Panel codes for aerodynamic analysis at NAL

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Abstract: NAL's panel code capability buildup has been highlighted and several interesting applications are discussed to bring out the utility of panel methods in aerospace research and development.

1. Introduction

Even at the present juncture, when advances made in computer architecture and algorithms have made it possible to compute complex flow situations based on non-linear flow equations, the linear formulation, underlying the so-called panel methods, continues to occupy a place of high utility in aircraft industries. While linearity masks some of the flow features, the capability of panel codes to handle very complex geometries typical of wing-body-tail-pylon-nacelle combinations has made it invaluable to the Aerospace design/development engineers. In practical situations there are several features of the flow field which can very accurately be brought out by the panel methods usually in and around the design point of the configuration, in purely subsonic or supersonic conditions.

The development in panel methods began during the pre-CFD era, i.e. before the seventies, and has culminated in sophisticated codes taking advantage of the continuous advances in computer architecture over the. past 20 years. As the literature indicates, the advantage of high-speed computing platforms with enhanced memory has resulted in the development of higher-order panel methods as well as in the cleverer use of lower-order panel methods for novel applications (Kraus 1976, Hess 1990, Hoeijmakers 1990).

The impressive growth made in Computational Fluid Dynamics over the past 20 years, with its clearly demonstrated capability to handle complex geometries and non-linear systems of flow equations, may tempt one to conclude that the days of the panel codes are over. But in reality it is unlikely to be so. What may be true is that further research into panel codes may not be warranted in countries where efforts over the years have already culminated in comprehensive and mature panel codes, *e.g.*, USSAERO, VSAERO, PANAIR, QUADPAN (all American), HISSS(German), AURORE, ECOPAN (both French) and BAe Mk II (British).

This however does not imply that the use of the panel codes in industrial applications would cease eventually, even in advanced countries. It may be safely said that about 60 to 80% of CFD effort in any aircraft design is still shared by the panel codes - that too quite often by a hierarchy of panel codes varying in their complexities and capabilities; computing economy is of prime consideration in industry, and it would not pay to use more sophisticated and expensive codes for all stages of design effort. This emphasis on computing economy also explains why with all the advances made in Navier-Stokes solvers and Euler and full-potential ones, one still looks to panel methods for useful data. Another attraction of panel codes has been the ease with which complex geometries can be handled; the requirement of discretisation of only the surface, rather than the discretisation of the entire flow domain, considerably eases the problem of grid generation which is still an impediment to success with other higher-order approximations of the Navier-Stokes equations.

That the use of panel codes may not cease eventually is also true of NAL, where over the years, the analysis capability of panel codes was sought for many in-house and outside requirements. It is much more true in recent times as demonstrated by the considerable demands on panel codes for NAL's civil aviation activities involving the design and development of a two-seat trainer and of a light transport aircraft.

It is also relevant to mention here that most of the present and earlier efforts in panel codes have been in adapting and improving Woodward's panel code (Woodward 1973) and its variants. It turns out that owing to the pressure of data generation from time to time we seem to have skipped attempts at developing indigenous panel codes. Our keenness in, and attraction to, state-of-the-art CFD codes, including transonic flow codes, have also underplayed efforts in developing indigenous panel codes; it is well-nigh impossible to coax anyone these days to work in the area of panel codes, which is considered archaic by many.

The aim of the present paper is to bring out the utility of the available panel codes at NAL to many applications. It is hoped that these illustrations would bring about some interest or resurgence in the development of an indigenous panel code at NAL. It is also hoped that the illustrations would bring home two important aspects related to utilitarian CFD: One, one should have a hierarchy of codes of varying degrees of sophistication to be used economically at different stages of design and development, the main aim being cost effective computing; and two, courageous and clever use of CFD codes even when short of perfection, for engineering application, based on confidence gained with validation/calibration in respect of data which the code may predict, well. Before going over to the illustrations of application of the panel codes, it would be useful to have some background and a historicalperspective of our activities in panel methods at NAL.

2. Background and historical perspective

In hindsight, it was by pure chance that the panel code activity came to be started in NAL; it was in 1975-76, while collecting computer codes from various sources for an AR&DB project, we chanced upon a code published in a NASA Contractor Report by Woodward (1973) capable of analysing aircraft-like configurations. But at that time there was no computer facility available that was capable of handling a code of this size. The DEC-1077 at TIFR, Bombay and the IBM-370/165 at IIT, Madras were just being installed and access to these systems, because of their out-station locations, was limited. The IBM-360/44 at IISc commissioned around 1970 was a small system with no disk storage and editing facility.

Our efforts took nearly two years and several trips to Bombay and Madras for debugging the code of about 4500 cards and validating it against the sample input and output as given in the report NASA CR-2228.

Woodward's panel code has the capability for subsonic and supersonic flows and can deal with wing-body shapes. But as is now well known, Woodward's code available in the report NASA CR-2228 contains several bugs and many aircraft companies had personally invited Woodward to help in removing some of the bugs. During the mid-seventies, there were several attempts at improving Woodward's code, and some of these have led to the development of well-known panel methods cited in literature, for example, USSAERO, HISSS, *etc.* There are several versions of Woodward's code, some developed earlier at NLR, Netherlands, MBB, Germany, *etc.*

After NAL acquired the UNIVAC-1100/60-H1 mainframe computer system in 1983, handling of the code became routine and soon several bugs were confronted as mentioned earlier and also many difficulties in handling particular types of wing geometries.

With Woodward's code becoming operational at NAL, many users were interested is using it for several configurations, mainly wings or axisymmetric bodies; in particular there were requests from HAL for the analysis of wings (conceptual stage versions of combat wing shapes) and also from ARDE, Pune, for the analysis of projectile shapes in supersonic flow regimes. From the feedback got from the users, indications were that the predictions made by the code were reasonable and acceptable, which was a comforting thought, more so in the absence of the availability of an alternative tool.

Things looked better and there was a substantial increase in our panel code analysis capability when, in 1985-86, we acquired two more panel codes - (a) an earlier but simpler version of Woodward's code and (b) an advanced version capable of handling complex geometries.

The former code, NALSOF 0509, could handle axisymmetric fuselage shapes with complex wing and tail planforms. Its main attraction for application was its quick and good predictions of overall force characteristics and its design option which was added on subsequently; in this mode one could obtain optimum wing camber and twist for prescribed lift and pitching moment while minimising drag.

The latter code, NALSOF 0519, has the capability of analysing any complex aerodynamic shape at subsonic speeds. Because of better flow modelling, this code gives better results, especially the pressure distributions compared to Woodward's code for subsonic regime.

As the presently available codes reasonably meet our immediate requirements, especially at subcritical speeds, they are going to be our main tools for some more time to come. However the need for the developement of an indigenous version of a panel code with better flow modelling both in subsonic and supersonic speeds is there.

With the formation of the Computational and Theoretical Fluid Dynamics Division in 1988, much focus was given to the application of codes to engineering design and analysis. When the Division acquired a more powerful Supermini computer in 1990, the problem of accurate simulation of complex shapes appeared to be within our capability geometrywise; but computationally, the computing speed of a mere 5 MFLOPS (sustained) continued to be the real bottleneck, Fortunately this too was soon to be removed with the development of NAL's parallel computer, Flosolver. This machine with its 5 Intel i-860 processors is capable of a sustained performance of upto 25 MFLOPS.

This encouraged parallelisation of the subsonic panel code. Considering the panel method formulation in terms of its two main ingredients - of formation of influence coefficients and of solution of the linear system of equations - the former was adequately suited to parallelisation inherently, but for the latter special care was required to parallelise the Gauss-Seidel scheme on the FLOSOLVER. As a result of this parallelisation, upto about 6000 panels can be handled with a CPU time of under an hour (Sinha 1992). This is very attractive from the point of view of applications in a design mode, where a large number of variants may have to be analysed in a short time.

The acquisition of IRIS Graphics Workstation in 1991 has further helped through its pre- and post-processing capability in practical applications where panel codes are constantly needed.

3. Applications of panel codes

3.1. Woodward's code

The first configuration analysed by Woodward's code after it was successfully made operational with the sample input, was a typical combat aircraft configuration (Fig. 1). There were many problems with this. First, there was an error in the code, the first bug to be encountered, in accepting data for the fin - a 'vertical' wing like component - both in geometry and velocity calculation parts. The error in the geometry part was set right straight away, but the error in the velocity part could not be located immediately. To get over the problem for the time being, only wing and fuselage configuration was taken for analysis. These went through and results were obtained for two typical Mach numbers one subsonic and the other supersonic speeds. The results 'looked' reasonable. This success gave us confidence in claiming the availability of a 3-D analysis code with us. This is how NAL's Panel code capability came to be started without any conscious (official) move to acquire it! This was in 1978.

The next opportunity for using Woodward's code came from ARDE Pune, for generating surface pressure data on some projectile shapes - axisymmetric bodies with cruciform fins. This was undertaken as part of a sponsored project (Ramamoorthy 1983). As a cross check, a code based on Jackson-Smith's second-order shock expansion theory for only axisymmetric bodies in supersonic flows was used and pressures from both the codes were compared and they were satisfactory (Fig. 2). Subsequently this panel code was applied to many configurations including those developed by the Aeronautical Development Agency.

A new challenge was the ability to handle multibodies, typical of launch vehicles in both subsonic and supersonic flows (Fig. 3). The version of the code as available had to be modified for multibodies, a validation of which is shown in Fig. 4, compared to wind tunnel results from NAL for subsonic flows. It is interesting to see a good prediction of the pressures particularly around regions between boosters and the core. Validation of this code for Multi-Strapon Launch Vehicle configurations is continuing under a sponsored project from VSSC (Narayana 1992).

3.2. NALSOF 0509 panel code

This code has the limitation of accepting only axisymmetric fuselage configurations. However, it has the capability of accepting complex wing and horizontal tail shapes. This code, being simple and fast, has the special attraction that the analysis is fast and that the overall wing characteristics such as C_{L_α} and C_{M_α} can be obtained. Figure 5 brings out comparison with NAL experiments for a delta wing-body configuration (Singh 1986), The flap deflections were also simulated. The comparison shown is considered rather good. This code also has design capability, *viz.*, calculating camber shapes for given total lift, C_L, and pitching moment, *CM*, coefficients, it is a very useful tool. Figure 6 shows the camber and twist obtained for an earlier variant of a combat configuration (Desai 1985). Some of the othe configurations analysed include: combat aircraft, transport aircraft (LTA), satellite launch vehicles, and trainer aircraft (early versions of NALLA).

A recent application of this code has been to NAL Light Transport Aircraft (LTA). Figure 7 shows comparison with NAL experiments for this configuration. It is again seen that C_{M_α} prediction is particularly good (Viswanathan 1992).

This code has also been used to generate data for research on slender delta wings with cylindrical bodies. Figure 8 shows comparison with NAL experiments. Except for highly swept wings beyond 60° the comparison is seen to be good. Even for higher sweep angles it should be possible to improve upon these results with inclusion of the suction analogy of Polhamus.

3.3. The NALSOF 0519 code

This code is based on constant source distributions on surfaces and a vortex lattice on mean surfaces of lifting components. The code includes a compressibility correction through Goethert's rule and the incompressible version of this code has the capability of taking ground effect also into consideration. The capability of the incompressible version of NALSOF 0519 was extended to analyse aircraft configurations with free relaxed wakes behind wing like components (Narayana 1988), Figs. 9. Further details of the code can be obtained from Kraus (1970) and Ahmed (1973).

The compressible version of this panel code is presently our main analysis tool at subcritical speeds. Some of the configurations analysed with this code include: combat aircraft, transport aircraft (LTA), satellite launch vehicles, and trainer aircraft (early versions of NALLA). The wireframe of the LTA and typical results of the calculation using this panel code are shown in Figs. 10 and 11, respectively.

The effects of the wind tunnel walls on the loads of various aircraft configurations (wall interference) are being studied under different wall boundary conditions, *viz.*, solid, perforated, slotted, *etc.*, using this panel code.

Special mention should be made of the use of this code during the aerodynamic design phase of the NALLA, both in its pusher and tractor versions (Fig. 12). For the latter version, which is a traction configuration, interesting modifications could be made to wing-body junction area to arrive at a flow with well organised and spread out streamlines on the entire fuselage downstream of the critical wing-body junction. Figure 13(top) shows the streamlines of the flow over the modified fuselage, whereas the figure at the bottom shows the streamlines seen before the modfications were made.

The most recent application of this code is the analysis of the pressure distribution over the latest version of NALLA (Fig. 14). Another interesting application of this code was in the prediction of loads on wings with flap deflections. Figure 15 shows the excellent agreement of pressures from this panel code with a 2-D exact calculations on a William's two element airfoil. This will be very much useful in using the code for the prediction of part wing-span flap deflections on a complete aircraft configuration.

The above cited applications indicate the versatile capabilities of this code and its almost endless possible applications. However, one should not lose sight of the fact that the results of its predictions would be limited by the assumptions on which its theory is based.

3.4. Parallelisation of the panel code

In order to accurately simulate added complexities such as additional components of the configuration, and the details of the wall support system, a capability to handle a large number of panels would be essential, a realistic aircraft configuration needs typically 5000-7000 panels to resolve flow complexities due to nacelle, pylon, sting, strut, tunnel walls, *etc.* On the UNIVAC system, apart from the problems posed by its slow processing speed, the larger number of panels posed additional problem due to the considerable demand on the I/O time needed to transfer the data from disk to memory and back. This bottleneck was adequately removed in the Flosolver MK3, a parallel processor based on five i-860 processors. Table 1 gives details of the times achieved on Flosolver for upto 6060 panels. Some improvement in the timings was brought about by parallelising of Gauss-Seidel iteration procedure (Sinha 1992). A recent comparison of the Flosolver Mk-3 (5 i-860 processors) with the HCL Magnum Supermini, for the NALLA-2 configuration, with 3906 panels is given in Table 2.

4. Future directions

As mentioned earlier in the introduction, special efforts should be made to develop a comprehensive indigenous panel code capable of handling multi-bodies and supersonic flows, with higher order accuracy. Many interesting applications are beginning to be made as a result of improved in-house computing platforms and civil aircraft projects at NAL. Specific mention may be made of the possibility for simulating wind tunnel wall interference for aerospace configurations and for the analysis of many surface transport systems where ground effect is important.

5. Conclusions

Many interesting and need based applications have demonstrated the utility of panel codes for data generation of complex aerospace configurations for which methods based on grid generation and higher-order approximations of the Navier-Stokes equations are yet to develop into routine application codes.

Acknowledgement

It is with deep gratitude that we acknowledge the support and encouragement received from Prof. R. Narasimha, Director, for sustaining and promoting the panel code activity in this Laboratory. We would also like to thank Dr. T.S. Prahlad, Project Director, Technology Development, ADA for the opportunity for application of our panel codes to their project.

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Table 1. Comparison of execution times on sequential and parallel machines.

Number of Panels	Time Taken (h:m:s)		
	Flosolver Mk2 Intel 80386/80387 4 nodes of 4 processors each	Flosolver Mk3 i860 Single Processor	UNIVAC
3050	09:22:40	01:50:00	CPU=12:51:33 I/O = 08:18:31
6060	44:14:22	06:30:00	not tried
6060	–	00:44:49 5 processors	not tried

Table 2. Execution times for complete NALLA-2 configuration (3906 panels).

Tasks	Magnum Multi-RISC	Flosolver Mk3.05
Velocities and influence co efficients	0:38:11	0:16:27
Matrix solution (G-S)	6:30:14 (Disk I/O)	0:08:16 (No Disk I/O)
Velocities and pressures	0:37:00	0:05:16
Total	7:45:25	0:29:59

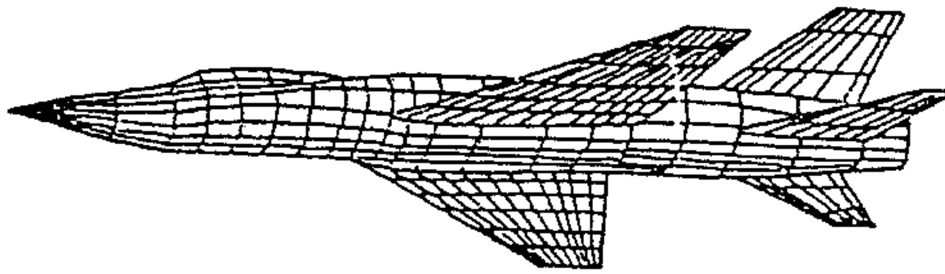


Figure 1. Wireframe of the first configuration studied using panel methods at NAL.

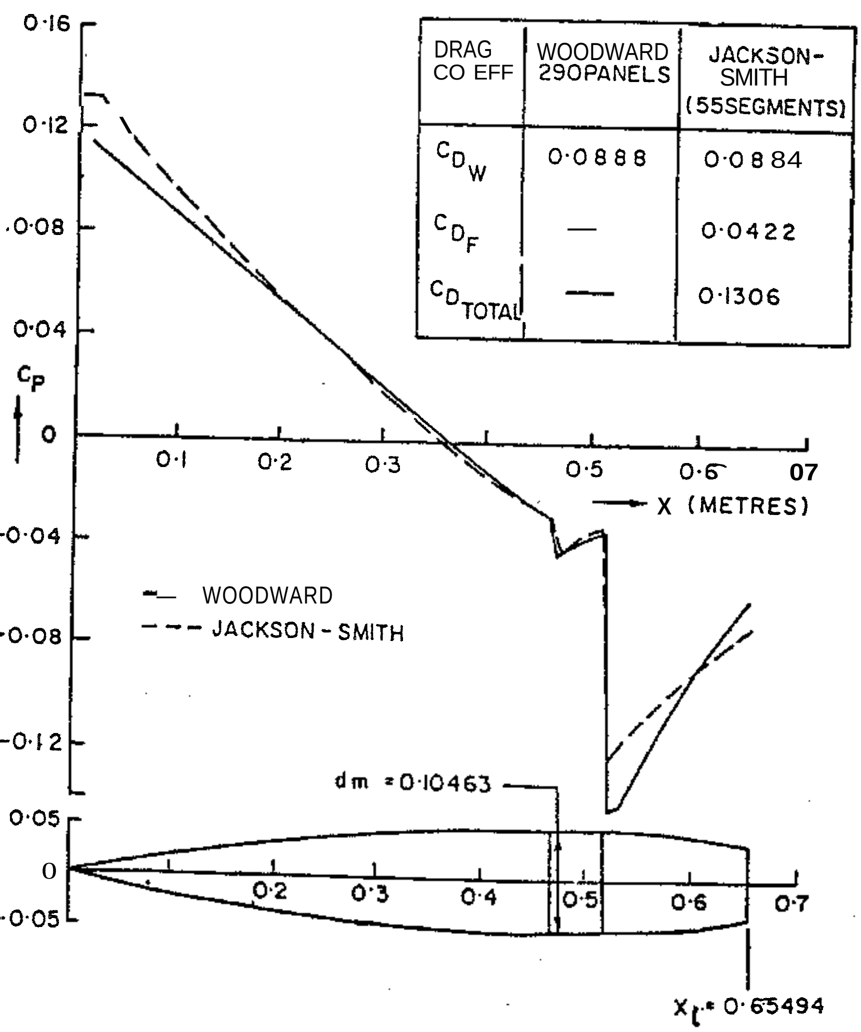


Figure 2. Computed pressure distribution on an axisymmetric body - computed using **Woodward's** panel code.

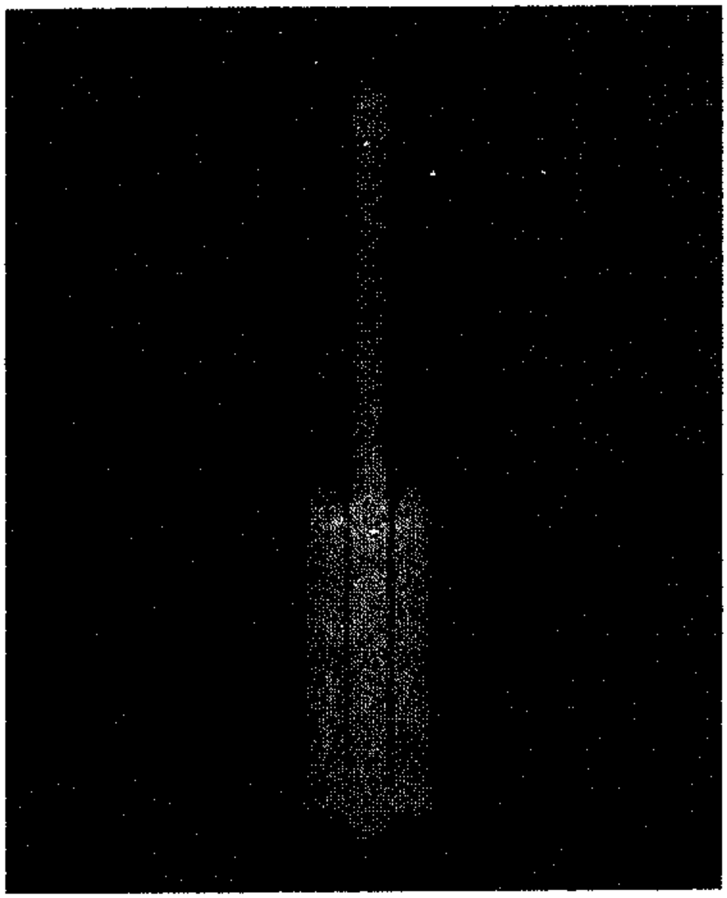
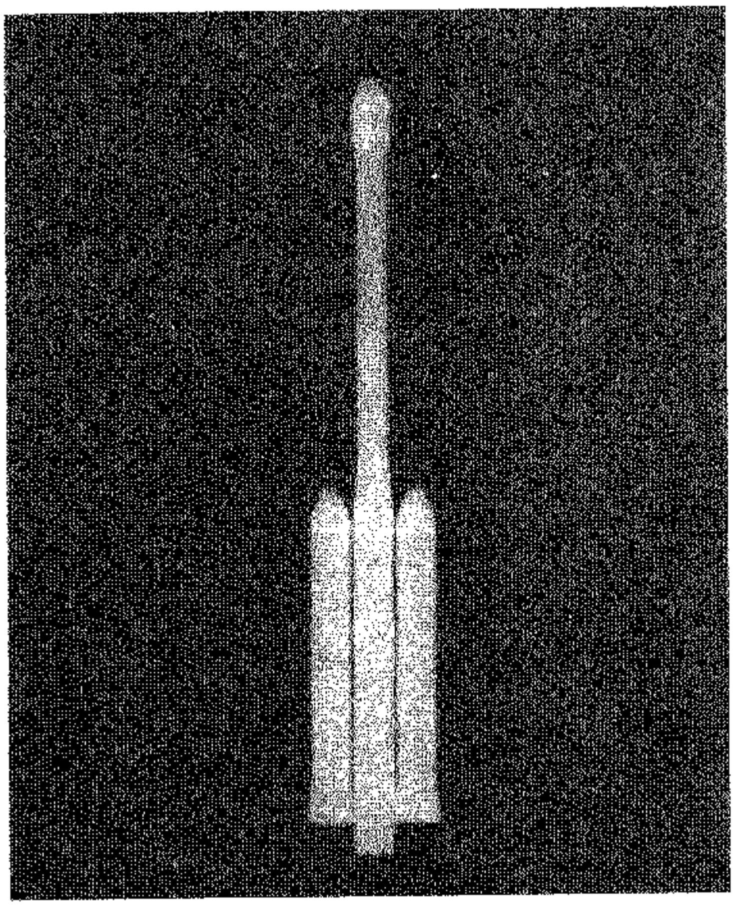


Figure 3. Computed surface pressure contours around a satellite launch vehicle with two strap-on boosters.



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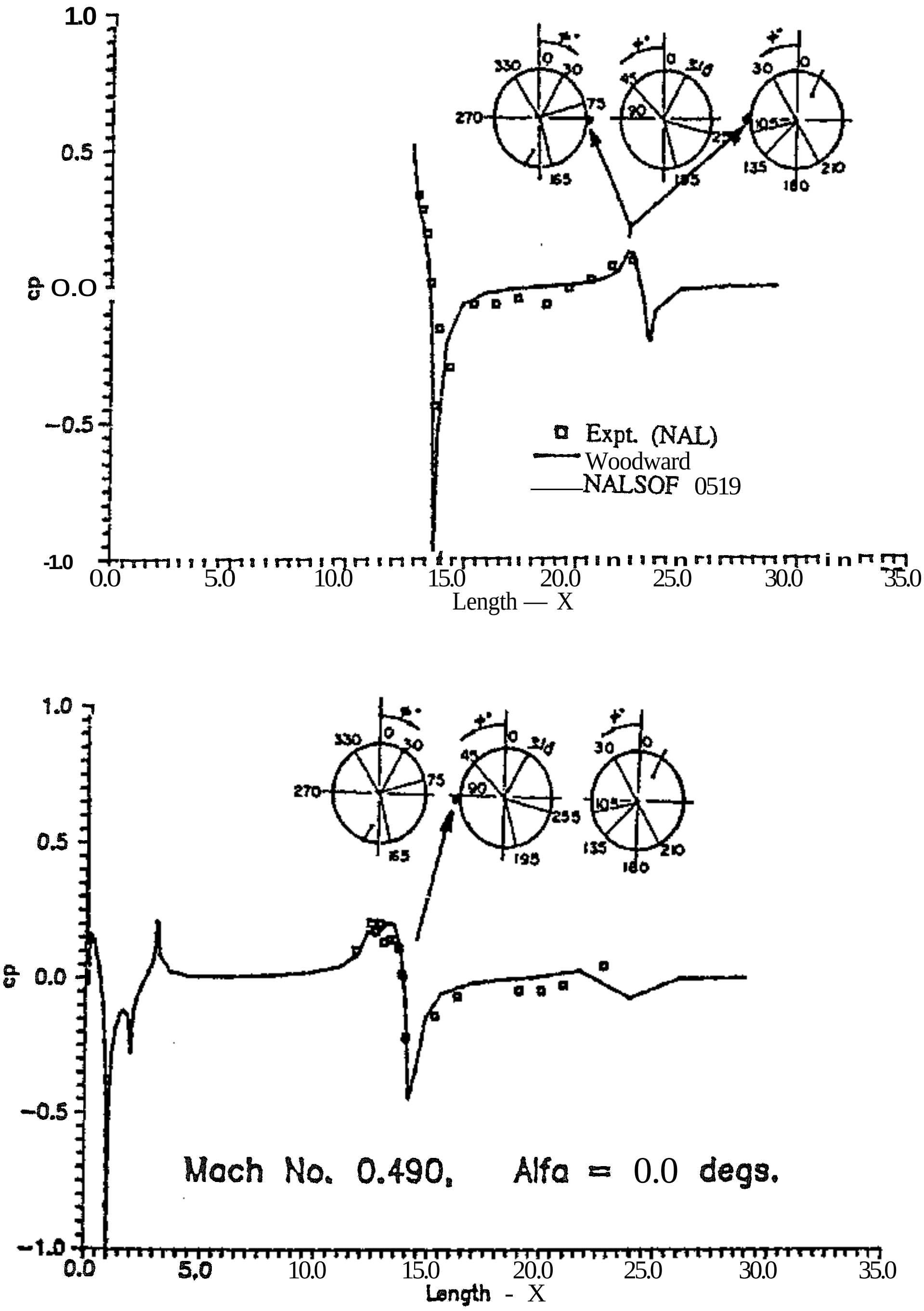
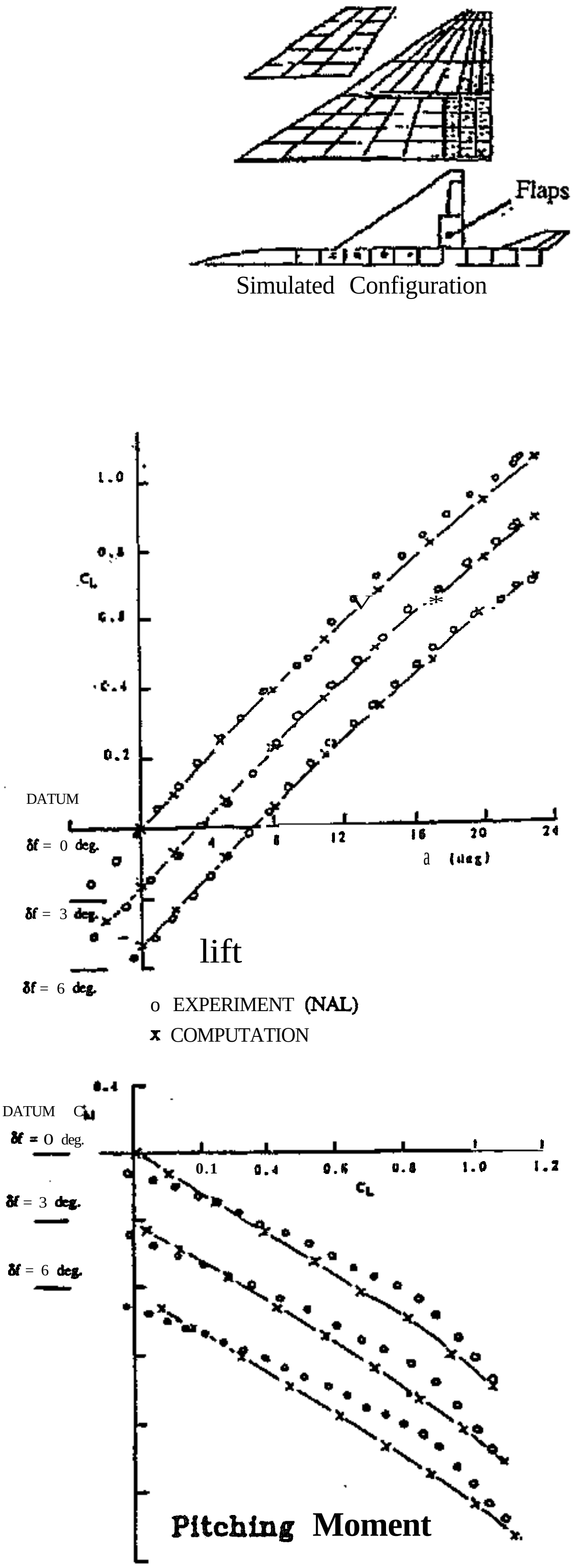


Figure 4. Axial variation of the computed surface pressure coefficient on the strap-on booster and main rocket engine - computed using Woodward's panel code.



Hgure 5. Aerodynamic coefficients computed using NALSOF 0509 panel code for a wing-body combination with flap deflections.

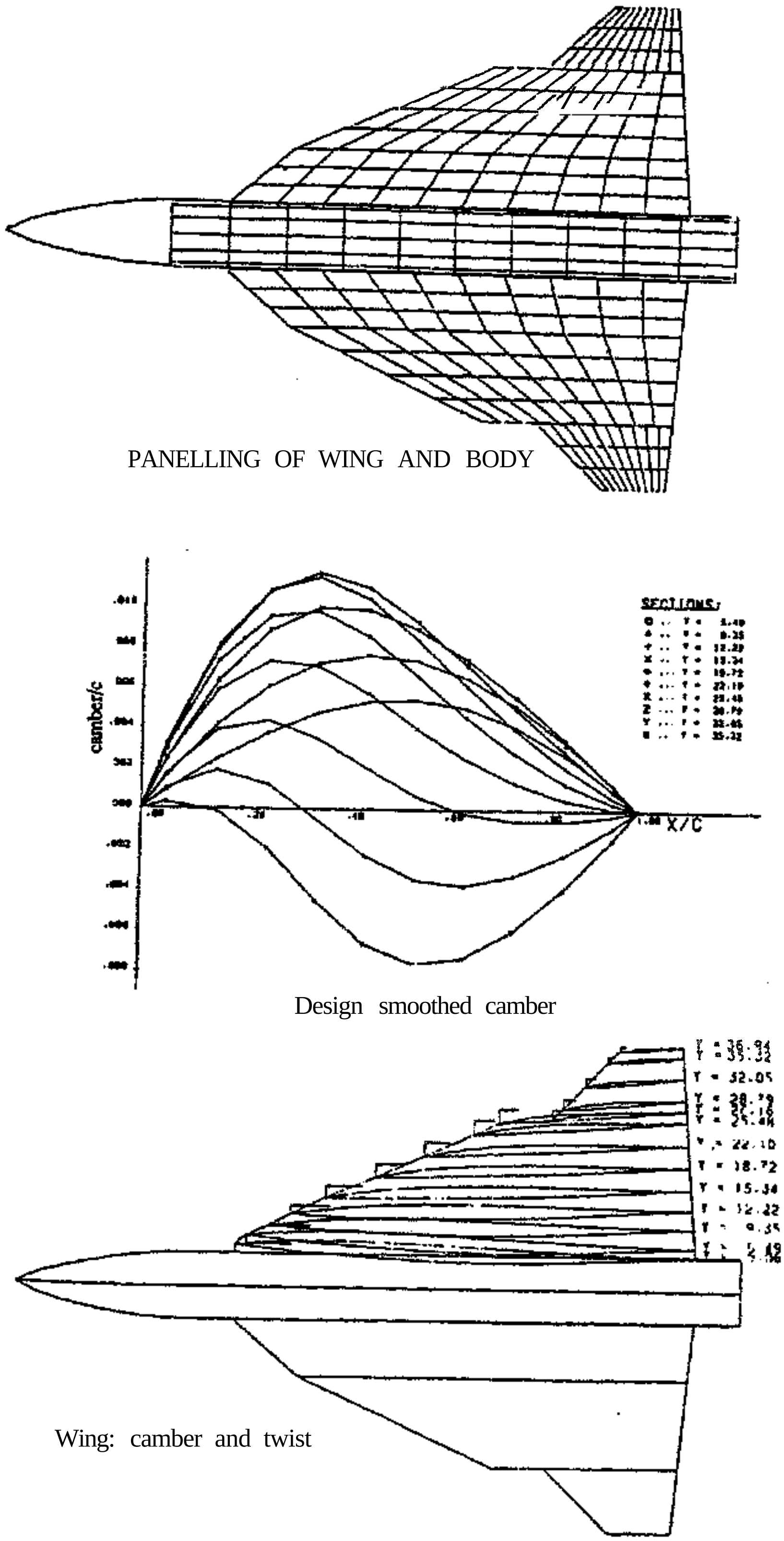


Figure 6. Design of twist and camber of a wing-body combination using NALSOF 0509 panel code.

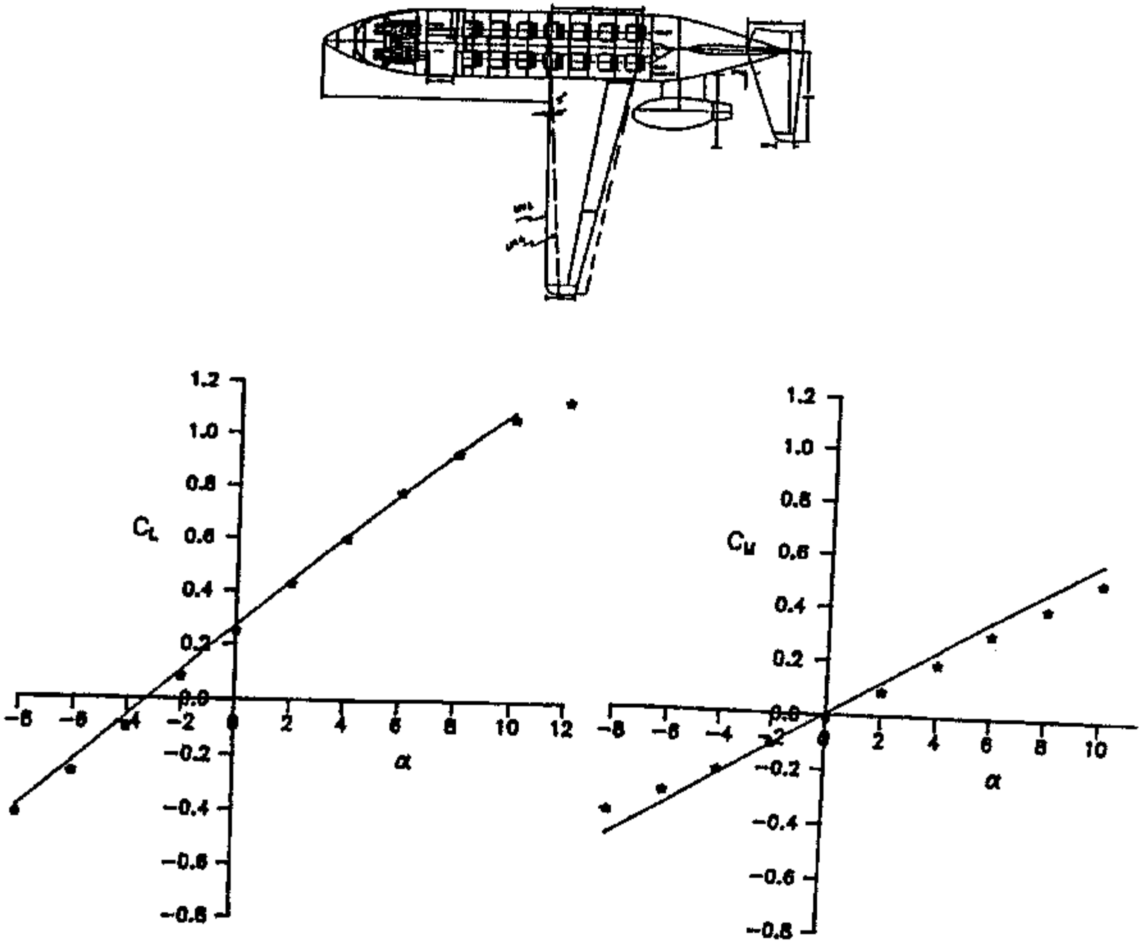


Figure 7. Variation of computed lift and pitching moment coefficients with angle of attack for a light transport aircraft - computed using NALSOF 0509 panel code.

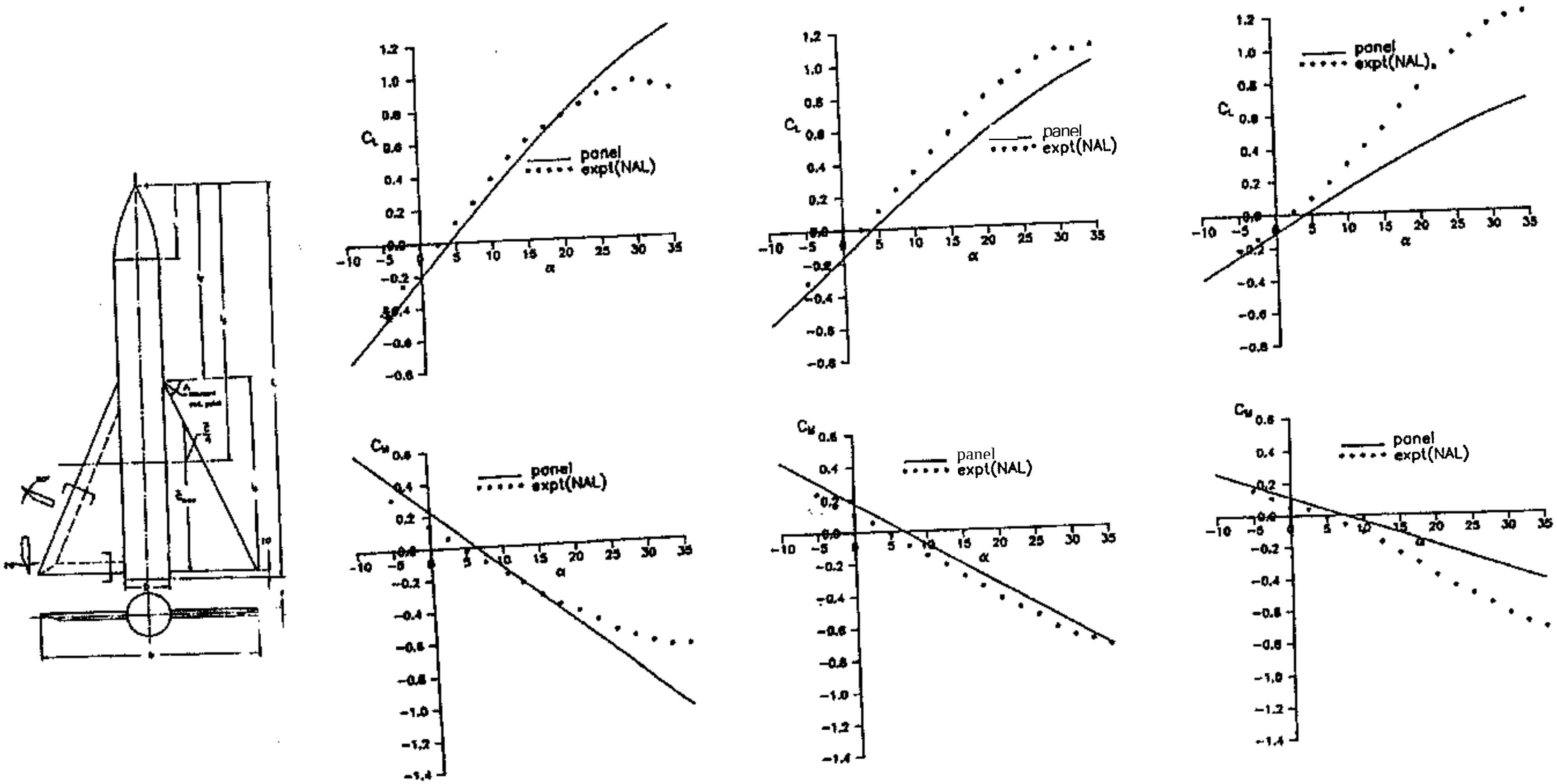
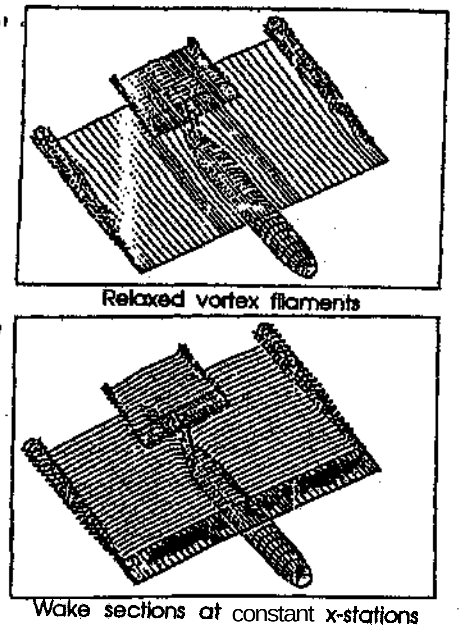
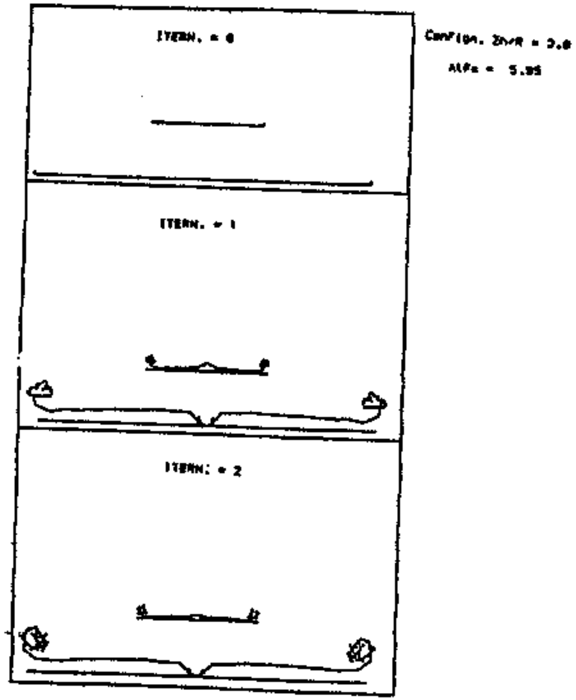


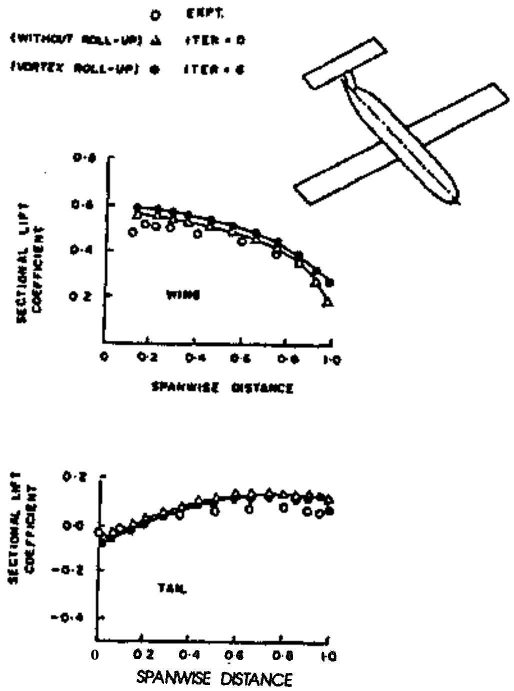
Figure 8. Variation of computed lift and pitching moment coefficients with angle of attack for a delta wing-body combination with different sweep angles - computed using NALSOF 0509 panel code.



(a) **Rolled-up** wake



(b) Sectional view of the rolled-up wake.



(c) **spanwise** load distribution

Figure 9. Application of the **NALSOF** 0519 panel code in the study of aircraft configurations with free relaxed wakes.

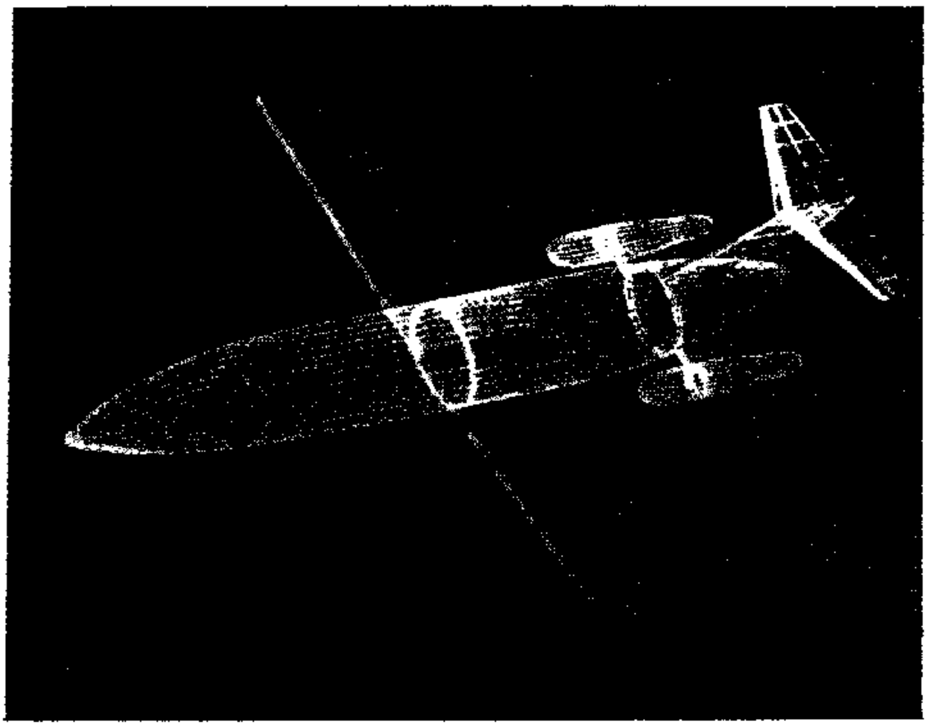


Figure 10. Wireframe of the Light Transport Aircraft (LTA).

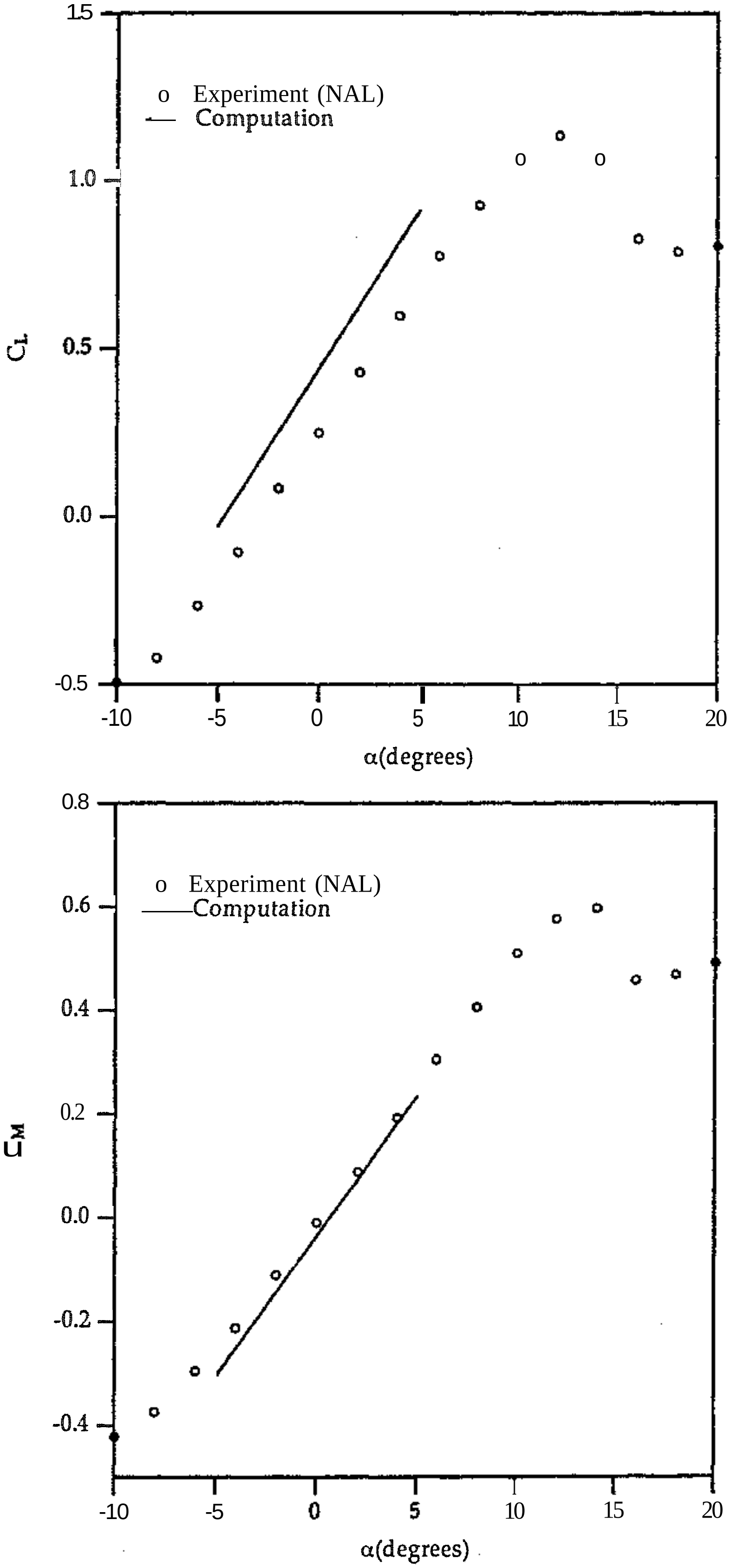


Figure 11. LTA aerodynamic coefficients computed using the NALSOF 0519 panel code.

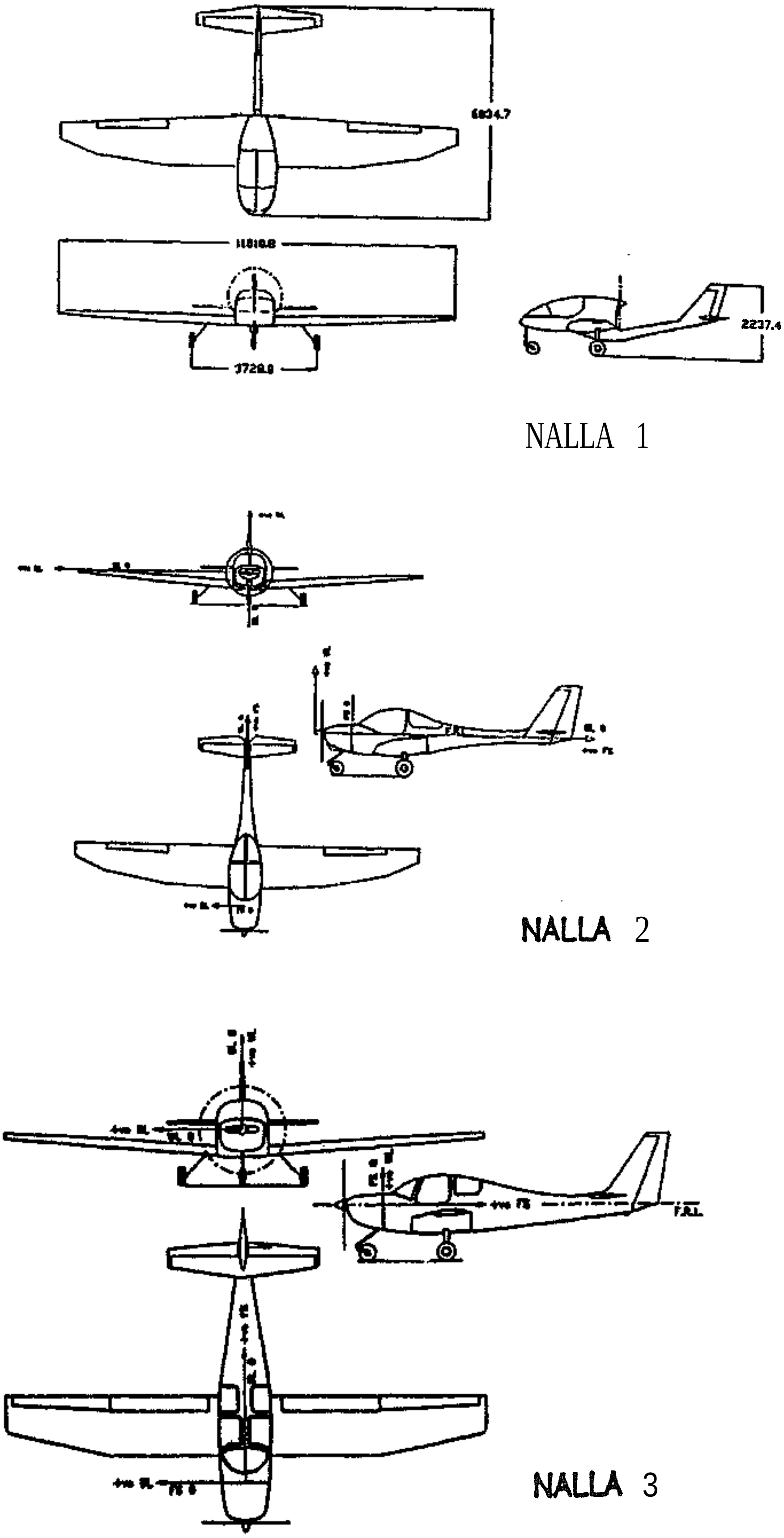


Figure 12. Different versions of **NAL's** Light Aircraft (NALLA) studied using the **NALSOF** 0519 panel code.

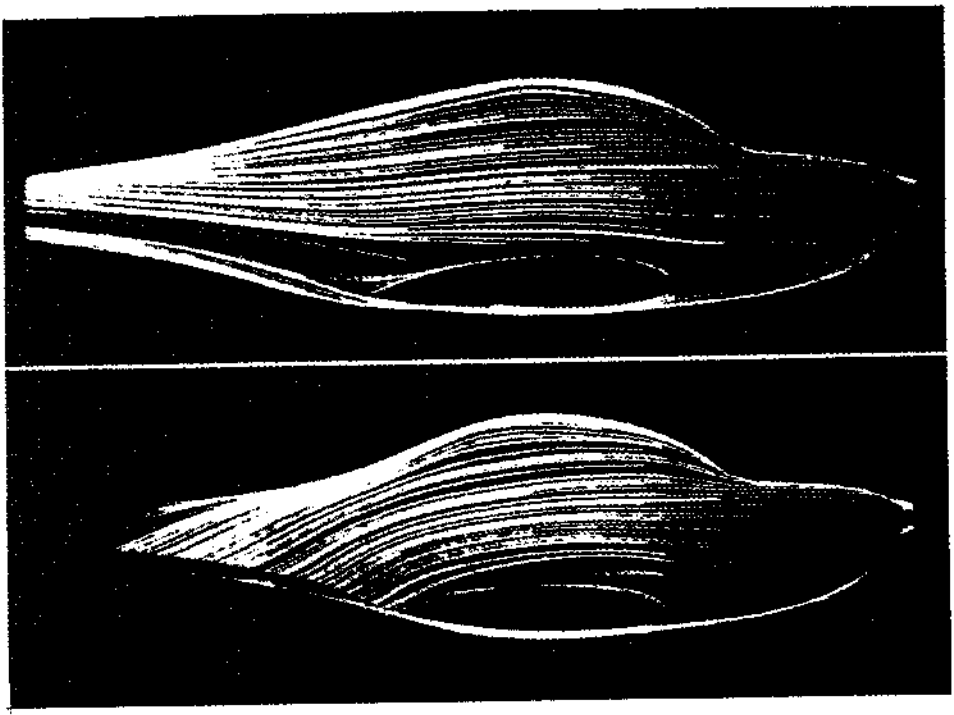


Figure 13. Use of a panel code in designing wing-body junction for proper flow management on the rear fuselage.

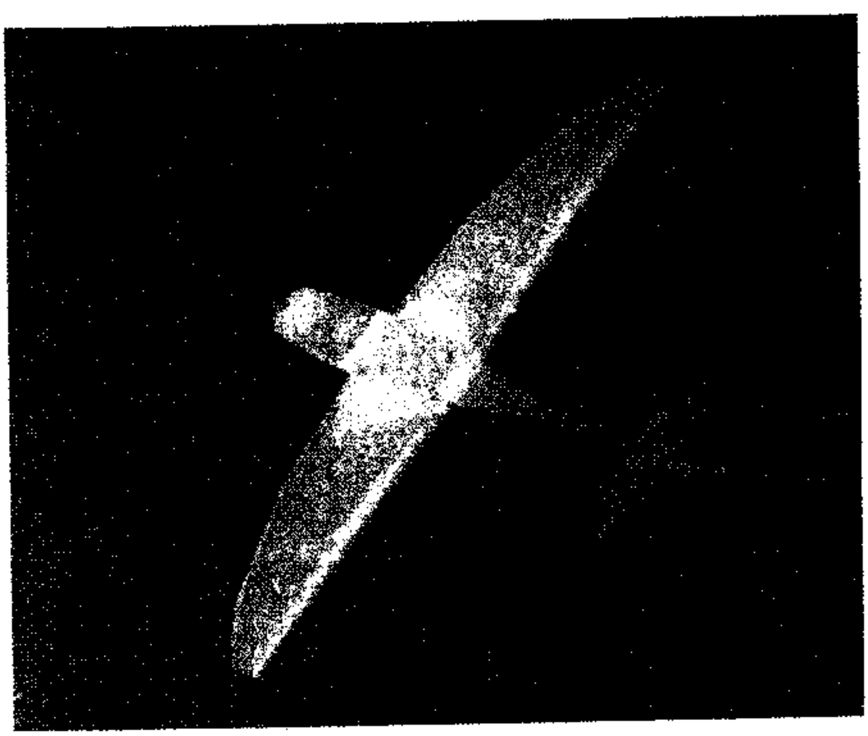


Figure 14. Computed surface pressure contours for NAL Light Aircraft (NALLA).

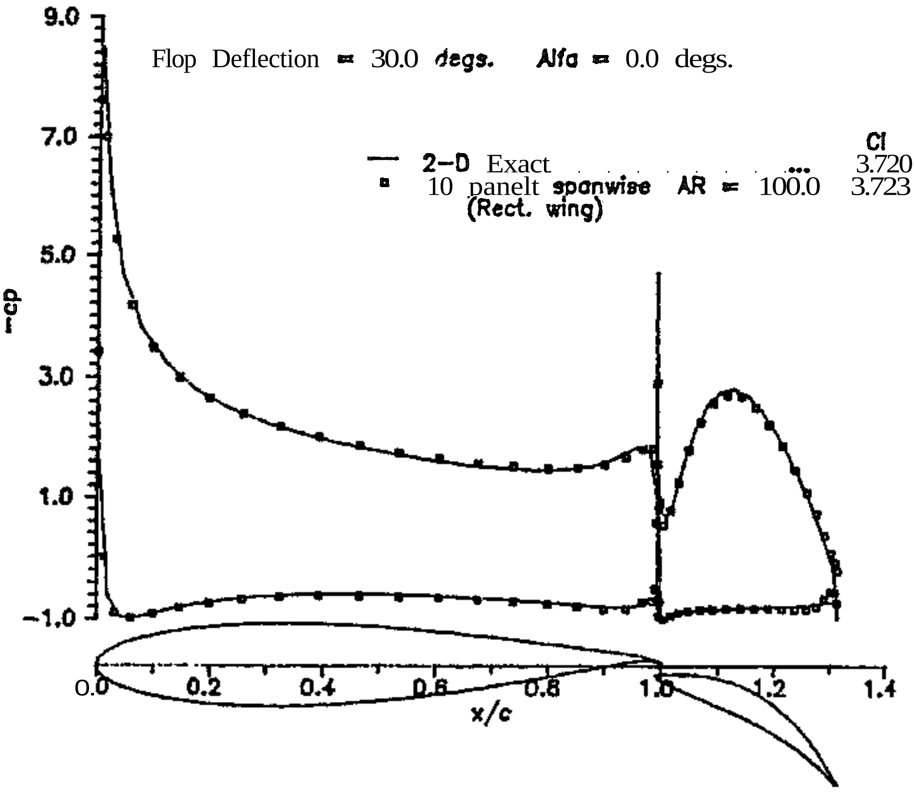


Figure 15. Pressure distribution around William's two-element airfoil computed using the NALSOF 0519 panel code.