THE FRANCO-GERMAN EXPERIMENTAL PROGRAM FOR THE EVALUATION OF A SUPERCRITICAL WING FOR A COMBAT AIRCRAFT APPLICATION (1)

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Abstract

The program has the purpose to investigate the practical applicability of supercritical wings to subsonic combat aircraft using the Franco-German Alpha Jet as a test vehicle. Specific points of interest are:

- 3-D effects on moderate aspect-ratio wings
- performance of a supercritical wing in a broad C_L-M-region
- effectiveness of maneuver flaps on a supercritical wing
- the behaviour beyond the buffet boundary and at the maneuver limit.

The paper first describes the theoretical and experimental work which preceded the flight test program. Following that, the time plan of the program is shown. Results of the first design cycle are presented as well as the resulting improvements in performance.

1. Introduction

After many attempts to push the drag rise and separation boundaries of airfoils a little bit beyond the critical Mach number, R.T. Whitcomb of NASA was the first to present airfoils with large supersonic regions which did not cause high drag and shock-induced boundary layer separation. (1,2) Since theoretical methods of calculation for mixed subsonic-supersonic flows around lifting round-nosed airfoils were lacking at that time, these first supercritical airfoils seem to have been developed by a combination of intuition and a great deal of wind tunnel work. The most obvious application of these new airfoils were transport aircraft with high subsonic cruise speed, for which either an increase of wing thickness, a decrease of wing sweep or an increase of cruise speed can be achieved. It was recognized at an early stage that the wind tunnel results needed confirmation by flight testing, mainly because the Reynolds number would have a stronger influence on the flow field than with conventional airfoils. Therefore, three flight demonstration programs were initiated by NASA, using a T2-C, a F-8 and a F-111 as test vehicles, with first flights in 1969, 1971 and 1973, respectively. In spite of the fact that combat aircraft were used as test vehicles, at least in the first two cases the application to transport aircraft was the goal of the investigations. The YC-15 prototype seems to be the first actual application of the supercritical wing, but almost all new civil transport projects employ it too.

When experimental results showed that it was possible to design supercritical wing sections also having good off-design performance, the question of the potential benefit to subsonic combat aircraft arose. In this case the need for flight test confirmation is even more urgent, because

- the smaller aspect ratio wings of combat aircraft lead to stronger three-dimensional effects for which theoretical methods are less developed,
- the performance in a large M-C_L-area is important where the theoretical analysis of the flow is more difficult and wind tunnel results are less reliable,
- the dynamic effects determining the limits for aggressive and evasive maneuvers can be predicted from wind tunnel results neither quantitatively nor qualitatively and
- the effectiveness of maneuver flaps on a supercritical wing is an additional point of interest.

These considerations led the German Ministry of Defense (BMVg) to the decision to sponsor a program comprising the design, manufacturing and flight testing of a supercritical wing with maneuver flaps. DORNIER GmbH of Friedrichshafen was selected as prime contractor and VFW-Fokker of Bremen as subcontractor who were responsible in the first design cycle for the design of the maneuver flaps and for the manufacturing of all wind tunnel models. The program was started in July, 1974. In May, 1975, ONERA joined the program. Their main contribution is to carry out two- and three-dimensional wind tunnel tests in their transonic facilities at Modane, and also to participate in the aerodynamic design and in the evaluation of the flight tests.

The Dassault-Breguet/Dornier Alpha Jet

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(1) The German part of this work is sponsored by the German Ministry of Defense within its KEL program

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was selected as a test vehicle. This aircraft which made its first flight in 1973 will enter service with the French and German Air Forces as an advanced trainer and CAS aircraft, respectively. The selection of this aircraft as test vehicle offers the following advantages:

- it is representative of the class of combat aircraft for which the largest benefit from supercritical wing technology is expected
- wind tunnel models and prototypes with complete flight test equipment are available
- the standard wing can easily be exchanged for the supercritical wing, because it is simply bolted to the central fuselage frame and because the the landing gear is connected to the fuselage.

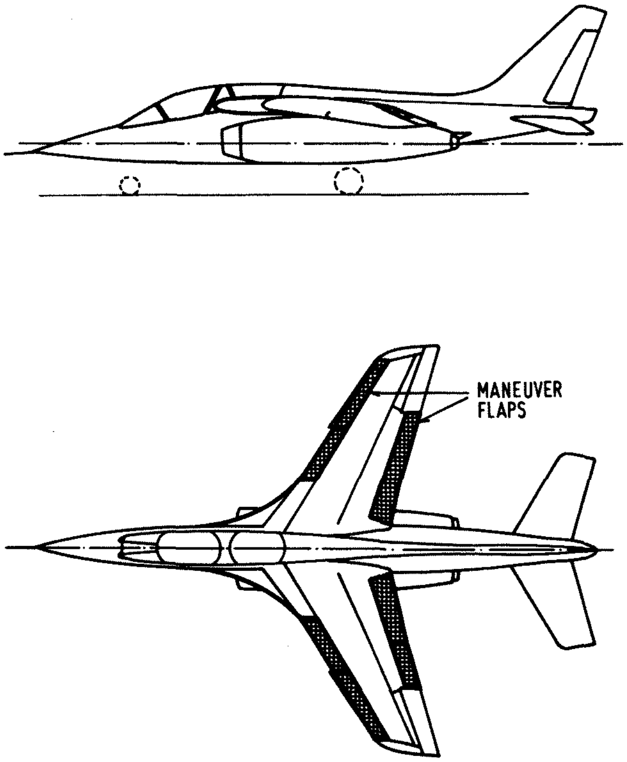


Fig. 1 Alpha Jet with supercritical wing

Fig. 1 shows the Alpha Jet equipped with the supercritical wing. It will differ from the production aircraft in three respects:

- it has thicker, supercritical wing sections
- it has wing-fuselage blending with curved leading edge
- the wing is equipped with maneuver flaps at the trailing edge and at the leading edge

There will be no modification to the fuselage and empennage, either aerodynamically or structurally.

2. Preliminary Work

The importance of the supercritical wing for both military and civil aircraft was recognized in Europe several years ago. However, one could not afford the large amount of wind tunnel work which probably has been done in the U.S., and their results were not available in Europe. Therefore, the availability of rational theoretical methods for calculating transonic viscous flows was considered essential. Such methods and corresponding computer programs have been developed at DORNIER GmbH and ONERA systematically since 1972.

		DIRECT	INVERSE	WITH B.L.
2-D	WING SECTIONS	1972	1973/74	1973/74
3-D	WINGS	1973	1975	1975
	WING + INFINITE BODY	1974		
	WING + FINITE BODY	1976		

Common features of all inviscid flow methods:

- **Transonic small pertubation equation**
- **Computation in the physical space**
- **Cartesian coordinates**
- **far field boundary conditions**
- **wing boundary condition on plane $z = 0$**

Fig. 2 theoretical methods developed at Dornier

The work done at DORNIER is summarized in Fig. 2. The starting point was to write a computer program for the method of Krupp (3) for 2-D potential flow. It was preferred to more exact methods using the full potential equation or using coordinate transformations because it could easily be extended to 3-D flows. In the inverse methods, following Langley (4) the pressure boundary condition is transformed into a surface slope boundary condition by means of the condition of irrotational flow. In the 3-D boundary layer calculations an integral method based on the method of P.D. Smith (5) is used. Such a method has also been developed at ONERA by Michel and Cousteix (6).The latest state of development of the potential flow methods is described in the paper by Schmidt and Hedman (7) presented at this Congress.

Since theoretical methods of calculation are but one component in the design of practical wing shapes, it was considered essential to collect design experience as early as possible. Therefore, as a first step three sections for transport aircraft with t/c = 0.12 have been designed and tested (8), one of which is compared in Fig. 3 with a section representing the state of the art of the A 300-B. These sections were intended as a starting point for 3-D design work with the goal of reducing the sweep angle compared to the A 300-B standard while keeping t/c constant. Fig. 3 shows a considerable improvement in both drag rise and buffet boundaries which allows a reduction of mid-chord sweep from 25° to 18° for the given cruise condition. Based on this section, two wing-body-combinations were designed and tested as summarized in Fig. 4. These wings achieved similar drag rise boundaries as the A 300-B wing while having 7 degrees less sweep and greater wing root thickness.

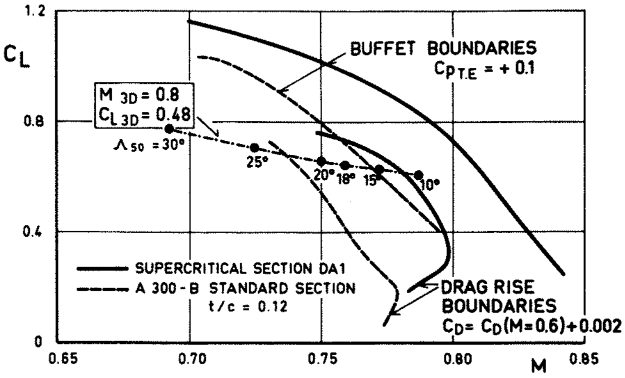
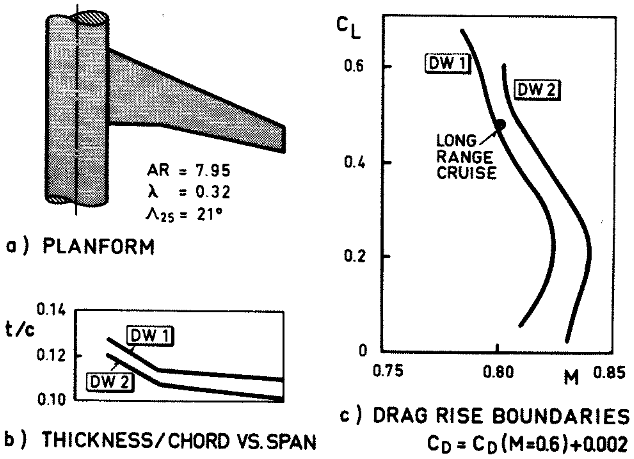


Fig. 3 wing section for civil transport aircraft



a) PLANFORM

b) THICKNESS/CHORD VS. SPAN

c) DRAG RISE BOUNDARIES $C_D = C_D(M=0.6)+0.002$

Fig. 4 swept wing for civil transport aircraft

3. Working Plan of the Flight Evaluation Program

It was felt that these encouraging results formed a good basis for the launching of a flight evaluation program for a combat aircraft. The program was started in July 1974, and the time plan is shown in Fig. 5.

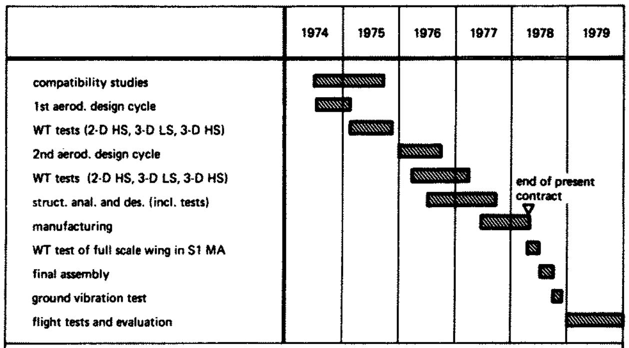


Fig. 5 time plan of the flight evaluation program

The compatibility studies had the purpose of investigating the feasibility of simply exchanging the wing without any modifications of the fuselage and tail surfaces, and to define flight envelope limitations resulting from this fact.

The first aerodynamic design cycle started with the selection of the main design point, then proceeded with the design of a 2-D wing section which formed the basis of the 3-D wing design. It also comprised the design of the leading edge and trailing edge maneuver flaps. 2-D high speed wind tunnel tests were carried out in the Göttingen transonic tunnel of DFVLR and later, after ONERA joined the program, in their S3 tunnel at Modane. The 3-D wing design was tested in the transonic regime using a 1/10 scale model in the S2 tunnel of ONERA at Modane and with a 1/5 scale model in the low speed tunnel of DFVLR at Göttingen. Following evaluation of these tests, a second aerodynamic design cycle was started and the resulting wing shape will be tested again in the same tunnels.

Following the final definition of the wing geometry the structural analysis and design will be completed as well as the manufacturing of the wing. Before the assembly of the wing to the aircraft, it is planned to test one full scale half wing in the S1 wind tunnel of ONERA at Modane at Mach numbers up to about 0.9. These tests will include balance measurements, wake surveys, surface pressures and buffet measurements using accelerometers and transient pressure pick-ups. The comparison of these results with those obtained on the small scale models will provide information on Reynolds number effects under more exactly defined conditions than is possible in flight tests.

Thereafter, the wing will be installed on the aircraft and a ground vibration test of the complete aircraft will be made to provide input data for a final flutter analysis. After that, the flight tests will begin, which will consist of two parts. The first part which will be carried out by the DORNIER flight test department with assistance by ONERA will have the following purpose:

- adjustment of the pitch control system to the pitching moment and downwash characteristics of the new wing. This system includes a nonlinear stick-to-elevator transmission and an artifical feel system dependent on the dynamic pressure. It partially compensates for the trim changes due to speed changes and due to flap extension.
- clearing of the flight envelope for several maneuver flap positions. During these tests,structural loads and vibrations will be monitored by strain gages and accelerometers
- to give a first impression of the achieved performance and flying qualities, maximum level speeds, maximum steady load factors and maneuver limits will be determined at a few altitudes and (where applicable) Mach numbers. Also stalling tests will be made at different altitudes and deceleration rates.

In the second part of the flight tests which will be carried out in cooperation by DORNIER, ONERA and the flight test center of the German Air Force, the complete performance data and drag polars will be established.These tests will permit a comparison of theoretical results, wind tunnel data on small scale models and on the full scale wing, and flight test results.

The test of the full scale wing in the S1 tunnel, the assembly of the wing and the aircraft and the flight tests are not covered by the present contract and detailed planning has not yet been made for these parts of the program. The reason is that the date of the availability of the aircraft is still uncertain, depending on the progress of the Alpha Jet flight test program.

4. Results of the compatibility studies

It is well known that the supercritical wing design can be used either to reduce the sweep angle, to increase the wing thickness or to increase the drag rise Mach number. The first possibility was ruled out because the requirement to use the original horizontal tail did not allow any changes in wing planform except minor changes like a curved inboard leading edge. To exploit all the potential of the supercritical wing to increase drag rise Mach number would make no sense because the maximum level speed would become thrust limited. Therefore it was chosen to increase t/c, which varies over the wing span between 8.5 and 10.2 per-cent for the original Alpha Jet wing, by about 2 per-cent chord. This would keep M_D at low C_L about constant while increasing it at high C_L.

The increased wing thickness made it possible to use an original Alpha Jet wing box and cover it with aluminum honeycomb which is then milled to the correct shape as

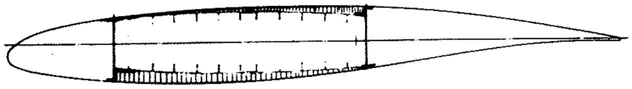


Fig. 6 wing box covered with aluminum honeycomb

shown in Fig. 6. The first 3-D wing design showed that this posed no intolerable restriction to wing twist. Thus the structural strength of the airframe is the same as on the original Alpha Jet while the pitching moment of the rear loaded wing is much greater, and even more so with maneuver flaps extended. Fig. 7 shows the estimated C_{MO} of the clean wing body combination and the maximum C_{MO} which is limited by horizontal tail power at low speeds and by structural strength at higher speeds.

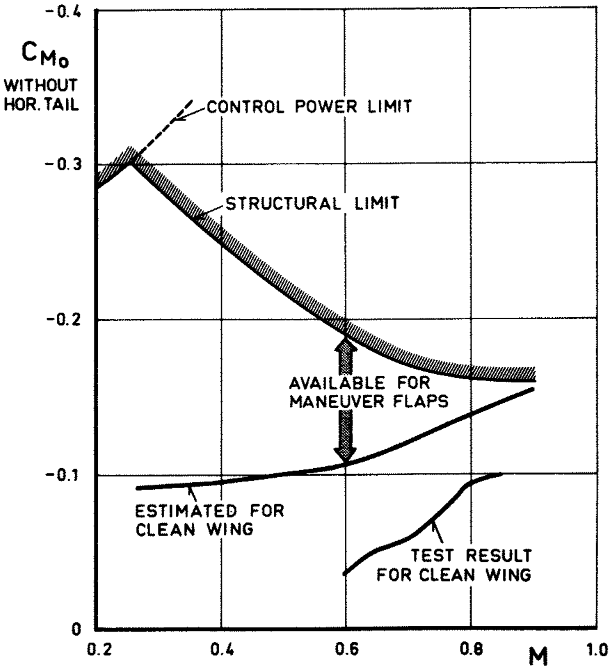


Fig. 7 pitching moment limits for SCW and maneuver flaps c.g. position 20 per cent M.A.C.

The C_{MO} increment available for the maneuver flaps decreases with Mach number so that the maximum flap angle must accordingly be decreased. Fig. 8 shows the resulting flight envelope restriction in terms of the altitude below which the maximum load factor tolerable by the wing would lead to too large rear fuselage bending moments. This restriction does not affect the demonstration of the aerodynamic performance of the wing because the altitude above which C_{Lmax} may be flown is still determined by the wing structural strength rather than the fuselage strength

Except for the increase of C_{MO}, only minor changes of the aerodynamic derivatives were expected. An analysis of the longitudinal and lateral stability showed that a possible forward shift of the neutral point due to the curved wing leading edge and the slats would reduce the aft c.g. limit when flying with external stores which possibly will be included in the flight test program at a later stage. An increase of rolling moment due to yaw due to the curved wing leading edge causes some decrease in dutch roll damping of the unaugmented airplane which is, however, of no consequence because the aircraft is equipped with a yaw damper. An investigation of longitudinal and lateral dynamics in the extended C_L-M-flight envelope of the supercritical wing, including roll-to-pitch coupling during rapid roll maneuvers, showed no particular problems.

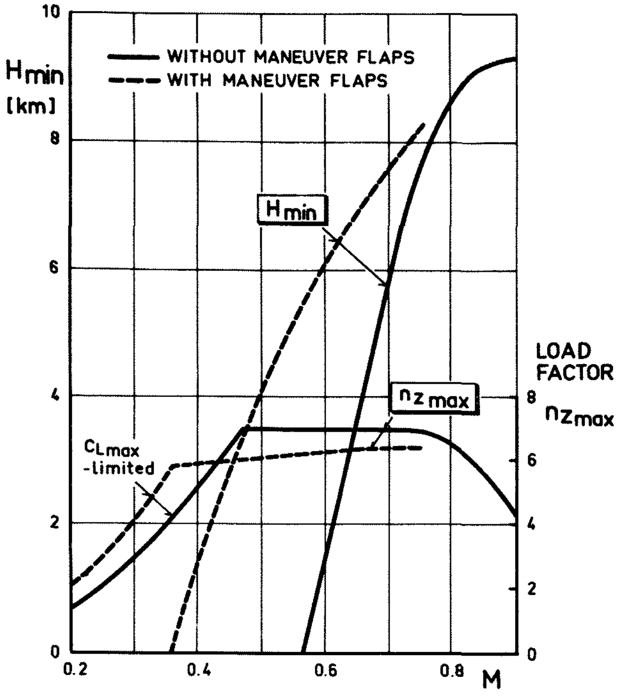


Fig. 8 flight envelope restrictions

$n_{z_{max}}$: max. values tolerable by the wing structure

H_{min} : above this altitude $n_{z_{max}}$ is tolerable by the rear fuselage structure.

A flutter analysis showed that the increased wing mass due to the honeycomb covering has negligible influence on the flutter characteristics of the clean wing. With trailing edge flaps extended, sufficient damping is obtained in the whole flight envelope only with a rather stiff flap-to-wing connection with an uncoupled natural frequency of at least 40 cps, which can, however, be achieved by proper design. A flutter analysis with slats extended has yet to be made. The complete flutter analysis will be repeated later based on the results of the ground vibration test.

The structural design of the wing is made as simple as possible in order to keep the program cost low. The use of an original Alpha Jet wing box was already mentioned. Thus the possible saving in wing weight due to the increased thickness cannot be demonstrated in this program. Furthermore, no wing fuel tanks are used. The maneuver flaps have no drive mechanism but are fixed in their various positions on the ground.

5. Results of the first aerodynamic design cycle

With an aspect ratio of 4.8, the aerodynamic performance of the wing to be designed is largely determined by the section shape. Therefore the starting point of the aerodynamic work was the design of a basic wing section. If this is assumed to be similar to a section normal to the mid-chord line of the 3-D wing at midspan, it would have a t/c of about 0.12 compared to about 0.10 for the original Alpha Jet wing. Fig. 9 shows the drag rise boundaries of a RAE 103 section with t/c = 0.10, on which the Alpha Jet wing design is based and of the DA 1 supercritical section for a civil transport aircraft which was mentioned earlier in this paper (Fig.3). Since a combat aircraft operates at low C_L during high speed, low level flight, an increase of M_D at low C_L was required which necessitated a decrease in rear camber. The resulting decrease of pitching moment would also alleviate the structural problems

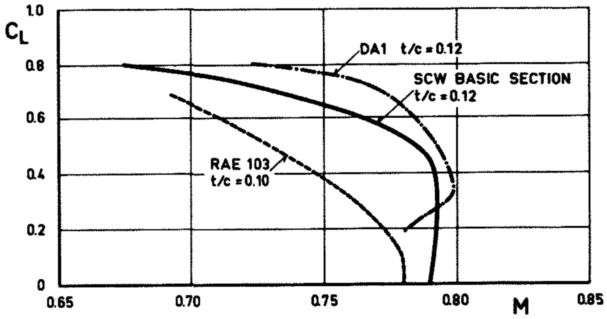
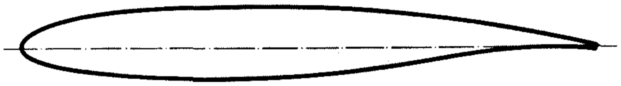


Fig. 9 drag rise boundary of wing sections

$C_D = C_D$ (M=0.6) + 0.002



max. thickness	t/c = 0.1207
max. thickness position	x/c = 0.3600
T.E. thickness	0.5 per cent of chord
L.E. radius	1.6 per cent of chord

Fig. 10 SCW basic section shape

mentioned above. On the other hand, some decrease of M_D at high C_L had to be accepted. Thus a target drag rise boundary was defined which was very similar to the actually achieved one which is shown in the figure. Fig.10 shows the section shape and Fig. 11 shows calculated and measured pressure distributions at the main design point. The difference of angle of attack corresponds to the wind tunnel wall correction. The Garabedian-Korn method gives a slightly better agreement with the experimental results than the Murman-Krupp method. In both cases the boundary layer is taken into account. The comparison of the drag rise boundaries shown above and of the buffet boundaries shown in Fig. 12 demonstrates that the improvement of performance due to supercritical wing sections is not at all limited to a narrow region near the design point.

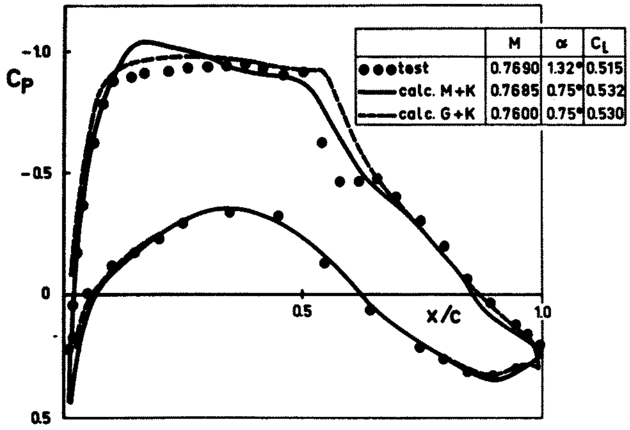


Fig. 11 pressure distribution of basic section at the design condition

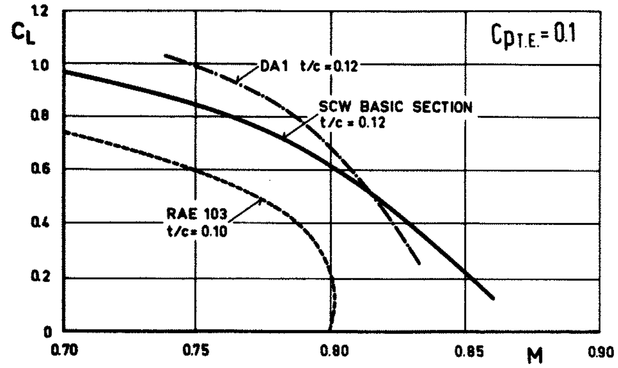


Fig. 12 buffet boundaries of wing sections

The maneuver flaps were also first designed for and tested on the 2-D model. The design had to rely largely upon experience with low speed high lift devices and incompressible flow calculations because no theoretical methods for transonic flow past multi-element airfoils were available at that time. One such method which has recently been developed is presented at this congress by B. Arlinger (9). Fig. 13 shows the resulting shapes of the leading edge and trailing edge devices. Because slat 1 has poor performance at high Mach numbers, slat 2 was later designed by ONERA which removes the sharp corner and is much thinner. Recent tests showed much better results, but so far it has not been tested in combination with the T.E. flap nor on the 3-D model. Fig. 14 compares the lift curves of the 2-D section with both slats and without slat

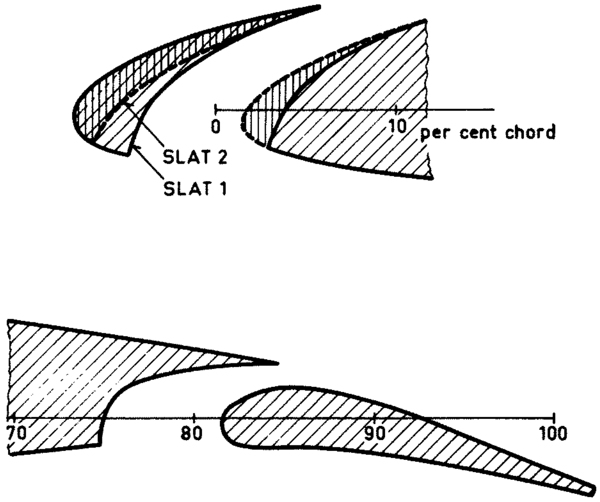


Fig. 13 maneuver flaps tested on 2-D model

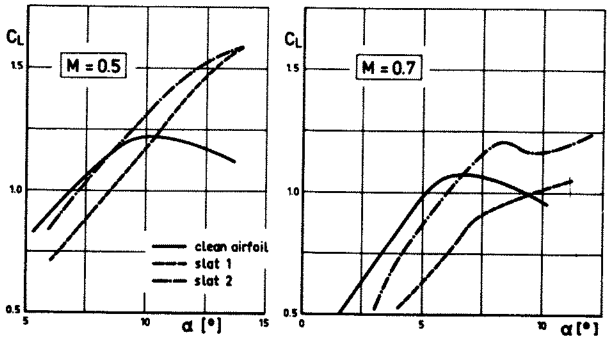


Fig. 14 2-D lift curves with two different slat shapes

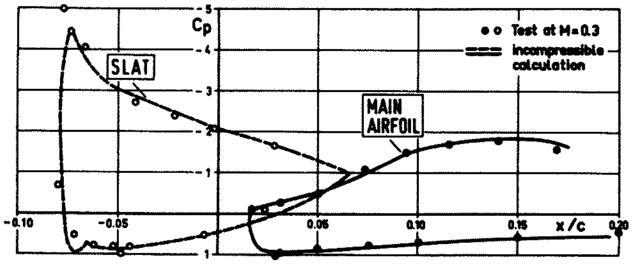


Fig. 15 pressure distribution on 2-D airfoil with slat 2 at two Mach numbers. While at M = 0.5 both slats are effective, at M = 0.7 only slat 2 gives an increase of $C_{L_{max}}$ over the clean airfoil. Fig. 15 shows a good agreement between theoretical inviscid incompressible pressure distribution and experimental results at M = 0.3 on the airfoil with slat 2. This indicates the absence of flow separation for this slat shape. The rounded shape of this slat leads to a small gap on the lower surface in the retracted position which results in a small drag increase corresponding to about 3 knots of maximum level speed. The flap chord was limited to 25 per-cent and the fixed wing trailing edge position to 85 per-cent wing chord in order to keep the pitching moment small. Fig. 16 presents the increase of buffet boundary due to the maneuver flaps in various positions. It shows that the T.E. flap is very effective up to high Mach numbers while slat 1 gives an additional improvement only at moderate Mach numbers. On the 3-D wing, the slat occupies the whole span from the end of the curved part of the leading edge to the wing tip. The flap has the same span-wise extent as the landing flaps of the original Alpha Jet wing in order to keep the same aileron span.

The 3-D wing shape was defined with the help of 3-D transonic calculations with the goal to obtain pressure distributions similar to those of the basic section over a large part of the span.

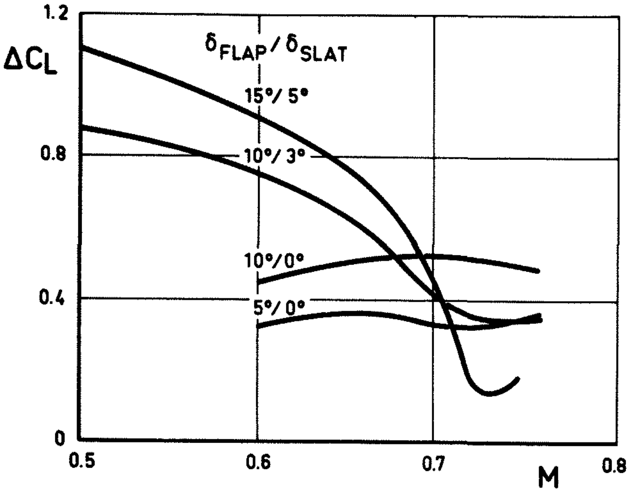


Fig. 16 increase of buffet boundary due to maneuver flaps, 2-D test (slat 1)

To achieve this, a large variation of section shape over the span is necessary. On the outboard wing the rear loading was reduced in order to ensure sufficient aileron power at high Mach numbers. The wing shape is defined by four sections between which the surface is generated by linear lofting on the outboard wing and by curved lofting on the inboard wing.

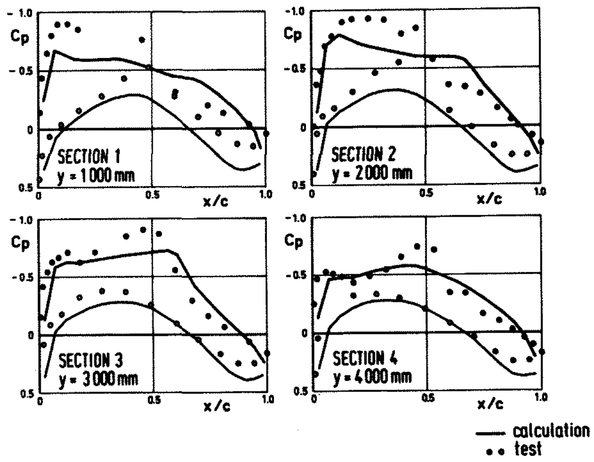


Fig. 17 theoretical and experimental pressure distributions at M=0.835, $\alpha = 2^{\circ}$, Re=$2.5 \cdot 10^{6}$

Fig. 17 compares theoretical and experimental pressure distributions at the design condition at four span-wise stations. The agreement is poor especially near the wing root and the wing tip. Other comparisons for wing body combinations of simpler shape have shown better agreement. One such comparison is described in the paper by Schmidt and Hedman (7) presented at this congress. The reason for the poor agreement in this case seems to be the curved leading edge, which necessitates a very large number of mesh points, the complicated shape of the fuselage cross section, which is too coarsely represented in the calculation, and the strong thickness taper of the wing near the root, which necessitates the use of the exact boundary condition and the inclusion of additional terms in the transonic small perturbation equation. Work to improve the computer programs in this direction is under way. Especially, ONERA is developing a program based on the full potential equation. In addition to the wing with the curved inboard leading edge, a second wing with a straight leading edge was tested, the outboard portions of both wings having identical shape. In Fig. 18 the drag rise boundaries of both wings are compared to that of the Alpha Jet.

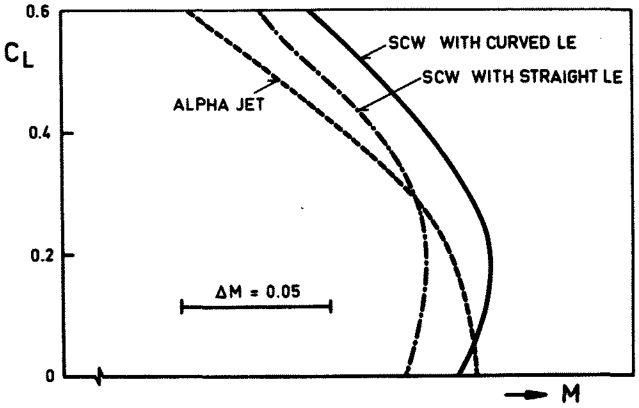


Fig. 18 comparison of drag rise boundaries $dC_D/dM = 0.1$

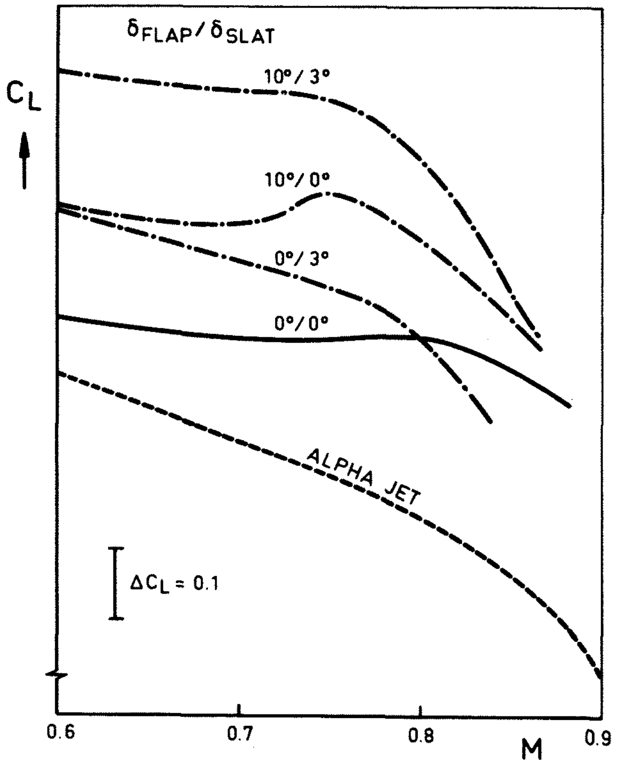


Fig. 19 comparison of buffet boundaries

The improved area distribution due to the curved leading edge increases M_D by about 0.02 over a large C_L range. With this wing, the goal to get about the same M_D at low C_L and increased M_D at high C_L is achieved. It has to be kept in mind that the tickness of the SCW is greater than that of the Alpha Jet wing by 20 per-cent. Fig. 19 shows a great increase of buffet C_L compared to the Alpha Jet, especially at the high end of the Mach number range. An additional increase is obtained from the maneuver flaps. While the T.E. flap is very effective, further improvement is certainly possible with the slat as mentioned above in connection with the 2-D results. The buffet boundaries shown are determined from wing root strain gages. An alternative method using transient pressure measurements at several points on the wing surface is being developed at ONERA. Fig. 20 shows good agreement of buffet boundaries determined by the two methods. It is expected that with the second method it will be possible to determine buffet intensity beyond the buffet onset from wind tunnel measurements.

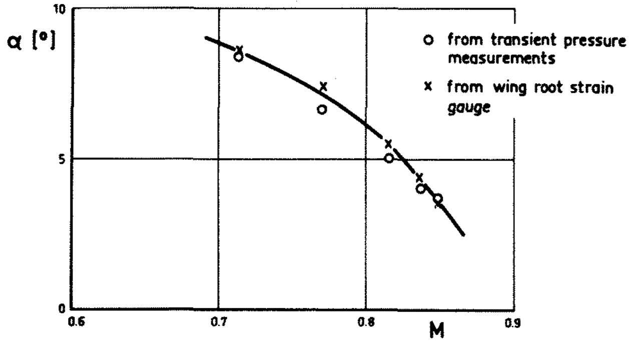


Fig. 20 divergence of wing root bending moment as determined by two different methods

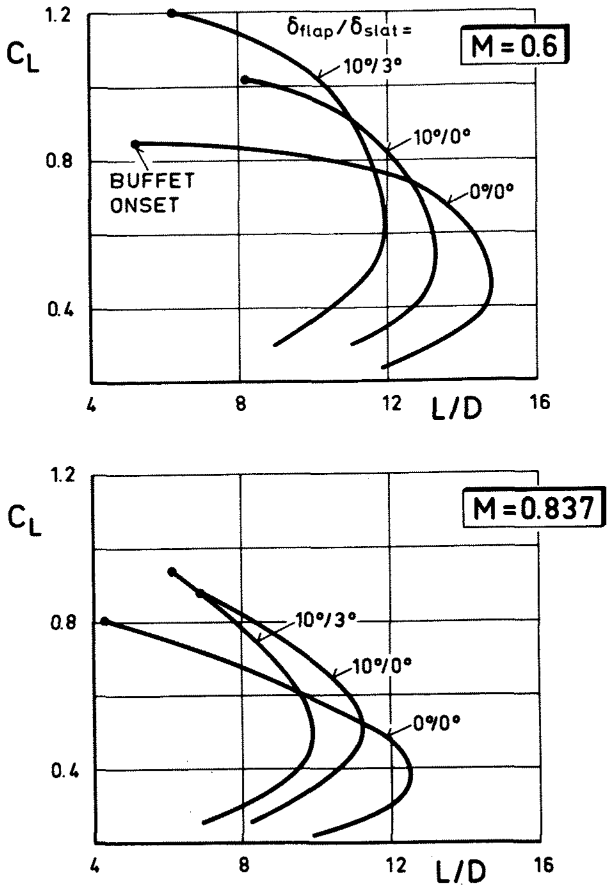


Fig. 21 lift to drag ratio for various flap positions

Fig. 21 presents some drag data in terms of L/D vs. C_L for various flap settings at two Mach numbers. By selecting the optimum flap setting as a function of M and C_L, considerable drag reduction can be achieved during high C_L maneuvers.

6. Influence on aircraft performance

Using the aerodynamic data of the first design cycle, maneuver performance was calculated and compared with the standard Alpha Jet. Fig. 22 shows an appreciable increase of the Mach number-altitude range in which a given load factor can be exceeded in a steady turn. Fig. 23 shows the same for a given level of SEP. It must be recalled again that the SCW achieves these improvements of performance in spite of its 20 per cent greater thickness. The maneuver flaps do not increase steady g's (except at low Mach numbers) and certainly not SEP because the corresponding C_L valves are too low. But at

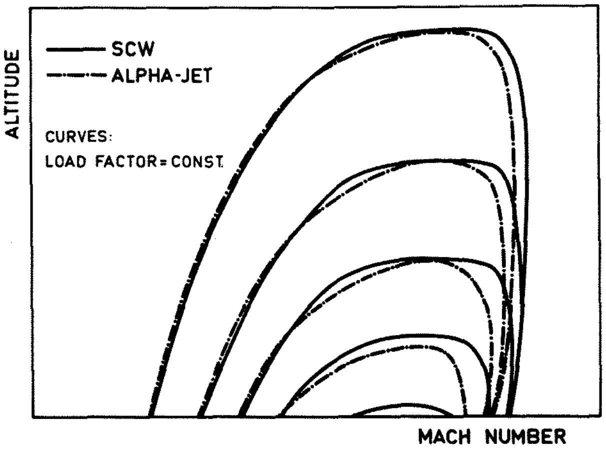


Fig. 22 comparison of steady turn performance

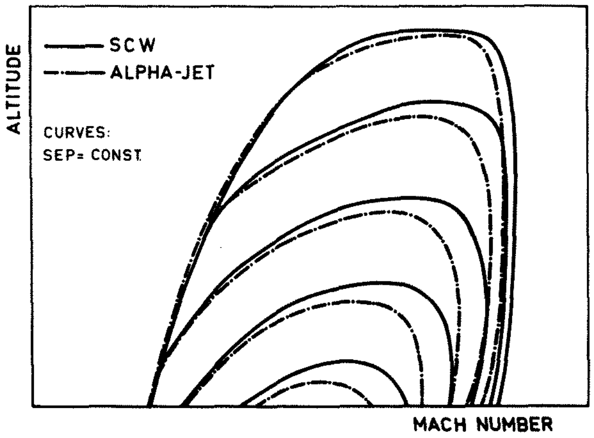


Fig. 23 comparison of specific excess power

higher g's extending the maneuver flaps will reduce the loss of altitude and/or flight speed.

The main purpose of the maneuver flaps will however be to increase the maneuver limits. The lift coefficients at which precise aiming becomes impossible and at which the aircraft becomes uncontrollable cannot be predicted from wind tunnel tests with the present state of the art. Therefore, in Fig. 24 buffet boundaries are shown instead of the actual maneuver limits which are unknown for the SCW. The figure shows that the Mach number-altitude-range in which 7.5 g (about the maximum value tolerable by the pilot) can be flown without incurring buffet is considerably increased with the SCW and still more with maneuver flaps extended.

7. Conclusions

In a program comprising the development and flight testing of a supercritical wing for a combat aircraft application, the first design cycle has been completed. From the results obtained, the following conclusions can be drawn:

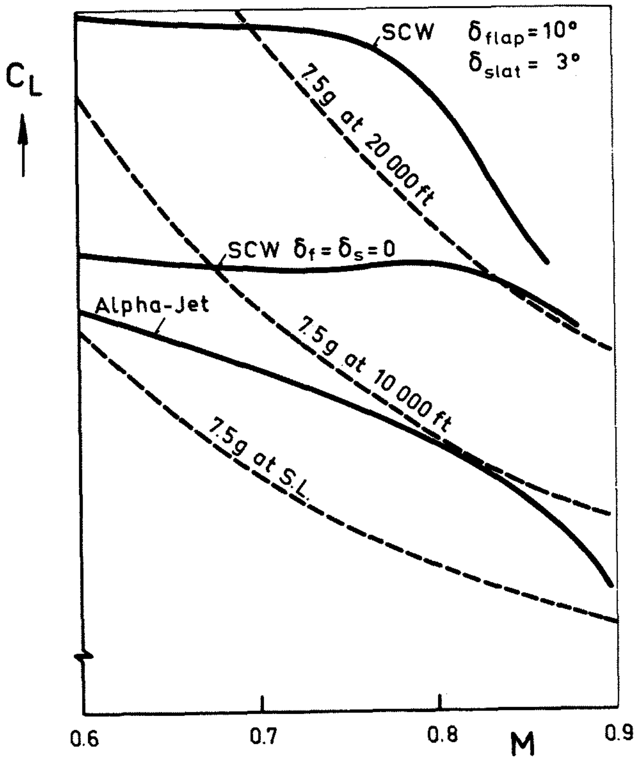


Fig. 24 buffet boundaries and maneuver limits

(1) It is possible to limit the modifications of the test vehicle to an exchange of the standard wing for the SCW.
(2) The development of theoretical methods of calculation for inviscid and viscous, 2-D and 3-D transonic flows, which has been done in the past years in a systematic manner, as well as some previous design experience with supercritical sections and wings, formed a good basis for the aerodynamic design of the SCW.
(3) It is possible to design a SCW with good performance in a large C_L-M-range.
(4) With a thickness greater than that of the standard wing of the test vehicle by about 20 per cent, the SCW has about the same drag rise Mach number M_D at low C_L, higher M_D at high C_L and a considerably higher buffet boundary. A further increase of buffet boundary is obtained with maneuver flaps as well as a further drag reduction at high C_L.
(5) These aerodynamic improvements lead to an increase of specific excess power, of steady turn performance and unsteady turn performance, especially at high altitudes. If the wing were built for an operational aircraft, additional improvements of performance and mission capability would result from the decrease of wing weight and increase of fuel volume.

(6) Without the restrictions posed by the test vehicle, trade-off studies might result in the selection of a different combination of thickness, sweep and aspect ratio leading to even greater performance improvements.

(7) The flying qualities of the SCW near the maneuver limits, which to a large extent determines actual combat performance, can only be evaluated by flight testing.

(8) The cooperation between an aircraft manufacturer and a research establishment in a specific project of this type has proved to be very beneficial.

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