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AN ENGINEERING METHODOLOGY FOR SUBSONIC STORE TRAJECTORY PREDICTION

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Abstract

A new engineering methodology is presented to predict the loads on a store in the nonuniform flowfield beneath an aircraft. The method requires that only the flowfield beneath the aircraft, the carriage loads and the store freestream aerodynamics are known. The flowfield beneath the aircraft is readily obtainable from CFD computations. Assuming a linear velocity gradient in the vicinity of store, the components of the velocity gradient tensor as well as the local mean flow are determined by interpolation of the flowfield, and the antisymmetric part of the velocity gradient tensor used to define an effective store rotation rate. The loads on the store due to the mean flowfield as well as the flowfield non-uniformity can then be computed using the known store freestream aerodynamics and dynamic derivatives. This method is used to predict the separation of an air-layed sea mine from a P3C maritime patrol aircraft, and the results are compared with another CFD-based store trajectory prediction method.

Introduction

One of the most important and most difficult tasks in predicting the trajectory taken by stores following their release from the parent aircraft is the determination of the aerodynamic loads on the store in the highly nonuniform flowfield beneath the aircraft. This paper presents a new, fast engineering methodology for the prediction of these aerodynamic loads on the store when the flow is subsonic.

Whereas most current CFD-based schemes for computation of the store aerodynamic loads require multiple calculations of the aircraft/store configuration with the store at a number of different locations/orientations[1], the present method requires only two CFD calculations; one full calculation to determine the store carriage loads and a second to determine the flowfield beneath the aircraft, the latter calculation being performed without the presence of the store. This accounts for the speed of the method relative to other CFD-based methods.

The method makes the assumption of a linear velocity gradient tensor in the vicinity of the store. For this assumption to hold, the store size should be small compared with the aircraft, there should be subsonic flow in the vicinity of the store and store flowfield interference effects should be negligible.

The method is presented in the next section. A comparison is then made between the present method and another computational method for a subsonic store release and comments are made on the comparison in the Conclusions.

Method

The velocity field below the aircraft, $u_i(\mathrm{x})$, $(i = 1, 2, 3)$, is expanded in a Taylor Series about a location which is the geometric centre of the store if it were in the flowfield, x_o.

$$u_i(\mathrm{x}_o + \Delta\mathrm{x}) = u_i(\mathrm{x}_o) + \frac{\partial u_i}{\partial x_j}(\mathrm{x}_o)\Delta x_j + \frac{\partial^2 u_i}{\partial x_j \partial x_k}(\mathrm{x}_o)\Delta x_j \Delta x_k + \ldots \quad (1)$$

Here $\mathrm{x} = \mathrm{x}_o + \Delta\mathrm{x}$ and the components of x are $x_i,\ i = 1, 2, 3$.

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An approximation to the flowfield in the vicinity of the store begins by discarding terms of $\mathcal{O}(\Delta x^2)$ or greater in the expansion. The first term, $u_i(\mathbf{x}_o)$, is the average velocity vector in the vicinity of the store and defines the effective store angle of incidence and sideslip. The term $\frac{\partial u_i}{\partial x_j} = A_{ij}$ is the velocity gradient tensor containing nine components. All twelve unknowns are calculated from the given flowfield using a least squares fit from data contained in a rectangular volume surrounding the store (see Figure 1). The velocity gradient tensor is then split into symmetric and antisymmetric components i.e.

$$A_{ij} = S_{ij} + W_{ij} \quad (2)$$

where $S_{ij} = \frac{1}{2}(A_{ij} + A_{ji})$ is the symmetric component and $W_{ij} = \frac{1}{2}(A_{ij} - A_{ji})$ is the antisymmetric component. The antisymmetric component is related to the vorticity of the fluid through

$$W_{ij} = \begin{bmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{bmatrix} \quad (3)$$

where the vorticity vector is given by $\bar{\omega}^T = \{\omega_x, \omega_y, \omega_z\}$. The angular velocity of the fluid w.r.t. a non-rotating frame of reference E (the store) is

$$\bar{\Omega}_{FE} = \frac{1}{2}\bar{\omega} \quad (4)$$

and conversely, the angular velocity of the store w.r.t to the fluid is $\bar{\Omega}_{EF} = -\bar{\Omega}_{FE}$.

The present method is known as Flowfield Decomposition (FFD) from the the decomposition of the approximated flowfield's velocity gradient tensor into symmetric and antisymmetric components.

Given the effective angle of incidence, angle of sideslip and store rotation rates, loads on the store are then calculated from the store's freestream aerodynamic database, and may be used to update the store location using a six degree-of-freedom flight dynamic model of the store.

Implementation

The method requires that the flowfield $u_i(x_j)$ is known in a volume, called the scan volume, beneath the carriage position through which the store is likely to pass. Figure 1 shows a diagram of the bounding box of the scan volume for the test case presented below. A second volume, known as the surrounding volume and shown in Figure 1, is the box enclosing the store. Data from the surrounding volume, intepolated from the scan volume, is used to compute the approximate flowfield i.e. Equation 1 without $\mathcal{O}(\Delta x^2)$ terms. The dimensions of the surrounding volume are determined by the user, but from our experience, a volume approximately twice that of the store itself gives good results.

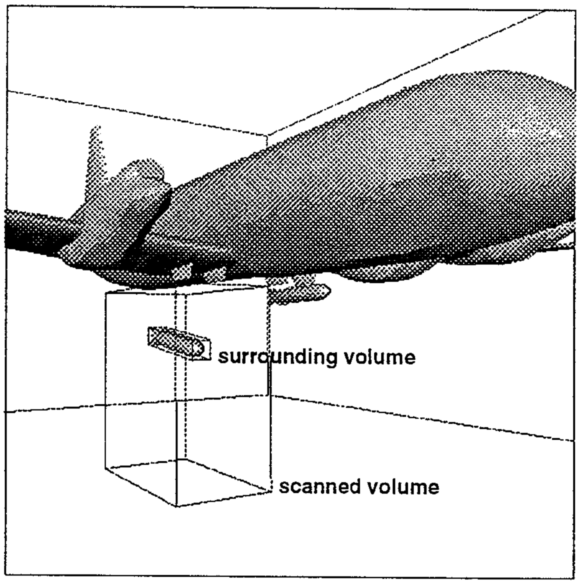

Figure 1: Scan volume and surrounding volume.

When the store is at or very close to the carriage location, the interference effects of the store on the surrounding flowfield are considerable. In addition, points inside the surrounding volume lie outside the scan volume and the decomposition of the flowfield becomes unreliable. Therefore, the carriage loads are used in the trajectory computations until the store is sufficiently far away from the carriage location (about one store diameter) so that the surrounding volume lies fully within the scan volume.

Computed Release

To test the effectiveness of the present method, the trajectory taken by a Mk65 air-launched sea mine from a P3C Orion maritime patrol aircraft flying a 1000ft and at 240KIAS has been calculated. At these

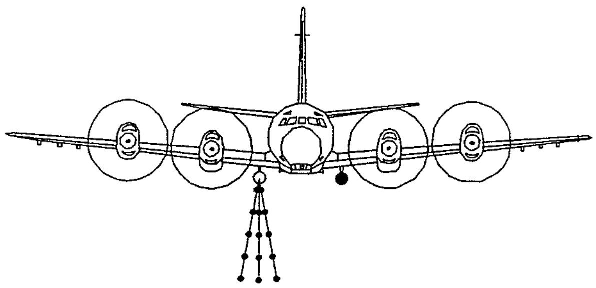

Figure 2: Release configuration and grid for loads computations: o, released store; •, installed store.

release conditions, the flow is everywhere subsonic ($M_\infty = 0.365$) and not complicated by interference shocks. The store is mounted on the outboard of the two pylons inboard of the engines (station 12) (see Figure 2).

The trajectory computations were performed using both the present method as well as, for the purposes of comparison, the more conventional 'grid' technique for the evaluation of the aerodynamic loads. In the latter case, the loads on the store are evaluated for a range of orientations at each point in a grid of locations beneath the store's carriage position (see Figure 2), and this aerodynamic grid database is interpolated during the trajectory computations.

The loads on the store at the carriage location and at the grid of locations and orientations as well as the flowfield beneath the aircraft are all evaluated using a commercial CFD panel method.

Firstly, the ability of the method to compute aerodynamic loads at different locations below the carriage position is assessed. Figure 3 shows force and moment coefficients on the store computed using both the present method and the grid method at five radial locations from the carriage position ranging from one to nine calibres. The Euler angles, ϕ, θ, ψ, relative to the carriage orientation are all zero. Freestream conditions are the same as for the trajectory computations. The agreement in the trends and, to a lesser extent, the absolute values of the coefficients is reasonably good.

In Figure 4, the ratio of the aerodynamic force due to flowfield rotation to that due to the average flowfield is given versus distance along the central ray of the grid. The plot is given in logarithmic co-ordinates,

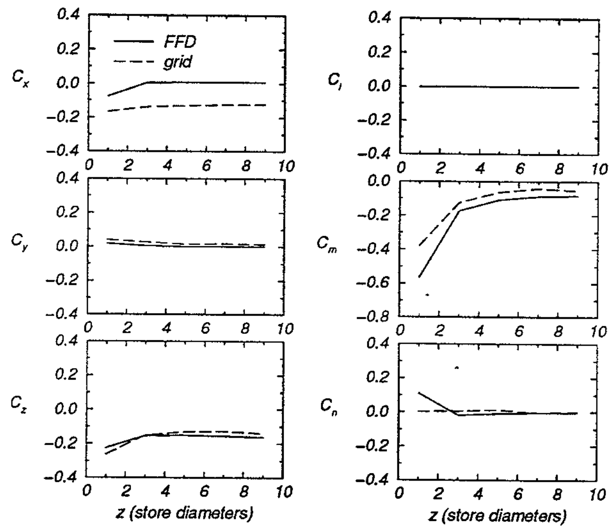

Figure 3: Aerodynamic loads computed on the central ray of the grid using the present method (FFD) and the grid technique: $\phi = \theta = \psi = 0$.

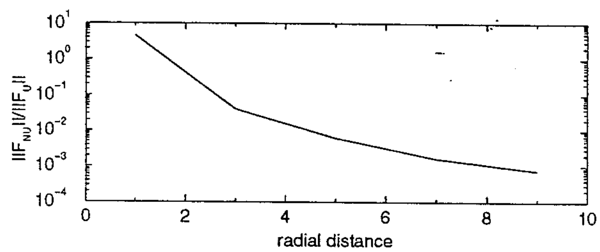

Figure 4: Ratio of component of aerodynamic force due to nonuniform flowfield to the component of aerodynamic force due to average flowfield versus distance along the central ray of the grid.

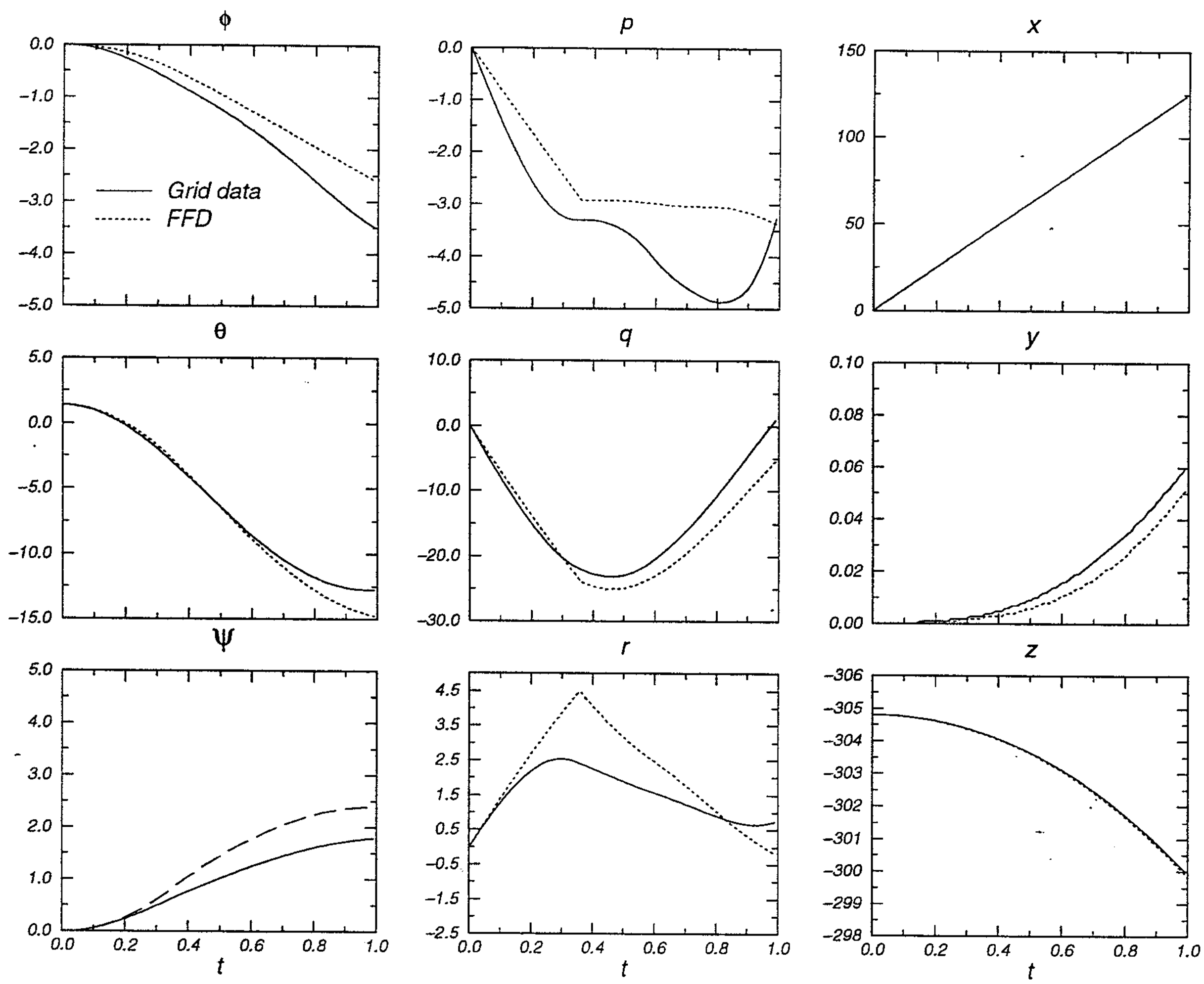

Figure 5: State variables of the Mk65 following release from the P-3C at 1000ft and 240kts.

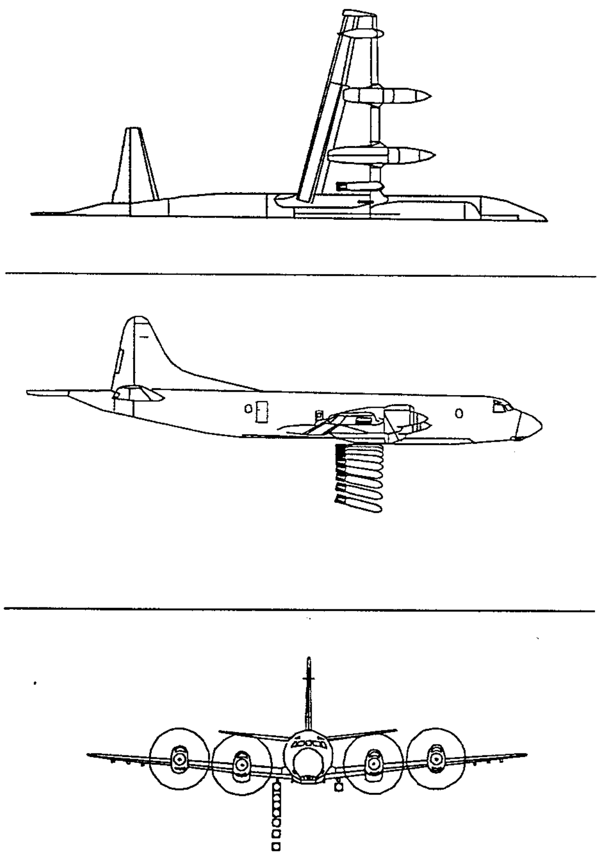

Figure 6: Mk65 release, present method

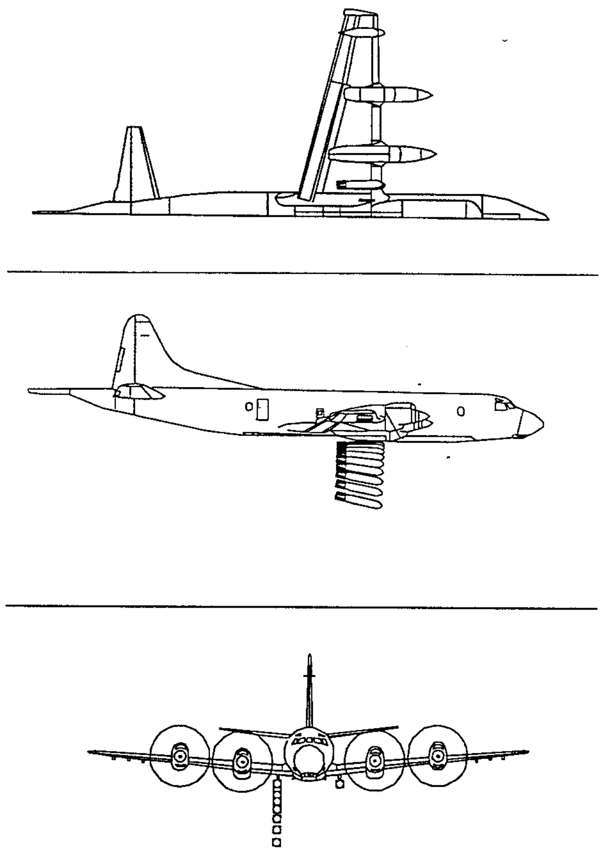

Figure 7: Mk65 release, grid technique

highlighting the large decay rate with distance of the influence of W_{ij} on the aerodynamics of the store.

The time histories of the state variables of the store following release as calculated using the two methods are given in Figure 5. Shown are the evolution of the Euler angles (ϕ, θ, ψ), rates of rotation (p, q, r) and components of the position vector (x, y, z). The agreement between trajectories generated using the two methods is reasonably good for the first second of the release, after which the store is far enough away from the aircraft for the non-uniformity of the flowfield to have diminished significantly. The most significant motion of the store is a pitch down and the agreement in the evolution of θ is very good. Agreement in the trends of roll and yaw as well as the rotation rates is also good. The trajectories are generated from an integration of the equations of motion, and as integration tends to smooth any errors in time derivatives of state variables due to errors in evaluation of the aerodynamic loads, the agreement in a qualitative sense between the trajectories calculated using the two methods is excellent (see Figures 6 and 7). Nevertheless the agreement in trajectories has also been assisted by the demonstrated ability of the present method to evaluate aerodynamic loads to a reasonable level of accuracy.

Computation Time

The strength of the present method lies in its speed. On a Silicon Graphics R10000 computer, the average time taken for a converged panel method solution of a full aircraft with stores installed is approximately

20 minutes. Assuming the freestream aerodynamics of the store are known, the present method requires only two panel method computations: one for the evaluation of the carriage loads on the store, the second for the determination of the flowfield below the carriage position. The time taken for the computations involving the evaluation of the aerodynamic loads within the six degree-of-freedom program is, in comparison to the CFD calculations, negligible and so total computation time is around 40 CPU minutes. In contrast, a grid-based method requires at least 180 panel method computations (5 radial location $\times$ 3 polar locations $\times$ 3 roll angles $\times$ 2 pitch angles $\times$ 2 yaw angles for a coarse grid) taking about 60 CPU hours, a two order-of-magnitude increase in solution time compared with the FFD method. Time-accurate CFD computations[2] (theoretically the most accurate CFD-based technique for trajectory computation) generally require in the order of twice as much CPU time again as the grid method.

Conclusions

Aerodynamic loads and store trajectories computed using the present method for the evaluation of aerodynamic loads have demonstrated good agreement with another, more mature CFD-based method, the grid technique. The case chosen to demonstrate the present method was a benign, low Mach number release at low dynamic pressure in comparison to the more problematic releases routinely encountered by aircraft releasing stores at transonic Mach numbers. Nevertheless, the principle of the technique has been demonstrated and the large reduction in computation time possible using this method provides the impetus for investigating its feasibility at higher Mach numbers.

References

[1] L.E. Lijewski and N.E. Suhs. Time-accurate computational fluid dynamics approach to transonic store separation trajectory prediction. *J. of. Aircraft*, 31(4):886–891, 1994.

[2] David M. Tidd. *FPI - Flight Path Integrator Users' Manual.* Analytical Methods Inc., Redmond WA USA, 3.1 edition, November 1996.