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A verification study on low-order three-dimensional potential-based panel codes

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Abstract

A verification study of two different panel codes for three-dimensional potential flow is performed by grid convergence studies. The two codes used in this study implement low-order potential-based panel methods and were conceived for propeller applications. The results of the grid convergence studies are presented for the benchmark problem of the non-lifting potential flow past an ellipsoid with three unequal axes. Conventional non-orthogonal grids and orthogonal grids are used. The effect of the grid orthogonality near the grid singularity is investigated. An oscillating behaviour of the solution is observed in grids with extreme deviations from orthogonality, which are typical of conventional grids used on lifting surfaces. The oscillations disappear as the grid approaches orthogonality. Results of error norms are presented for the metric components, perturbation potential, surface velocity components and pressure. Near second-order convergence is achieved for the potential for the two grid types. The error in the pressure appears to be strongly related to the metric errors. For the range of grid densities used in this study, which goes beyond the grid densities used in practice for lifting surfaces, the results for the surface velocity components and pressure may be still far from reaching their asymptotic behaviour. However, for properly chosen grid densities, error levels can be found for the velocities and pressure which are acceptable for practical applications.

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1. Introduction

For more than three decades panel codes have been used for analysis and design purposes in a wide range of aerodynamic and hydrodynamic applications [1,2]. In the marine field panel methods have been extensively used for the hydrodynamic analysis of propellers [3–7]. Propellers operate mostly in the ship's wake, which causes unsteady periodic flow behaviour on the blades. Often, unsteady cavitation phenomena occur in the flow around the propeller blades and in the propeller wake. The complex unsteady flow around the propeller blades in the presence of three-dimensional sheet cavitation is amenable to modelling by potential-flow theory and computation by panel methods, as reviewed by Kinnas [8]. Despite its limitations, this model still offers the only feasible approach at the present time for three-dimensional unsteady flow computations in the presence of sheet cavitation, as viscous flow computations with Reynolds-Averaged Navier–Stokes (RANS) equations are still under development for cavitating flows.

Although the panel method can handle rather different propeller blade geometries, considerable difficulties are still found to obtain reliable pressure distributions in the propeller tip region when the blade section chord approaches zero at the tip or when the blade is highly skewed [9,10]. In such cases it may be difficult to ensure a zero pressure loading at the trailing edge, as required by the Kutta condition, without the occurrence of unrealistically high pressure peaks. Such peaks are in many practical situations unacceptable, as they artificially increase the tip loading and may spoil the convergence of sheet cavitation models.

From the physical point of view, the use of a potential-flow model to describe the pressure distribution behaviour near the tip of a lifting surface may be questioned in most cases, as there may be a strong viscous–inviscid interaction occurring in the tip flow. Nevertheless, even within the potential-flow model, errors of different nature and from various sources may contribute to the erroneous behaviour of the pressure distribution in the tip region. They include the discretization error, which is related to the type of panel grid used at the tip, and the error due to lack of wake alignment with the flow locally at the tip combined with the type of implementation of the Kutta condition [10].

In the present paper we investigate the discretization error by performing a verification study for an ellipsoid. Both code verification and calculation verification in the sense used by Roache [11,12] have been carried out. The benchmark problem selected for the verification is the flow past an ellipsoid with three unequal axes at 0° of incidence. This benchmark case has been used in the past to investigate the accuracy of the potential and pressure computation with a panel code [13] but no formal error analysis has been made.

The systematic grid convergence studies are carried out with two types of grids on the ellipsoid: conventional grids, as generally used for propeller analysis, and orthogonal grids, which may offer some advantages in skewed propellers [9].

Two panel codes, described in [14,15], have been used in the verification study. Both codes are based on Morino's formulation for the perturbation potential [16,17] in which a combination of dipole and source singularities is used. This formulation has proved to be very efficient and well suited for the analysis of thin foils [18]. We note that the benchmark problem treated here could be addressed using a source distribution only, but in order to relate the results to the propeller blade case we use the same formulation as developed for this case.