FLOW ALONG A LONG THIN CYLINDER

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Summary Calculations have been performed for the flow along long thin cylinders using a variety of methods, from a boundary layer code with a turbulence model to a full, time accurate, Navier-Stokes solver. The results have been validated by comparison with those from experiments. It has been found that there are major differences between the flow on a cylinder and the equivalent flow on a flat plate, with the wall shear stress tending to a constant mean value far downstream. Calculations of the power spectral density of the surface pressure fluctuations show that the noise generated by the turbulence initially increases as the radius of the cylinder is decreased, but eventually decreases as the radius is decreased further.

INTRODUCTION

The external flow along a long thin cylinder has been the subject of relatively few studies compared with that on a flat plate or in channels and pipes. The results that do exist show significant differences in the flow as compared with that for a flat plate. For both laminar and turbulent flows the velocity profile is fuller and the wall shear stress is higher than in the equivalent flow on a flat plate. All available experimental results show turbulent flow, even for Reynolds numbers of $O(10^2)$. Also, perhaps surprisingly, for long cylinders, in practice the drag per unit length appears to be constant, indicating a constant mean surface shear stress. Experimental results for higher Reynolds numbers ($O(10^5 - 10^6)$) show that the noise from the turbulent pressure fluctuations at the surface of the cylinder increases as the Reynolds number decreases. In practice, this implies that the noise increases as the cylinder radius decreases. Clearly this trend cannot continue to the limit of zero Reynolds number. Our interest is in investigating the behaviour for the flow along long cylinders, typical of the towed sonar arrays used for underwater sensing. This may have aspect ratios of up to $O(10^5)$, with a length of the order of a kilometre and a radius in the order of centimetres. Clearly it is impractical to perform a full Navier-Stokes calculation for a bodies of this size. Hence a series of problems, as outlined below, was studied, with validation using the results of the different model problems and comparison with experimental results.

SIMULATIONS USING A TURBULENCE MODEL

A series of calculations were performed for a cylinder aligned with the flow governed by the boundary layer equations with a variable viscosity given by the Spalart-Allmaras turbulence model. Very long cylinders with Reynolds numbers, Re, of $O(1)$ to $O(10^6)$ were considered, where $Re = U_\infty a/\nu$, a is the radius of the cylinder, and U_∞ the freestream velocity. Turbulent flow was predicted in all cases. A detailed comparison was made of the numerical results with the experimental measurements of Willmarth *et al* [1] and Lueptow *et al* [2], for flows with Reynolds numbers from 482 to 92310. Values for the displacement thickness, momentum thickness and friction velocity, and for the Reynolds stress across the boundary layer, showed excellent agreement, i.e. within the expected experimental error. There was also excellent agreement between the predicted and experimental velocity profiles, as can be seen in Figure 1. Note that the difference in the curves for the lowest Reynolds number in the far field comes from the difference in the numerical and experimental values for the friction velocity used to scale the velocity, when the radius of the cylinder is smallest, and the largest experimental errors might be expected. In all these calculations, standard values were used for the parameters

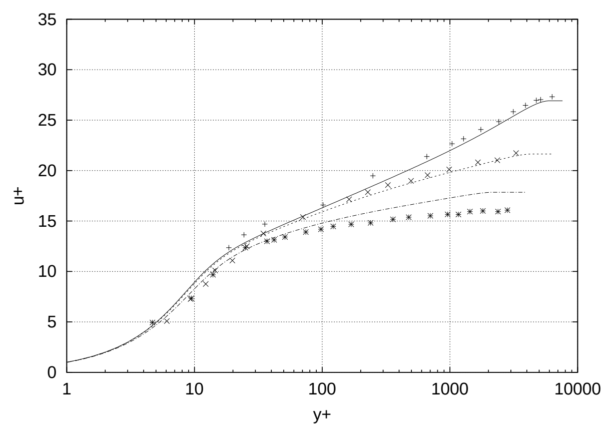

Figure 1. Velocity profiles in wall coordinates. Lines are numerical and symbols experimental from Willmarth *et al*: lower $Re = 736$, middle $Re = 4330$, top $Re = 74260$.

in the turbulence model, i.e. no tuning of the model was performed. In agreement with experimental observations, the calculations predicted that the far downstream value of the shear stress was essentially constant. Also, the values predicted for the drag per unit length are consistent with those obtained from towed arrays when deployed.

DNS AND LES SIMULATIONS

Although the enormous computational requirement rules out a full unsteady Navier-Stokes calculation, a model problem can be formulated for the far downstream region when the mean wall shear stress is predicted to be constant. This consists a finite region of the cylinder in which the flow is assumed to be periodic in the streamwise direction, with the boundary layer growing in thickness in time. A series of calculations was performed for Reynolds numbers from 500 to 10^5. For the lower Reynolds numbers (2000 or less) a Direct Navier-Stokes (DNS) calculation was performed, with no approximations. For higher Reynolds numbers, a Large Eddy Simulation (LES) approach was employed. A standard subgrid model was used for the LES, i.e. again, no tuning was performed. A basic prediction is that the mean wall shear stress obtained from this problem should tend toward the value predicted by the turbulence model, and by implication, the experimental values. That this occured can be seen from Figure 2 which shows the spatially averaged shear stress for $Re \leq 2000$. A similar level of agreement was found for the higher Reynolds numbers. The convection (phase) speed of the turbulence

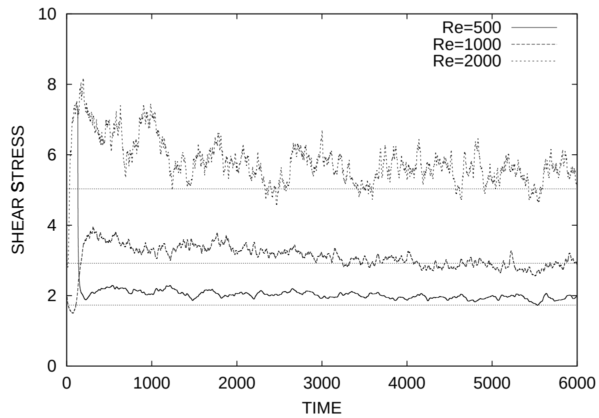

Figure 2. Spatially averaged wall shear stress against time for $Re = 500$ (bottom), $Re = 1000$ (middle), and $Re = 2000$ (top). Also shown are the far downstream values obtained using the Spalart-Allmaras turbulence model.

was estimated from the cross spectrum of the pressure fluctuation at two different points. This was approximately 70% of the free stream velocity, consistent with experimental values. Power spectral densities for the surface pressure fluctuations were calculated. These predicted that while for the noise from the turbulence at the surface would increase as Reynolds number (radius of the cylinder) decreased for the higher Reynolds number, as would be expected, eventually the noise would decrease with Reynolds number (radius).

CONCLUSIONS

Calculations have been performed for the zero mean pressure gradient turbulent boundary layer on a long thin cylinder over a wide range of Reynolds numbers. The Spalart-Allmaras turbulence model has been validated for this problem for the Reynolds numbers for which detailed experimental results are available. Both experimental and numerical results show that the boundary layer on a cylinder is thinner and has higher shear stress than for the equivalent flow on a flat plate. For all practical purposes the mean shear stress on the surface of the cylinder tends to a constant downstream. When this occurs the flow near the surface is independent of the downstream coordinate, while the outer part of the boundary layer continues to evolve, with the boundary layer growing in thickness as the square root of the distance.

Calculations have also been performed for flow on a finite section of the cylinder using a Navier-Stokes solver, including where necessary a subgrid model. There is good agreement with the results obtained using the Spalart-Allmaras turbulence model. Also, the predictions of the convection speed are consistent with those obtained in experiments.

Calculations of the power spectral density of the pressure at the surface show that for the higher Reynolds numbers, the noise from the turbulence increases as the radius of the cylinder decreases, consistent with experimental results. However, when the radius is reduced sufficiently, the noise peaks, then decreases, at least for the lower frequencies.

References

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[2] Lueptow R.M., Leehey P., Stellinger T.: The thick, turbulent boundary layer on a cylinder: mean and fluctuating velocities. *Phys Fluids* **28**:3495–3505, 1985.