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Computational Simulation of Turbulent Vortex Merger and Decay

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Abstract

IN recent years, many theoretical[1-4] and experimental[5-7] studies have been conducted to gain a better understanding of corotational vortex merger in connection with the pairing of organized vortex structures observed in mixing layers and with the attenuation of wake-vortex hazard associated with wide-body aircraft. The latter is accomplished by modifying the wing such that two or more corotating vortices are shed from each half-span. The merger of these vortices can result in a redistribution of vorticity such that the hazard to trailing aircraft is considerably reduced compared to the conventional wing. In the present investigation, the interaction and merger of corotational vortices and the decay of a single vortex have been studied by employing zero-, one-, and two-equation turbulent flow models in an attempt to bridge the gap between the theoretical models and experimental observations. The zero- and one-equation formulations utilize a mixing-length model which incorporates the streamline curvature effect by prescribing a particular spatial variation. In the two-equation model, a turbulence kinetic energy equation and a rate of dissipation equation modified to include streamline curvature correction are solved. The computed results corresponding to the different flow models are compared with the available experimental data.

Contents

The mathematical model for the simulation of wake-vortex flowfield is described adequately by the conservation of mass and momentum equations when an incompressible flow is considered. The flow variables are decomposed into mean and fluctuating quantities, and the equations are time-averaged for turbulent flow studies. The Reynolds stress terms in the governing equations for the mean flow are expressed in terms of the mean velocity gradients and an eddy viscosity. Considerable computational simplification is achieved by using an "unsteady analogy." The gradients in the streamwise direction are neglected as they are relatively small. The resulting unsteady two-dimensional equations for pressure p and velocity components v and w are integrated in time in a cross-plane where time is analogous to the downstream distance. The integration is performed numerically by applying an implicit finite-difference procedure.[8] The method uses clustering transformations to accurately resolve the regions of large spatial gradients (like near the vortex centers) and utilizes an approximate factorization technique to maintain computational efficiency.

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Flow Models

The zero-equation model simulates the effect of turbulence by specifying the eddy viscosity. The authors use a mixing-length model to relate the eddy viscosity to mean velocity gradients. For the study of a single vortex decay, the mixing length is defined by $\ell = \alpha r$ for $r \le r_0$ and $\ell = \alpha r_0^2/r$ for $r > r_0$. This is similar to the models used in other theoretical studies. The authors extend this definition to study the merger of two vortices by writing $\ell = \lambda + \alpha\sqrt{r_1 r_2}$, where λ and α are arbitrary constants, and r_1 and r_2 are the distances from the centers of the two vortices.[4] The zero-equation model, however, gives no insight into the behavior of any turbulence quantity directly. Therefore, the authors consider a one-equation model which requires solving an additional equation governing the dynamics of turbulence kinetic energy k. The latter, coupled with the mixing-length model, define the eddy-viscosity distribution. Both of these flow models, however, suffer from the arbitrariness of the mixing-length models.

The two-equation model provides a means of eliminating this empiricism of the mixing-length hypothesis. A model equation[9] for isotropic dissipation ϵ contains the direct effect of streamline curvature resulting in a decrease of ϵ when the angular momentum of the mean flow increases with radius and the reverse holds for the regions where the angular momentum decreases with radius. Further mathematical and computational details are described in Ref. 10.

Single Vortex Decay

Simulation of the decay of a single vortex is considered to study the role of turbulence as predicted by the one-and two-equation models. The initial velocity field corresponds to a circular Betz vortex shed behind an elliptically loaded wing. The associated pressure field is initially computed by solving the appropriate Poisson's equation. The local value of the turbulent kinetic energy is initially assigned to be 5% of the local mean kinetic energy. The initial ϵ distribution is given by $\epsilon = k^{3/2}/\ell$. The corresponding variation of the normalized total turbulent kinetic energy with downstream distance is shown in Fig. 1 by the curves labeled case 1. For identical initial conditions, the results of the one-equation model are in agreement with those of the two-equation model incorporating curvature correction. However, the agreement with experimental data is poor.

An alternate way of initializing ϵ distribution is utilized whereby the model equation ϵ is integrated independently while p, v, w, and k distributions are kept unchanged. The converged values of ϵ provide the initial estimate. The corresponding results are shown in Fig. 1 by the curves labeled case 2. The results of the two-equation model are in good agreement with the experimental values. The results of the one-equation model with appropriate choices of constants are

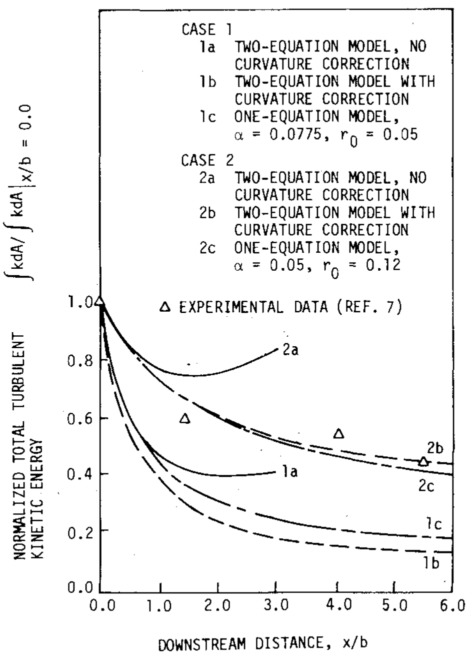

Fig. 1 Variation of normalized total turbulent kinetic energy with downstream distance for a single Betz vortex decay.

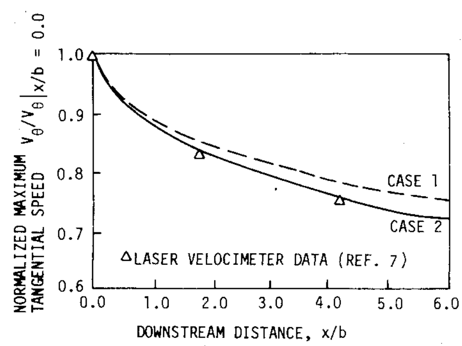

Fig. 2 Decay of normalized maximum tangential speed with downstream distance for a single Betz vortex.

in close agreement with those of the two-equation model. The significant influence of the streamline curvature on the flowfield is clearly demonstrated by the computational simulation.

The decay of maximum tangential speed with the downstream distance is shown in Fig. 2. The behavior of the results is in accordance with the results shown in Fig. 1.

Corotational Vortex Merger

The initial velocity field in the numerical simulation is generated by superimposing two circular Betz vortices with like sense of rotation separated by a specified distance. Each is shed by an elliptically loaded wing. The distance between them is subsequently monitored by tracking a set of particles initially tagged with each vortex. The variation of the distance between the centroids of the two sets of particles with the downstream distance provides a measure of the merging distance. The accuracy of the results corresponding to the different flow models is evaluated by a comparison with the experimental merging distance criterion.[4]

The variation of the downstream merging distance with the specified initial separation distance is shown in Fig. 3 for two equal-strength corotating vortices. A comparison of curve 1 with curve 5 shows the inadequacy of the inviscid flow model to simulate vortex merger. The results of the zero- and one-equation models are in closer agreement with the experimental data than those of the two-equation model. The initial ϵ distribution for the latter is in accordance with case 2

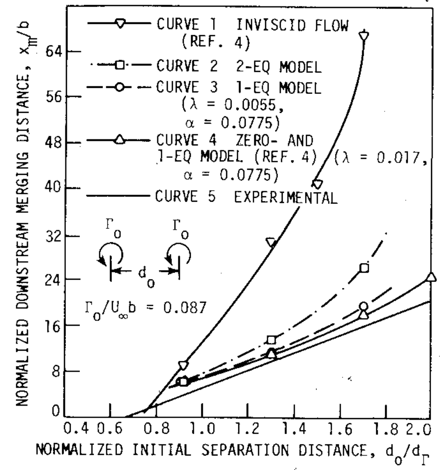

Fig. 3 Comparison of merging distances for two equal strength corotating vortices corresponding to different flow models with experimental data.

for single vortex decay described previously. The discrepancy may be attributed to the possible inaccuracies in the initialization of k and ϵ distributions as the computed results are found to be strongly dependent on ϵ distribution and to the three-dimensional effect ignored here, especially in the vicinity of the point of merger. In addition, the available experimental data correspond to vortices with much smaller cores than could be used in computational simulation due to numerical difficulties. The results of all three turbulence models, however, show considerably closer agreement with experimental data than does the inviscid solution. In the opinion of the authors, further computational and experimental studies are required to arrive at an accurate and reliable turbulent flow model to further the understanding of the phenonenon of vortex merger.

Acknowledgments

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