THE FRANCO-GERMAN EXPERIMENTAL PROGRAM FOR
THE EVALUATION OF A SUPERCRITICAL WING FOR
A COMBAT AIRCRAFT APPLICATION (1)
M. Lotz (2) and B. Monnerie (3)

Abstract
The program has the purpose to investi-
gate the practical applicability of su-
percritical wings to subsonic combat air-
craft using the Franco-German Alpha Jet
as a test vehicle. Specific points of in-
terest are:
- 3-D effects on moderate aspect-ratio
  wings
- performance of a supercritical wing in
  a broad C_M-region
- effectiveness of maneuver flaps on a
  supercritical wing
- the behaviour beyond the buffet boun-
dary and at the maneuver limit.
The paper first describes the theoreti-
cal 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 im-
provements in performance.

1. Introduction
After many attempts to push the drag rise
and separation boundaries of airfoils a
little bit beyond the critical Mach num-
ber, 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 calcula-
tion 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 rec-
ognized at an early stage that the wind
tunnel results needed confirmation by
flight testing, mainly because the Rey-
olds number would have a stronger in-
fluence on the flow field than with con-
ventional airfoils. Therefore, three
flight demonstration programs were initi-
ated by NASA, using a T2-C, a F-8 and a
F-111 as test vehicles, with first
flights in 1969, 1971 and 1973, respec-
tively. In spite of the fact that combat
aircraft were used as test vehicles, at
least in the first two cases the appli-
cation to transport aircraft was the goal
of the investigations. The YC-15 proto-
type seems to be the first actual appli-
cation of the supercritical wing, but al-
most all new civil transport projects em-
ploy it too.

When experimental results showed that it
was possible to design supercritical wing
sections also having good off-design per-
formance, 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 com-
bat aircraft lead to stronger three-di-
imensional effects for which theoreti-
cal methods are less developed,
- the performance in a large M-C-area
is important where the theoretical
analysis of the flow is more difficult
and wind tunnel results are less reli-
able,
- the dynamic effects determining the
limits for aggressive and evasive ma-
euvers 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 Mi-
nistry of Defense (BMVg) to the decision
to sponsor a program comprising the de-
sign, manufacturing and flight testing of
a supercritical wing with maneuver flaps.
DORNIER GmbH of Friedrichshafen was se-
lected as prime contractor and VFW-Fokker
of Bremen as subcontractor who were res-
ponsible in the first design cycle for
the design of the maneuver flaps and for
the manufacturing of all wind tunnel mo-
dels. The program was started in July,
1974. In May, 1975, ONERA joined the
program. Their main contribution is to car-
y out two- and three-dimensional wind tun-
nel tests in their transonic facilities
at Modane, and also to participate in the
aerodynamic design and in the evalua-
tion of the flight tests.

The Dassault-Breguet/Dornier Alpha Jet

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159
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 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.

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Common features of all inviscid flow methods:
- Transonic small perturbation 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

\[ C_L \]

\[ M = 0.8 \]

\[ C_L = 0.48 \]

\[ \Lambda_0 = 30^\circ \]

\[ \Lambda_0 = 25^\circ \]

\[ \Lambda_0 = 18^\circ \]

Fig. 3 wing section for civil transport aircraft

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.

\[ AR = 7.95 \]

\[ \Lambda = 0.32 \]

\[ \Lambda_0 = 21^\circ \]

a) PLANFORM

\[ t/c \]

\[ C_D \]

\[ C_L \]

\[ C_{D_0} = C_{D_0}(M=0.8) + 0.002 \]

b) THICKNESS/CHORD VS. SPAN

c) DRAG RISE BOUNDARIES

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.

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 artificial 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 tests of the full scale wing in the 31 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∞ 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 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 in 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 M0 of the clean wing body combination and the maximum C M0 which is limited by horizontal tail power at low speeds and by structural strength at higher speeds.

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The C M0 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 M0, 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_2-M-flight envelope of the supercritical wing, including roll-to-pitch coupling during rapid roll maneuvers, showed no particular problems.

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 aero-
dynamic 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 mid-span, it would have a t/c of about 0.12 compared to about 0.10 for the original

![Fig. 9 drag rise boundary of wing sections](attachment:image1.png)

C_D = C_D (M=0.6) + 0.002

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. 10 SCW basic section shape](attachment:image2.png)

max. thickness: t/c = 0.1207
max. thickness position: x/c = 0.3600
TE thickness: 0.5 per cent of chord
LE radius: 1.6 per cent of chord
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. 10 maneuver flaps tested on 2-D model

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. 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

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.

![Figure 16](image1.png)

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.

![Figure 17](image2.png)

Fig. 17 Theoretical and experimental pressure distributions at $M=0.835$, $\alpha=2^\circ$, Re=2.5x10^6

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.

![Figure 18](image3.png)

Fig. 18 Comparison of drag rise boundaries $\Delta C_{D}/\Delta M = 0.1$
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 measure-
ments.

$\delta_{\text{FLAP}} / \delta_{\text{SLAT}}$

10° / 3°

10°/0°

0°/3°

0°/0°

$\Delta C_L = 0.1$

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 thickness 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 men-
tioned 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

$C_L$

$\delta_{\text{FLAP}} / \delta_{\text{SLAT}}$

10°/3°

10°/0°

0°/3°

0°/0°

$M = 0.6$

BUFFET ONSET

L/D

4

8

12

16

Fig. 21 lift to drag ratio for
various flap positions

$C_L$

$\delta_{\text{FLAP}} / \delta_{\text{SLAT}}$

10°/3°

10°/0°

0°/3°

0°/0°

$M = 0.837$

L/D

4

8

12

16

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 op-
timum 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 stand-
ard Alpha Jet. Fig. 22 shows an apprecia-
ble 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 thick-
ness. The maneuver flaps do not increase
steady g's (except at low Mach numbers)
and certainly not SEP because the corre-
sponding $C_L$ values are too low. But at

$\alpha [^\circ]$

Fig. 20 divergence of wing root
bending moment as deter-
mmined by two different
methods

Fig. 22 $\alpha$ vs. $M$

$\alpha$ from transient pressure
measurements
$x$ from wing root strain
gauge

0.6

0.7

0.8

0.9

$M$

166
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:

(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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