Wakes of Idealized Propeller Shafts With Sleeves

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ABSTRACT

The rotation of a bare propeller shaft on a twin screw ship can have a significant effect on the flow into the propeller plane, with consequent effects on the propeller efficiency and cavitation characteristics. TRANSOM, the DRDC Atlantic flow solver, was used to determine whether covering the shaft with a non-rotating sleeve along part of its length would improve the propeller inflow. Two sets of calculations were performed. In the first a semi-infinite cylindrical shaft protruded from a flat plate. The shaft was covered along part of its length by a zero thickness stationary sleeve.

To gain an understanding of the effects of the diameter of the sleeve relative to the shaft, a second set of calculations was performed in which the diameter of the sleeve was larger than that of the shaft. To avoid complications in gridding this configuration, the flat plate was removed; the shaft was infinite in both directions with a change in radius and a change from non-rotating to rotating in the middle.

These calculations suggest that a sleeve will reduce the wake fraction in the propeller disk by delaying the formation of a vortex that entrains velocity deficit from the hull boundary layer. The sleeve also keeps the entrained velocity deficit closer to the shaft where it is less likely to induce cavitation. As the mismatch in radii of the sleeve and shaft increases, the entrained velocity deficit increases, so thinner sleeves should be preferred.

1 INTRODUCTION

At moderate to high speeds, the predominant source of radiated noise for a naval ship is cavitation on its propellers. The cavitation is strongly influenced by the inflow into the propeller disk. Regions of low velocity due to the hull boundary layer or the wake from the propeller shaft tend to increase the angle of attack seen by the propeller sections thereby reducing the pressure on the suction face and increasing the likelihood of cavitation.

Recent calculations[4] have shown that the rotation of a bare propeller shaft on a twin screw ship can have a significant effect on the flow into the propeller plane, with consequent effects on the propeller efficiency and cavitation characteristics. The changes to the propeller inflow are principally due to a vortex rotating in the opposite sense to the shaft, which entrains velocity deficit from the shaft and plate boundary layers, then detaches from the shaft and migrates to the outer regions of the propeller disk.

The current paper describes extensions to these calculations in which the shaft was covered along part of its length with a non-rotating protective sleeve. The DRDC Atlantic flow solver TRANSOM[1, 3] and the Spalart-Allmaras turbulence model[5] were used for all calculations.

2 ZERO THICKNESS SLEEVE

In the first set of calculations a semi-infinite cylindrical shaft protrudes from a flat plate at an angle $\beta = 10^\circ$; the incident flow meets the shaft at an angle $\alpha = 6^\circ$: see Figs. 1 and 3. The thickness of the boundary layer on the plate is roughly $1.5D$, where D is the diameter of the shaft. The Reynolds number based on shaft diameter is 10^5. The boundary conditions on the shaft surface are set so that it is non-rotating for a distance

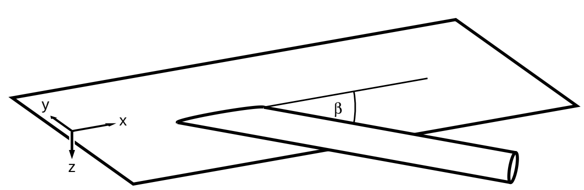

Figure 1: The shaft

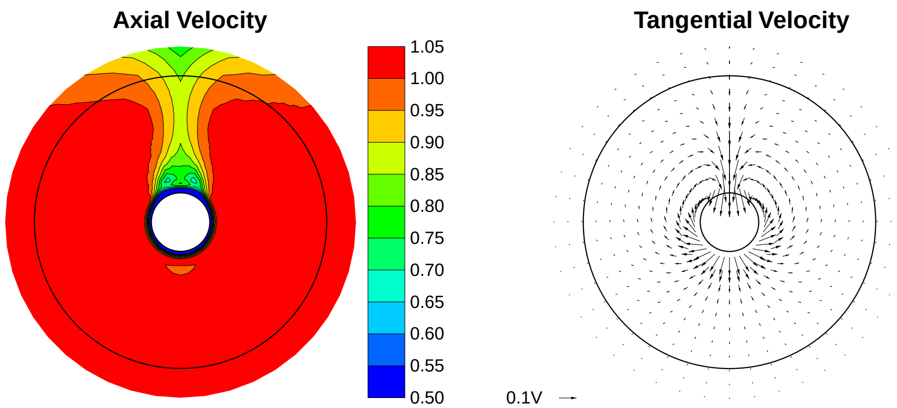

Figure 2: Inflow to the propeller disk with no rotation and no cross-flow

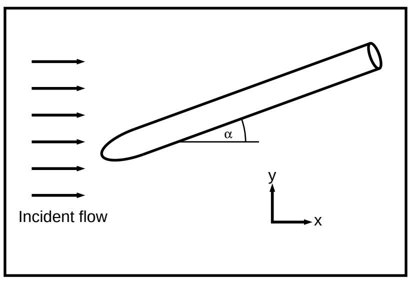

Figure 3: The shaft seen from directly below. The z coordinate extrudes vertically from the page.

S from the shaft/plate junction, rotating after that. A small transition region of length $0.5D$ was used to ramp up the rotating portion of the shaft so that the boundary conditions did not change in a discontinuous fashion. The grids used are the same as those described by Hally[4].

The rotation rate of the shaft is quantified by the non-dimensional rotation parameter Ω:

$$\Omega = \frac{\omega D}{2V} \tag{1}$$

where ω is the shaft rotation rate and V is the speed of the free stream. Therefore Ω is the speed of the fluid at the the shaft surface relative to the speed of the free stream.

Calculations were performed for $S = 3D$, $8D$ and $13D$ and displayed in a nominal propeller disk at a distance of $20D$ from the shaft/plate junction. The cases $S = 0D$ (bare shaft) and $S = 20D$ (non-rotating shaft) were also available from earlier calculations.

For reference, Fig. 2 shows the wake in the nominal propeller disk when there is no shaft rotation and no cross-flow. The tangential velocity shown in this and subsequent figures is the velocity projected onto a plane perpendicular to the free stream direction. This is not the usual convention of projection onto a plane perpendicular to the shaft, but it has the advantage of highlighting the vortices that are convected primarily by the free stream.

Fig. 4 shows the inflow to the nominal propeller disk for $S = 3D$, $8D$, $13D$ and $20D$ with $\Omega = -0.6$. The bowing of the wake to the right is caused by the cross-flow. The vortex on the right side of the disk is caused primarily by the shaft rotation but with a small contribution due to the cross-flow. It forms to the right of the shaft close to the junction of the shaft and the plate. It is initially very weak but is strengthened considerably as it is convected beyond the point where the shaft begins to rotate. The vortex detaches from the shaft and is convected by the free stream, moving upwards away from the shaft. The vortex captures velocity deficit from the shaft and plate boundary layers and transports it away from the shaft to the upper regions of the propeller disk.

For $S = 3D$, the wake is very similar to the no-sleeve case reported by Hally[4]. As the sleeve is lengthened, the strength of the vortex decreases as it sees less influence of the shaft rotation before the propeller disk is reached. It also moves closer to the shaft, where it originally forms, having less time to be convected upwards by the free stream. The amount of velocity deficit captured by the vortex also decreases for two principal reasons.

1. Because the vortex is weaker, it is not as efficient at entraining the velocity deficit.
2. Because the strengthening of the vortex by the shaft rotation does not occur until the shaft is below the plate boundary layer, there is less velocity deficit available to entrain.

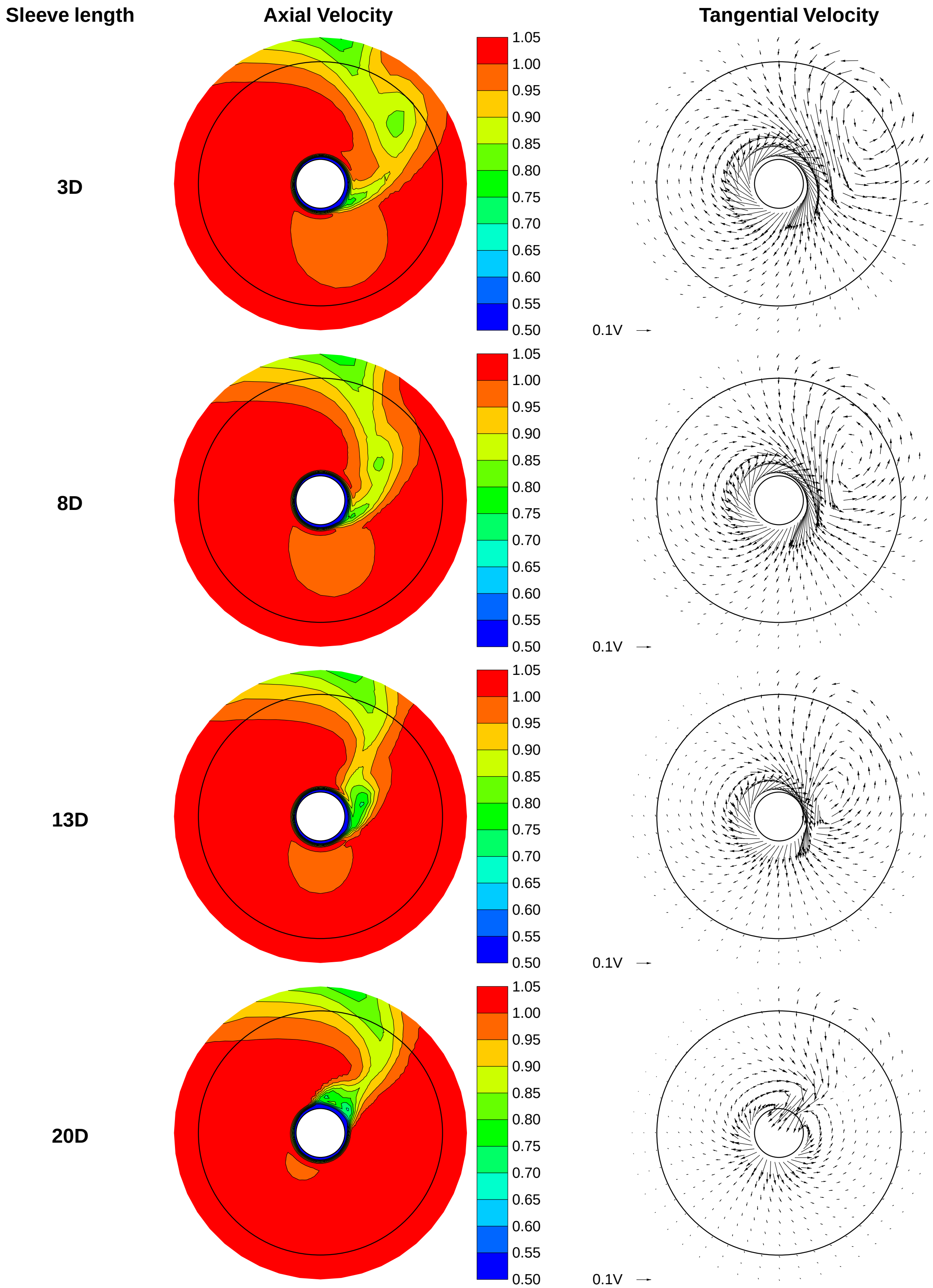

Figure 4: Inflow to the propeller disk with sleeves of different length: $\Omega = -0.6$; $\alpha = 6^{\circ}$; $\beta = 10^{\circ}$.

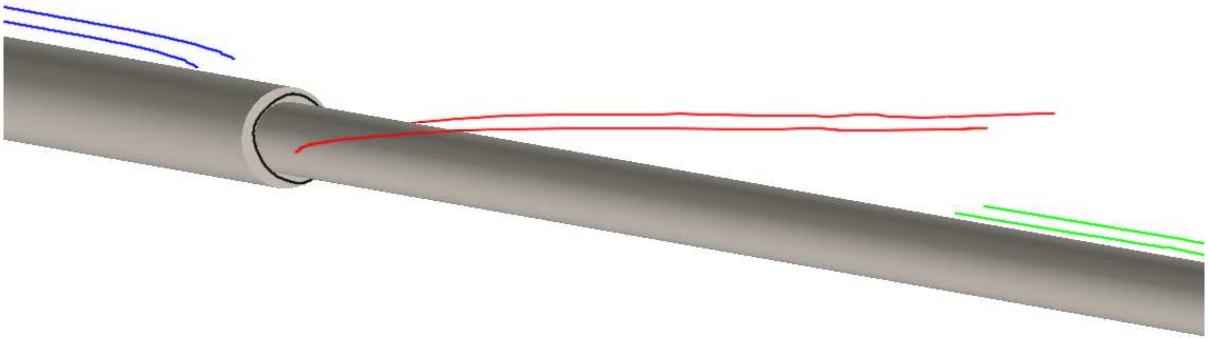

Figure 5: The cores of the principal vortices for a non-rotating shaft with a $0.2D$ lip

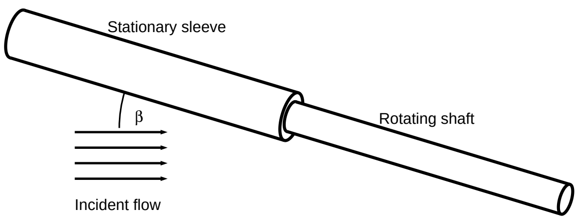

Figure 6: The infinite shaft with a sleeve

3 Finite Thickness Sleeve

The previous calculations suggest that a sleeve is effective at reducing the velocity deficit in the propeller disk caused by shaft rotation. However, while it is common to have a sleeve over the shaft for some portion of its length, the mismatch in radius between the shaft and the sleeve is often substantial. To gain an understanding of the effect of this mismatch an addition series of calculations was performed in which the diameter of the sleeve was 0%, 10%, 20%, 40% and 100% larger than that of the shaft. To avoid complications in gridding this configuration, the flat plate was removed; the shaft was infinite in both directions with a change in radius and a change from non-rotating to rotating in the middle: see Fig. 6.

Where the radius changes will be called the lip and the difference in radii at the lip will be denoted by s. Thus the five configurations tested have $s = 0D$, $0.05D$, $0.1D$, $0.2D$ and $0.5D$.

On the face of the lip the velocity was ramped linearly from zero at the top to the shaft rotation velocity at the bottom. For the case with $s = 0D$, the velocity was ramped up linearly over a distance of $0.5D$.

In all cases the angle of inclination with the flow is 8°. This is somewhat smaller than the 10° used for the previous calculations. The decrease reflects the fact that for real propeller shafts the inclination of the flow to the shaft typically decreases from about 10° or 12° where the shaft leaves the hull to about 5° or 6° at the propeller disk. In the previous series of calculations 10° was used because the flow near the shaft/plate junction was of principal interest. For the current calculations, a value of 8° was considered more typical of the flow inclination near the end of the sleeve.

3.1 The effect of the lip with no rotation

Figs. 5 and 7 illustrate the effect of the lip alone, with no shaft rotation. For both these figures the size of the lip is $s = 0.2D$. Fig. 5 shows the locations of the cores of the principal vortices in the flow; these were determined by a vortex tracker based on the algorithm described by Haimes[2]. Fig. 7 shows the flow in three disks at different locations along the shaft. The uppermost wake in this figure is the wake in a disk far upstream of the lip; for the three lower wakes the disk is at $x = 9.9D$, $15.8D$ and $19.4D$ where x is the distance downstream of the lip.

In the upstream wake the velocity deficit is confined to the shadow of the shaft and there are two weak counter-rotating vortices in the lee of the shaft, though these are difficult to discern in the tangential velocity plot because they are aligned with the shaft and not the free-stream. The cores of these vortices are shown as the blue lines in Fig. 5. As the vortices approach the lip they are distorted by the upstream effects of the lip until they are lost by the vortex tracker. In the lee of the lip there is a necklace vortex, shown in black, which circles the shaft. Two new vortices, shown in red, form at the sides of the shaft downstream of the lip. They then detach from shaft and are convected upwards carrying some entrained velocity deficit which causes a bulge in the axial wake contours, seen in the lower three wakes of Fig. 7. As the size of the lip increases, the strength of the detaching vortices is mag-

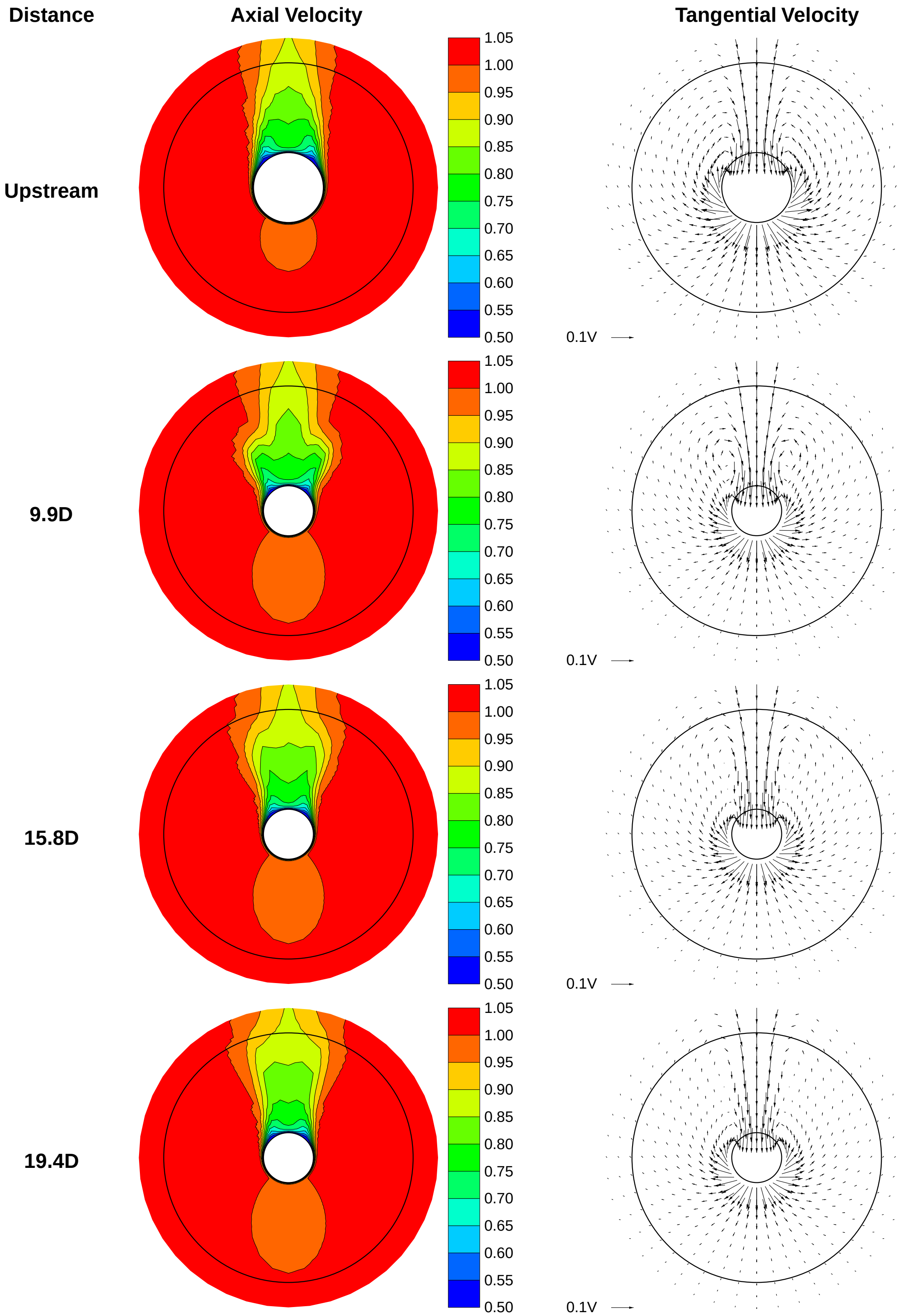

Figure 7: Inflow to the propeller disk at different distances from the lip: no rotation; $s = 0.2D$.

nified causing a corresponding increase in the bulge. Due to the convection of the velocity deficit by the vortices, the width of the bulge is greater than the width of the upstream wake. Therefore the lip, by itself, causes a deterioration in the wake experienced by the propeller. The separation of the flow at the lip provides a mechanism for the upstream boundary layer velocity deficit, which normally stays close to the shaft, to be convected upwards through the propeller disk where it can cause more cavitation.

Far downstream of the lip, two counter-rotating vortices form again in the lee of the shaft (the green lines in Fig. 5).

3.2 The effect of the lip with rotation

The rotation of the shaft causes the vortices to be shifted sideways in the direction of the rotation. The vortex on the left of the disk is weakened, while the vortex on the right is strengthened. However, the rotation does not substantially increase the overall amount of velocity deficit in the wake; its primary effect is to redistribute the existing velocity deficit pulling it down and to the right of the shaft.

Fig. 8 shows the wakes at a distance $x = 15.8D$ for rotation rates of $\Omega = 0.0$, 0.5 and 1.0. As was found earlier by Hally[4], once the magnitude of the rotation rate exceeds roughly $|\Omega| = 0.5$, higher rotation rates cause very little additional change in the wake (compare the two lower wakes in Fig. 8). Since typical rotation rates for ships are in the range $|\Omega| = 0.5$ to 1.0, one needs only consider three rotation states when evaluating the effect of the shaft on the propeller inflow: not rotating (i.e. fully protected by a sleeve), rotating outward over the top, or rotating inward over the top. The actual rotation rate is of lesser importance.

The effect of the size of the lip is shown in Fig. 9. There is a clear increase in velocity deficit as the lip size increases. This is primarily due to the extra velocity deficit introduced by the lip itself (see Sec. 3.1) which is then redistributed by the shaft rotation.

4 CONCLUSIONS

These calculations lead to the following general conclusions. A vortex is generated at the end of the sleeve by the transition from a stationary to a rotating boundary. The strength of the vortex depends only weakly on the length of the sleeve. However, when the sleeve is present, the vortex initially forms farther from the hull where there is less boundary layer velocity deficit to entrain. Therefore, the sleeve does help to reduce the wake fraction in the propeller disk. The delay of generation of the vortex also gives it less time to migrate outward from the shaft as it detaches. Therefore the concentration of velocity deficit in the propeller disk is closer to the hub for longer sleeves. This can have a significant effect on cavitation as it keeps the velocity deficit away from the critical areas near the edge of the propeller disk.

The mismatch in radius between the sleeve and the shaft causes two counter-rotating vortices to detach from the shaft, even when there is no rotation. These vortices can cause significant transport of velocity deficit from the shaft/sleeve boundary layer to the outer portions of the propeller disk, likely leading to an increase in the production of cavitation. Increasing the radius of the sleeve increases the amount of velocity deficit transported, primarily because there is more velocity deficit in the lee of the lip that can easily be entrained by the vortices.

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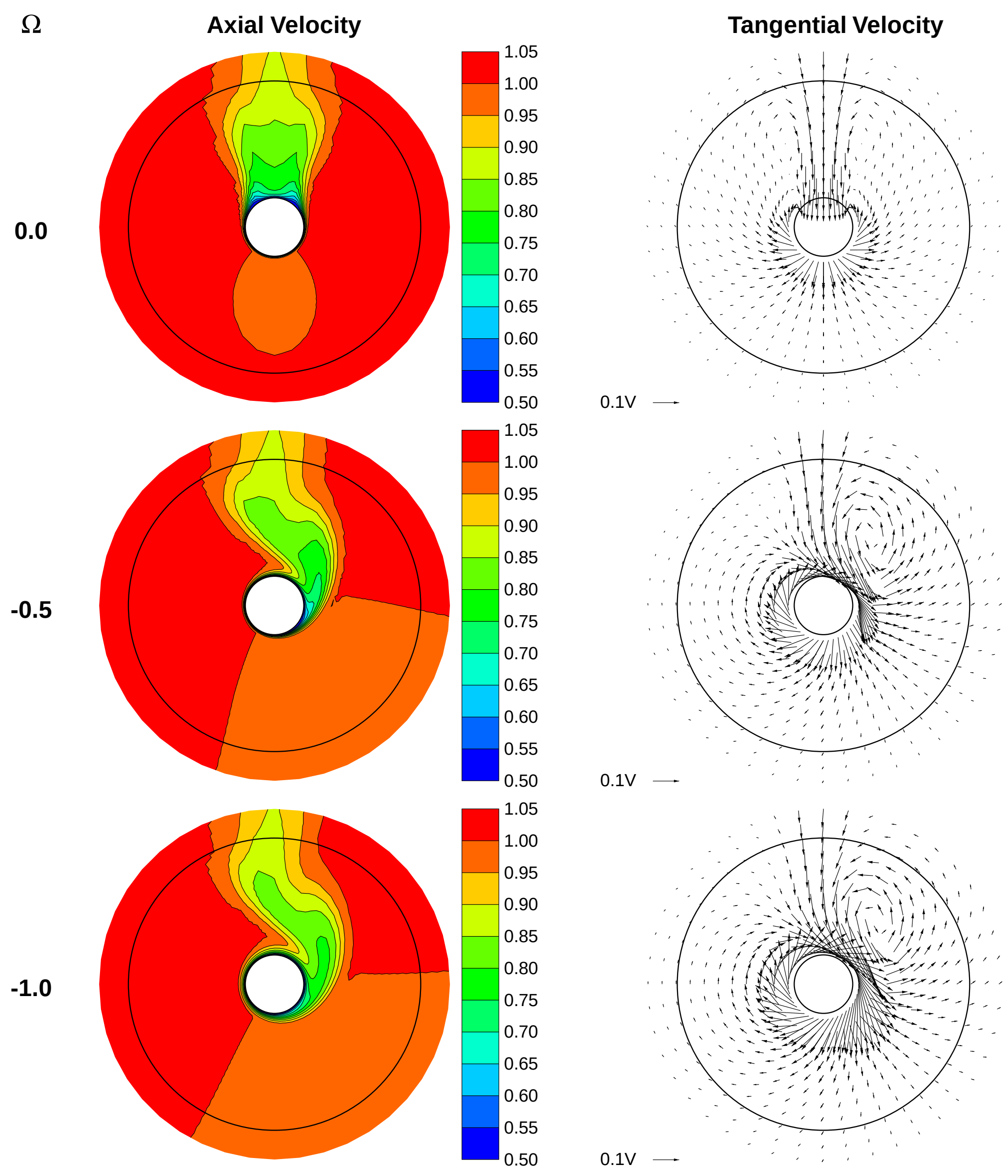

Figure 8: Inflow to the propeller disk at different rotation rates: $x = 15.8D$; $s = 0.2D$.

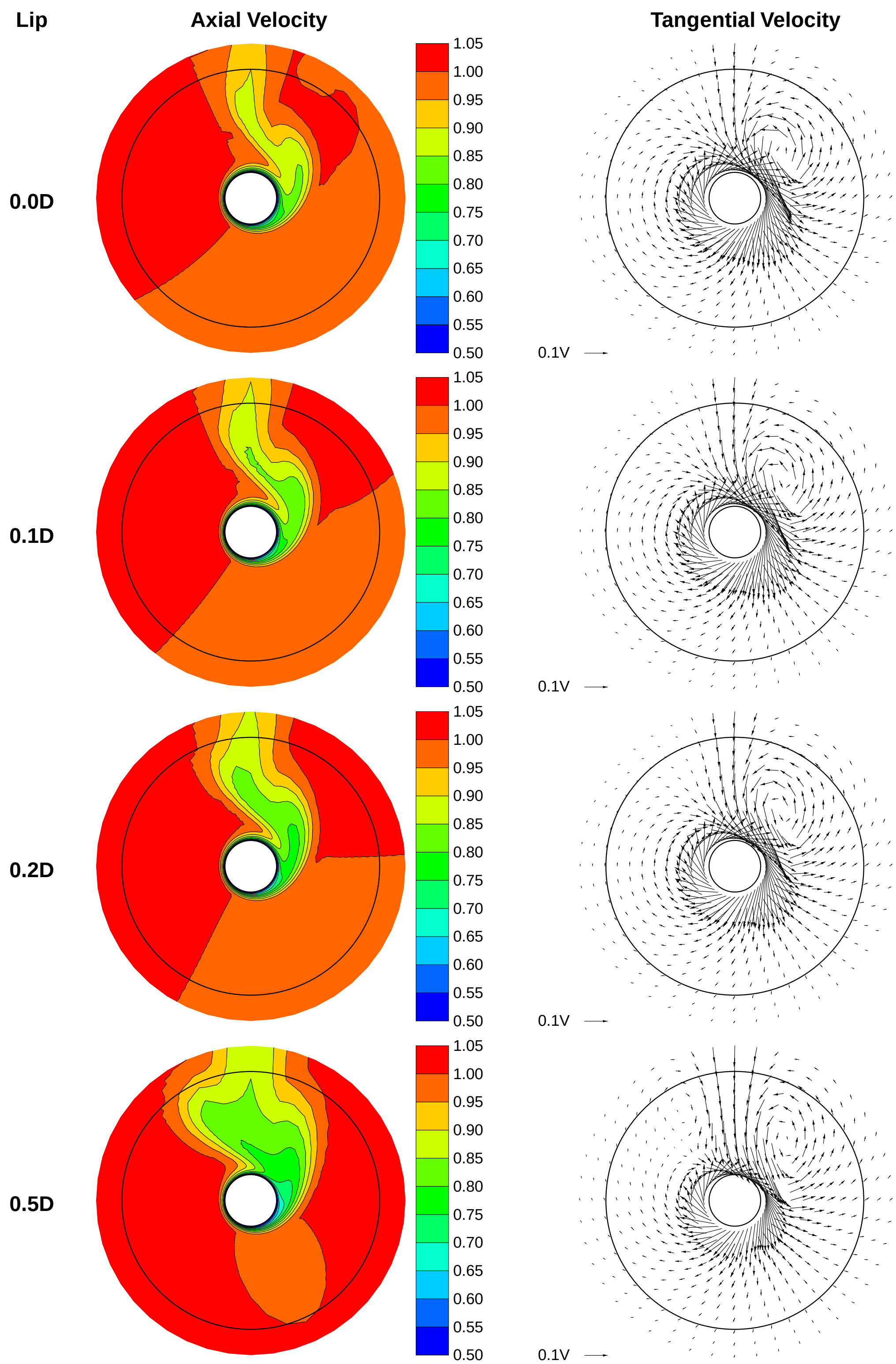

Figure 9: Inflow to the propeller disk for different lip sizes: $x = 15.8D$; $\Omega = -1.0$.