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ARL-FLIGHT-MECH-TM-404 AR-005-543

AD-A212 442

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Flight Mechanics Technical Memorandum 404

DEVELOPMENT OF A VSAERO MODEL OF THE F/A-18

by

R. TOFFOLETTO

Approved for Public Release

MARCH 1989

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SUMMARY

VSAERO (an acronym for Vortex Separation AEROdynamics) has been used to produce an aerodynamic model of the aircraft. When fully developed, results from the model will be compared with results obtained from experiments planned to be carried out in the ARL wind tunnel. The velocity field and wake geometry in the vicinity of the aircraft, and the pressure distribution on the aircraft have been calculated for various flight conditions. Calculated lift coefficients for the whole aircraft were compared with wind tunnel results obtained from McDonnell Aircraft Company (Ref 6). The model was also used to study the effect of engine intake velocity on the aerodynamics of the aircraft.

The major problem encountered during the development of the model was a numerical instability caused by the complicated vortex/vortex and vortex/body interactions in the vicinity of the tail of the aircraft. During this time, a new version of VSAERO was installed at ARL which promised greater stability in this area. It also allowed for a denser grid in the wake structure. Comparisons were made between the old and new versions to determine the extent of the improvements.

DSTO ARL
MELBOURNE

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Contents

1 Introduction

The F/A-18 fighter aircraft recently acquired by the Royal Australian Air Force uses many advanced technologies, such as the use of fibre composite in the structures, advanced flight control systems and advanced aerodynamics. The aerodynamic features include Leading Edge Root Extensions (LEX's) which increase aerodynamic efficiency and also enable the aircraft to fly at very high angles of attack (The F/A-18 can fly at angles of attack in excess of 40.0 degrees). The effect of the LEX's is to produce vortices which develop lift in much the same way as the leading edge vortices on conventional delta winged aircraft. A picture of a model of the F/A-18 in a water tunnel illustrating the vortices produced is shown in Figure 1.

During the course of flight tests, it has been discovered that the vortices produced by the LEX's may burst and cause a highly turbulent flow near the empennage. This turbulent flow has, in turn, caused some structural problems. Figure 2. illustrates the effect of the burst vortices on the empennage.

The aircraft has been structurally strengthened in the affected areas, but there is still a need to establish details of the vortex flow around the aircraft, and particularly the vortex bursting. Studies are under way at several research centers, including ARL, where a joint wind tunnel and computational fluid dynamics (CFD) approach is planned. Construction of a 1/9 scale wind tunnel model commenced in 1988. Meanwhile the CFD code VSAERO (Vortex Separation AEROdynamics) supplied by Analytical Methods Inc. has been applied to the F/A-18 configuration.

Results obtained with VSAERO are intended to be used for the following purposes:

1. To assist in the design of the wind tunnel model, specifically in the area of intake design. By varying the 'flow-through' velocity in the intakes the influence, if any, of the intakes on the aerodynamics of the aircraft will be investigated.

2. As a complement to the wind tunnel model results. Pressure distributions and total forces and moments will be compared and analysed. The comparisons will assist in the development and the verification of the VSAERO result. VSAERO will then be used to extend the results of the wind tunnel tests.

3. To determine the path of the LEX vortices. VSAERO cannot predict vortex bursting.It can, however determine the path of these vortices. Again, the results will complement those from the wind tunnel model.

This paper documents the first stages of the development and use of VSAERO. The effect of including a flow through engine intake on the aerodynamics of the airplane was investigated. In addition, calculated lift coefficients were compared with experimental results of wind tunnel tests performed by the McDonnell Aircraft Company. At this stage, the effect of vortices originating from the LEX's is not included. The angle of attack was limited to lower values where this deficiency would have little effect.

2 Method Description

Three-dimensional panel methods represent wing and body surfaces by an assembly of polygonal panels with singularities distributed over their surfaces. Panel methods have an advantage over the simpler codes in that thickness and camber effects may be included. Wakes are represented by a planar doublet sheet shed from the trailing edge of lifting surfaces in the free-stream direction. Panel methods can model some non-linear effects such as wake roll up and the effects of boundary-layer growth on the potential flow solutions. Panel methods are a good compromise between the simple yet limited codes and the more exact yet complex codes. They are able to model complex flows such as three dimensional vortex flows, yet are not so complicated as to create a large demand on computer resources. For this reason panel methods have been used to great advantage in solving problems with complicated 3-D geometry or where vortex interactions occur (Refs 3,4,5).

VSAERO (Ref 1) is a surface singularity panel method in which the whole flow field is treated as a potential flow with viscous regions confined to infinitely thin boundary layers, free shear layers and to vortex cores of small diameter. The basic formulation of the VSAERO panel method is by way of Green's theorem and is described in Reference 2. For completeness, a brief description of the method is presented here.

The surface configuration is approximated by a set of flat quadrilateral panels of uniform source and doublet singularity strengths. The panel source values are determined by the local external Neumann boundary condition. The panel doublet values are solved from a set of simultaneous linear equations specifying explicitly the internal Dirichlet boundary condition that the total velocity potential on the interior surface of each panel shall be equal to the free-stream velocity potential there (i.e. the condition of zero perturbation potential inside the volume). This particular formulation gives a doublet source combination which is just one of an infinite set (other forms were considered earlier for VSAERO).

The wake surfaces (i.e. the free shear layers) are represented by flat quadrilateral panels of uniform doublet singularity strengths. The variation in strength from panel to panel in the streamwise direction can be either constant or vary linearly, depending on the wake type used. For conventional wing type wakes the doublet distribution is constant in the streamwise direction, whereas for separated wakes the doublet distribution has a linear variation. The wake surface cannot support a load; therefore, the doublet distribution on the wake surface must satisfy a zero-force condition. Doublet values at the point of separation are determined by the conditions at the surface panel column from which the wake is shed. The jump in doublet strength between adjacent wake columns causes the junction to act as a vortex filament. In the wake, the initial vortex-line geometry is usually prescribed. In subsequent solutions, vortex lines are relocated along calculated mean streamlines in an iterative procedure

The output from the code provides doublet values, non-dimensional velocities and pressure coefficients at the surface panel centroids. The program computes force and moment coefficients for both the entire configuration and specified subsections. It will calculate paths of surface and off-body streamlines, and it will calculate the flow velocity at arbitrary or user-specified points in the flow field. Surface velocities are determined from the gradient distribution. Pressure coefficients are referenced to a non-dimensional onset velocity equal to 1.0. The utility of the code is enhanced through the generation of a complete plot file of geometric and aerodynamic data.

3 Results and Discussion

3.1 *Configuration Description*

The panelled geometry of the F/A-18 configuration used for the modelling is shown in Figure 3. The aircraft's general dimensions are presented in Figure 4. The model comes in two main forms. The first, with a total number of panels of 1492, is illustrated in Figure 3. The second has a denser distribution of panels over the wing and center section of the fuselage, with a total of 2052 panels.

The model is broken up into 12 patches and two components. The two components are, the wing and the body (fuselage). The wing comprises two of the 12 patches. They are, the wing (excluding the LEX) and the wing tip (the tip patch is used to effectively "close off" the end of the wing). The fuselage comprises the remaining 10 patches which include the LEX, the engine intake and exhaust and a small portion of the root section of the wing.

The VSAERO model differs in a few significant aspects from the real aircraft, the most notable being the lack of aerodynamic tail surfaces. These surfaces were not included in this preliminary model as it was thought that the extra complication needed to include them would not be warranted by the benefits gained. The model has since had the horizontal stabilizers included set to an angle of zero degrees. An illustration of the new geometry is shown in Figure 5. Results, however, are not presented as they are not as yet available. At this early stage of development, it was thought more important to get the general configuration correct before going on and producing a more complex model. The model also has a few necessary simplifications to allow reasonable modelling by VSAERO. Among these are the omission of wing tip pylons and the omission of boundary-layer bleed air slots. The wing tip pylons were not included as it was thought that their effect on the overall aerodynamics would be limited to the wing tips and hence have no great effect on the root vortices of interest in this model. The only allowance made for the bleed slots is the modelling of the exterior dimensions of the boundary layer splitter plate. These devices were modelled in this way because the VSAERO program models boundary layers as being infinitely thin, (i.e. the program is a basically inviscid code with allowances for viscosity effects). On the aircraft, the effect of the slots is to remove the low energy air in the boundary layer before it reaches the engine intake. In the model, the boundary layers are infinitely thin, hence the effect of the bleed air slots is lost. As a result, this modelling was seen as adequate.

The wake panelling is similarly divided into two parts, the wing wake and the exhaust wake (future models will also need to include the LEX wake). The wing wake is a regular "wing" type wake with a uniform doublet distribution in the streamwise direction. The exhaust wake is a "separated" type wake with a linear doublet distribution in the streamwise direction, with the doublet gradient specified as a jump in tangential velocity across the wake (in this case, the jump in tangential velocity is specified by the user). For the results presented here, the interior velocity of the exhaust wake was specified as twice the free-stream velocity. Other types of wake that are available in VSAERO include a "propeller" type wake and an advanced dual-energy (closed separation) wake, where the doublet distribution is linear in the streamwise direction with the gradient determined as part of the solution.

VSAERO Version C is limited to 30 wake grid planes, and hence the number of wake panels is limited to 653. Because of the limited number of wake grid planes, version C would have difficulty modelling the entire wake including the vortices originating from the LEX. In version D, however, the maximum allowable number of wake grid planes has been increased to 155, allowing the use of a much denser wake grid. The model used with version D had 50 wake grid planes and 1125 wake panels. In future models, this number will need to be increased to accommodate the LEX wake (to include the LEX wake, the wake will need to start at the leading edge of the LEX instead of the trailing edge of the wing where it starts in the current model). Figure 6 shows the wake structure for a typical solution at an angle of attack of 8.0 degrees.

VSAERO allows normal velocities to be specified on groups of panels to allow inlet and exhaust flows to be modelled. There is, however, no requirement to satisfy continuity for the total internal flow. This capability has been used to model both the engine inlet and the jet exhaust. For most of the results presented here, the exhaust velocity was set at 2.0 times the free-stream velocity and the nominal inlet velocity was set to 0.0. However, the effect of inlet velocity was studied with the results presented in a latter section. It should be noted here that VSAERO can only specify normal velocities for panels.

3.2 Effect of Aircraft Angle of Attack (α)

The model was used to obtain the characteristics of the aircraft at low angles of attack. Solutions were obtained for α varying from 0.0° to 12.0°. For angles of attack less than 4.0 degrees the solution was quite stable, however, as α was increased the solution became less stable. The instabilities in the solution arose from three areas:

1. The vortex/body interactions,

2. The vortex/vortex interactions and

3. The tendency for the wake to cross the line of symmetry

During the shape iterations at higher angles of attack, the wake geometry varied quite markedly in areas of strong vortex interaction. This is demonstrated in Figure 7, which shows the converging process over six wake shape iterations for two cross-sections of the wing wake at α 5.0°. As can be seen, even after six iterations, the solution has not yet fully converged. With further wake shape iterations the solution would still not converge. In some cases (α larger than 6.0°.) the solution would start to diverge if more iterations were attempted. A limit of six wake shape iterations was imposed on the solution process. The limit chosen was a compromise between computer time and solution accuracy. It was also noted that in some cases the solution would become numerically unstable with further wake shape iterations past six. In many solutions, as illustrated in Figure 6, the wake may come close to or even penetrate the body panels. As a result, the pressure coefficients tended to vary considerably over the tail section for any one solution. The stability of the solution was improved by changing the parameters used by VSAERO for the Gauss-Seidel iterative solver used to invert the influence matrix. These were the Gauss-Seidel residual limit or the convergence limit and the relaxation factors. By changing these parameters the instability was decreased but not eliminated. Also, the computer time required for any one solution was effectively doubled.

The lift coefficients obtained from the model are compared with experiment in Figure 8. Included in this graph is the contribution of the wing to the overall lift coefficient. Although the C_L curve for the model remains close to that of the experimental results, the results show a tendency to deviate, at some points, from the constant lift curve slope of the experimental data. This deviation is not as apparent in the lift curve slope calculated for the wing alone. Hence it appears that the deviation is mainly due to the instability in the solution in the empennage region. The average lift curve slope for the model is 3.882/rad compared with that from the experiment which has a lift curve slope of 4.317/rad. – a difference of 10%. It should be noted that the lift coefficients obtained from the model were not expected to be completely accurate due to the lack of tail surfaces and the inviscid flow characteristics of the VSAERO program. The comparison with experimental data was intended primarily to show whether the model could produce reasonable results.

For the larger angles of attack (6.0° and above) it was noticed that the pressure distributions around the exhaust pipes tended to become positive, ie. the local velocities were being retarded. This seems to suggest that the model needs a separation line in this region. The position of the separation line could be determined at each individual angle of attack by investigating the flow characteristics around the tail pipe from an initial run with the separation line around the perimeter of the exhaust pipe. The separation line could then be moved to the appropriate position on the aircraft and the model could then be used to obtain the updated solution. Further investigations are needed to determine whether this refinement in the model is warranted.

3.3 Effect of Inlet Velocity

The engine inlet velocity was varied from the nominal 0.0, or no inlet velocity, to 2.0 times the free-stream velocity. The variation of inlet velocity was studied as to determine the importance of this parameter on the solution. The results obtained using this model of the F/A-18 will be used to decide whether the effect of the flow through the intakes is important enough to be included in the low speed wind tunnel model currently being manufactured. The effect of this parameter is not included in the McDonnell results.

Figure 9 illustrates the effect of inlet velocity on overall lift coefficient at an angle of attack of 8.0°. Included in this graph is the calculated wing lift coefficient and the experimental data for this angle of attack. The latter is included as a reference. The effect of inlet velocity seems to be greatest when the inlet velocity is around 0.4 times the free-stream velocity. At this point the lift coefficient has decreased from 0.4067 to 0.3510 -- a 13% decrease. When the velocity is increased beyond that point the overall effect decreases (e.g. at an intake velocity of 1.5, C_L = 0.3856).

The main effect of varying the inlet velocity is to vary the local pressure distribution on and around the engine inlet (ie. mostly in front of the inlet). As the intake velocity is increased from 0.0, the area of stagnation on the face and in front of the intake disappears. The face of the intake becomes a region of high suction for high intake velocities. On panels in the vicinity of the intake, pressures are also modified. On panels ahead of the intake, the effect of a high intake velocity is to decrease the pressures, from near stagnation pressure to a slight suction. On the panel immediately behind the intake, the effect on pressure is the reverse of those ahead; that is, pressures vary from slight suction for low intake velocities to slightly positive pressure coefficients for high intake velocities. The effect of the intake velocity seems to be mainly local, but the effect is noticeable on the overall aircraft pressure distribution (and hence total force and moments), as is shown in Figure 9. The variations in pressure distributions ahead of the intake suggests that the intake flow-through velocity would have an effect on the vortices emanating from the Leading Edge Extensions. From these results, it appears that the wind tunnel model should include flow-through inlets.

3.4 Comparison between VSAERO version C and D

During the course of developing the model, a new version of VSAERO was installed at ARL. The new version includes improvements in a number of areas. They are, increased limit on the number of wake grid planes, a mini restart (saves only the last solution calculated and hence saves on memory), and improvements in the surface streamline tracking and boundary-layer calculations. It was also claimed that the new version would be more robust in its treatment of vortex interactions. It was decided to model the aircraft using this new version of VSAERO and to make a comparison with the old version.

The two versions of VSAERO were compared for an angle of attack of 6.0°. The model used in each case was exactly the same, so as to directly compare the two versions. Figure 10 shows the final wake geometry for each case. As can be seen, the new version displays a marked improvement over the old. The wake shape is a lot less chaotic and there was a major improvement in numerical stability. As is demonstrated in Figure 10, the main difference between the two versions is the wake geometry in the vicinity of the fuselage of the aircraft. Version D has greatly improved this aspect of the solution, and hence tends to show that version D, as it claims, is much more numerically stable than the older version. The total lift coefficient for the aircraft did not, however, vary much between the two solutions. It must be noted here, that VSAERO version C was unable to produce a solution for angles of attack of greater than 6.0°, whereas version D has been able to produce a solution for all angles of attack attempted so far (up to 12.0°).

Version D allowed an increase in the number of wake grid planes, and also offered improvements in the jet wake definition (type 4 wake). With these improvements in mind, version D was used with a suitably modified model to produce the results presented in this paper. With the extra wake grid planes available in version D, VSAERO will now be able to model the wake originating from the LEX with an ample density of wake grid planes. With version C being limited to only 30 wake grid planes, it would be doubtful if it could have modelled the complete aircraft wake satisfactorily.

4 Conclusions

VSAERO has been applied to the F/A-18 fighter aircraft. A model with 2052 body panels and 1125 wake panels, has been used to predict the aerodynamic characteristics of the aircraft at angles of attack ranging between 0.0 and 12.0 degrees. The model exhibited numerical instability in the areas where strong vortex interactions occur. This problem was alleviated slightly when the new version of VSAERO became available. The new version proved to be more robust in areas of vortex interactions and also allowed the inclusion of a greater number of wake grid planes which in turn also helped to improve the numerical stability. The problem, however, was not totally eliminated and more work needs to be done in this area.

The model was originally intended to be used for high-angle-of-attack work. However, to move into this area the model needs to take into account the modified structure of the aircraft and its flow field at these angles of attack. The modifications would include:

1. The inclusion of leading edge and trailing edge flaps.
2. Modifications to the separation lines around the exhaust pipes (individualized for each angle of attack).
3. The inclusion of the fins and horizontal tails and
4. The inclusion of the LEX wake.

The model has been expanded to include the horizontal tail at a tail setting angle of 0.0° as is illustrated in Figure 5. It should be noted here, that a different model is needed for each tail setting angle.

The package used in this paper has performed adequately and has produced quite acceptable results for the model chosen. Future modifications of VSAERO that would make it more useful in the study of models with complex geometries would be an improved method of modelling intersections between components such as the wing/body intersection. Methods of improving the modelling of vortex interactions would also be of great assistance to the user.

Acknowledgments

I wish to acknowledge Bruce Fairlie for his help and guidance during the course of this project.

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FIGURE 1 MODEL OF F/A-18 IN WATER TUNNEL

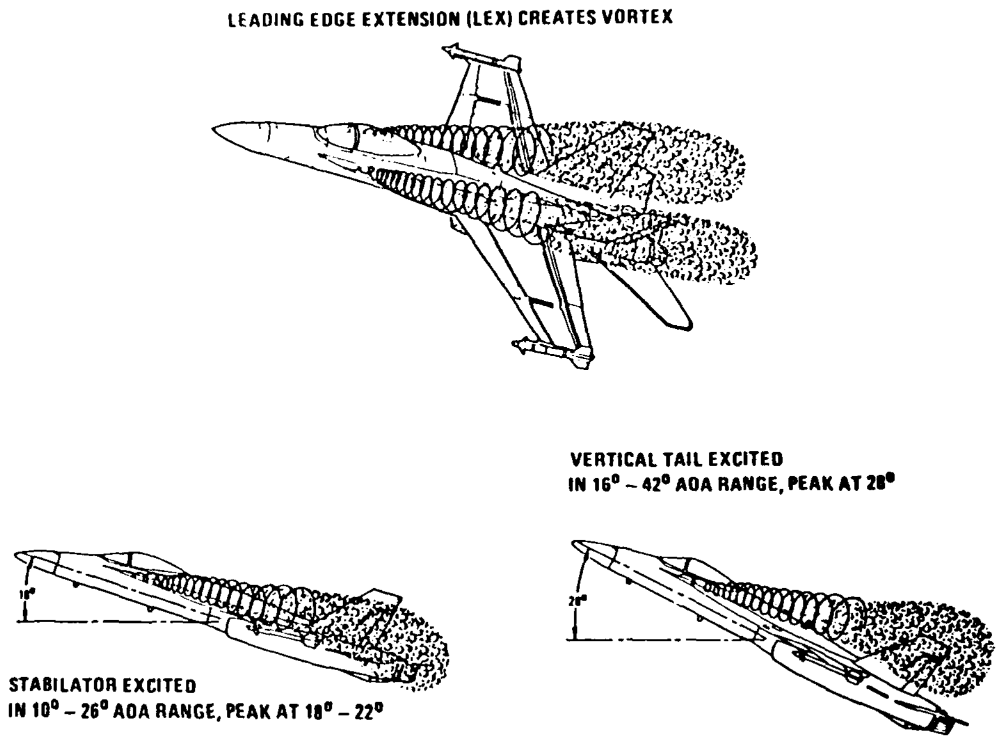


Fig. 2 The F/A-18 Aircraft and the general form of the leading edge extension vortex, which causes the fatigue damage to the stabilator and the vertical stabiliser.

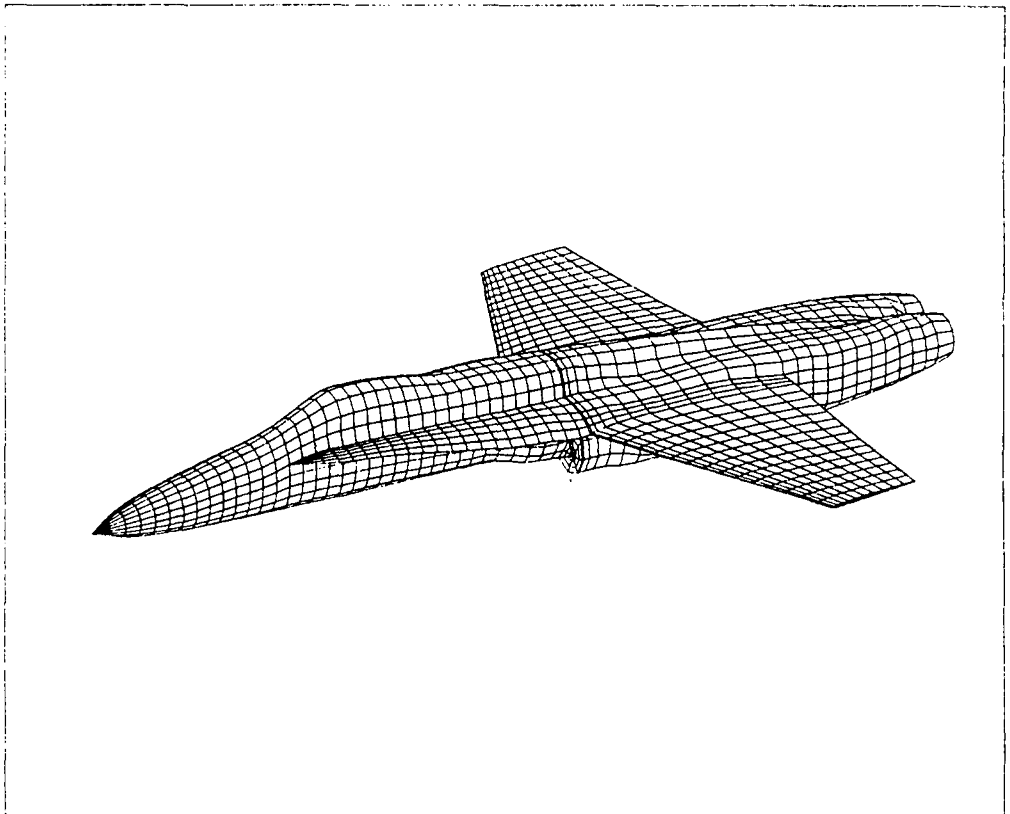
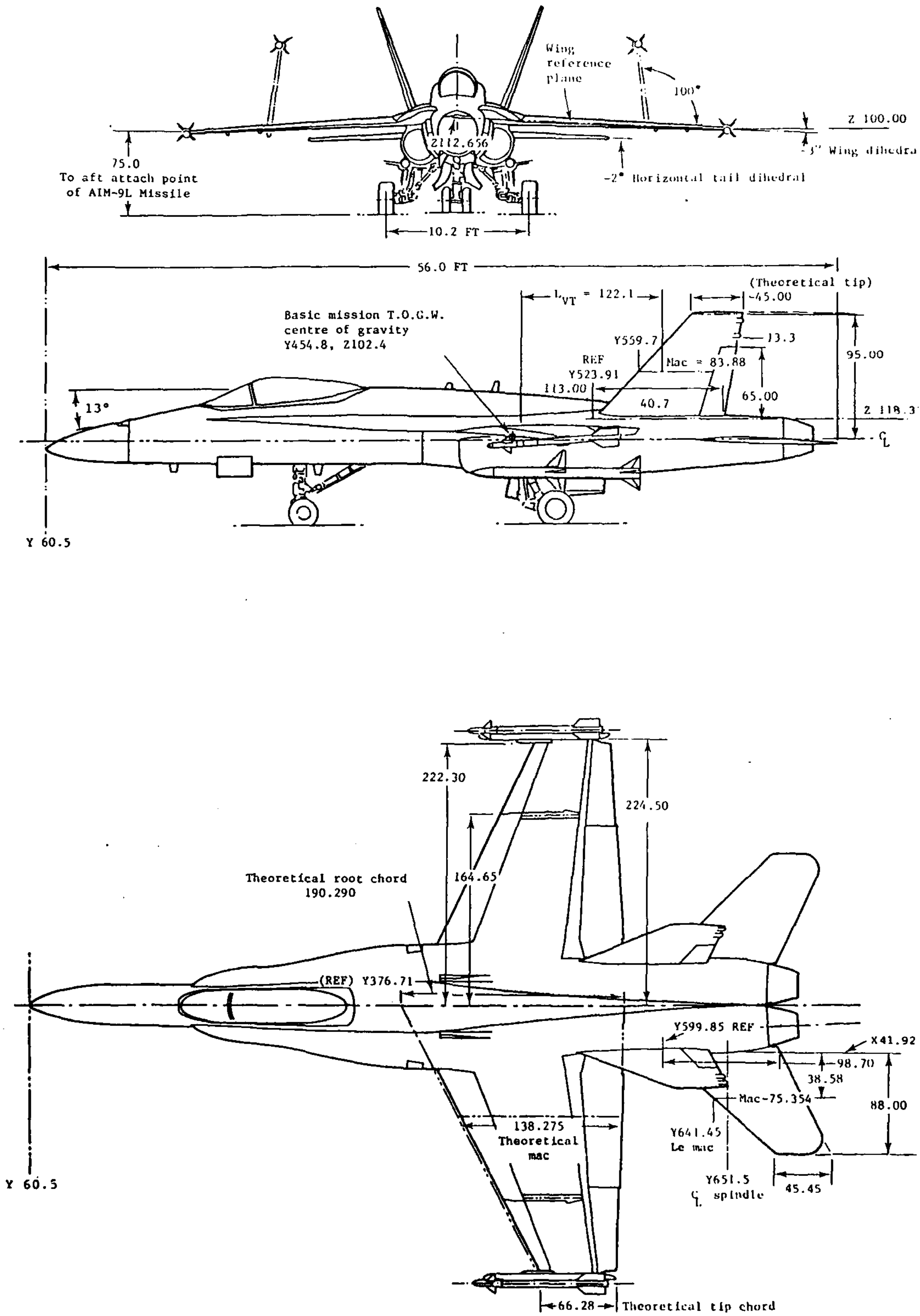


Figure 3. Example of Model geometry : 1492 panels

Figure 4. General dimensions of F/A-18



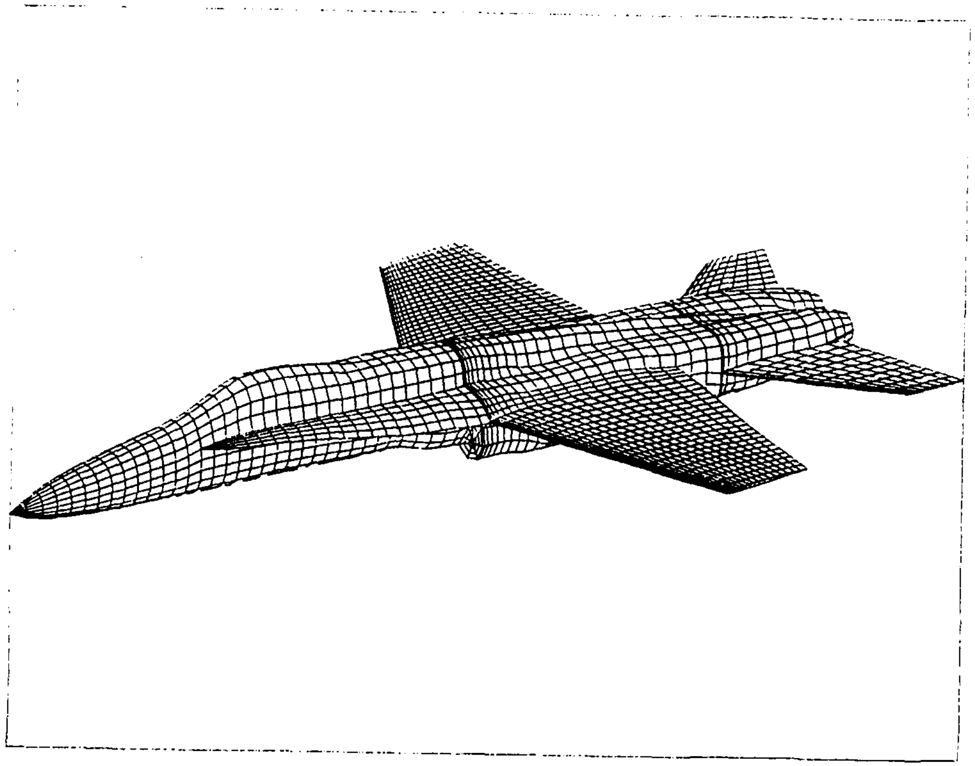


Figure 5. Example of new Model geometry : 2311 panels

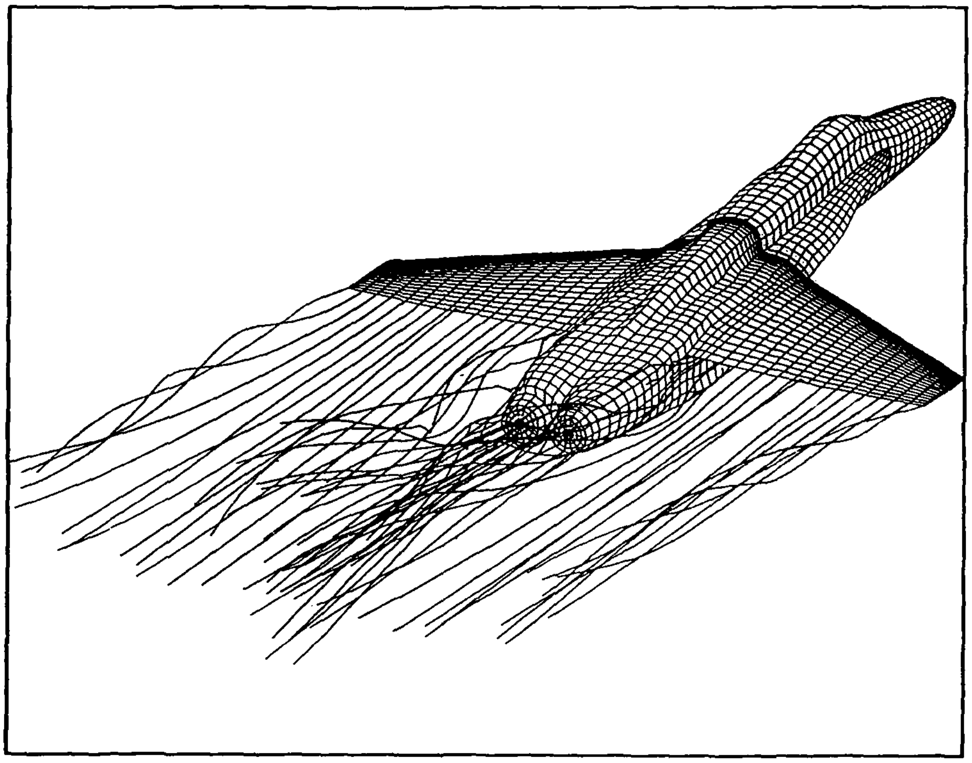


FIGURE 6 WAKE GEOMETRY OF A TYPICAL SOLUTION.
ANGLE OF ATTACK = 8.0 DEGREES.

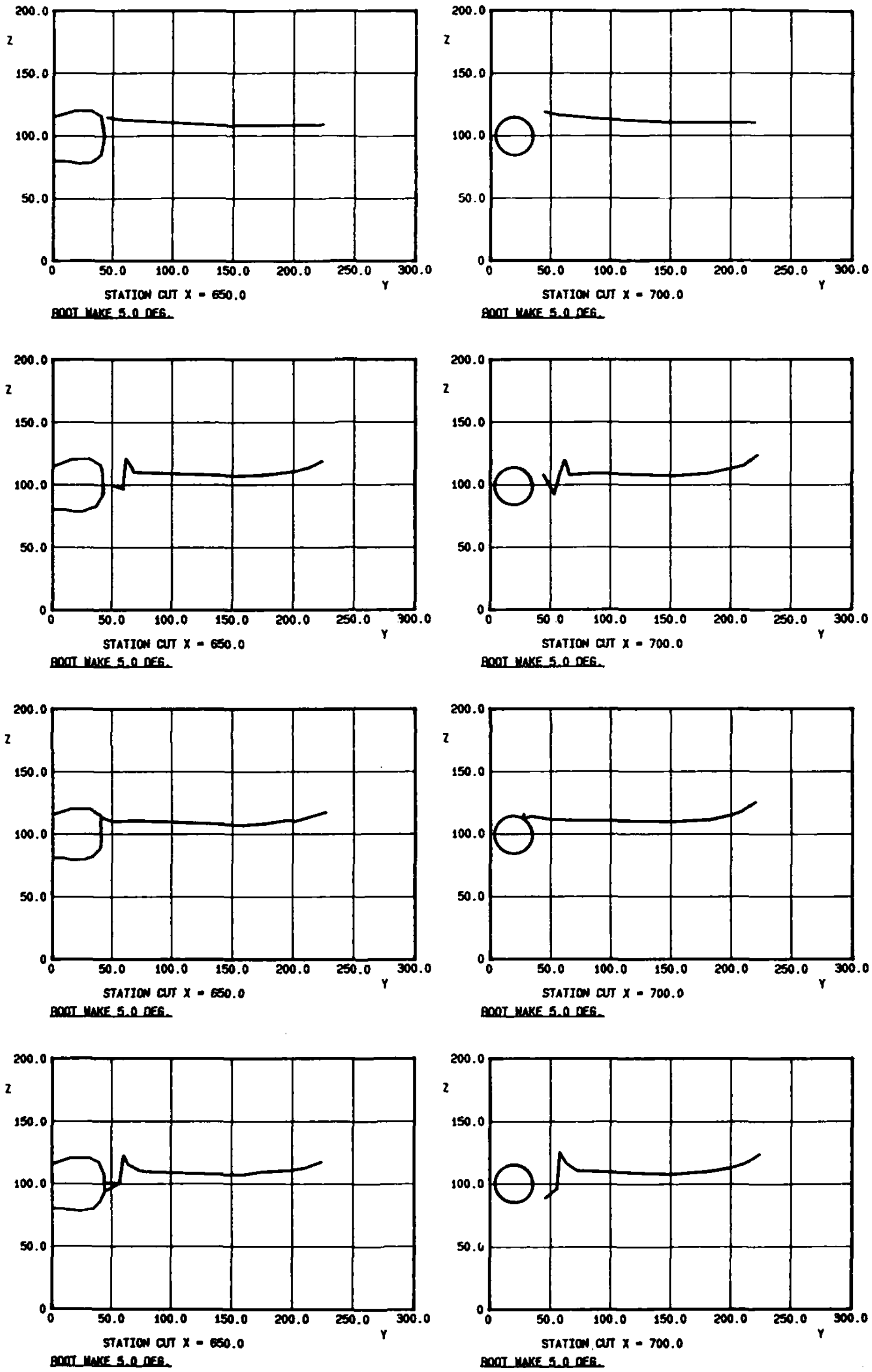


FIGURE 7 ITERATION PROCEEDURE FOR WAKE

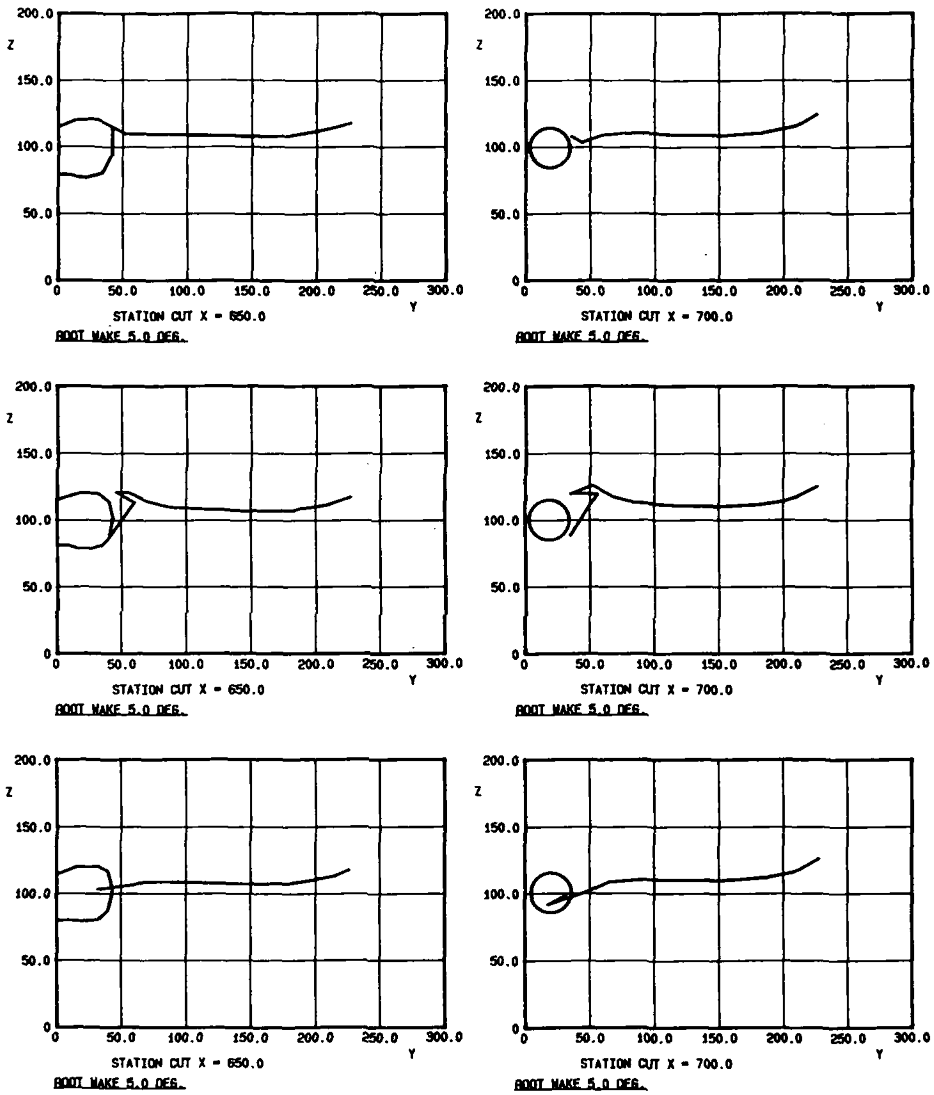


FIGURE 7 CONTINUED

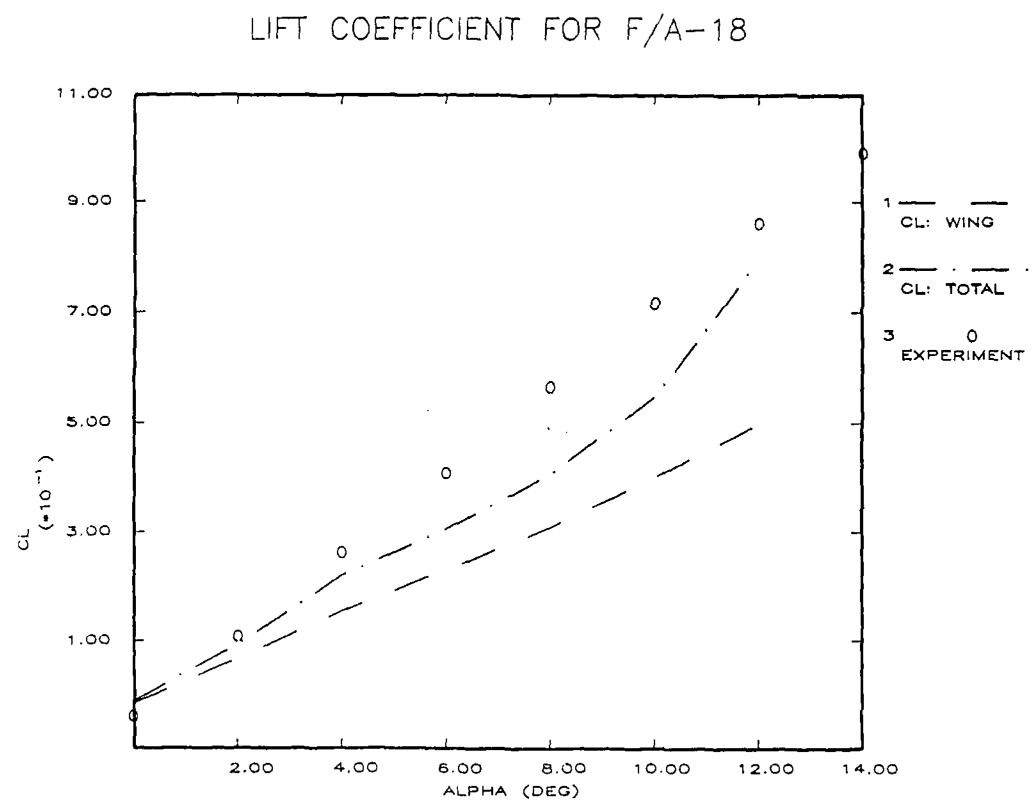
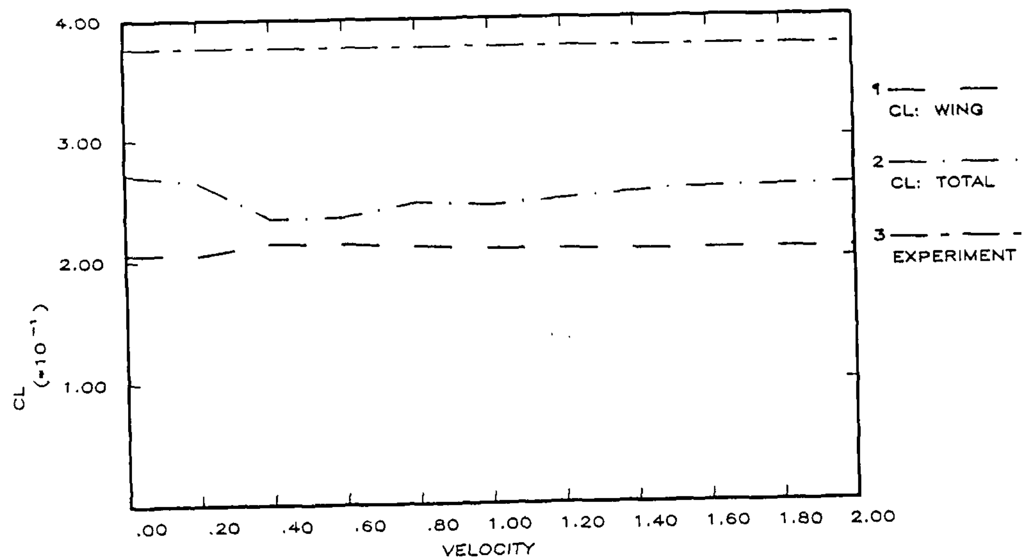


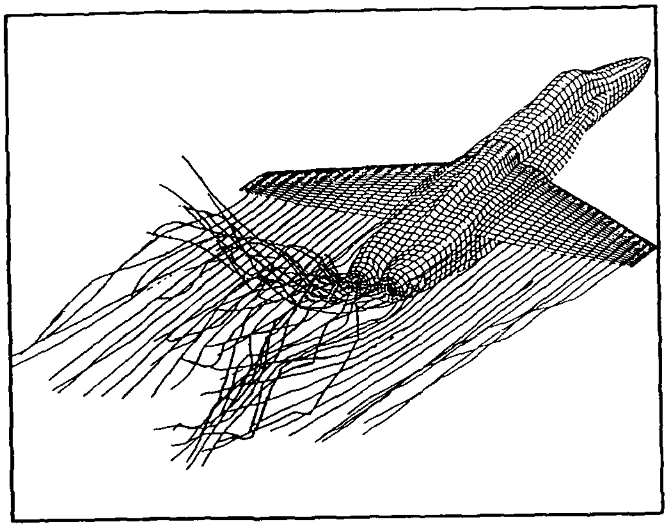
FIGURE 8 VARIATION OF LIFT COEFFICIENT WITH ANGLE OF ATTACK

VARIATION OF INLET VELOCITY

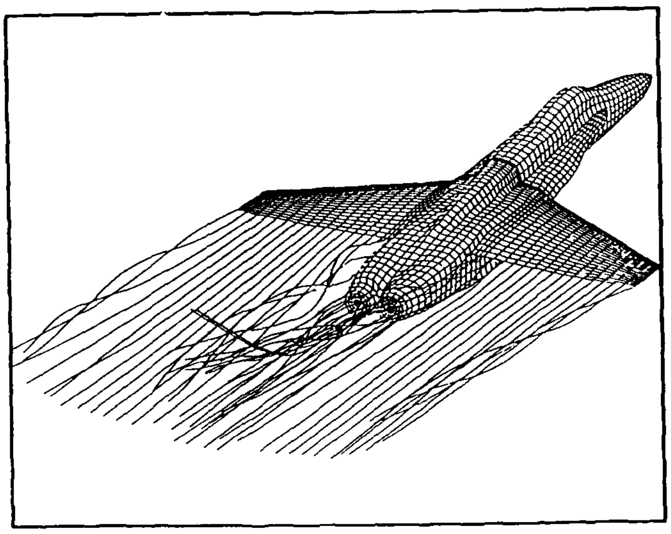


LIFT COEFFICIENT FOR F/A-18

FIGURE 9 VARIATION OF LIFT COEFFICIENT WITH ENGINE INTAKE VELOCITY



VSAERO VERSION C.   ALPHA=6.0 DEG



VSAERO VERSION D. ALPHA=6.0 DEG

FIGURE 10 COMPARISON BETWEEN VSAERO VERSION C AND VSAERO VERSION D

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DOCUMENT CONTROL DATA

PAGE CLASSIFICATION
UNCLASSIFIED

PRIVACY MARKING

1a. AR NUMBER	1b. ESTABLISHMENT NUMBER	2. DOCUMENT DATE	3. TASK NUMBER
AR-005-543	ARL-FLIGHT-MECH-TM-404	MARCH 1989	DST 88/027

4. TITLE

DEVELOPMENT OF A VSAERO MODEL OF THE F/A-18

5. SECURITY CLASSIFICATION (PLACE APPROPRIATE CLASSIFICATION IN BOX(S) IE. SECRET (S), CONF.(C) RESTRICTED (R), UNCLASSIFIED (U)).

DOCUMENT	TITLE	ABSTRACT
U	U	U

6. NO. PAGES
23

7. NO. REFS.
6

8. AUTHOR(S)
R. TOFFOLETTO

9. DOWNGRADING/DELIMITING INSTRUCTIONS
Not applicable

10. CORPORATE AUTHOR AND ADDRESS

AERONAUTICAL RESEARCH LABORATORY
P.O. BOX 4331, MELBOURNE VIC 3001

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14. DESCRIPTORS

F/A-18 aircraft
VSAERO (computer program)
Velocity distribution
Wakes

15. DRDA SUBJECT CATEGORIES
0051A

16. ABSTRACT

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16. ABSTRACT (CONT.) was also used to study the effect of engine intake velocity on the aerodynamics of the aircraft.

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17. IMPRINT

AERONAUTICAL RESEARCH LABORATORY, MELBOURNE

18. DOCUMENT SERIES AND NUMBER	19. COST CODE	20. TYPE OF REPORT AND PERIOD COVERED
FLIGHT MECHANICS TECHNICAL MEMORANDUM 404	535005	

21. COMPUTER PROGRAMS USED

22. ESTABLISHMENT FILE REF.(S)

C2/208

23. ADDITIONAL INFORMATION (AS REQUIRED)