Experimental analysis of a pump equipped with an axial rotor with variable speed

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Abstract. In hydropower systems among hydropower plants there are storage pump units. In order to ensure higher flow rate, the pumps have constructive differences besides regular. Consequently, the complex shape of the suction-elbow with symmetric inlet generates an unsteady flow which is ingested by impeller. These phenomena also generate stronger unsteady flow conditions, such as stall, wakes, turbulence and pressure fluctuations, which affect the overall mechanical behaviour of the pump with vibration, noise and radial and axial forces on the rotor. Alternatively, an axial rotor can be installed in front of the impeller. In this case, the non-uniformity flow will be decreased, and the static pressure will be increased at the impeller inlet. Consequently, the efficiency behaviour practically remains unchanged while the cavitational behaviour is improved. The paper investigates experimentally a pump system with the axial rotor having variable speed, while the pump impeller has constant speed. First, the paper presents the experimental test rig, the control and acquisition system. Secondly, is presented the pump system equipped with the clutch in order to have variable speed for the axial rotor. Thirdly, the experimental results concentrate on the axial rotor influence on the efficiency behaviour. The last section draws the conclusions.

1. Introduction

In last decades, the market policy was focused on renewable energy development. The renewable energy (solar and wind) introduces a large fluctuating component in the electrical grid. The solution to compensate the fluctuating component is provided by the storage pump units (SPUs). The SPUs are constructively different than regular pumps in order to ensure higher flow rate. The three-dimensional complex shape of the suction-elbow induces a non-uniform flow field which is ingested by impeller, [1][2]. As a result, the unsteady hydrodynamic phenomena are generated leading to a worse cavitational behaviour [3] and a diminished lifetime of the mechanical components [4]. The SPUs are expensive and cannot be replaced completely, preferably being refurbished.

An inducer can be one feasible technical solution in order to greatly reduce the risk of cavitation. An inducer is a device attached to the impeller eye that is usually shaped like a screw that helps to increase the pressure at the impeller. The inducer actually transfers the “low pressure” point from the eye of the pump impeller to the entrance of the inducer itself. The inducer is manufactured with constant blade thickness and rounded leading and trailing edges [5]. Usually is installed on the pump shaft together with the impeller having the same speed. The non-uniformity flow generated by the suction elbow at the impeller inlet is also diminished by the inducer. Consequently, both cavitational and dynamic behaviours of the pump are improved by the inducer. Moisa et al. [6] designed an axial rotor with 3 blades. The axial rotor design procedure is based on inverse design method where the inflow and outflow conditions are known. Axial flow is considered as upstream condition while the downstream swirling flow is suited for the pump impeller inlet. The key ingredient in this procedure is the function of loading shape which provides the distribution of blade loading from leading edge to trailing edge.
The axial rotor terminology has been coined by Schilling et al. [7],[8]. According to Schilling, the axial rotor is an axial bladed rotor; the main task is to generate a sufficiently high-level pressure in front of the pump impeller in order to avoid any kind of cavitation of the pump inlet. Our experimental investigations had clearly assessed the cavitation behaviour improvement of the pump with the axial rotor at constant speed of 3000 rpm [9].

A new concept was explored in order to assess the cavitation behaviour improvement on a wide operating range for a pump system. This new method proposes variable speed for the axial rotor, while the speed of the pump impeller is constant [10]. Extensive numerical investigations have been performed; the speed of the axial rotor was varied with ±20% from the speed of the pump impeller. The results showed the increase of the minimum pressure when the speed of the axial rotor is reduced with 15% from the speed of the pump impeller. Moreover, the pressure coefficient plotted on the pump impeller blades improves with 8% when the speed of the axial rotor is slow down [11].

The paper investigates experimentally a pump system where the speed of the axial rotor is slow down, while the pump impeller has constant speed. Firstly, the experimental test rig, the control and acquisition system are presented. Next, the pump clutch is described and analysed, taking into consideration that this system was especially designed to ensure controlled lower speed for the axial rotor. Thirdly, the experimental results are concentrated on the axial rotor influence on the efficiency curves, when the speed is slow down. The conclusions are drawn in last section revealing a synopsis overview on the influence of slowing down the speed of the axial rotor.

2. Experimental test rig.
The experimental test rig developed at Politehnica University Timisoara serves assessing global performances (efficiency and cavitational) of centrifugal pumps. The test rig is completely manufactured from stainless steel. It is equipped with two tanks (each with the capacity of 1 m³), pipes, DN80 electromagnetic flow meter, valves which allow isolation of test section for quick mounting of different pump impellers which will be tested. The inlet and outlet pipes diameters are 0.1 m and 0.08 m. The test rig has mounted a symmetrical suction elbow scaled model (which is manufactured by Plexiglas), used in general for the pumping stations units [11].
Figure 1. The experimental test rig from UPT. Top view with main hydraulic components (up) and lateral view with electronic equipments (down).

Figure 2. The investigated pump impeller (left), the axial rotor (middle) and the combination between (right).
At the inlet of the pump impeller (pipe diameter 0.1 m), the test rig is equipped with a gauge transducer able to measure the pressure range between -1 and 2.5 bar, while a manometer registers the pressure range between 0 and 6 bar at the outlet of the pump. All the electrical signals from different sensors are connected to a dedicated acquisition data system, [13]. The main hydraulic pump parameters are presented in the table below:

Table 1. Hydraulic parameters from the test rig components.

| Parameter                  | Value | Unit |
|----------------------------|-------|------|
| Nominal pumping head $H_n$ | 44    | [m]  |
| Nominal discharge $Q_n$    | 0.0335| [m$^3$/s] |
| Nominal speed $n$          | 2900  | [rpm] |
| Power at nominal discharge $P_n$ | 20  | [kW] |
| Nominal efficiency         | 72    | [%]  |
| Characteristic speed $n_q$ | 30    | [-]  |

Design specifications for axial rotor [6]:

| Rotational speed $n$  | 2900 | [rpm] |
| Tip diameter $D_t$    | 0.103| [m]   |
| Hub diameter $D_h$    | 0.04 | [m]   |
| Blade number $z$      | 3    | [-]   |
| Blade thickness $t$   | 0.003| [m]   |
| Designed flow rate $Q$| 0.030| [m$^3$/s] |

An experimental study was performed separately, in order to evaluate the efficiency and cavitation behaviour when the axial rotor is mounted on different axial positions in front of the pump impeller. The analysis concluded that the axial position of the axial rotor does not modify the efficiency and cavitation behaviour, [15]. This analysis served in designing the axial rotor with the magneto-rheological clutch for variable speed.

3. Pump clutch

According with numerical investigations performed on the pump system (pump impeller and axial rotor with variable speed), when the axial rotor is slowing down with maximum of 15% from the speed of the pump impeller, the minimum value of the static pressure on both axial rotor and impeller blades is increasing, [11]. As a result, on the experimental investigations the axial rotor only slows down by using as a speed controller a magneto-rheological clutch.

Magnetic fluids have been developed at the beginning of the 1948, when Rabinow [16] developed a clutch device. According with Rabinow, the advantages of using this kind of clutch with magnetic fluids are: the amount of electrical power necessary to control is small and the time response is also small. Since then, the magnetic fluids have been implemented in many applications. Several important applications can be found in: brakes, seals (especially in the case of gas transporting installations), sensors and dampers.

Magneto-rheological clutches are an important research direction concerning these smart materials. Some of the advantages are convenient low-power control (through electrically generated magnetic field) and have a very good torque to weight ratio. The possibility of using the electrical control (the magnetic field can easily be electrically generated and controlled) is a very important advantage. The next figure present a sketch of our pump system equipped with the magneto-rheological clutch for slow down the axial rotor speed.
Figure 3. Sketch of the pump system with the magneto-rheological clutch attached (up) and picture form the laboratory tests (down).

With blue color is represented the fixed part of the pump system (the collector, the bearings). The components with brown color parts have constant speed as the electric motor (2500 rpm) and with green color is represented the lower speed for the axial rotor combined with all mechanical parts. An important component of the magneto-rheological clutch represents the coil, which helps to modify the magnetic field inside the clutch and viscosity of the magneto-rheological fluid responsible for speed control. At the beginning of the pump tests, for the clutch was measured the coil power and the magnetic field inside the gap where magneto-rheological fluid is inserted, see Figure 4.

Figure 4. Measured coil power (left) and the magnetic field inside the clutch gap where magneto-rheological fluid is inserted (right).

In order to control the magneto-rheological clutch, it is necessary to use a power of maximum 10 W, with a maximum electrical current of 0.4 A. From the magnetic field, inside of the clutch can be observed that the construction material didn't reach the saturation point, and the coil is well controlled, up to an applied voltage of 30V.
4. Results and analysis

A first experimental evaluation was to measure the speed of the axial rotor for three separated cases, as observed in Figure 5. In order to measure the speed, a waterproof proximity sensor was mounted close to the axial rotor blades and was connected in the acquisition data system. In the first case (axial rotor runaway speed), the axial rotor was connected at the shaft without the clutch, for the second case (axial rotor with MR clutch 0 V) the axial rotor was connected with the magneto-rheological clutch but no electrical current was applied. For this case, only the viscous effects of the magneto-rheological fluid have been taken into account.

![Figure 5. Speed of the axial rotor for three cases: runaway speed, with magneto-rheological liquid inside the clutch at 0V for the coil clutch and with magneto-rheological liquid inside the clutch at 30 V for the coil clutch.](image)

For the third case, the magneto-rheological clutch was connected at the DC source and 30 V were applied at the coil, accordingly the viscosity of the magneto-rheological fluid was increased. The speed measurement of the axial rotor gives us the operating range for each case. As a result at the maxim flow rate of 44 l/sec, the axial rotor has the same speed for all three cases (2500 rpm). When operated at runaway speed, the axial rotor is blocking (0 rpm) at 9 l/sec. When the axial rotor is attached at the magneto-rheological clutch and 0 V applied voltage, the minimum speed is approximately 1400 rpm (44 % less than the pump impeller speed). When the magneto-rheological clutch is active (30 V applied voltage at the coil), the minimum speed for the axial rotor is approximately 1750 rpm (30 % less than the pump impeller speed).

Next, a second experimental analysis consisted to evaluate the pumping head and the efficiency for the classical configuration in pumps (rigid pump impeller and axial rotor) and the cases when the clutch is connected with the axial rotor at 0 V and 30 V applied voltage at the coil.
According with Figure 6 (left) the total pumping head remains approximately constant, with a variation of ±1 m, for all investigated cases. Even if the axial rotor has variable speed for two cases (MR clutch at 0 and 30 V) the total pumping head remains constant for all regimes, while the pumping head for the axial rotor and pump impeller is balanced between. Also, the results for the total pumping head validate the numerical investigations performed with variable speed for the axial rotor,[11]. In case of the measured electrical power, is observed a difference of 15% larger for cases with magneto-rheological clutch for small flow rates. This is related to the fact that a series of new bearings and seals have been mounted on the pump system for the shaft of the pump impeller and for the shaft of the axial rotor. Also this difference is observed in the efficiency of the pump, which is smaller in the case of using the magneto-rheological clutch. As a conclusion for the experimental tests performed up to now, the total pumping head remains approximately constant, while the power and the efficiency is smaller in case of using the magneto-rheological clutch for the pump system due to new bearings and seals. Further cavitation experimental investigations will indicate if the cavitation behaviour can be improved, as it was demonstrated in numerical simulations performed up to now.

5. Conclusions

A new method proposes variable speed for the axial rotor while the speed of the pump impeller remains constant. Extensive numerical investigations reveal the efficiency of this method. The results establish
the increase of the minimum pressure when the speed of the axial rotor is reduced with 15% from the speed of the pump impeller. [11].

The paper experimentally investigates the pump system where the speed of the axial rotor slows down using a magneto-rheological clutch. The pump clutch is described and analysed, taking into consideration that the system was especially design to ensure controlled lower speed for the axial rotor. The coil power and the magnetic field were measured, in order to evaluate the functionality of the clutch.

The experimental results are focusing on the speed of the axial rotor in three cases: runaway speed, clutch with magneto-rheological fluid inside (0 V) and clutch with magneto-rheological fluid inside and applied magnetic field (30 V). The energetic measurements prove that the total pumping head remains constant, even if the axial rotor has variable speed. The efficiency is diminished due to the seals attached to all pumping system. Further, experimental cavitation investigations, will indicate the efficiency of the new method.

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