

Water Turbopump Inducer Performance with and without a Stability Control Device

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Abstract- Operating conditions for a turbopump are often limited by the inducer. Extreme operating conditions can cause an inducer to fail. This paper explores the effect that a stability control device has on the performance of an inducer with and without the presence of cavitation. Numerical studies performed show that the head rise through the inducer is about the same for all cavitation numbers but the radial loads on the inducer are significantly less when a stability control device is incorporated.

Introduction

Inducers are one of the most important parts of machinery in turbopumps. Because of the high rotational speeds involved in turbopumps, the liquid pressure is susceptible to dropping below the vapor pressure, resulting in cavitation. Cavitation is a major flow event that can lead to unstable operating conditions and pump failure. In order to avoid cavitation in the turbopump, an inducer is positioned in the first stage of the turbopump. Its purpose is to pressurize the fluid sufficiently, such that cavitation does not occur in the rest of the turbopump. Even though an inducer is designed to operate under cavitating conditions, significant cavitation can lead to failure.

Two main cavitation events include rotating cavitation and cavitation surge. Rotating cavitation is due to a local imbalance where an asymmetric cavity rotates from blade to blade

causing a periodically varying radial load. This can result in large shaft orbits and possible pump failure. Cavitation surge is generally related to the growth and collapse of cavitation at the inducer inlet at low, off-design flow rates. The growth and collapse of cavitation leads to oscillations in the mass flow rate and pressure levels in the system that may also cause failure in the pump.

Failure in the pump can be caused by large radial loads that effectively shake the pump to failure or by aerodynamic blockage that causes the pump to stall. When the aerodynamic blockage is significant, small changes in operating pressure results in a large decrease in performance. This phenomenon is known as breakdown.

Another source of instability within the inducer is the reversed flow at the blade tip. Figure 1 shows an inducer operating with a significant amount of reversed flow. The core flow is going left to right in this figure. The axial velocity contour plot has been clipped to show only



Figure 1 Reversed flow from the blade tip can create instabilities in the flow

where the flow is going right to left. The reversed flow accelerates the core flow, making it more susceptible to cavitation. The core is accelerated due to the decrease in flow area and an increase in the mass flow rate of the core.

In order to delay breakdown and pump failure, many researchers have attempted to understand the significant cavitation events that ultimately lead to breakdown. Blade sweep, blade thickness, tip clearance, and other blade characteristics have all been shown to play a role in how stably the inducer can operate under cavitating conditions [1], [2]. Japikse invented a device that captures fluid from a region of back flow near the leading edge of the inducer and reintroduces it into the flow upstream of the inducer [3]. This device is known as a stability control device, SCD, and is shown in figure 2.

Previous research has shown that the implementation of an SCD suppresses the reversed flow at the blade tip and increases the stability for a flat plate inducer [4]. This would allow for smaller inducers with better high suction performance. The current research performs numerical simulations on an actual inducer to confirm the preliminary results.

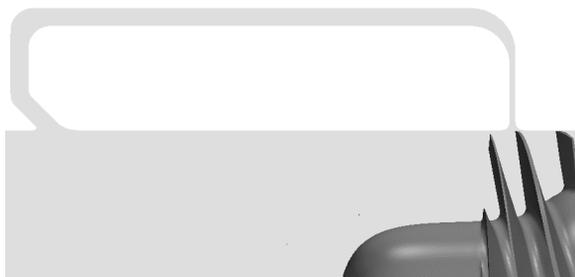


Figure 2 Image of an inducer with a stability control device

Methodology

The performance of the inducer with and without the SCD was analyzed at the design flow coefficient with water as the working fluid. The flow coefficient is defined as:

$$\phi = \frac{Q}{A_{LE}U_{tip}}$$

Where Q is the volumetric flow rate through the inducer, A_{LE} is the cross-sectional area of the inducer at the leading edge of the blade, and U_{tip} is the blade tip speed.

Meshing of the geometries and the numerical simulations were performed using the computational fluid dynamics software StarCCM+. The meshes contained nominally 6 million polyhedral cells. Turbulence was modeled using the Realizable k- ϵ model. The Volume of Fluid multiphase model was employed to model the cavitation. The simulations used a rotating reference frame, spinning at the speed of the blade.

Steady state, non-cavitating analysis was performed as a baseline for the cavitating solutions. Multiphase, time-accurate solutions were used to determine the machine breakdown curve for the inducer with and without the SCD. A breakdown curve is generally plotted as the head coefficient versus cavitation number.

The head coefficient is defined as:

$$\psi = \frac{P_{02} - P_{00}}{\rho U_{tip}^2}$$

Where $P_{02} - P_{00}$ is the change in total pressure from the inlet of the inducer to the trailing edge of the blade and ρ is the fluid density.

The cavitation number is a non-dimensional number that is a measure of the amount of cavitation present for the given flow conditions. The cavitation number and the amount of cavitation are inversely proportional. It is defined as:

$$\sigma = \frac{P_{00} - P_v}{\frac{1}{2}\rho U_{tip}^2}$$

Where P_v is the vapor pressure of the fluid.

In order to obtain the breakdown curve, various simulations were run by changing only the outlet pressure. The blade speed and the mass flow rate through the machine were held constant.

Recirculation through the SCD increases the local mass flow rate through the core of the inducer. The increase in mass flow rate is referred to as the mass flow gain factor and is calculated by the mass flow rate at the leading edge of the inducer divided by the inlet mass flow rate. The increase in mass flow can have a significant effect on incidence. Incidence is also an important flow parameter that has an effect on the stability of the inducer. Incidence, γ , is defined as the difference between the blade angle at the leading edge of the inducer and the flow angle.

Results and Discussion

Single Phase

Figure 3 shows an axial velocity contour plot for an inducer without the SCD. The darker section near the blade tip represents the section of reversed flow. This is the design flow rate for the inducer so the reversed flow at the blade tip is minimal. At low flow coefficient, the reversed flow increases substantial, as seen in figure1. Figure 4 shows a similar axial velocity

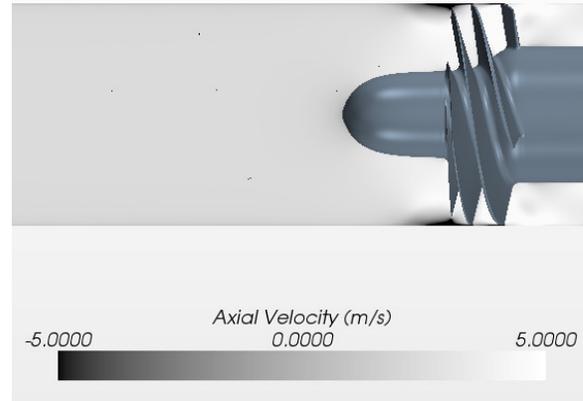


Figure 3 Axial velocity contour plot for an inducer without an SCD

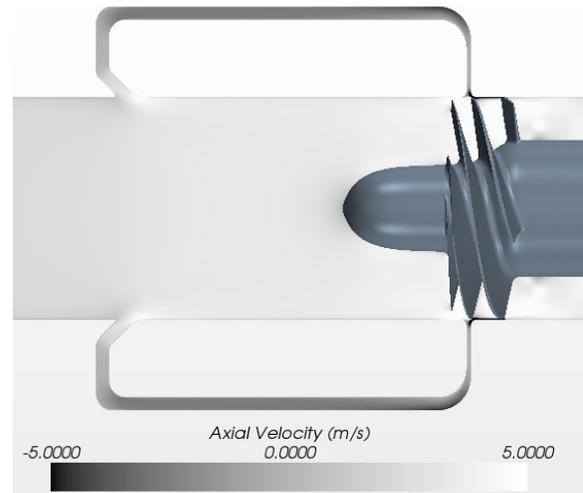


Figure 4 Axial velocity contour plot for an inducer with an SCD

contour plot for the inducer with the SCD. The region of reversed flow has been removed. Reversed flow is a major source of instabilities related to cavitation in the inducer and the radial forces on the inducer.

Recirculation through the SCD increases the mass flow rate at the leading edge 40%. The increase in mass flow rate increases the axial velocity of the fluid through the inducer. It is expected that the increase in axial velocity would have a significant effect on the incidence.

Figure 5 shows the incidence angle for an inducer with and without the SCD compared to the span of the blade. The SCD has very little effect on the incidence at these conditions. The most significant change in the incidence is seen at a blade span of greater than 0.8, where the reversed flow has been eliminated. Reversed flow effectively decreases the core flow area for the fluid. The decrease in area accelerates the axial velocity in the core similar to the effects of the mass flow gain through the SCD.

Negative effects from the reversed flow at the blade tip can be easily seen when the head coefficient is compared. The inducer with the SCD has more than a 10% increase in the head coefficient. Eliminating the reversed flow significantly decreases the losses near the blade.

It is apparent from these results that an SCD can effectively eliminate the reversed flow at the blade tip. Eliminating the reversed flow decreases losses near the blade and can have a significant effect on the inducer performance and stability.

Multiphase

The influence of the SCD cannot be fully understood without analyzing the performance of the inducer while it experiences cavitation. Multiphase simulations were run to explore what effects the SCD had in the presence of cavitation.

One measure of inducer performance with cavitation is known as a breakdown curve. The breakdown curve plots head coefficient versus cavitation number. Figure 6 shows a machine breakdown curve for the inducer with and without the SCD. The head coefficient has been normalized by the steady state head coefficient

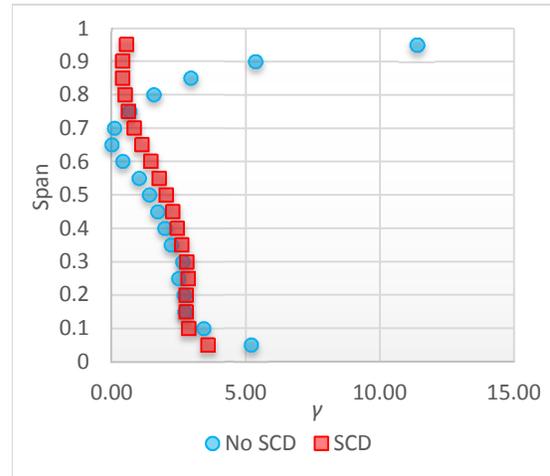


Figure 5 Incidence plots at the blade leading edge, with and without the SCD

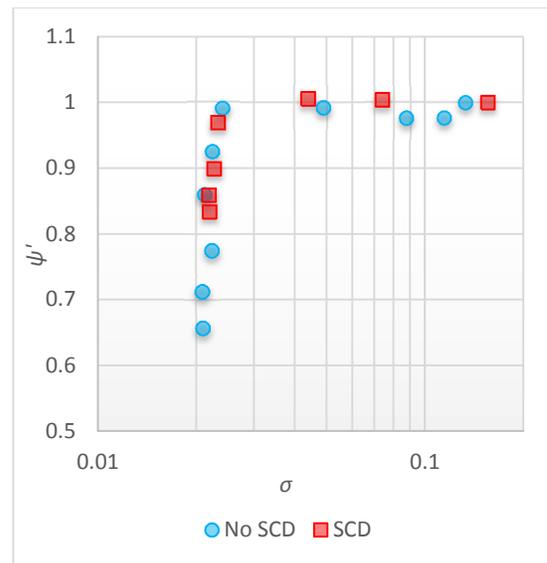


Figure 6 Machine breakdown curves for the inducer with and without the SCD

for each case. There is little difference between the two breakdown curves. The head coefficient remains constant until the cavitation number drops to 0.022. At this cavitation number, cavitation has started to significantly block the flow between the blades. This causes the blades to stall and the performance of the inducer becomes unstable. The head coefficient drops rapidly with small changes in the inlet pressure.

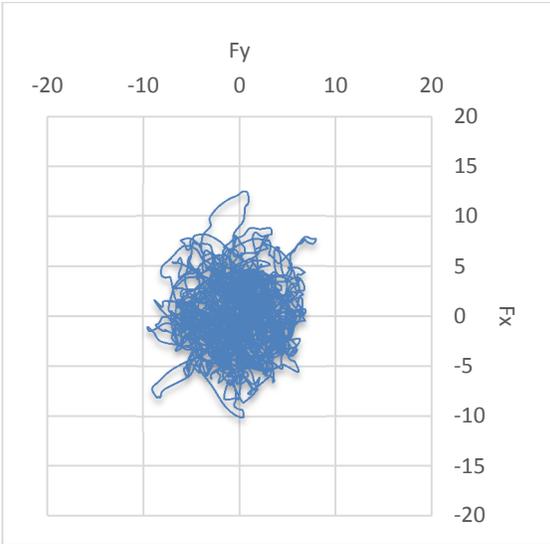


Figure 7 Orbit plot for an inducer without the SCD at $\sigma=0.022$

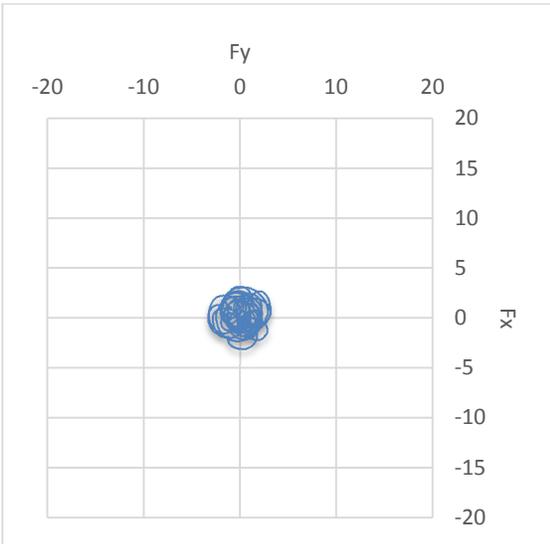


Figure 8 Orbit plot for an inducer with the SCD at $\sigma=0.022$

Radial forces on the blade are caused by an asymmetric pattern of cavitation on the blade. When the forces become strong enough, the inducer orbits become large and can cause the inducer to fail. Figure 7 shows an orbit plot for an inducer without the SCD at a cavitation number of 0.022. The orbit plot is a plot of the radial forces on the rotor in the y direction versus the radial forces on the rotor in the x direction. Plotting this parameter over time shows the orbit of the forces on the inducer.

Without the SCD, forces reach up to approximately 10 N. The forces on the rotor are unsteady, represented by the jagged edge of the orbit plot. Figure 8 shows an orbit plot for an inducer with the SCD at a cavitation number of 0.022. The magnitude of the forces are nominally 50% lower than the inducer without an SCD. The orbit plot is circular without jagged edges, suggesting that the forces on the rotor are more stable. By decreasing the magnitude of the forces and making them more stable, an SCD could increase the range of acceptable operating conditions for the inducer.

Conclusions

Numerical simulations have been performed on an inducer with and without the presence of an SCD at the design flow coefficient. Analysis has shown that when an SCD is included for this inducer, there is little change in the performance of the inducer at the design flow coefficient. The breakdown curves were shown to be nearly identical. The increased mass flow at the leading edge from recirculation through the SCD only produced slight changes in the incidence. The reversed flow at the blade tip was eliminated when an SCD was present. This resulted in a moderate decrease in the radial loads that the inducer experiences. Because of the decrease in the radial load, it is possible that the addition of an SCD could allow an inducer to more stably operate at lower operating pressures.

Additional studies need to be performed at a flow coefficient lower than the design flow coefficient. At low flow coefficients, the suction performance of the inducer is better and the inducer can operate at lower cavitation numbers. Operating at lower cavitation numbers also introduces more flow instabilities into the flow, such as significantly more

backflow from the blade tip. Because the implementation of an SCD has shown that it is capable of eliminating the reversed flow and diminishing the radial loads on the inducer, the benefits of the SCD would be more noticeable at the lower flow coefficients.

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It is also important to note that this inducer was designed to operate without an SCD and the design does not take full advantage of the benefits that an SCD can provide. Aerodynamic blockage between the blades can be delayed by increasing the area between the blades. This is done by increasing the inlet blade angle. Without the SCD, increasing the blade angle would also increase the incidence. If the incidence becomes too large, the flow can become unstable. With the SCD, the mass flow gain increases as the inlet blade angle increases. This would allow the inducer to keep acceptable incidence values while increasing the flow area between the blades.

References

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