Proper orthogonal decomposition of the turbulent flow in an impeller of a centrifugal pump

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ABSTRACT

The flow field in the channels of a centrifugal pump impeller contains eddy motions of a wide range of time and length scales and identifying coherent structures and their dynamic behavior is not a trivial task. Thus, modal decomposition techniques have been used in order to improve the knowledge on turbulence and coherent structures. In this work, the proper orthogonal decomposition (POD) method is employed to identify the occurrence and development of the dominant unsteady flow structures in a centrifugal pump impeller. For this, experiments using a time-resolved PIV system for different operating conditions of pump impeller were carried out. The results show that in the range of the pump's best efficiency point (BEP) there is no significant flow separation. As the flow rate starts to decrease from the BEP flow rate, unstable flow phenomenon begin to appear and develop in the impeller. The POD analysis reveals that for low flow rates, the flow is dominated by large-scale structures with higher energy, while for the BEP and high flow rates, the flow is dominated by smaller-scale structures.

1. Introduction

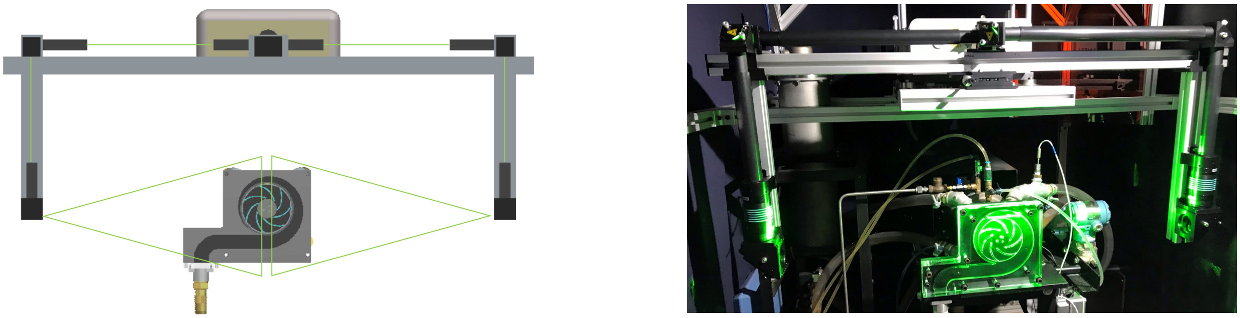
Flow in turbomachinery is a constant research topic in fluid dynamics, with applications in different engineering systems, from airplanes to oil facilities. This subject is particularly relevant for centrifugal pumps, which often operate out of their optimum condition. The internal flow structure in the impeller, which is the core component of the centrifugal pump, is quite complex at off-design conditions. When operating in these conditions, flow usually contains high temporal and spatial velocity gradients, high vorticity regions, flow separation zones, and high turbulence levels (Keller et al., 2014; Zhang et al., 2021).

One way to assess the characteristics of the flow fields in these devices is the application of optical techniques. Investigations using visualization techniques, mainly particle image velocimetry (PIV), were carried out over the years and they usually focused on flow features and global flow patterns (Pedersen et al., 2003; Li et al., 2020). However, as the flow field in the impeller is extremely complex, conventional visualization analyses are ineffective in determining turbulent flow structures. The proper orthogonal decomposition (POD) method (Lumley, 1967) has received increasing attention for assessing the flow, given its ability to extract coherent turbulent structures.

In this work, the POD method is used to decompose and analyze the large and small-scale flow structures in a centrifugal pump impeller. For this, experiments using real-time PIV for different pump operating conditions were carried out.

2. Experimental facility

A centrifugal pump was designed and built out of a transparent material for flow visualization purposes (Fig. 1a and 1b). The impeller has a radial geometry with seven channels of constant height and a small aspect ratio (about $h/D \approx 5\%$) to reduce the three-dimensional flow effects. The impeller outer radius is 55 mm and the inner radius is 22 mm. The volute spiral has a maximum radius of 32 mm. The pump was installed in a hydraulic circuit with instruments to measure pressure, temperature and flow rate.



(a) Illustrative scheme of experimental facility

(b) Photograph of the experimental facility

Figure 1. Experimental facility with focus on the PIV system and centrifugal pump prototype.

A 2D2C-PIV *DualPower 30-1000* time-resolved system from Dantec Dynamics Inc. obtained the velocity fields in the centrifugal pump impeller. The main components of the system are a laser, a high-speed camera (*Phantom VEO640*) and the DynamicStudio® software, used to control PIV measurements, obtain instantaneous velocity fields and perform POD analysis. Water was used as the working fluid. Fluorescent particles of PMMA doped with rhodamine B and average diameter of 50 μm were added to the water to serve as tracers. The pump prototype is illuminated from both sides by a dual light guide system composed of beam splitters, mirrors, and light-sheet optics. A high band-pass filter for the wave lengths above 545 nm is mounted on the camera lens, filtering all the light scattered by the interfaces and capturing the light fluoresced by the seeding particles. In the present work, the PIV acquisitions were performed at a fixed pump rotational speed of 900 rpm, while the water flow rate was varied at 0.3Q_{BEP}, 1.0Q_{BEP} and 1.5Q_{BEP}, where Q_{BEP} = 2.2 m^3/h is the pump's Best Efficiency Point (BEP). The rotational Reynolds number $Re = (\omega D)/\nu$ was of the order of 1×10^7.

A total of 4900 pairs of images were captured for each experimental condition. In order to compute reliable and consistent PIV velocity results, an image processing algorithm was used to mask out the impeller blades and volute regions from the PIV raw acquisition before sending the images to the PIV cross-correlation software. The PIV adaptive method (Scarano & Riethmuller, 1999) with initial and final interrogation regions of 64 and 32 px, respectively, was chosen. In addition, a procedure to remove the angular displacement of the impeller (in order to define a rotating frame of reference) was implemented based on the work of Liu et al. (2021).

A convergence test was performed for the POD analysis for three sets of image pairs (98, 490, and 4900) for the $0.3Q_{BEP}$ condition. The double frame real-time PIV acquisitions were conducted with a frequency of 735 Hz. With this temporal resolution, the impeller could complete a full revolution after 49 images. However, since the impeller has an angular symmetry of 51 degrees, it was considered that the flow in the pump impeller channels completed a full cycle after 7 images. From Fig. 2, it can be seen that there is a reasonable convergence for 98 acquisitions, i.e., after 14 complete cycles. However, all the results reported in this manuscript have been obtained from 490 pairs of images (70 cycles) in order to ensure well-converged velocity fluctuations fields.

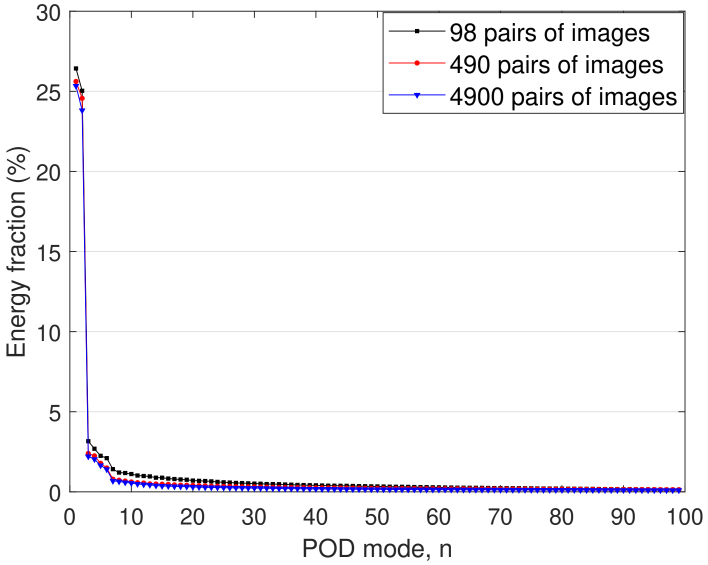
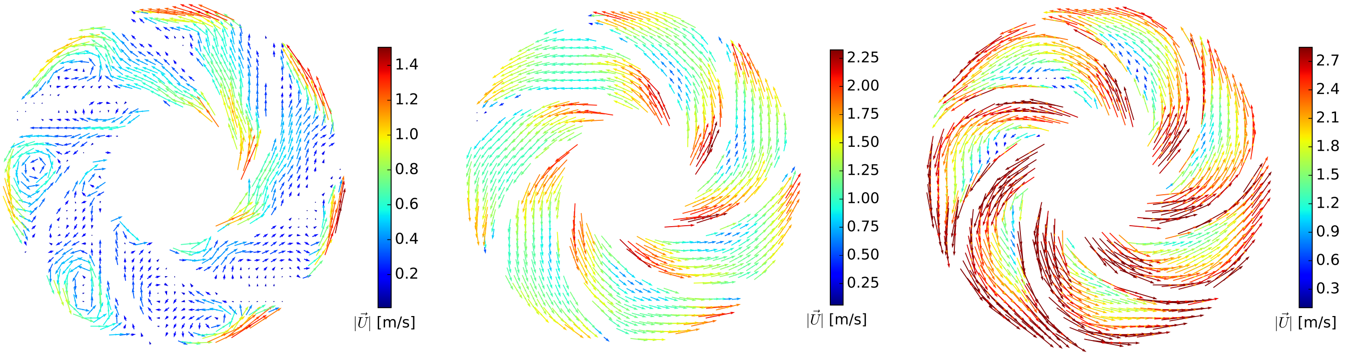


Figure 2. Convergence test of PIV acquisitions for POD analysis.

3. Results and discussion

The results of the phase-ensemble averaged velocity field under the different flow rates ($0.3Q_{BEP}$, $1.0Q_{BEP}$ and $1.5Q_{BEP}$) is shown in Fig. 3. As can be seen, in the range of the BEP ($1.0Q_{BEP}$), velocity vectors follow the geometry of the blades without significant flow separation. As the flow rate decreases to $0.3Q_{BEP}$, the flow tends to have re-circulation zones, making it unstable. This is associated with the secondary flows of the boundary layer caused by flow transition from pressure blade to suction blade and apparent forces (our frame of reference is non-inertial). In addition, for the flow rate higher than the BEP, the formation of small flow instabilities is noticed, which may be associated with the detachment of the boundary layer caused by an adverse pressure gradient (in addition to apparent forces).



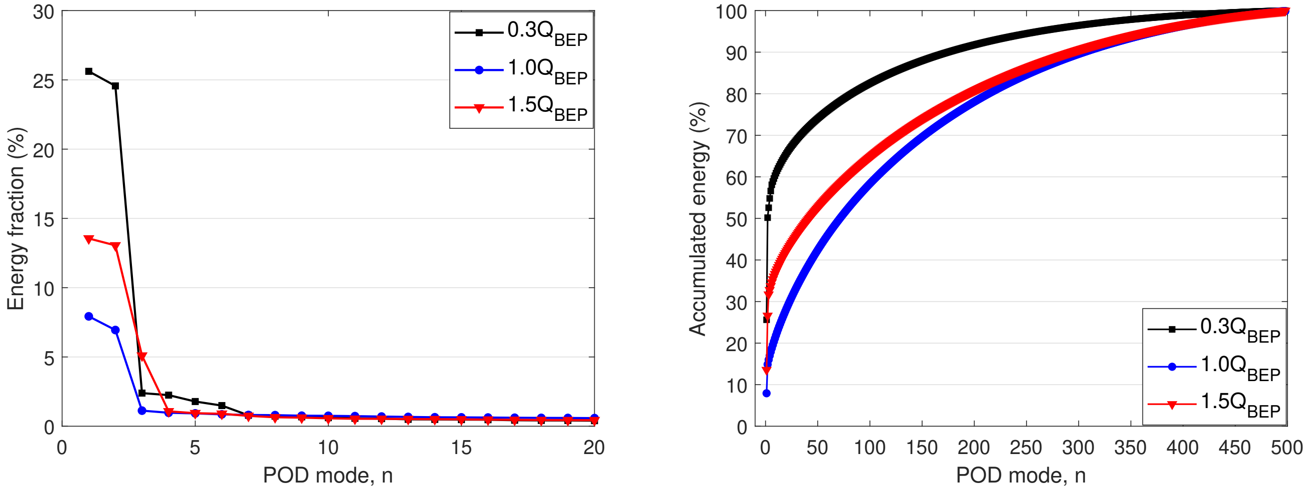
(a) $0.3Q_{BEP}$ (b) $1.0Q_{BEP}$ (c) $1.5Q_{BEP}$

Figure 3. Average velocity distribution in the centrifugal pump impeller.

Figure 4 shows the turbulent energy distribution as a function of the POD modes of the velocity fluctuation field, while Figs. 5–7 show the energy distribution of the first two modes from the three studied flow rate conditions. Note that for the lowest flow rate condition ($0.3Q_{BEP}$), 50% of the turbulent energy in the flow is concentrated in the first and second POD modes. This is due to the presence of large turbulent structures in the flow in this condition. It can be observed from Fig. 5 that there are regions with more intense reddish tones in these modes. This means that the velocity fluctuations in this region tend to be correlated. So looking at the first few modes for this condition is sufficient to identify dominant coherent motions.

For the design ($1.0Q_{BEP}$) and higher flow rate conditions ($1.5Q_{BEP}$), the first two modes are responsible for only 15% and 27% of the turbulent energy, respectively, with 70 and 40 modes being necessary to reach 50% of the energy (Fig. 4). From Figs. 6 and 7 it is observed that the flow velocity fluctuations for such conditions tend to be less correlated. This suggests that the large-scale flow with higher energy is broken into small-scale flow structure with lower energy, a process called in turbulence theory as cascade effect (Pope, 2000). Therefore, it is expected that the flow, in such conditions, to follow the impeller blade curvature smoothly.

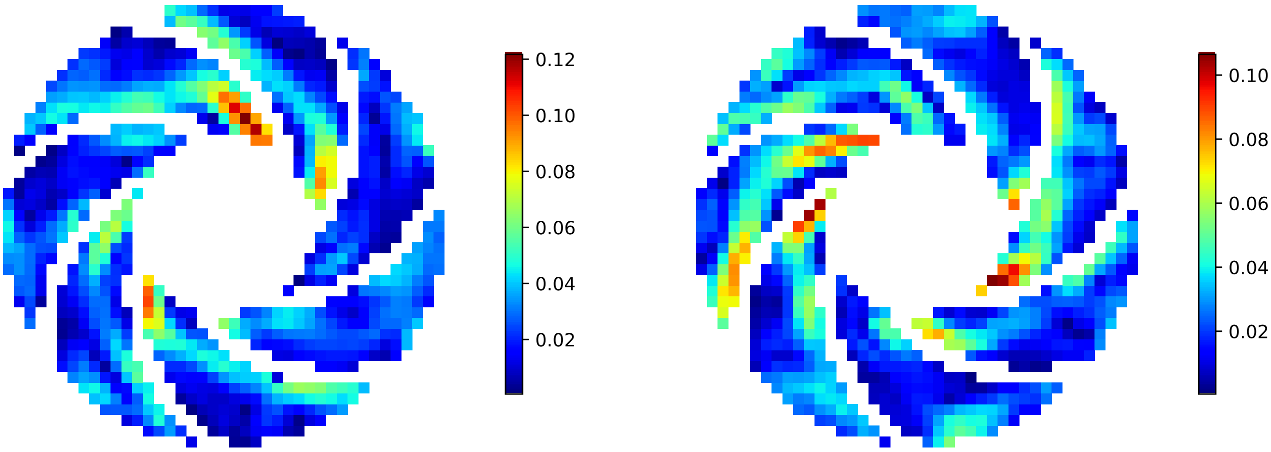
It is also expected that due to the uniformity of the flow at the BEP, more modes are needed to reconstruct the flow field in this condition. However, due to the presence of structures with high energy levels for the lowest flow rate and the formation of instabilities for the highest flow rate condition, a smaller number of modes will be needed for these cases.



(a) Energy fraction

(b) Accumulated energy

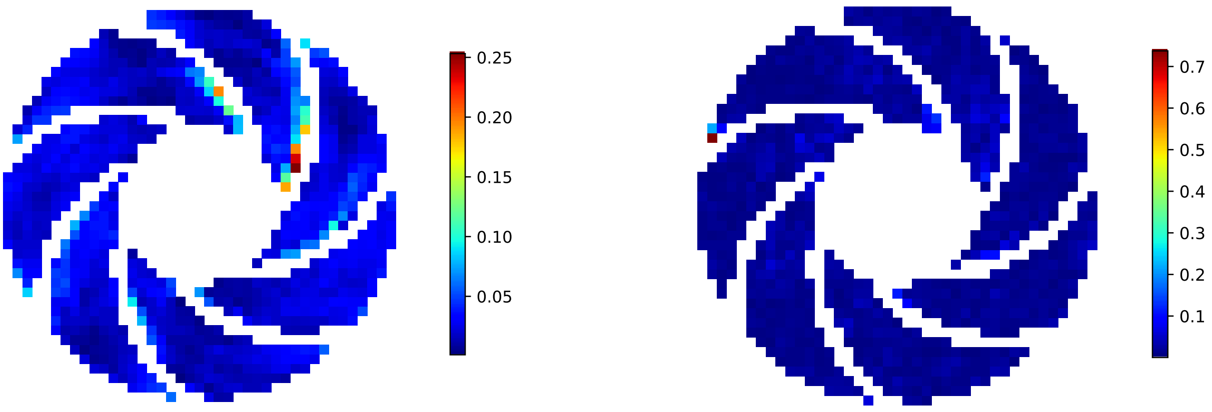
Figure 4. Energy distribution in the centrifugal pump impeller.



(a) Mode 1

(b) Mode 2

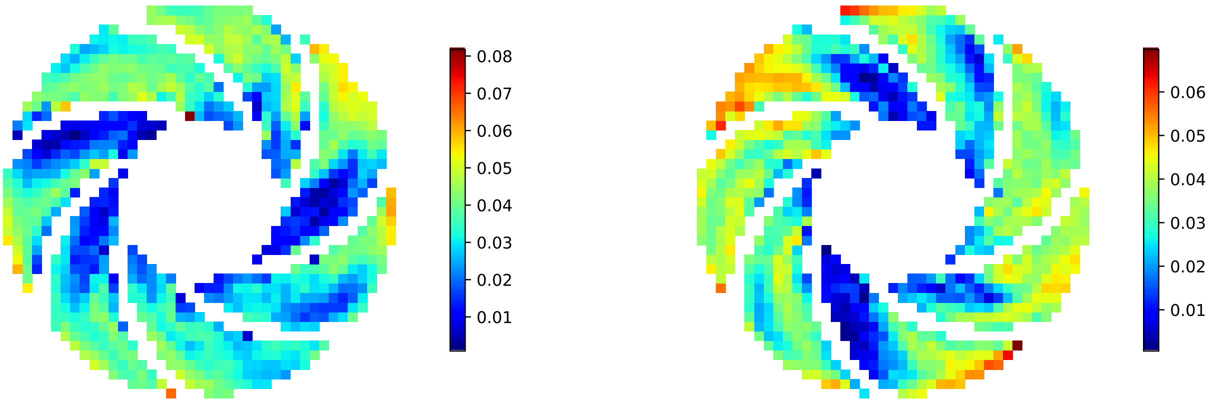
Figure 5. Spatial distribution of POD modes in the centrifugal pump impeller ($0.3Q_{BEP}$).



(a) Mode 1

(b) Mode 2

Figure 6. Energy distribution in the centrifugal pump impeller (1.0Q_{BEP}).



(a) Mode 1

(b) Mode 2

Figure 7. Energy distribution in the centrifugal pump impeller (1.5Q_{BEP}).

4. Conclusions

The POD method is used to identify the energetic flow modes with dominant unsteady flow patterns in a centrifugal pump impeller. Experiments using a time-resolved PIV system were performed at a fixed pump rotational speed of 900 rpm, while the water flow rate was varied at 0.3Q_{BEP}, 1.0Q_{BEP} and 1.5Q_{BEP}, being Q_{BEP} = 2.2 m^3/h the pump's BEP. The results indicated that for the lowest flow rate condition, several re-circulation regions started to develop. From the POD analyses, it was found that the first pair of modes are correlated, and 50% of the total turbulent energy is contained in these modes. Such results suggest the occurrence of possible coherent structures for this pump operating condition. As the flow increases to the design flow (1.0Q_{BEP}), the flow tends to organize itself and more POD modes are needed for flow reconstruction, an indication that such a condition is dominated by turbulent structures of smallest scales. The same is observed for the higher flow rate condition.

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