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Design of a contra-rotating booster pump

Ingrid Befring Hage, Helene Njølstad Dagsvik and Pål-Tore Storli

Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway

E-mail: ingribef@stud.ntnu.no

Abstract. In Norway there are many existing hydropower plants located on sites suitable for pumped storage. By exchanging the turbine with a reversible pump turbine the retrofitting of the plant can become an economically viable investment. However, the problem of cavitation in the reversible pump turbine must be solved. In the case of Roskrepp hydropower plant installing an axial booster pump has been proposed as a solution. To reduce the swirl of the flow after the booster pump, a contra-rotating design would be beneficial. Alternatives that can provide a solution for lifting the booster pump up from the flow when the reversible pump turbine is in turbine mode is also being investigated. For this, utilizing the same concept as the rim-driven thruster can be an option. This paper discuss the strengths and weaknesses of these concepts with the intent of using the information for design of the booster pump.

1. Introduction

1.1. Motivation

At the same time as climate change is becoming more and more prominent, the world's need for energy is ever increasing. As a result of this, the interest in renewable energy sources is increasing. Most of the renewable sources vary in the amount of energy it can produce over time. Sources such as wind power and solar power are entirely reliant on the presence of wind and sunlight, only generating energy when the conditions are suitable. For wind farms in Denmark, it is common to experience hourly fluctuations of 10% [1]. This variation creates an unstable electricity grid. However, by utilizing energy storage technology, the variability of renewable resources can be stabilized.

There are different technologies for energy storage, but Pumped Hydroelectric Storage (PHS) is deemed the most mature and commercially available method [2] and accounts for approximately 97% of the world's total storage capacity [1]. This method is suitable for hydropower stations with an upper and lower reservoir, where the water from the lower reservoir is pumped to the upper when energy demand is low. By doing this, there is water available for energy production when the demand is higher. The electricity from fluctuating energy sources such as wind and solar power can be used to power the process of PHS, making the energy available for production when energy demand is high [1].

In Norway, hydropower is a widespread source of energy, but the use of PHS is not. However, according to NVE, 20 hydropower plants are located between two reservoirs of substantial size that can potentially be retrofitted for PHS [3]. By utilizing this technology to store energy, Norway could provide a battery service for the rest of Europe and stabilize the European electricity grid. If this is to be accomplished, research must be done into retrofitting the

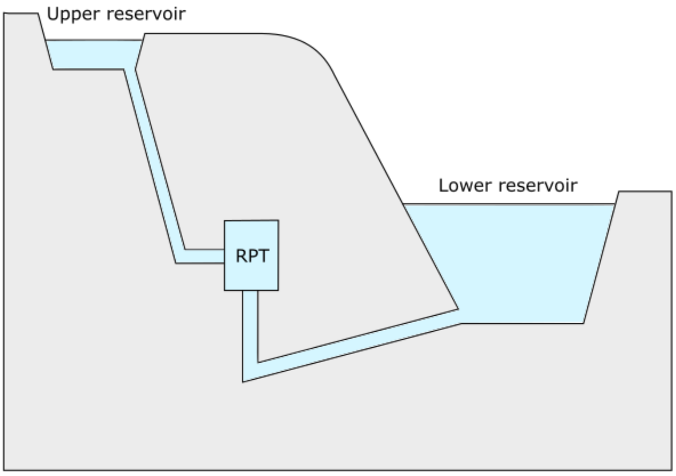

Figure 1. PHS diagram

existing hydropower plants. The most used turbine in these plants is the Francis turbine, which could be replaced by a Reversible Pump Turbine (RPT). This replacement is a much more economical option than constructing entirely new plants in locations where hydropower is not already established, as the existing structures and components in the plant can be used with an RPT as well.

The main issue with retrofitting for PHS is cavitation. This occurs when the static pressure is lower than the vapor pressure, and the implosion of vapor cavities follows. When the RPT is placed in the same area as the conventional turbine, the RPT is not submerged enough to avoid cavitation when it is in pumping mode. As cavitation is a serious problem, solutions to this is necessary. This can be solved by submerging the RPT more, but this will lead to more construction work. This increases the cost of retrofitting for PHS. Solutions that prevent both cavitation and construction work will therefore be of interest.

To solve the cavitation problem, the idea of installing a booster pump in front of the RPT in pumping mode has been proposed. A booster pump will increase the pressure at the inlet of the RPT in pumping mode, reducing the risk of cavitation at the same time as it can increase the overall pressure head from the RPT. The booster pump must conform to the needs of the RPT. The outlet flow of the booster pump should preferably be without any rotational component or swirl. To solve this, the contra-rotating type of machine, in combination with axial pumps, is being assessed as a possible solution. The axial machine can have a tangential component in the outlet flow, but by using a Contra-Rotating Axial Pump (CRAP), the swirl of the front rotor will be canceled by the swirl of the rear rotor.

When the RPT is in turbine mode, the booster pump will affect the flow in the outlet. One option to solve this is to utilize the same concept as the Rim-Driven Thruster (RDT), which could provide an option to lift the CRAP up from the flow when the RPT is in turbine mode. Similar to RDTs, some tidal turbines have the generator in the periphery of the impeller. This can also be a source of information on how to implement the hubless concept to this machine design.

1.2. Objective

This paper will investigate the possibility of a contra-rotating booster pump placed in front of the RPT at Roskrepp hydropower plant. The investigation will be done by performing a literature review of previous research conducted in the fields of contra-rotating machinery and machinery with the motor placed in the periphery of the rotor. The information presented in this paper will be used when choosing a design philosophy for the booster pump in the further work on this project. To limit the scope of work, the focus it put on axial machinery in this paper.

2. Previous work

To investigate the CRAP's abilities in the role of a booster pump, a literature review is conducted. The following sections will describe different concepts that are being considered for the booster pump.

2.1. Contra-rotating machinery

Contra-rotating machinery consists of two rotors placed on the same axis, operating in opposite directions. Figure 2 illustrates a typical contra-rotating machine. This concept can be used to have the rear rotor cancel out the swirl that is imposed on the flow by the front rotor. In Figure 3 this can be seen in the velocity diagram that is typical for contra-rotating pumps and fans.

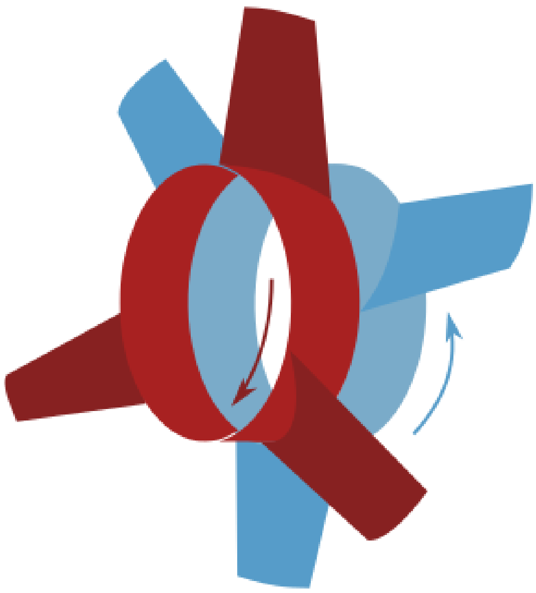

Figure 2. General depiction of the contra-rotating concept.

The contra-rotating type is most commonly used in propellers, also called Contra-Rotating Propellers (CRP), which are frequently used in marine propulsion. The CRP has several advantages compared to single rotors. Cavitation can be prevented by having a lower blade loading. CRPs also display higher efficiencies than single rotors. This is because the rotational energy of the flow behind the unit is reduced [4]. However, the two rotors cause a more complex mechanical structure.

Introducing the contra-rotating concept in axial pumps has been investigated by several researchers. Furukawa et al. has done research on this with the aim to develop an axial flow pump for higher specific speeds [5]. For single-rotor axial flow pumps, the efficiency and cavitation performance deteriorate with a higher specific speed. They found that for rotors with the same rotational speed cavitation occurred at the tip region of the rear rotor and not at the front rotor at off-design conditions. This indicated a drop in static pressure between the two rotors. There was also observed notable disturbances in the velocity and potential fields. This phenomenon is called blade rows interaction. This leads to repetitive stress that can cause an unsafe and unreliable operation. As a consequence of this, Furukawa et al. proposed using the rotational speed optimization methodology to achieve better results regarding cavitation and blade rows interaction at off-design conditions.

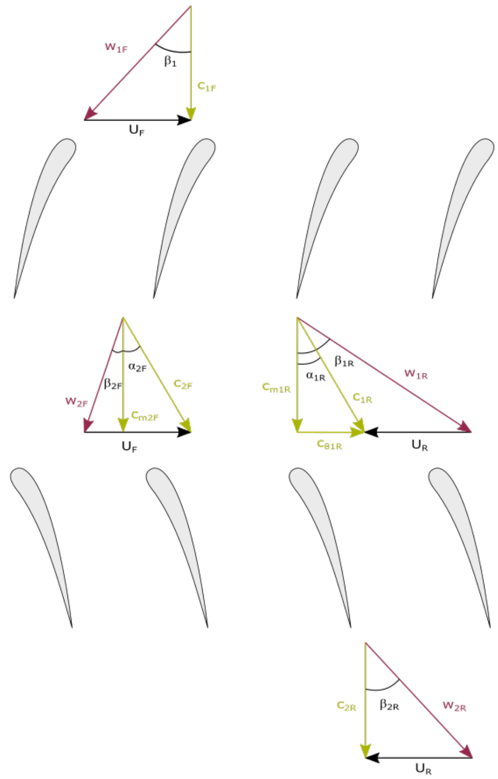

Figure 3. Velocity diagram for a contra-rotating type machinery. In the figure, U is the blade speed, c is the fluid flow velocity and w is the relative velocity.

Cao et al. focused on the understanding of the internal flow in the CRAP [6]. This was because the rear rotor showed unsatisfactory performance at off-design conditions in the form of a steep positive slope head rise. They conducted both experiments and numerical simulations. It showed that the internal flow was complicated with strong secondary flow, and the rear rotor affected the outlet flow of the front rotor at lower flow rates. In the rear rotor, corner separation was observed on the suction side. When the flow rate was reduced more, the corner separation increased. This in turn reduced the incidence angle as the corner separation blocked the inlet flow and turned it towards the tip side. Tip leakage vortex flow was also observed from the leading edge. The reduction in incidence angle causes the weakening of the tip leakage vortex due to reduced blade loading. The tip leakage vortex is then assumed to travel into the blade passage, which creates another blockage. This is assumed to be the reason for the unsatisfactory performance.

2.2. Shaftless machinery
Axial machinery is also used in tidal energy production. The Straflo turbine is an axial flow turbine, used for low head and large flow rates [7]. Unlike other turbine types, the Straflo turbine and generator are one single unit. The generator is mounted around the runner and thereby eliminates the need for a shaft connecting the two components. Even though the operating conditions makes it suitable for tidal power, there is only one successful installation of the Straflo turbine. This is the Annapolis Tidal Generating Station, which has been in service since 1984 [8]. In the 1987 article *The Annapolis Experience*, the authors Rice and Baker conclude that the project had been a success and that the issues regarding a large scale machine in saltwater had been resolved satisfactorily. Other tidal turbines have also been developed, but the development is still at an early stage. This means that there are no standard approaches to the design method. One company specialized in marine turbines generating tidal energy is OpenHydro. Their turbines utilize the same concept as the Straflo turbine, where the generator is in the periphery of the runner. Documented cases of failures in marine renewable energy devices encouraged de la Torre et al. to investigate the OpenHydro turbines under accelerated life tests [9]. For this, they only employed one blade and a sector of the rotating ring. They found the structural integrity of the ring steel substructure to be satisfactory. However, the connection of the blade to the ring showed non-symmetrical behavior. This would need to be further investigated on a full tidal turbine, and the findings could be attributed to the method of using a clamping load saddle to transfer the load. Unfortunately, the company OpenHydro was liquidated in 2018 by their owners, and no further investigations have been conducted [10].

Figure 4. RDT designed by Brunvoll. Image from [11].

Using the same concept as the Straflo and OpenHydro turbines, an RDT is a hubless propeller surrounded by the motor. The RDT is mainly used in marine propulsion as an integrated motor propulsor. Comparing the RDT with the conventional shaft-driven thruster, many factors are favoring the RDT. Some of these are the compact design that makes installing and arranging more flexible and a higher motor efficiency with a broader speed range. Cao et al. investigated the hydrodynamic performances of the RDT by doing numerical simulations of four cases [12]. One of these cases was also chosen to be subject to an experiment. The four design cases were of equal diameter and varying blade geometry. As there is no radial circulation at the tip of the RDT, the blade loading is different from a conventional shaft-driven thruster. There is no clearance between the blades and the rim, meaning that the tip leakage vortex, which can cause cavitation, should not appear. The result in the article states that tip leakage vortices were only observed in two of the cases. However, a vortex did appear around the roots of the blades in each case. If these root vortices were to act like a typical tip vortex, this could result in a strong root vortex in the flow. However, there is an indication that both the root and tip vortices could be reduced by having the right blade loading distribution. The cavitation performance of the RDT was investigated by Zhang et al. employing numerical simulations. The cases of an RDT in uniform flow and non-uniform flow were used. They found that sheet cavitation appears on the suction side of the blades for both cases. The tip vortex cavitation common in shaft-driven thrusters did not appear for the case of uniform flow.

3. Discussion

There are several advantages to using the contra-rotating type. Higher efficiency and reduced blade loading are reasons for choosing this. For the specific task in this report, the canceling of outlet swirl is an important factor. However, the challenges tied up to the contra-rotating type must be discussed and solved. The challenges that Furukawa et al. discuss are mostly tied to a machine at off-design conditions. The cavitation that they observed at the tip region of the rear rotor for equal rotational speed was attempted solved by utilizing rotational speed optimization methodology. As this report is interested in using the same concept as the RDT for the CRAP, it can be assumed that the findings of Cao et al. and Zhang et al. are relevant. This would be beneficial, as the tip vortex cavitation in the article of Furukawa et al. could be avoided. The root vortices that appeared for the RDT must be assumed to cause problems. A strong root vortex from the rear rotor outlet would be problematic as this flow is the inlet flow for the RPT. This flow needs to be uniform and without any swirl. As stated in the article of Cao et al., the problems regarding root and tip vortices is likely to be constrained by adjusting the blade loading distribution. In addition, the problem regarding the booster pump being in the way of the flow when the RPT is in turbine mode can be solved using the concept of the RDT. This is because the machine will be easier to lift out of the flow when the booster pump is not needed.

Another issue that must be addressed is the blade row interaction between the front and rear rotors. This was also proposed solved by means of rotational speed optimization by Cao et al., with results indicating that this approach is applicable. This suggests that having a lower rotational speed for the rear rotor should be investigated further. The axial distance between the two rotors could also be deciding for the interaction between the impellers. Wei et al. found that for contra-rotating tidal turbines, a large axial distance is favorable [13]. However, they also found that with an increase in axial distance, the front rotor performance is improved, but the rear rotor is not influenced as much.

4. Conclusion

A literature review regarding the possibility of utilizing the contra-rotating and RDT concepts has been conducted. The information that this review yielded will form the background for the design process of the CRAP.

5. Further work

The next step is to decide on the design philosophy for the CRAP. The review of existing research in this paper will be fundamental when deciding this. The design must consider the different advantages and disadvantages of the contra-rotating type and RDT. From the findings in this paper, it is likely that choosing to remove the hub from the design will improve the CRAP's performance, due to the tip leakage vortices connected to the shaft-driven type being removed. However, other problems might occur. Because of this, numerical simulations will be performed on the designed model, using Computational Fluid Dynamics (CFD). This will be used to evaluate if the booster pump design fulfills the requirements for use in Roskrepp hydropower plant.

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