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Original Citation

Asim, Taimoor and Mishra, Rakesh (2015) Numerical Investigations on Vortical Structures in the Near Tongue Region of a Centrifugal Pump during Transient Operation. In: FLUVISU 2015, 16th-20th November, Pleumeur-Bodou/Lannion, France. (Unpublished)

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Numerical Investigations on Vortical Structures in the Near Tongue Region of a Centrifugal Pump during Transient Operation

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1. Abstract

Centrifugal pumps are considered to be an integral part of process industries around the world. The flow structure within centrifugal pumps is very complex due to the interaction between the rotating impeller and the geometric features around it, such as tongue. Researchers have been analysing the effects of the interactions between impeller blades and the tongue, however, most of these studies are based on steady-state approximations where the impeller blades are modelled using frozen-rotor approach which leads to discrepancies in the predicted flow fields. In the present study, fully transient numerical investigations, on the generation and dissipation of vortical structures in the vicinity of the tongue region, have been carried out using a commercial Computational Fluid Dynamics (CFD) based solver. The instantaneous behaviour of a centrifugal pump is studied using the Sliding Mesh technique. Simulations have been carried out on both a constant rotating speed and under decelerating conditions. The second invariant of the velocity gradient tensor i.e. Q-criterion, has been employed to identify the generation and dissipation of vortical structures near the tongue region of the pump. The results indicate that the Q-criterion is fairly non-uniform downstream the tongue region due to the complex interaction between the impeller blades and the tongue. Furthermore, it has been observed that as the rotational speed of the centrifugal pump decreases, the Q-criterion in the near tongue region remains constant. The generation, expansion and subsequent mixing of two distinct vortical structures have been noticed downstream the tongue (within the volute), whereby the strength of these structures has been observed to be decreasing as the distance from the tongue increases.

2. Introduction

Centrifugal pumps have an important role in many different engineering applications. The design and performance prediction process of centrifugal pumps is quite complex. For this reason, CFD based analysis is currently being employed for the hydrodynamic design of various pump types as numerical simulations offer reasonably accurate information on the fluid behaviour within various systems, assisting the engineers to obtain performance envelope of a particular design [1-10].

There are several methods for the detection of vortical structures, where the method which is based on the velocity gradient tensor has been adopted in the present study. The vorticity and strain-rate tensors can be represented as:

$$\omega_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i}\right) \tag{1}$$

$$SR_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{2}$$

The velocity gradient tensor is:

$$D_{ij} = \omega_{ij} + SR_{ij} = \frac{\partial u_i}{\partial x_j} \tag{3}$$

The characteristic equation for the velocity gradient tensor is:

$$\lambda^3 + P\lambda^2 + Q\lambda + R = 0 \tag{4}$$

where P, Q and R are the three invariants of the velocity gradient tensor. The second invariant is known as Q-criterion, and can be represented as:

$$Q = \frac{1}{2}(\|\omega\|^2 - \|SR\|^2) \tag{5}$$

The Q-criterion defines vortex as a connected fluid region with a positive second invariant of the velocity gradient tensor i.e. $Q > 0$. This criterion also adds a secondary condition on the pressure, requiring it to be lower than the ambient pressure in the vortex. A close examination of equation (5) reveals that it is the local balance between shear strain-rate and the vorticity magnitude, defining vortices as areas where the vorticity magnitude is greater than the strain-rate [11-13].

3. Numerical Modelling of HCP Bends

The centrifugal pump that has been numerically modelled is model FH32/200AH Perdrollo. This pump has five backward type impeller blades, where the impeller diameter is 215mm. The inlet and outlet of pump have a diameter of 50mm and 32mm respectively. Detailed geometric dimensions of this pump model are available on the web. Figure 1 depicts the numerical model of the pump under consideration. It should be noted that both the inlet and the outlet of the pump have been connected to 0.5m long pipe sections in the numerical modelling in order to mimic real-world scenarios.

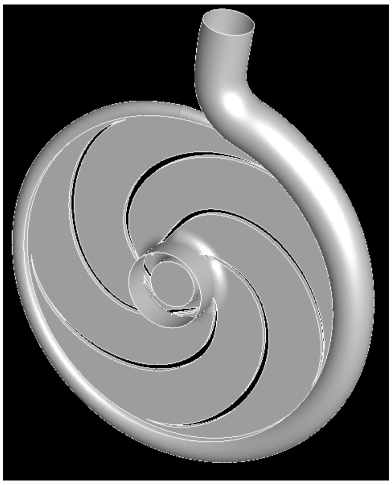

Figure 1 Numerical model of the pump

Hybrid meshing technique has been employed in the present study, where the inlet and outlet pipes connected to the pump have been meshed using hexahedral elements, whereas the pump itself has been meshed using tetrahedral elements. The mesh element sizing in the inlet/outlet pipes and the pump region are 3mm and 1.2mm respectively. Using these sizing, the flow domain comprises of 2.14million elements.

Three dimensional Navier-Stokes equations, along-with the continuity equation, have been numerically solved in an iterative manner for the flow of water within the centrifugal pump in the present study. Transient simulations have been carried out using Sliding Mesh technique, in which instantaneous prediction of flow features is possible. Furthermore, analysis has been carried out on two different rotational speeds of the impeller i.e. 2900rpm (design rpm) and deceleration from 2900rpm to 2700rpm in one revolution of the impeller.

Shear Stress Transport (SST) k-ω turbulence model has been shown to predict flow parameters with reasonable accuracy for similar applications and hence has been employed in the present study. Mass flow rate and outflow boundary conditions have been specified at the inlet and outlet boundaries of the flow domain, where the mass flow rate of $9m^3/hr$ has been specified at the inlet boundary of the pump. It has been shown by Park et al. [8] that a time step size corresponding to 3° rotation of the impeller blades captures the complex flow phenomena within the centrifugal pump with reasonable accuracy, and hence has been specified in the present study. Furthermore, User Defined Functions (UDFs) have been employed to maintain appropriate time step size, to the corresponding speed of the pump.

4. Results and Discussions

As this study focuses on the analysis of vortical structures in the vicinity of the tongue region, focusing primarily on the downstream sections of the tongue, five equally spaced planes have been created in the volute of the centrifugal pump. It can be seen in figure 2 that these planes are located on the downstream sections of the tongue, where the spacing between these planes, and between the tongue and the 1st plane, is 5mm. Q-criterion variations have been plotted on these planes, first at 2900rpm, and then when the centrifugal pump is decelerating from 2900rpm to 2700rpm in one revolution of the impeller.

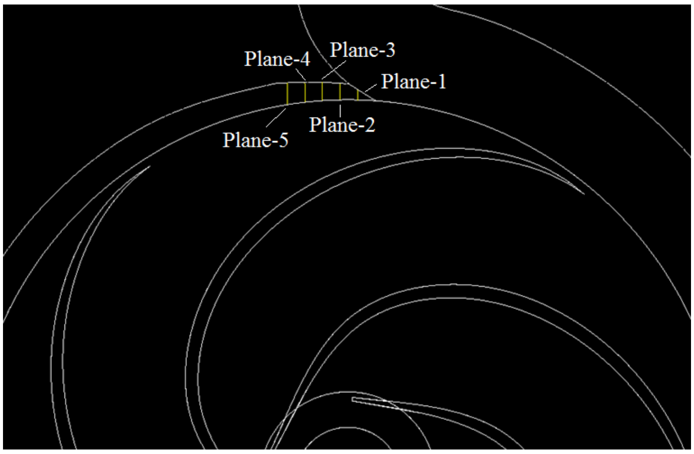

Figure 2 Analysis Planes

Figure 3 depicts the variations in the positive Q-criterion on the aforementioned planes. Only positive Q-criterion values have been plotted as it has already been discussed earlier that vortical structures are those that have higher vorticity magnitude than the shear strain-rate. Hence, the contours shown in figure 4 represent only those areas of the planes where there is more vorticity than the shear-strain-rate. The areas where this does not hold true are blank. The case under discussion is the one where an impeller blade is exactly inline with the tongue of the centrifugal pump. Furthermore, the scale of the colomap has been adjusted so that the scale remains constant throughout this study, for effective comparison purposes. It can be seen in the figure that vortical structures are formed downstream the tongue region, and their strength decreases as the distance from the tongue increases. Hence, vortical structures are most prominent in the near tongue regions only. Furthermore, closely examining the figure reveals that there is a set of two vortical structures that are being formed on either ends of plane-1. These vortical structures increase in size, hence losing their strength, as the distance from the tongue increases. Moreover, these vortical structures tend to come closer to each other in the farther downstream sections, where they are anticipated to combine together to form a single big, but very weak, vortical structure.

In order to analyse the transient mechanisms related to the generation of these vortical structures downstream the tongue region of a centrifugal pump, a scenario has been considered here when the tongue is exactly in between two impeller blades. This has been shown in figure 4. It can be seen that the overall vortical structures' generation and dissipation mechanisms remains the same, however, the strength of the vortical structures is significantly higher in the present scenario.

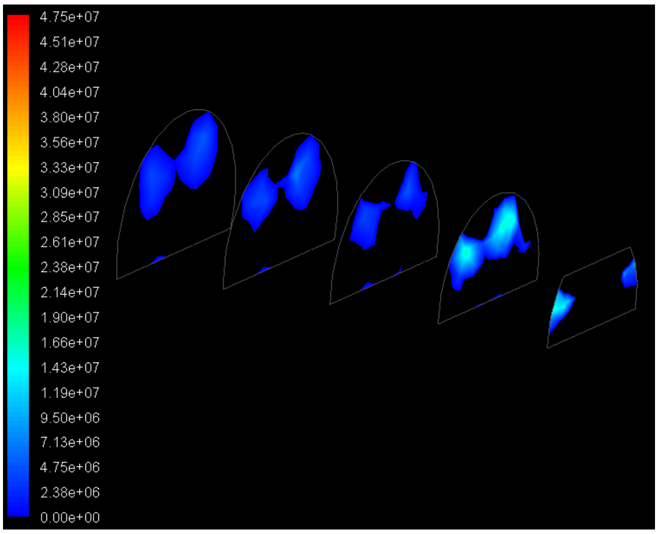

Figure 3 Q-criterion variations downstream the tongue region at 2900rpm and an impeller blade at the tongue

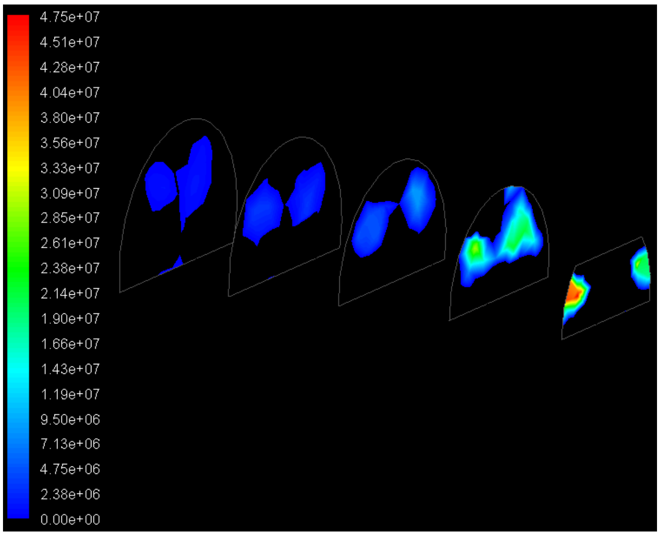

Figure 4 Q-criterion variations downstream the tongue region at 2900rpm and the tongue in between two impeller blades

It has been shown that the vortical structures are weak when the impeller blades are inline with the tongue of the centrifugal pump, and are strong when the tongue is in-between two impeller blades. However, this is true at a constant rotational speed of the impeller. Investigations need to be carried out on what happens when the pump decelerates/accelerates. In the present study, as discussed earlier, deceleration in the centrifugal pump has been numerically simulated, where the pump decelerates from its design rpm (i.e. 2900rpm) to 2700rpm in one revolution of the pump. Figure 5 depicts the variations in the Q-criterion on the planes downstream the tongue when the pump has reached 2700rpm. The case under discussion corresponds to an impeller blade inline with the tongue. It can be seen in the figure that the Q-criterion variations match closely with figure 3 i.e. when the pump was operating at 2900rpm. This suggests that the rotational speed of the pump has no effect on the generation and dissipation mechanisms of the vortical structures downstream the tongue region of a centrifugal pump. However, figures 3-5 provide only a few scenarios, whereas a complete depiction of the variations in Q-criterion needs to be analysed. Hence figure 6 shows the instantaneous variations in the maximum Q-criterion on the different planes throughout the operation of the pump considered in the present study. From 0° to 360° (revolution 1), the rotational speed of the pump is constant at 2900rpm, whereas from 360° to 720° (revolution 2), the rotational speed of the pump decreases from 2900rpm to 2700rpm.

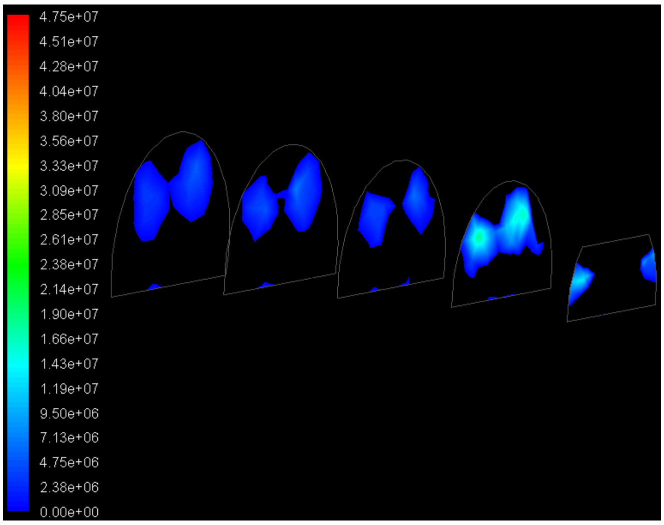

Figure 5 Q-criterion variations downstream the tongue region at 2700rpm and an impeller blade at the tongue

It can be seen in figure 6 that Plane-1, which is nearest to the tongue region, has the maximum Q-criterion. As the distance from the tongue region increases, the maximum value of Q-criterion decreases significantly, where the difference between planes 3, 4 and 5 is insignificant. Furthermore, it can be seen that the Q-criterion shows cyclic variations on Plane-1, where the peak-to-peak distance, the positive peaks and the negative peaks show consistent values of Q-criterion. This cements the earlier statement that the rotational speed of the centrifugal pump has no effect on the generation of the vortical structures downstream the tongue region. It is further anticipated that the generation and diffusion mechanisms of these vortical structures are dependent only on the geometric parameters of the tongue.

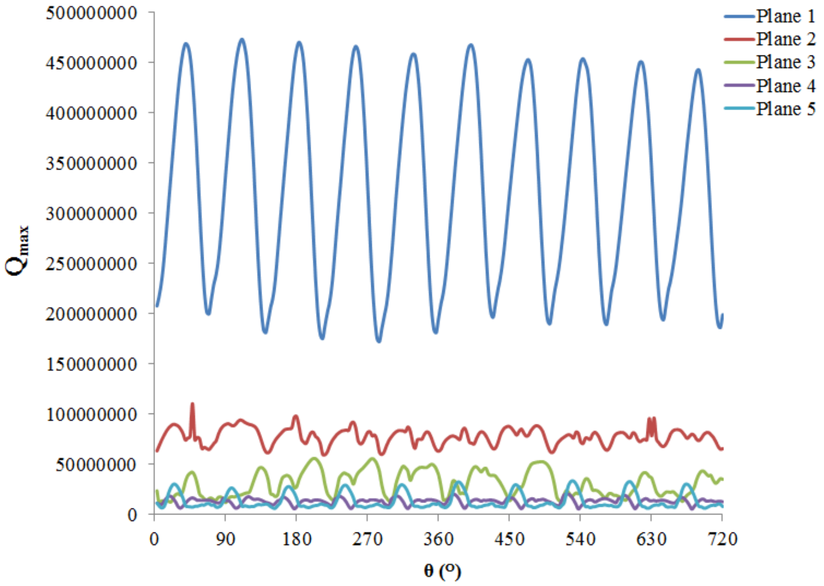

Figure 6 Instantaneous variations in the maximum Q-criterion on the planes downstream the tongue region during both a constant rotational speed (0°-360°) and decelerating pump (360° - 720°)

5. Conclusions

Detailed numerical investigations, using advanced Computational Fluid Dynamics based tools, have been carried out on the Q-criterion variations in the vicinity of the tongue region in a centrifugal pump. The results indicate that the Q-criterion is fairly non-uniform downstream the tongue region due to the complex interaction between the impeller blades and the tongue. Furthermore, it has been observed that as the rotational speed of the centrifugal pump decreases, the Q-criterion in the near tongue region remains constant. The generation, expansion and subsequent mixing of two distinct vortical structures have been noticed downstream the tongue (within the volute), whereby the strength of these structures has been observed to be decreasing as the distance from the tongue increases. Moreover, it has been concluded that the vorticity magnitude and the shear strain-rate are independent of the rotational speed of the pump.

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