 110 or 130 μs depending on the flow rate.

P.I.V. snapshots have been recorded by two identical CMOS cameras (Phantom V9). A home made software developed by the Laboratoire de Mécanique de Lille has been used for the images treatment (cross-correlation was used with a correlation window size of 32 * 32 pixels^2 and an overlapping of 50%. Correlation peaks were fitted with a three point's Gaussian model). The results consist in fields of 80 x 120 mm^2 and 81 x 125 velocity vectors with a temporal resolution of 980 velocity maps per second during 1.6 seconds and so about 49 velocity maps every impeller rotations during 32 impeller revolutions. For each flow rate and each laser sheet height in the diffuser, two acquisitions of about 1500 velocity maps have been realised. The PIV system sends a signal to the LMS Difa-Scadas acquisition system in order to synchronize the pressure measurements and the velocity maps. Measurements were realised for 6 flow rates: the pump design flow rate and 5 partial flow rates: 0.26 Q_d, 0.45 Q_d, 0.56 Q_d, 0.66 Q_d and 0.75 Q_d

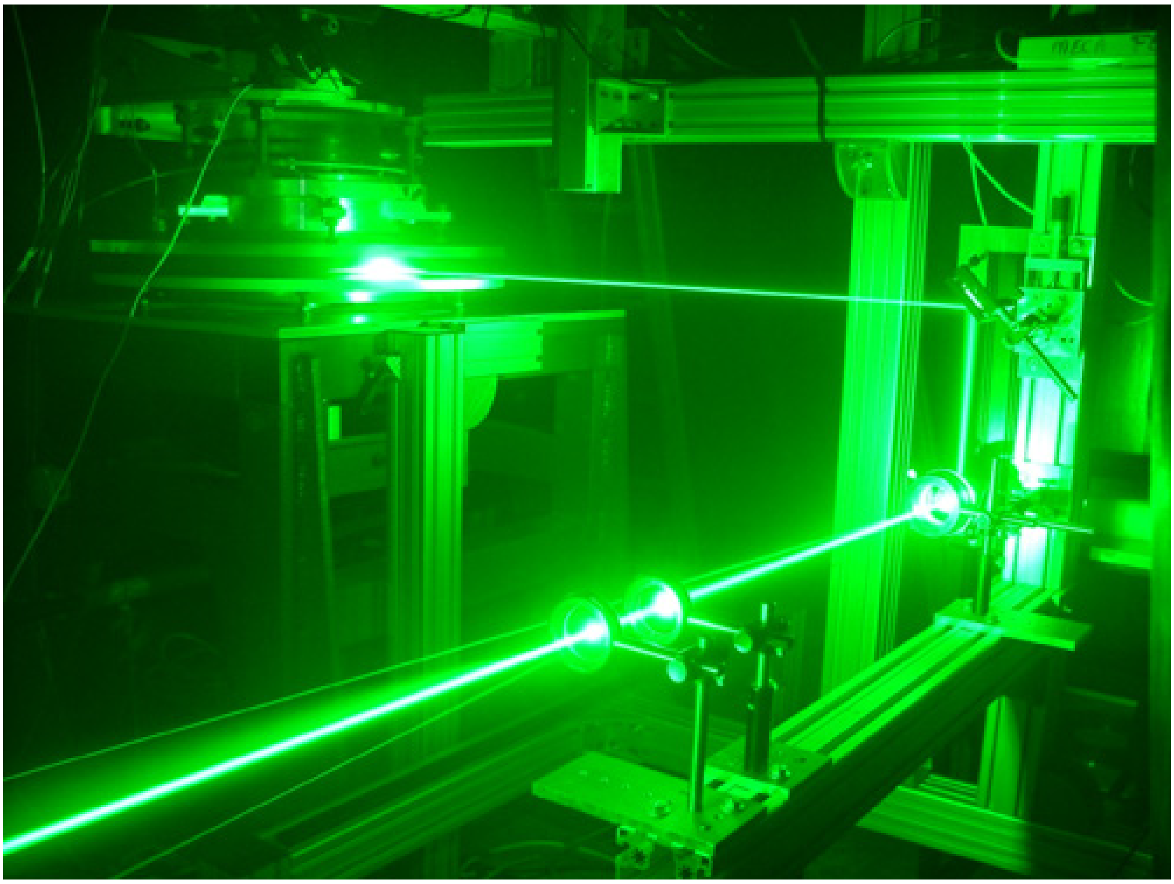
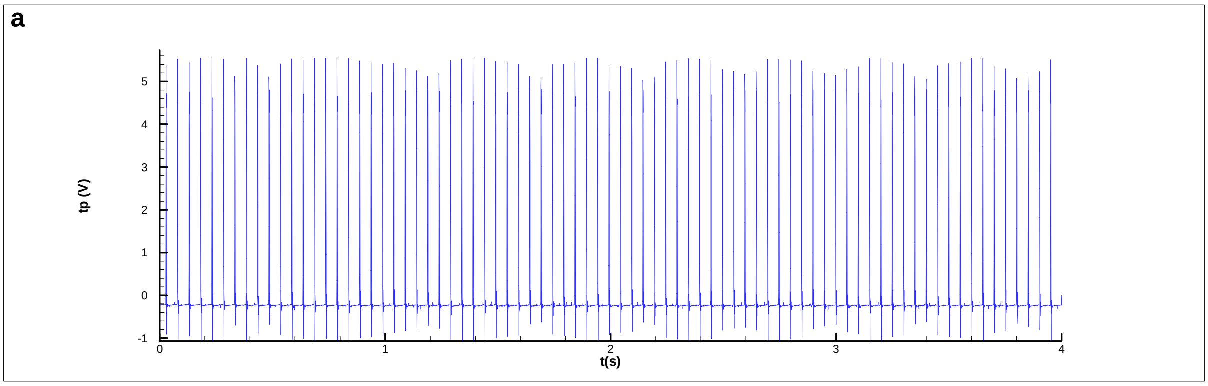


Fig 4 : experimental set-up

Determination of the instantaneous Impeller Velocity

The impeller velocity in this experimental test rig is usually obtained by a photoelectric cell pointing at a reflecting target pasted on the impeller shaft. It delivers a pulse at each impeller rotation. Examples of the signal delivered by the photoelectric cell during steady state operation and a start-up are presented in Fig. 5.



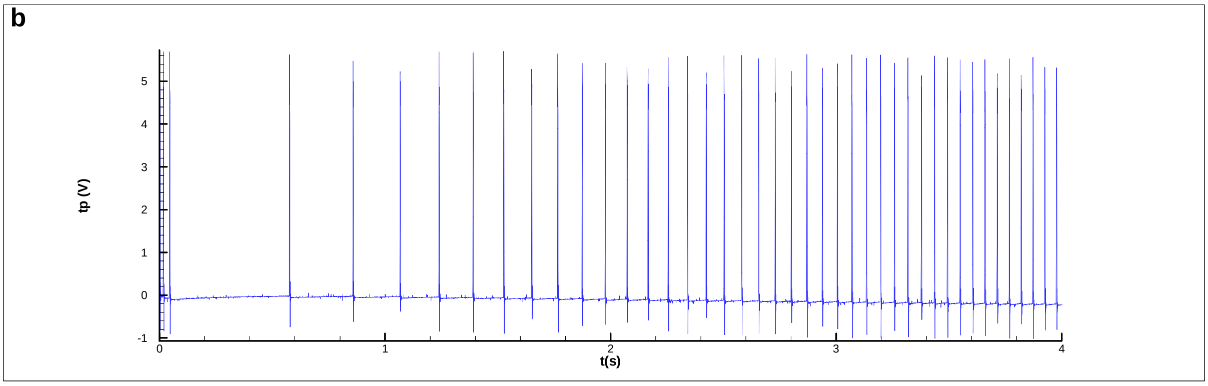


Fig. 5 : Signal delivered by the photoelectric cell during steady (a) and transient (b) operations.

The use of this kind of signal to determine the velocity of the impeller is efficient in the case of a constant impeller velocity (Fig. 5a) but is obviously not adapted to the case of a start-up. There is obviously a lack of information during the beginning of the start-up and especially during the first impeller revolution (0 to 0.5 s).
As a consequence, another technique has been used to determine the impeller velocity during the start-up. The idea is to use the unsteady pressure measurements obtained in the vaneless diffuser and to detect the blade passing frequency to deduce the instantaneous angular velocity of the impeller. For that purpose, a sliding Fourier Transform is performed on the pressure measurements: the time – frequency result of this operation is given in Fig 6.

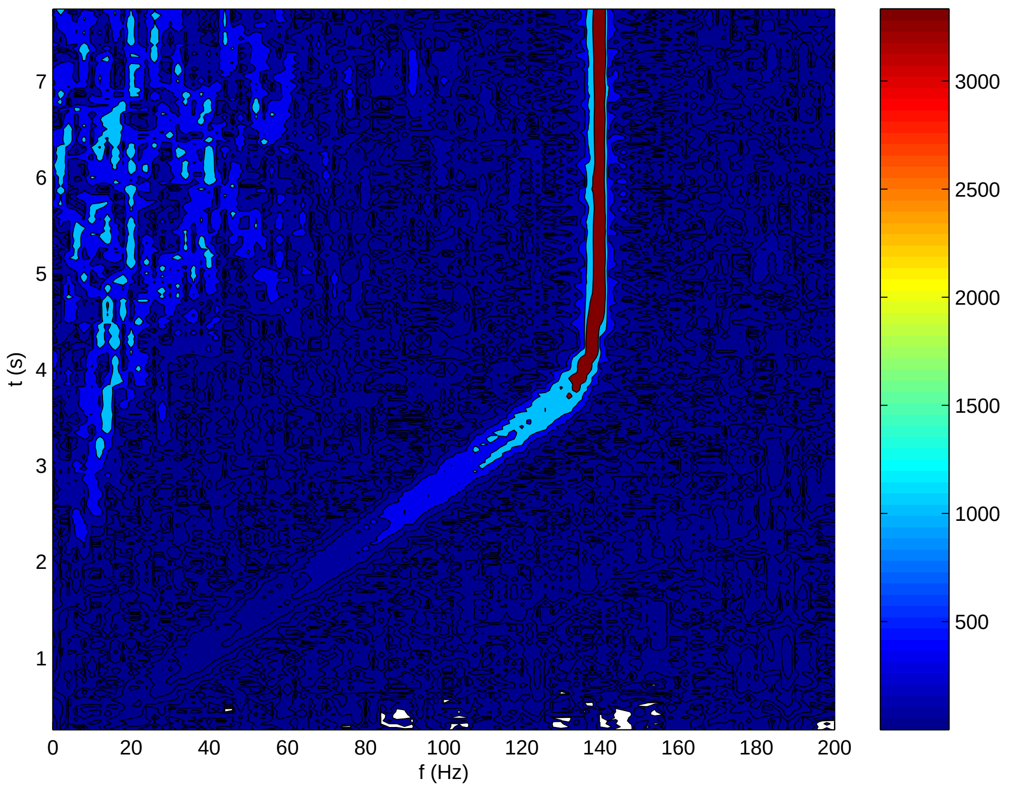


Fig 6 : Sliding Fourier Transform of the pressure measurements.

The high amplitude band corresponding to the blade passing frequency peak is obvious in this Fig. 6. The value of this frequency increases with time from zero to 140 Hz. At each time, the frequency location of this peak is detected and divided by the blade number to obtain the evolution of the rotation speed. (Fig. 7)

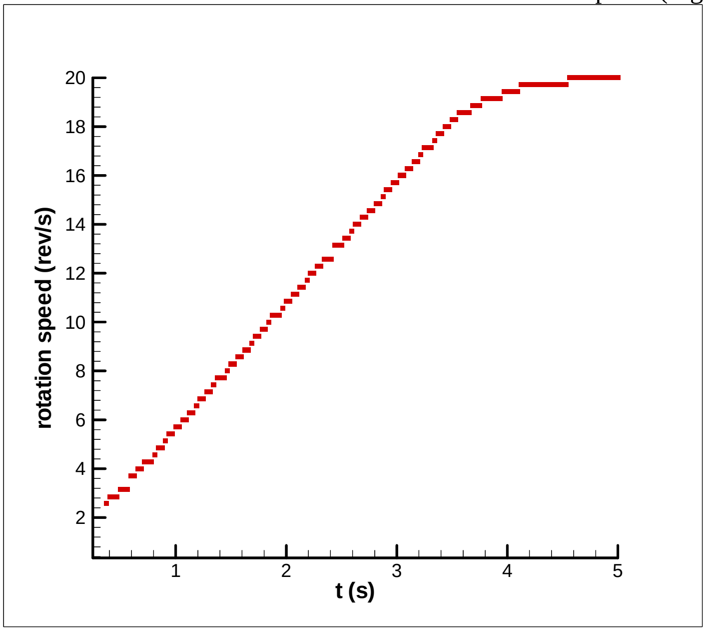


Fig 7 : Evolution of the rotation speed with time.

Problems encountered in the image processing.

Illumination problems

Performing PIV measurements in a turbomachinery is always a challenge because of uneasy optical access and light reflection on the walls.

During standard PIV measurements, the image recording is usually synchronised with the impeller rotation. Consequently, if some reflections occur, the corresponding overexposed zone in the images is fixed. On the contrary, during this measurement campaign the impeller is moving from one picture to another. As a consequence, the overexposed zone was also moving (Fig. 8).

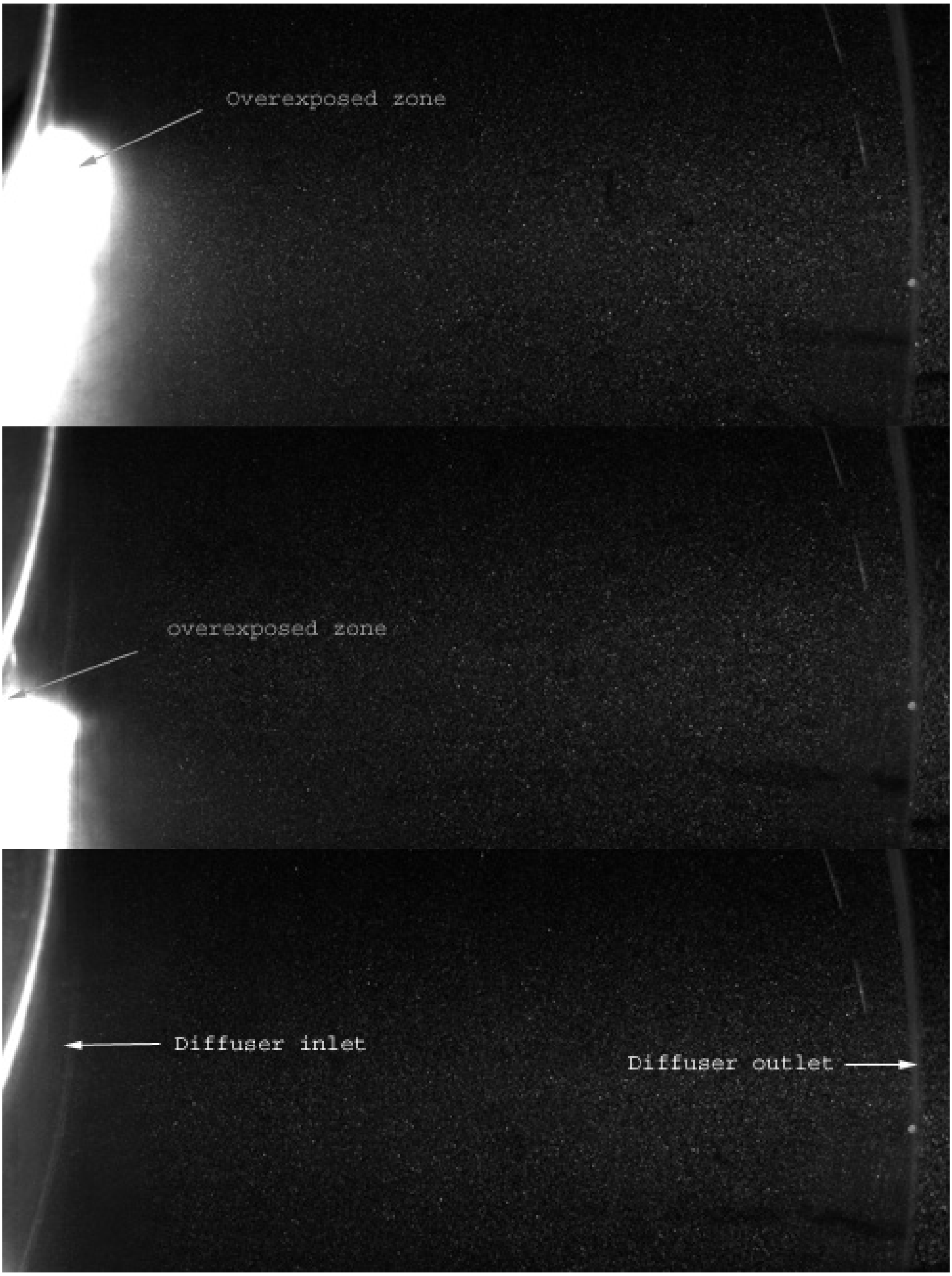


Fig 8 : 3 consecutives snapshots taken by one of the two cameras.

In order to estimate the total zone of the images that can be affected by the overexposure due the passage of the impeller an average image has been calculated over 1500 snapshots.

Fig 9 : Average image.

On the left side of this image, it appears that there is a large zone (about 200 pxls large) that is concerned with overexposure although the impeller has been painted in black to avoid reflection.

Another difficulty coming from this kind of measurements and illustrated Fig 9 is due to the weak energy delivered by the laser at each pulse (20 mJ, that is about 5 to 10 less than the energy delivered by the YAG Laser used in standard PIV). Consequently, it is difficult to have a large zone correctly illuminated by the light source. On Fig 9, it is clearly obvious than the upper side (zone 2) of the image is under exposed.

To estimate the effect of this under exposure on the quality of the PIV results, some statistics have been realised on the particles encountered in zone 1 and zone 2. The particle density in a interrogation spot of 32 x 32 pixels as well as well as their average diameter is reported in Table for zone 1 (correctly exposed zone) and zone 2 (underexposed zone). The RMS uncertainty (in pixels) due to the particle density and mean particle image diameter (Raffel et al 1997, Foucaut et al 2003) are also reported on the paper. Other parameters acting on the PIV accuracy are also reported in Table 1, in order to give the relative influence of the density and particle diameter difference between zone 1 and 2. It appears from results of Table 1, that in the underexposed zone, fewer particles are detected and with a smaller diameter. Consequently, as can be seen on Table 1, the RMS uncertainty increases slightly in zone 2 compared with zone 1.

Table 1 : Statistics on the mean particle image diameter and on the particle density for correctly exposed zone and underexposed zone.

	Zone 1	Zone 2
Particle density in a 32 x 32 pxls spot	16	10
RMS uncertainty due to particle density (pxls)	0.02	0.04
Mean particle diameter (pxls)	2.4	1.8
RMS uncertainty due to particle diameter (pxls)	0.02	0.04
RMS uncertainty due to stereoscopic reconstruction algorithm (pxls)	0.1	0.1
RMS uncertainty for a quiescent flow (pxls)	0.1	0.1
RMS uncertainty due to velocity gradient (pxls)	0.1	0.1
Total RMS uncertainty (pxls and % of the displacement).	0.34 pxl/ 3.8 %	0.38 / 4.2 %

Some techniques to improve the PIV algorithms in the case of problems of non uniform light intensity in the images does exist (Dazin 2003, Shavit et al 2006) and will be tested on this experimental results.

Conclusion

Some new experiments combining stereo time-resolved PIV and unsteady pressure measurements have been performed in the vaneless diffuser of a radial flow pumps in steady or transient conditions. The use of the pressure signals in the diffuser of the pump has been used to determine the impeller velocity during start-ups. The analysis of these experimental data should give results resolved both in time and space so some new information on unsteady phenomena like rotating instability in the vaneless diffuser of a centrifugal pump or flow behaviour during fast transients. Nevertheless the use of high speed PIV in a turbomachine has induced some specific difficulties (reflection on moving walls and non uniform intensity of the laser sheet that have been describe in this paper.) They effects of these problems have been quantified.

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