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CONTROL OF FLOW SEPARATION IN A WATERJET USING EXPERIMENTAL TECHNIQUES

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ABSTRACT

Research work undertaken by previous researchers has clearly shown that the boundary layer along the roof of a waterjet intake is likely to separate when the speed of the boat is relatively high. This paper discusses wind tunnel simulation work carried out to control flow separation in a waterjet. Investigations were carried out using vortex generators, boundary layer blowing and a splitter plate to ascertain the extent of flow improvement. Performance changes were related to impeller plane flow improvement. At high medium boat speed with an IVR of 0.55 the results of tests using vortex generators yielded the best Fractional Improvement (F.I.) of about 28%, while in the case of boundary layer blowing an F.I. of 53% was recorded under optimum blowing conditions. The splitter plate design provided a relatively good result with an F.I. of about 46% recorded at IVR of 0.55. It was further noted that in the case of vortex generators their location was very critical; the location of the splitter plate and its size were very important factors to consider for good performance. The optimisation of the blowing gap size and the blowing rate were found to be of utmost importance to achieve good results in the case of boundary layer blowing.

1. INTRODUCTION

Marine vehicles have undergone various phases of technological development over the years. Around the time of the industrial revolution, sailing ships (1830) could travel at 10 knots (1 knot is about 1.85 km/h) while clipper ships (1870) could manage 16 knots (Basin and Latorre, 1997). At the moment, very large catamaran ferries can cruise at 48 knots and by using aerofoil section superstructures designers are aiming at very high-speeds, in the region of 80 knots (Walker et al., 1997). Roy (1994) and Allison (1992) give interesting overviews of the development of waterjet propulsion.

As an alternative to conventional propellers the waterjet propulsion system is currently used on many medium and high-speed craft. Mechanical simplicity, good performance, high fuel efficiency, shallow draft, good manoeuvrability, high safety, low noise and vibrations are some of its key features.

The roof of a waterjet intake (Figure 1) is curved and this curvature subjects the fluid entering the intake section initially to a favourable pressure gradient and then to an adverse pressure gradient. It is known that the boundary layer along the roof of a waterjet intake separates when the boat is running at relatively high-speed, above 35 knots. The size of the separated region grows as the speed of the boat increases. The presence of a non-uniform flow impairs the performance of the impeller, which is designed to handle uniform flow. A reduction in the non-uniformity of flow at the impeller entry plane is expected to bring additional benefits such as minimising the likelihood of cavitation damage to the impeller and reduction, or at best elimination, of vibrations due to unbalanced loading of the impeller.

Most researchers in the area of intake design have been concentrating on intake design based on changing the geometric features using CFD methods (Seil et al., 1997 and Allison, 1997) while the current research has taken a different approach. In this research attention was directed at additional design features to existing intake geometry. Many different methods can be used to control flow separation (Schlichting, 1968). The methods used in this work are: vortex generators, boundary layer blowing, splitter plate and intake screen.

2. APPARATUS AND METHOD

The experimental work described in this paper was carried out in the re-circulating aeronautical wind tunnel of the Department of Mechanical Engineering, Canterbury University (New Zealand). The working section of the wind tunnel is 1.2 m wide, 0.9 m high and 2.4 m long. With a typical operating speed of 25 m/s the flow may be considered incompressible. Although the Reynolds number is much smaller when using air as the working fluid, as opposed to water, previous work at the University of Canterbury, by Griffith-Jones (1994), has shown the results to be applicable to the real situation.

Figure 2 shows the schematic arrangement of the experimental apparatus in plan view. An experimental waterjet unit, with a curved duct, was placed on one wall of the working section of the wind tunnel. No impeller was used and the stator section was bored out to just leave the outer casing. A length of pipe was attached to the unit just after the nozzle in order to ensure that at a downstream measuring plane there would be fully developed pipe flow. The results obtained from a rake of pitot tubes at this measuring plane were used with knowledge of the local static pressure to determine the mass flow rate through the intake with an accuracy of better than 5%.

Performance changes were related to the Intake Velocity Ratio (IVR), which is defined as the ratio of the mean velocity at the impeller plane (Vi), and the tunnel main flow velocity (V_b), the equivalent of the boat velocity. It is worth noting that low boat speed corresponds to high IVR and *vice versa.* A centrifugal fan was connected to the end of the pipe to assist the flow. The variation of IVRs was achieved by changing the tunnel and fan speeds.

A second rake of pitot tubes was built and placed at the impeller plane to record the extent of flow non-uniformity at this plane. Twenty-six pressure tappings were installed at roughly uniform increments along the roof to measure the pressure variation. The pneumatic tubes from the rakes and the pressure tappings were connected to a scanivalve pressure switch and a pressure transducer. The transducer was connected to an analogue to digital card and computer system, which recorded the data.

The first design modification involved vortex generators, which were placed along the roof of the intake, at two different locations corresponding to what was termed setup 1 and setup 2 (Figure 3). The second modification made use of a boundary layer blowing system, schematically shown in Figure 2, mainly consisting of an annubar, to measure the blowing flow rate, a pressure transducer and a plenum chamber. The boundary layer blowing device made use of tangential slot blowing, in addition an adjustable flap was used to vary the blowing gap. The third design modification consisted of fitting an adjustable splitter plate mechanism (Figure 4). The splitter plate was connected to an extension bar, with provision for translational and angular motions. Experiments were carried out to determine the effect of additional design features on the intake flow distribution, especially at the impeller plane.

3. RESULTS AND DISCUSSION

3.1 VORTEX GENERATORS

Figure 5 illustrates the impeller plane distribution of the non-dimensional stagnation pressure coefficient, c_{p0}. At high medium boat speed with a typical IVR of 0.55, there is a significant degree of flow non-uniformity at the impeller plane, especially for the bare intake. The non-uniformity of flow is reflected by the lower values of stagnation pressure coefficient in the region between the intake roof, $r = -1.00$ and the centre line, $r = 0.00$ (horizontal axis). As the boat speed increases to match an IVR of 0.4, the region of lower c_{p0} extends beyond the centre line up to about the middle of the impeller plane bottom half. It can be seen that vortex generators provide a marginal improvement in the flow distribution at the impeller plane compared to the bare intake, however it is still not near the ideal flow distribution ($c_{p0} = 1.00$ throughout). The region of stagnation pressure deficiency is representative of the size of the separated region. At low boat speed with an IVR of 0.97 experimental results showed that the c_{p0} deficient area was much smaller even for the bare intake situation. It is for this reason that flow separation from the roof is generally not a major problem at low boat speed range.

Results of Figure 5 (IVR=0.55, steup 1) represent a Fractional Improvement (F.I.)* of 27.8% and is better than the improvement recorded for setup 2. At low speed (IVR=0.97, setup 1) the F.I. was 14.5%. In the case of the high boat speed with an IVR of 0.4 vortex generators in the configuration of setup 2 provided better results with a "Fractional Improvement" of 9.5% as opposed to 6.8% for setup 1. Investigations were carried out, by trying to locate the vortex generators in different positions, and ultimately only setups 1 and 2 provided satisfactory results. These results suggest that vortex generators should be correctly positioned for them to be effective. The correct position was found to be just ahead of the separation point for the bare intake.

Figure 6 shows the distribution of the static pressure coefficient (c_p) along the "ramp-roof" surface of the waterjet intake. The results reveal information about the onset of separation, which is characterised by the beginning of a "plateau" region along the curve. The longer the length of the plateau the bigger the size of the separated region. Although the downstream movement of the separation point is not quite evident from Figure 6, it is possible to note the induced pressure gradient as a result of the presence of vortex generators along the roof of the waterjet intake. In addition, flow visualisation using cotton tufts revealed marginal downstream movement of the separation point.

3.2 BOUNDARY LAYER BLOWING

Figure 7 shows the effects of blowing high momentum fluid into the boundary layer, next to the waterjet intake "ramp-roof", on the quality of flow at the impeller plane, at IVR=0.55. The results of four different blowing rates are compared with those for the "no blowing" situation. For commercial reasons specific values relating to the blowing rate and gap opening are withheld. The general trend exhibited by experimental results was that

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* *Fractional Improvement (F.I.) is the ratio of the actual improvement in the area weighted overall stagnation pressure coefficient to the value of the improvement that would give an overall stagnation pressure coefficient of 1.0.*

higher blowing rates generated more uniform flow at the impeller plane and also produced a smaller separated flow region. From Figure 7, the bottom curve represents the c_{p0} distribution without blowing. A small amount of blowing generated an F.I. of about 20% (second curve upwards), while an increase in the blowing rate by a factor of 2.5 yielded a corresponding increase in F.I. of 83% (top curve), more than four fold. It is important to note that an increase in blowing rate does not necessarily yield a "proportional" increase in F.I..

It is vital to note that although theoretically it might be tempting to blow as much as possible in order to reduce the stagnation pressure deficiency at the impeller plane, in practice the higher the blowing rate the more the required supply pressure would be. And in real life a high externally supplied pressure would entail additional power or in the case of bleeding, some of the downstream high-pressure fluid would be used thereby reducing the propulsive thrust. With the above limitation in mind, the optimum blowing conditions (blowing rate and gap opening) produced an F.I. of about 53%.

3.3 SPLITTER PLATE

Figure 8 shows the stagnation pressure distribution at the impeller plane for an intake fitted with a splitter plate, with the boat operating at an IVR of 0.6. Under the above operating conditions an F.I. of 46% was recorded and a relatively good uniformity of flow at the impeller plane was noted. This performance compares fairly well, although slightly lower, with the optimum results achieved using the boundary layer blowing design. Figure 8 also shows that the stagnation pressure coefficient losses are significantly reduced resulting in the flow condition at the impeller plane to be closer to the ideal situation ($c_{p0} = 1.0$). Several splitter plates of different sizes were tested at different positions. It was noted that both the size and position of the splitter plate influenced its performance in controlling flow separation. Smaller plates tended to perform better because they produced smaller wake regions. While the boundary layer blowing technique presented some design and manufacturing complexities using a splitter plate method was simpler and cheaper.

A design consisting of a splitter plate and an aerofoil bar screen (Figure 4) was implemented and tested. Generally, experimental results revealed that the combined design generated nearly additive effects to the waterjet intake flow at the impeller entry plane. The results have indicated that this design was practical and viable for real jet boats, especially those involved in high-speed applications.

4. CONCLUSION

This paper has shown that it is possible to delay the onset of separation and reduce the size of the separated region along the roof of a waterjet unit using experimental methods. The experimental techniques used in this research employed vortex generators, boundary layer blowing and a splitter plate. The improvement of flow condition at the impeller plane was expressed in terms of Fractional Improvement (F.I.) and the following significant results were noted: at an IVR of 0.55 the best F.I. was approximately 28% for vortex generators, while 53% was recorded using boundary layer blowing technique with optimum blowing conditions. The splitter plate design provided relatively good results with an optimum F.I. of about 46% recorded at an IVR of 0.55. The research revealed that the effectiveness of vortex generators was dependent on their location just before the onset of separation. It was also noted that the size and location of the splitter plate in the intake duct were very critical to its performance. Although the boundary layer blowing technique appears to be the best of the three options, its design complexity tends to limit its scope of application.

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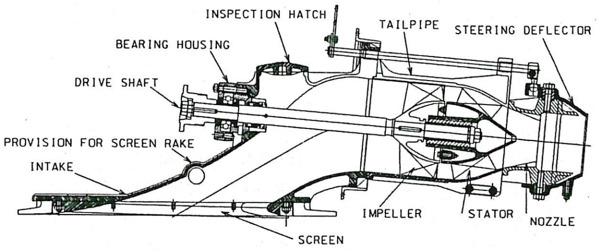

Fig. 1: A cross section view of a typical waterjet unit.

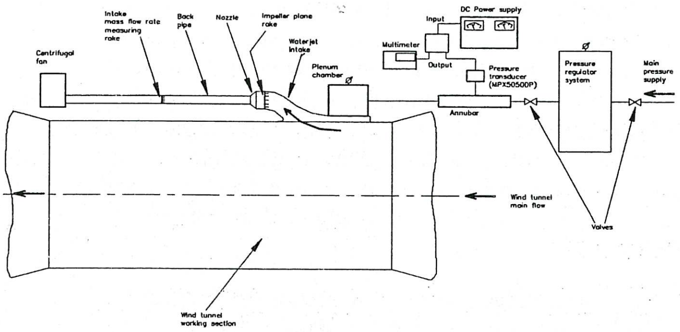

Fig. 2: Schematic of the experimental rig with boundary blowing setup.

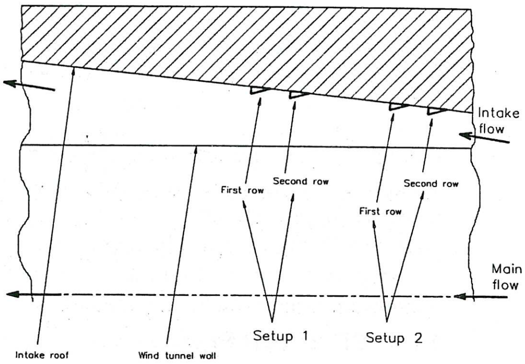

Fig. 3: Vortex generators on the "ramp-roof" surface of the waterjet unit.

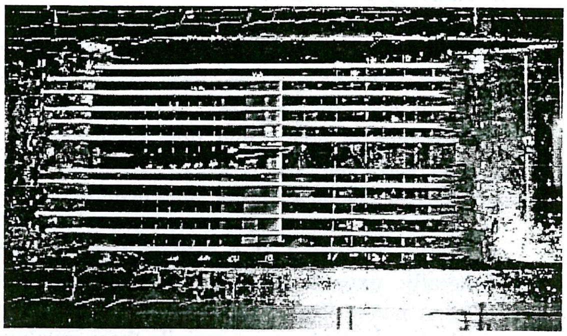

Fig. 4: Waterjet unit fitted with a splitter plate and a screen.

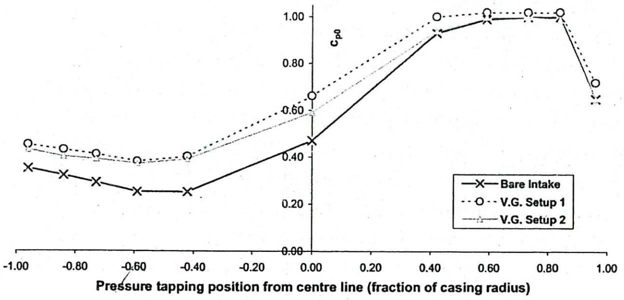

Fig. 5: Impeller plane stagnation pressure coefficient distribution at IVR=0.55 for an intake fitted with vortex generators.

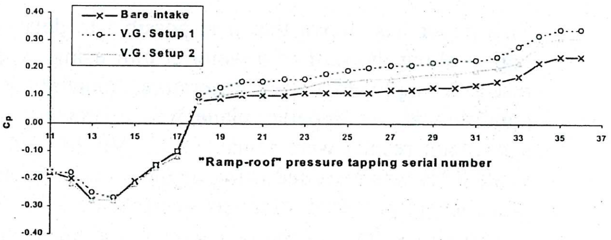

Fig. 6: Static pressure coefficient distribution along the "ramp-roof" at IVR=0.55 for an intake fitted with vortex generators.

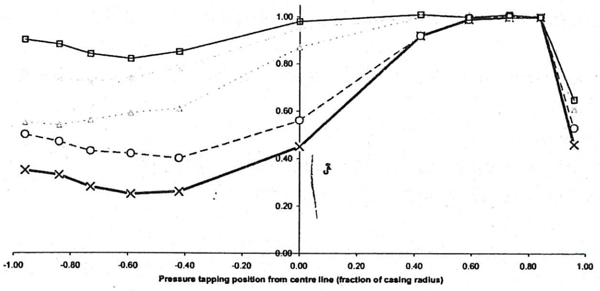

Fig. 7: Impeller plane stagnation pressure coefficient distribution at IVR=0.55 for a unit fitted with the boundary layer blowing setup (Bottom curve: No blowing; Top curve: High blowing).

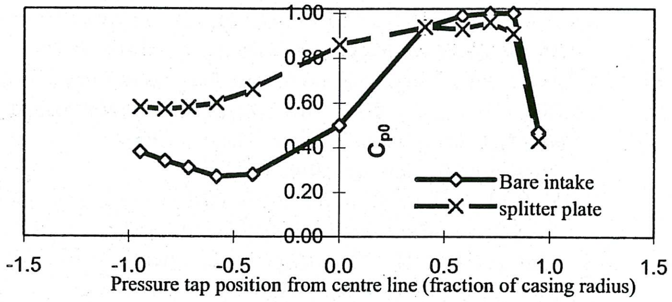

Fig. 8: Impeller plane stagnation pressure distribution at IVR=0.6 for an intake fitted with a splitter plate.