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Grid Survey Approach to Store Separation Trajectory Prediction

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Nomenclature

C_l, C_m, C_n	= rolling, pitching, and yawing moment coefficients
C_{lp}, C_{mq}, C_{nr}	= damping derivative due to roll, pitch, and yaw rates, per radian
C_X, C_Y, C_Z	= axial, side, and vertical force coefficients
X, Y, Z	= longitudinal, lateral, and vertical displacements
α, β	= pitch plane and side-slip angles of attack
α_T	= total angle of attack, $\sqrt{(\alpha^2+\beta^2)}$
ΔC_{lf}	= incremental C_{lf} due to α and β $[C_{lf(\alpha,\beta)} - C_{lf(\alpha,\beta=0)}]$
ΔC_{mf}	= incremental C_{mf} due to β $[C_{mf(\alpha,\beta)} - C_{mf(\alpha,\beta=0)}]$
ΔC_{nf}	= incremental C_{nf} due to α $[C_{nf(\alpha,\beta)} - C_{nf(\alpha=0,\beta)}]$
ΔC_{Yf}	= incremental C_{Yf} due to $[C_{Yf(\alpha,\beta)} - C_{Yf(\alpha=0,\beta)}]$
ΔC_{Zf}	= incremental C_{Zf} due to β $[C_{Zf(\alpha,\beta)} - C_{Zf(\alpha,\beta=0)}]$
ϕ, θ, ψ	= body axis roll, pitch, and yaw angles

Subscripts

f	= freestream
i	= interference

Introduction

OVER the past years, the advances in computational fluid dynamics (CFD) have greatly encouraged the development of various computational methods for predicting store separation trajectory,[1–3] the motivation being to reduce the engineer's dependence on traditional wind-tunnel tests, which are expensive and time-consuming to use. The present Note attempts to demonstrate the computational prediction of a store separation trajectory, carried out by employing the grid survey approach. The basic grid survey method has been used by engineers to predict store separation trajectory successfully in past decades.[4,5] Typically, a matrix of aerodynamic flowfield data in a region that encompass the anticipated trajectory path of the store are obtained using the captive trajectory system (CTS) in a wind-tunnel facility. A six-degrees-of-freedom (6DOF) program integrates the rigid-body equations of motion by the use of these aerodynamic flowfield data. The present study is based on a similar approach, but an Euler code is used to obtain the flowfield grid data instead of the CTS rig. A case study involving the trajectory of a body–tail store configuration separating from a clipped delta wing at transonic speed of Mach 0.95 is predicted and compared against available CTS results.[6] This test case has also been used by numerous researchers to verify the accuracy of their CFD results in past years.[1–3,7] Figure 1 presents the side view of the configuration with important dimensions illustrated.

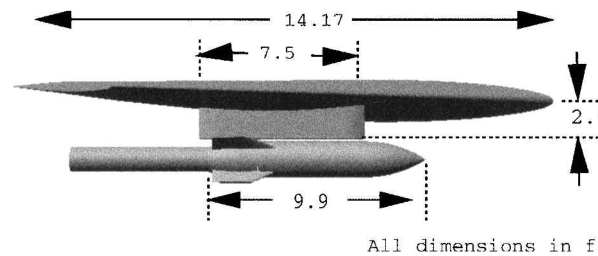

Fig. 1 Configuration geometry (side view).

Formulation

A detailed discussion on the grid survey method may be found in Refs. 4, 5, and 8. The author shall address the key challenge in the grid survey method, which requires the user to prepare the right amount and composition of grid data and apply appropriate aerodynamic modeling to characterize the flowfield of the configuration. The flowfield data required in the grid survey method consist of the freestream and the interference coefficients. The pitch plane freestream coefficients, (C_{Zf} and C_{mf}) are modeled as functions of α, whereas the yaw plane coefficients, (C_{Yf} and C_{nf}) are modeled as functions of β. The interference coefficients, for example, C_{mi} and C_{ni}, which account for the influence of the aircraft on the store are modeled as functions of the Z position relative to the aircraft. Studies have shown that the interference aerodynamics due to other positions (X and Y) and attitudes (ϕ, θ, and ψ) are small and may be neglected.[8] In the present study, these coefficients are obtained using a commercial Euler code, MGAERO.[9] The axial drag coefficient C_{Xf} is modeled as function of α_T, and C_{lf} is treated as zero at all α values. The dynamic derivatives, C_{lp}, C_{mq}, and C_{nr} are estimated using semi-empirical code, MISSILE DATCOM,[10] at $\alpha = 10$ deg, which gives values of −4, −38, and −38, respectively. A simple 6-DOF trajectory simulation program, TRASEP is then used to compute the separation trajectory from the instant of end of stroke, estimated to occur at $t = 0.055$ s, where the slope of the pitch rate of the store reverses in the CTS test. TRASEP is an in-house developed software using SIMULINK[11] under a MATLAB® environment.

From the preliminary result of the first trajectory simulation, the various combinations of α and β experienced by the store at discrete Z positions are obtained. The freestream aerodynamics at these combinations of α and β are then computed using MGAERO to obtain the aerodynamic coupling effect. These secondary effects, for example, ΔC_{lf} and ΔC_{mf}, are modeled as functions of the Z positions and incorporated in the second refined simulation. They are modeled as functions of Z instead of α and β to avoid the need to implement a two-dimensional linear interpolation scheme that would require a substantial increase in grid data. It is assumed that the (α, β) experienced by the store at various Z positions in the second trajectory simulation does not differ very much from the first simulation. The net static aerodynamic coefficients acting on the separating store is equal to the sum total of the freestream (including α–β coupling) and interference coefficients. As an illustration, the net C_m value is represented by the following mathematical expression:

$$C_m(\alpha, Z) = C_{mf}(\alpha) + C_{mi}(Z) + \Delta C_{mf}(Z)$$

Results and Discussion

Flowfield Data

The store-alone aerodynamic data in the pitch plane are computed using MGAERO for α up to 20 deg in steps of 4 deg at Mach

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0.95. The store with attached sting is embedded in a set of multigrids of about 0.5 million grid points, with the finest grid at the fifth level. The yaw plane aerodynamics C_{Yf} and C_{nf} are derived using the pitch plane aerodynamics by geometrical symmetry of the store. The aerodynamic characteristics of the captive store at various vertical Z displacements away from the wing are also computed. Because the store is oriented at zero angular orientations, the aerodynamic coefficients computed at the store constitute the interference aerodynamics from the wing and pylon induced on the store, except for C_x, which is equal to $C_{xi} + C_{xf}$. About 1.2×10^6 grid points are used with finest grid at the seventh level. The finest grid cell length for both the freestream and captive configurations is about 4% of the store's diameter, which ensures adequate resolution of the flow. These aerodynamic flowfield data (Tables 1–2), together with other input parameters such as the mass and inertia properties, end-of-stroke conditions, etc., make up the input data required to execute TRASEP.

Trajectory Simulations

The position of the store's center of gravity is predicted using TRASEP from $t = 0.055$ to 0.45 s and compared with CTS results in Fig. 2. In all three coordinate directions, the computational results match closely with the CTS data. However, there is some significant difference in the angular orientations between computation and CTS data, although the deviations are not serious and are less than 6 deg at the end of the trajectory. The α–β coupling effects computed at Z positions using MGAERO (Table 3) are then incorporated in flowfield grid data and TRASEP is reexecuted to obtain a second refined trajectory. The second simulation results are able to match more closely with the CTS data with the maximum deviations less than 3 deg at the end of the trajectory. The accuracy is good and appears comparable to that obtained using time-accurate CFD codes.[1–3]

Table 1 Flowfield data obtained using CFD, freestream aerodynamics

α, deg	C_{Xf}	C_{Zf}	C_{mf}
0	−0.342	0.000	0.000
4	−0.325	−0.363	−0.098
8	−0.300	−0.745	−0.282
12	−0.264	−1.175	−0.534
16	−0.220	−1.687	−0.932
20	−0.166	−2.282	−1.144

Table 2 Flowfield data obtained using CFD, interference aerodynamics

Z, ft	C_{Xi}	C_{Yi}	C_{Zi}	C_{li}	C_{mi}	C_{ni}
0	−0.345	−0.854	−0.604	0.0822	−1.570	1.409
0.5	−0.307	−0.683	−0.430	0.0187	−1.146	1.175
1.0	−0.292	−0.567	−0.346	0.0092	−0.995	0.997
1.5	−0.285	−0.488	−0.314	0.0045	−0.932	0.865
2.0	−0.275	−0.420	−0.265	0.0044	−0.824	0.758
2.5	−0.266	−0.630	−0.240	0.0006	−0.783	0.668
3.0	−0.259	−0.310	−0.204	0.0002	−0.701	0.583
4.0	−0.248	−0.241	−0.154	0.0002	−0.560	0.450
5.0	−0.236	−0.180	−0.113	0.0002	−0.456	0.359
6.0	−0.229	−0.139	−0.088	0.0001	−0.384	0.287

Table 3 Flowfield data obtained using CFD, α–β coupling effects

Z, ft	α, deg	β, deg	ΔC_{Yf}	ΔC_{Zf}	ΔC_{lf}	ΔC_{mf}	ΔC_{nf}
0.31	2.16	−0.69	0.0059	0.0065	−0.0015	−0.0020	−0.0145
0.78	4.07	−1.78	0.0155	0.0049	−0.0022	−0.0138	−0.0381
1.56	6.07	−4.14	0.0408	0.0233	−0.0025	−0.0512	−0.0943
2.11	6.89	−6.07	0.0611	0.0495	−0.0012	−0.0980	−0.1396
2.69	7.34	−8.22	0.0746	0.0965	0.0023	−0.1881	−0.1702
3.31	7.46	−10.5	0.0829	0.1646	0.0067	−0.3178	−0.1970
4.12	7.35	−12.3	0.0775	0.2183	0.0110	−0.4148	−0.1905
4.46	7.10	−14.0	0.0673	0.2623	0.0140	−0.4885	−0.1750
4.98	6.55	−16.2	0.0384	0.2965	0.0140	−0.5315	−0.1155
5.72	5.79	−18.1	0.0007	0.2761	0.0053	−0.4487	−0.0281

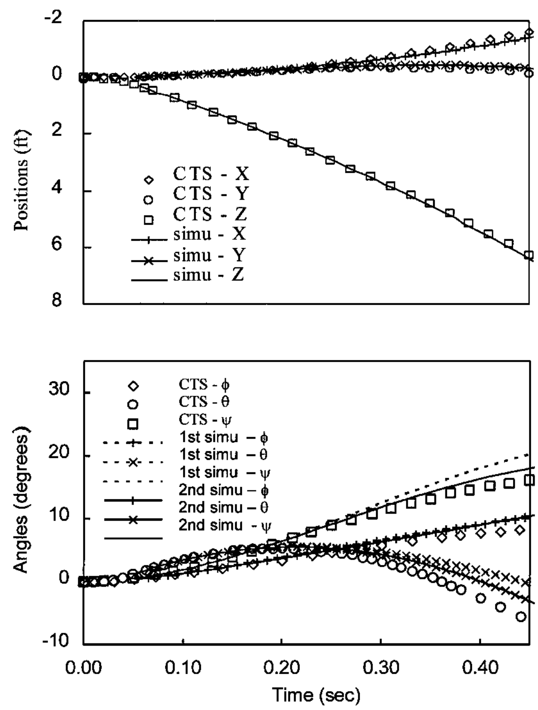

Fig. 2 Simulation results of store separation trajectory.

The sources of error in the trajectory prediction can be attributed to the limitations of the methodology itself and the integrity of aerodynamic data generated by CFD. First, the interference aerodynamics are assumed to vary only with the vertical displacement, which ignores the secondary effects due to other positions and orientations. There are also errors associated with interpolating the aerodynamic flowfield data. Finally, there are errors due to the failure of MGAERO to capture the high angle of attack and viscous flow behavior. Although not shown explicitly in this Note, there is significant deviation in the trend of C_{mf} at high α when compared with the available wind-tunnel data.[6]

The bulk of the engineering and computational effort in the grid survey method is spent on the modeling, grid generation, and execution of the Euler code. These steady-state CFD simulations are relatively undemanding compared to that required when using a typical time-dependent Euler code. The grid survey technique is also extremely versatile because the aerodynamic flowfield data need not come from a single source. The data may be obtained from a judicious mix of wind-tunnel test, CFD, or semi-empirical prediction codes.

Conclusions

The grid survey approach to predict the trajectory characteristics of a store separating at transonic speed of $M = 0.95$ has been shown to be effective. It is able to predict the trajectory characteristics reasonably well, with all major trends captured. The integrity of the aerodynamic flow data may be improved by incorporating the α–β coupling effects, which results in significant improvement in the accuracy of the trajectory predictions.

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Prediction of Vortex Breakdown Location on a Banked Delta Wing

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Introduction

AN experimental study of leading-edge vortex breakdown on a family of delta wings was conducted at the University of Notre Dame.[1,2] Flow visualization and image processing techniques were used to measure the location of vortex breakdown as a function of static angle of attack and roll angle.

Measurement of the location of vortex breakdown on slender flat-plate delta wings has been obtained by numerous investigators.[3–5] These studies examined breakdown on simple delta wing models for static conditions. Over the years, researchers have tried to determine what factors influence breakdown. Elle[6] showed that the sweep angle of the wing significantly affects breakdown. He found that increasing the sweep angle moves vortex breakdown downstream for a given angle of attack. Kegelman and Roos[5] presented results that showed that breakdown is influenced by the leading-edge geometry of the wing. The trailing-edge geometry might also have some influence on the location of vortex breakdown because it might affect the adverse pressure gradient at the trailing edge. O'Neil et al.[7] showed that the adverse pressure gradient is imposed by the trailing edge and that it has an effect on breakdown location. The sideslip angle is another parameter that influences breakdown.

In the present investigation, an attempt was made to approximate the static vortex breakdown location of a rolling 65-deg delta wing from vortex breakdown results in pitch for several wings of different sweep angles.

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Table 1 Delta wings

Sweep angle, deg	Chord, in. (cm)	Span, trailing edge, in. (cm)
50	8 (20.32)	13.43 (34.11)
55	8 (20.32)	11.20 (20.45)
60	8 (20.32)	9.24 (23.47)
65	14 (35.56)	13.06 (33.16)
70	14 (35.56)	10.2(25.91)
75	14 (35.56)	7.5 (19.05)
80	14 (35.56)	4.9 (12.45)

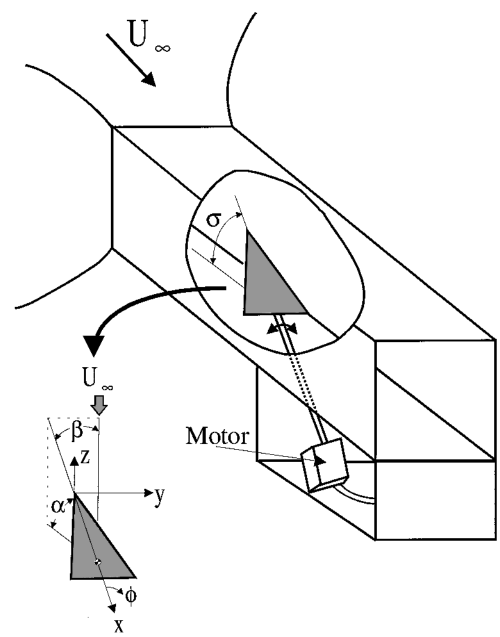

Fig. 1 Test section arrangement for rolling tests.

Apparatus

A family of flat-plate delta wings with sweep angles varying from 50 to 80 deg were built for this research program. Table 1 shows the dimensions of the wings as a function of sweep angle. All of the wings had a thickness of 0.25 in. (6.4 mm), a 45-deg bevel on the bottom surface and a blunt trailing edge. This Note will focus on the results for a 65-deg delta wing at a root-chord Reynolds number, $Re = 1 \times 10^5$.

All experiments were performed in a 2 × 2 ft (0.609 × 0.6096 m) indraft subsonic wind tunnel at the University of Notre Dame. Each wing was tested for different static angles of attack (no roll) and for different roll angles (for a fixed sting angle of attack σ). Figure 1 shows a schematic of the delta wing arrangement in the wind tunnel for the rolling experiments. For the experiments in pitch, a U-shaped pitching yoke was used.[1,8]

All tests were directed toward measuring vortex breakdown location as a function of the angle of attack and roll angle. For the flow visualization, titanium tetrachloride ($TiCl_4$) was injected into the flow near the apex of the wings. The dense white smoke generated by the reaction between the $TiCl_4$ and air moisture was entrained by the vortices over the wings, and breakdown could easily be observed.[9] A charge-coupled device video camera in super video home system mode was used to record the flow visualization data. Image processing equipment and software were used to analyze the flow images and to obtain measurements of the vortex breakdown location.

Results

Pitch Tests

Static pitching tests on the series of delta wings at $Re = 1 \times 10^5$ gave the results presented in Fig. 2. As was expected, vortex breakdown moved upstream (toward the apex at $x/c = 0$) with increasing angle of attack. Moreover, increasing the sweep angle