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# DESIGN AND EXPERIMENTAL VERIFICATION OF AN ADVANCED FOWLER FLAPPED NATURAL LAMINAR FLOW AIRFOIL

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## Abstract

An experimental evaluation of a new advanced laminar flow airfoil, PROFILE 76, was conducted at IAI's low speed wind-tunnel. The airfoil was designed to achieve a substantial amount of laminar flow at cruise conditions, while a specially designed Fowler flap was utilized to ensure the airfoil's high efficiency at intermediate and high lift coefficients.

The experimental results showed that PROFILE 76 met or exceeded most of the design goals regarding pressure-distributions, flow-quality, circulation control and maximum lift coefficients. The airfoil also proved to have an almost stall proof behavior with no pitching moment changes after the stall.

## Summary

A newly designed advanced laminar flow profile was evaluated experimentally, together with a well known reference profile (GAW-1), at IAI's low-speed wind-tunnel.

The newly designed laminar flow profile utilized the variable camber concept for meeting demands on optimum performance in the whole flight envelope.

The results obtained for the reference airfoil, GAW-1, were compared with the data published by NASA. The agreement was excellent for lift and moment, while the drag data compared less well due to the high turbulence level in the wind tunnel.

The test results for PROFILE 76 show:

- A favourable pressure gradient up to 30% chord at design point ($\alpha$ =0).
- Attached flow up to high angles of attack for maximum profile efficiency.
- Capability to increase CL up to 0.8, by deflecting the Fowler flap, without affecting the favourable pressure distribution.
- CLmax = 1.68 ($\delta_F$ = 5°).
- CLmax = 3.46 ($\delta_F$ = 30°).
- Cmo for the basic profile ($\alpha$ = 0) -0.10.

The high turbulence level in the wind tunnel prevented achieving the expected dragbucket, and the measured drag was typically 0.0030 - 0.0040 higher than expected.

PROFILE 76's stall was extremely gentle with virtually no liftloss after the stall.

## Design Goals

The design goals were to design a new wing profile being efficient in the whole flight envelope. The three constraining operating conditions were:

a) Cruise (CL: 0.4 - 0.6)
b) Climb (CL: 0.8 - 1.0)
c) Landing (CL: 2.5 - 3.0)

The solution of the first two design criteria was to use the variable camber concept for maintaining a favourable pressure gradient at higher lift coefficients without creating a suction peak at the L.E, while the demand of a high lift coefficient at landing was met by deflecting a powerful Fowler Flap;

The pitching moment was constrained to being not more negative than -0.1 for the basic profile in order to reduce trim drag.

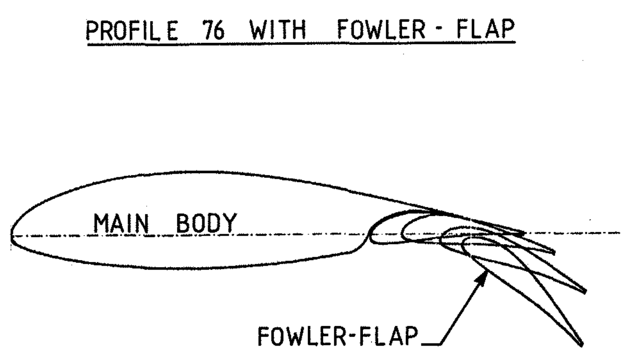



FIG 1: PROFILE 76 WITH FOWLER-FLAP.

## Airfoil Development

The airfoil was created by semi inverse computer codes internally developed at IAI.

The resulting geometry, as shown in fig 1, was a compromise on design constraints regarding lift, drag, pitching moment and geometry.

The final airfoil, in the future named PROFILE 76, features:

a) Favourable pressure gradient up to 30% chord.

b) Sliding Fowler flap for lift control at intermediate lift coefficients.

c) Full Fowler flap for maximum lift coefficients.

d) Large L.E radius for high nominal maximum lift coefficient.

e) Reduced T.E cusp for improved pitching moment coefficient and ease of manufacture.

f) t/c = 17.5%.

## Tests and Method

The experimental evaluation was performed at IAI's Low Speed Wind Tunnel. It was known in advance that the turbulence level was high (>1%), meaning that the measured drag would not reflect the values that would have been achieved in a low turbulence windtunnel.

The airfoil models were machined from a solid slab of aluminium with orifices for pressure measurements located both on the main body and on the T.E flap. The span of the model was 1.5 m and the chord 0.6 m.

A two dimensional test section was developed especially for this test. The test section was 3.0 meters long, 2.0 meters high and 1.5 meters wide.

The tests were performed at windspeeds from 30 to 75 m/s, which corresponds to section Re-nr ranging from 1 200 000 to 2 800 000.

The investigated angles of attack varied from -2.0 deg to +16.0 deg.

## Force Measurements

Force data were obtained through the main balance system and by integrating the pressure distributions. The drag for angles of attack with attached flow was measured by a wake rake downstream of the wing model.

Surface roughness was simulated by a 3 mm wide strip of # 100 grit at 8% chord from the L.E.

## Investigated Configurations

a) GAW 1 - Basic profile
b) PROF.76 - Nominal
c) PROF.76 - Climb flap ( $\delta_F = 3^\circ, 5^\circ$ )
d) PROF.76 - Fowler Flap ( $\delta_F = 20^\circ, 30^\circ, 40^\circ$ )

## Experimental Results

Reference Airfoil - GAW-1 (Fig 2 a-c)

As shown in fig 2 a-c there is excellent agreement between the test performed at IAI compared to the parallel test done by NASA, confirming the validity of the data obtained for PROFILE 76.

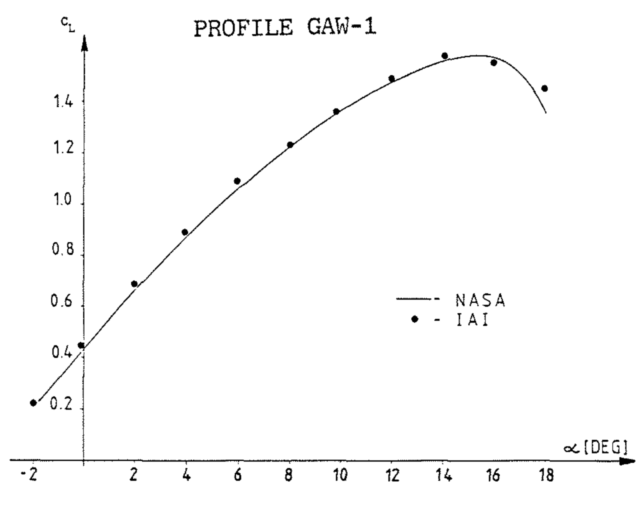



FIG 2a: TEST COMPARISON: IAI vs. NASA
Transition on, Re= 2 200 000

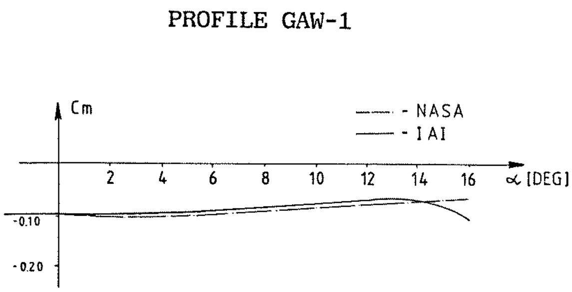



FIG 2b: TEST COMPARISON: IAI vs. NASA
Transition on, Re= 2 200 000

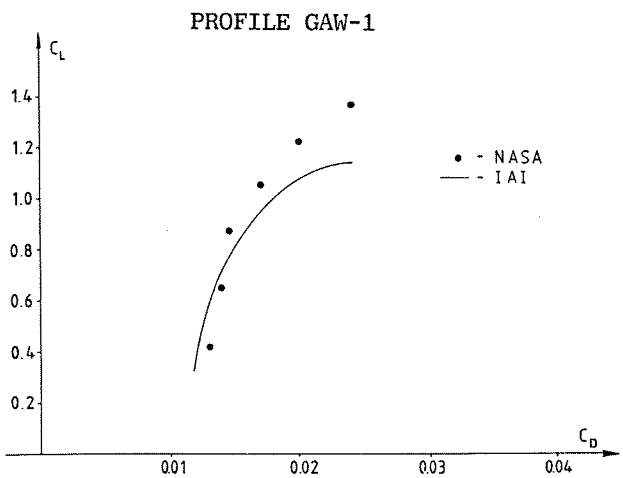



FIG 2c: TEST COMPARISON: IAI vs. NASA
Transition on, Re= 2 200 000

PROFILE - 76 (Nominal)

Lift (fig 3a)

The lift is presented for Re=2.2 $10^6$ with and without roughness.

The smooth airfoil has a lift curve slope of 0.117/deg with no deterioration up to 8 deg. angle of attack, proving that there is no premature T.E separation degrading the performance of the airfoil.

Lift at zero angle of attack is 0.52, while maximum lift coefficient is about 1.52.

The stall is extremely gentle with almost NO liftloss after the stall, resulting in a virtually stallproof profile.

Section roughness reduces section liftslope from 0.117 to 0.113. Maximum lift is reduced 5.5% from 1.52 to 1.44. The stall characteristics remain unchanged.

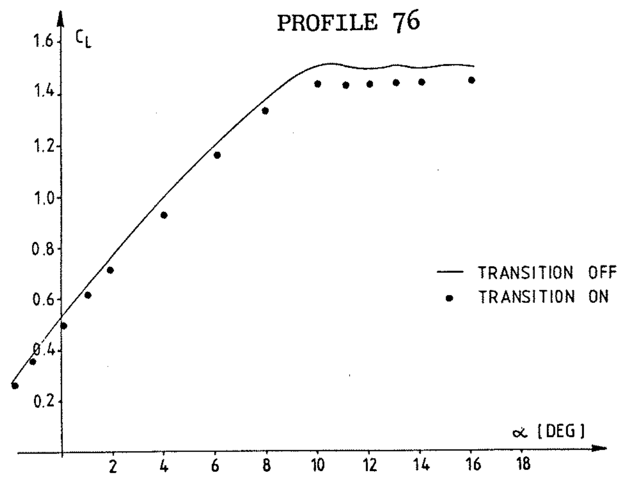



FIG 3a: PROFILE 76 - NOMINAL
Re= 2 200 000

Pitching Moment (Fig 3b)

Cm for the smooth profile is about -0.10. The moment curve is practically straight even after the stall.

The addition of roughness has no essential effect on the pitching moment curve.

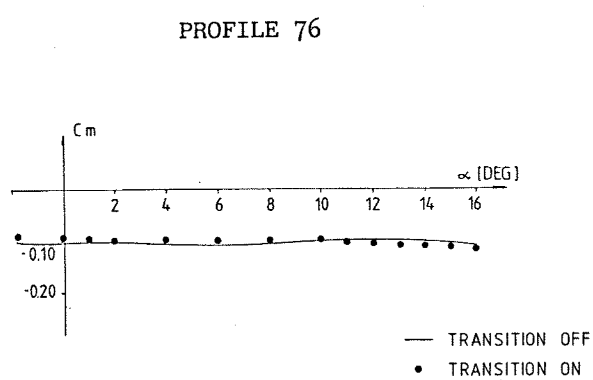



FIG 3b: PROFILE 76 - NOMINAL
Re= 2 200 000

## Drag (Fig 3c)

Fully extended laminar flow was not achieved due to the high free stream turbulence level (>1%). The measured drag levels were about 0.0080 - 0.0085 at design point.
The drag polar increases very gradually with CL, indicating the absence of the expected laminar drag bucket which would have existed in a low turbulence (<0.02%) wind tunnel.
Roughness adds about 0.0040 to the drag for all measured angles of attack.

For angles of attack higher than 10 deg the T.E separation is moving forward. However this liftloss is compensated by an increased nose loading, resulting in an almost constant lift coefficient and a virtually stallproof profile.

A redesign of the rear part of the profile would probably delay the T.E separation, and increase CL max.

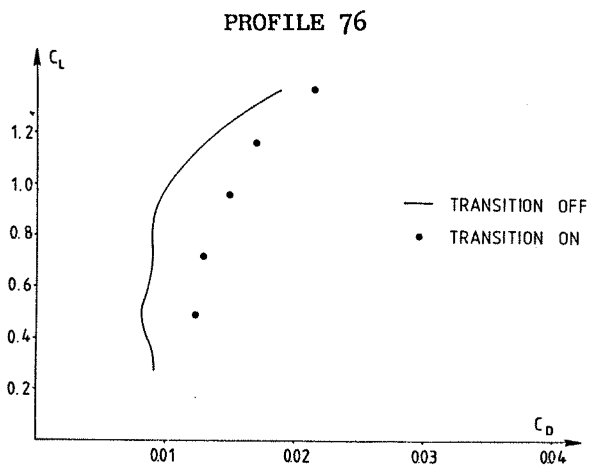



FIG 3c: PROFILE 76 - NOMINAL
Re= 2 200 000

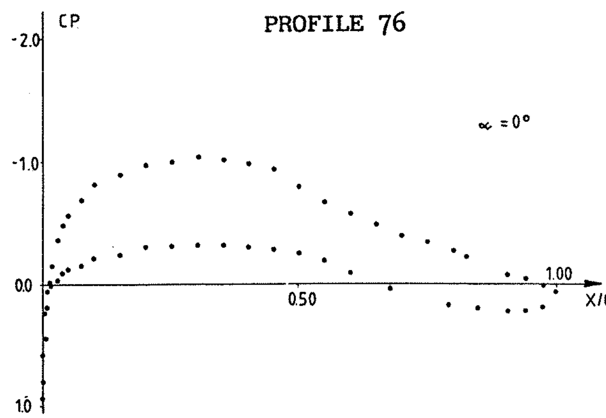



FIG 4a: PROFILE 76 - NOMINAL
Transition off, Re= 2 200 000

## Pressure Distribution (Fig 4a - 4d)

The measured pressure distribution shows a favourable pressure gradient up to 30% chord at $\alpha$ = 0 deg, with a smooth gradual pressure recovery on the upper side.

The lower side behaves excellently with a smooth pressure distibution, and the typical rear loading of a cusped profile.

As the angle of attack increases the pressure gradient on the upper surface becomes less favourable, but still there are no tendencies to build an L.E suction peak.

Only at $\alpha$ =6 deg (CL =1.10) can signs of a beginning L.E suction peak be seen.
T.E separation starts at about 9 deg angle of attack.

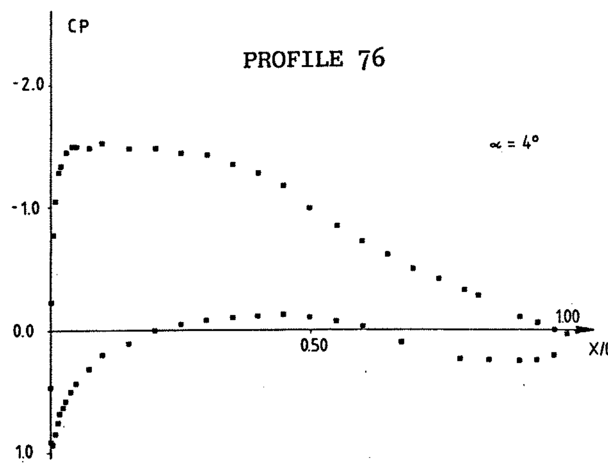



FIG 4b: PROFILE 76 - NOMINAL
Transition off, Re= 2 200 000

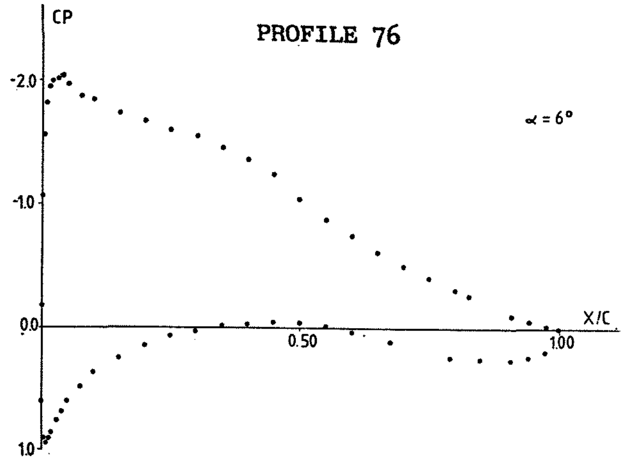
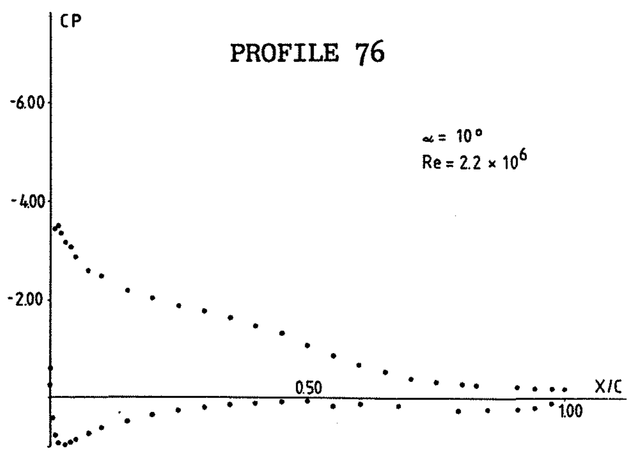



FIG 4c: PROFILE 76 - NOMINAL
Transition off, Re= 2 200 000




+FIG 4d: PROFILE 76 - NOMINAL
Transition off, Re= 2 200 000

## PROFILE 76 - Climb Flap ( $\delta_F$< 5 deg)

The effect of moderate T.E flap deflections was investigated in order to evaluate the possibility to increase section lift coefficient without changing the angle of attack.

## Lift (Fig 5a)

The lift is compared for the T.E flap deflected 0, 3 and 5 deg (smooth profile).

T.E flap deflections increase the liftslope from 0.117 to 0.128, and add 0.05 to CL for each degree of deflection.

CL max is increased to 1.64 for 3 deg of deflection and to 1.68 for 5 deg of deflection.

The almost stall proof behaviour of the profile is not changed with the deflection of the T.E flap.

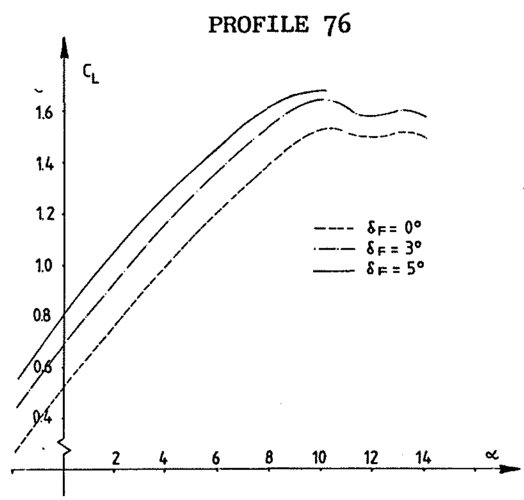



FIG 5a: PROFILE 76 - FLAPPED
Transition off, Re= 2 200 000

## Moment (Fig 5b)

Deflection of T.E flap adds -0.013 to pitching moment for each degree, while the basic character of the curve remains unchanged.

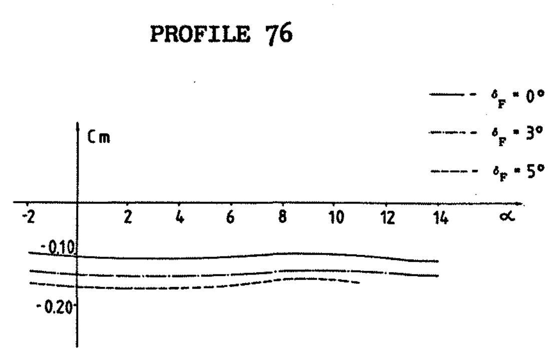



FIG 5b: PROFILE 76 - FLAPPED
Transition off, Re= 2 200 000

## Drag (Fig 5c)

No significant drag reductions were obtained for small T.E flap deflections since the high turbulence level at IAI's wind tunnel prevents the expected laminar drag bucket, and thus the drag gains by moving the drag bucket to higher CL with the T.E flap can not be achieved.

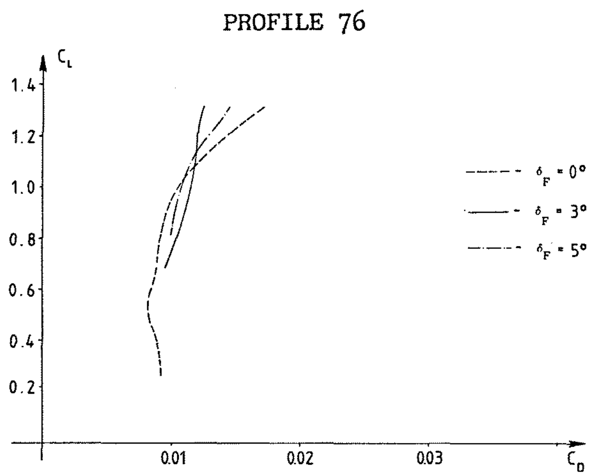



FIG 5c: PROFILE 76 - FLAPPED
Transition off, Re= 2 200 000

## Pressure Distributions (Fig 6)

The pressure distribution for various flap deflections at zero angle of attack shows that the flap works well as a "circulation generator". The velocities over the profile are increased, while the character of the pressure distribution remains unchanged. The favourable pressure gradient up to 30% chord is not affected by moderate T.E flap deflections.

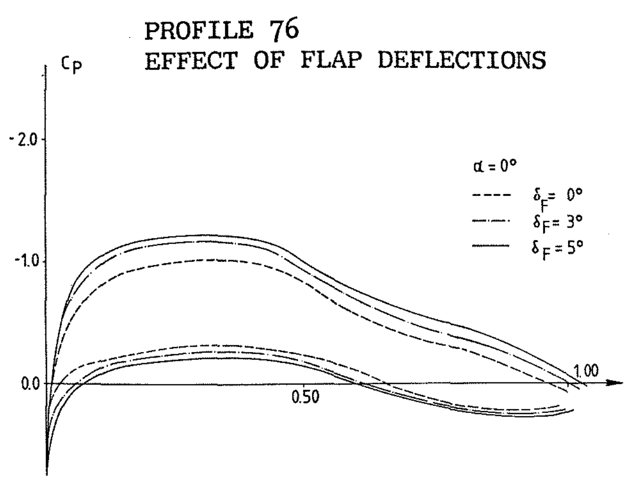



FIG 6: PROFILE 76 - FLAPPED
Transition off, Re= 2 200 000

## PROFILE 76 - Full Fowler Flap ($\delta_F$>20 deg) (Fig 7a -7b)

CL max = 3.46 was achieved for the smooth model with 30 deg deflection. For larger deflections than 30 deg the flap itself was stalled and there were no further lift gains.

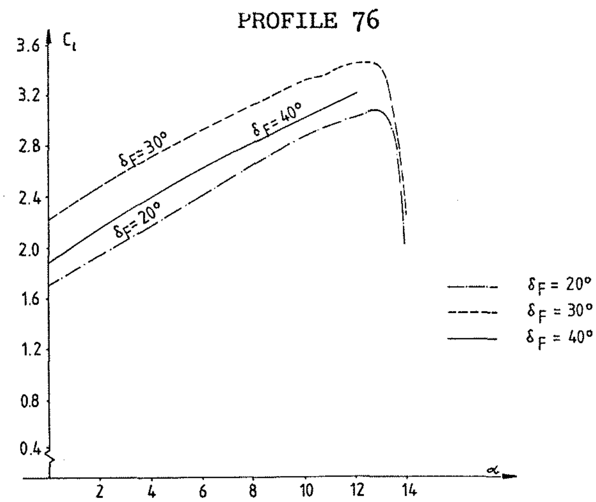



FIG 7a: PROFILE 76 - FLAPPED
Transition off, Re= 2 200 000

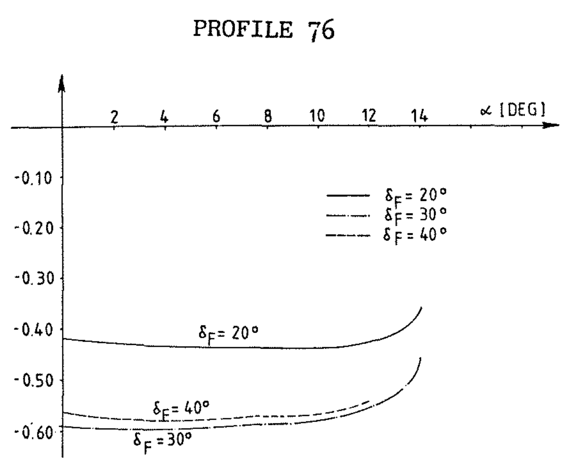



FIG 7b: PROFILE 76 - FLAPPED
Transition off, Re= 2 200 000

Comparison: PROFILE 76 vs. GAW-1, vs. NLF-0215

The lift, drag and moment are compared for PROFILE 76, GAW-1 and NLF 0215. NLF 0215 is included in the comparison since it might be regarded as a parallel profile to our own design, PROFILE 76. The values for NLF 0215 are published in NASA TP 1865. Unfortunately NASA did not perform a low Re-nr test, so the data describing NLF 0215 is based on Re = 3.0 10 , giving it a more favourable comparison. The values presented for PROF 76 and GAW-1 are based on the IAI LSWT data.

Lift (Fig 8a)

At = 0 PROFILE 76 has slightly more lift than GAW-1. NLF 0215 is a heavily rear loaded profile with the resulting high lift at zero angle of attack.

The lift slope for PROFILE 76 is almost unaffected up to 8 deg. angle of attack, while for the two other profiles the liftslope starts to decrease at $\alpha$ = 4 (NLF 0215), and at $\alpha$ = 2 (GAW-1) This emphasizes PROFILE 76's ability to maintain attached flow up to high angles of attack, while the two other profiles suffer from premature T.E separation already at low angles of attack.

The maximum lift coefficient is almost the same for PROFILE 76 and NLF 0215 (1.52 - 1.56). GAW-1 employing a larger L.E radius enjoys a max lift coefficient of 1.63.

The stall is quite abrupt for GAW-1 and NLF 0215, while PROFILE 76 is almost stallproof.

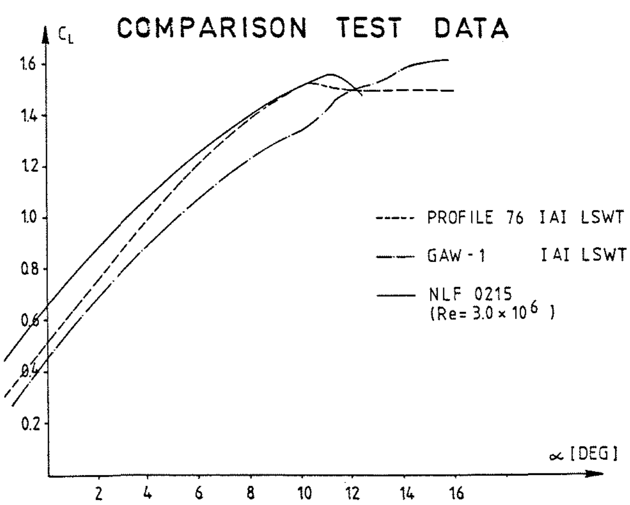



FIG 8a: Profile comparison, IAI LSWT Transition off, Re= 2 200 000

Moment (Fig 8b)

The pitching moment of PROF. 76 is almost identical to GAW-1 at low angles of attack (Cm = - 0.10). NLF 0215 has a much more negative pitching moment, Cm= - 0.15, than the other two profiles due to its very loaded aft part.

At high angles of attack both GAW-1 and NLF 0215 suffer from a creeping instability due to the premature T.E separation. PROFILE 76's moment curve remains almost straight, pointing out its smooth stable behaviour.

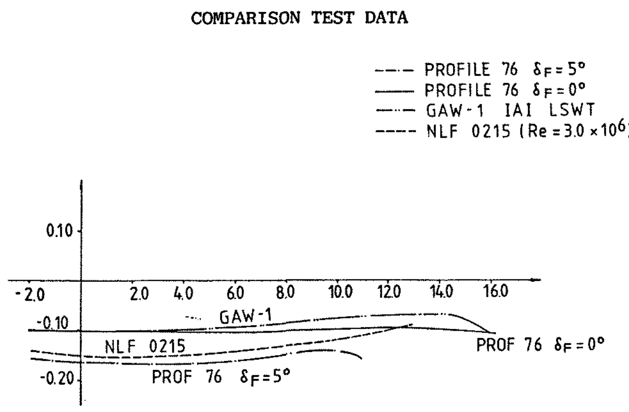



FIG 8b: Profile comparison, IAI LSWT Transition off, Re= 2 200 000

Drag (Fig 8c)

The drag polar for NLF 0215 is not included in the comparison, since its drag was measured in a low turbulence wind tunnel and a comparison with the data obtained at IAI is quite meaningless.

Fig 8c shows that PROFILE 76 has a drag advantage of about 0.0020 at the design point relative GAW-1. This is explained by the fact that the favourable pressure gradients of PROF. 76 manage to maintain a higher degree of laminar flow than GAW-1, in spite of the turbulent environment.

For increasing CL PROFILE 76's drag polar remains essentially straight, while the drag increases quite fast for GAW-1 with higher CL. At CL = 1.0 the difference between the two profiles is about 0.0070 in PROFILE 76's favour.

COMPARISON TEST DATA

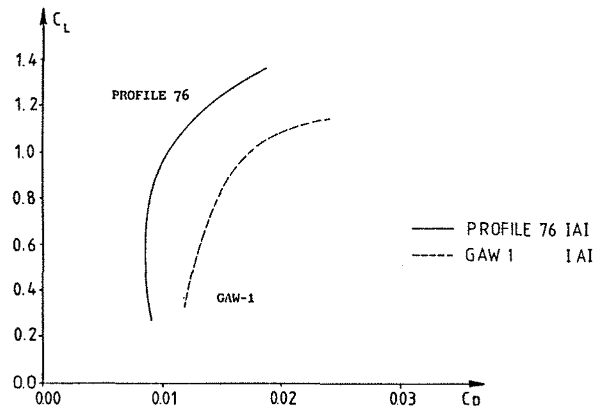



FIG 8c: Profile comparison, IAI LSWT
Transition off, Re= 2 200 000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PROFILE 76's stall was extremely gentle with virtually no liftloss after the stall.


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