Vortex Flow Dilemmas & Control on Wing Planforms for High Speeds

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ABSTRACT

Aircraft for sustained supersonic flight usually feature low aspect ratio wings with varying (reducing) leading edge sweep over the outer portion to achieve an 'adequate' low-speed performance.

A high-speed "cruise" wing then becomes subject to mixed flows at low-speeds, including strong Vortical flows. Dilemmas then arise whether to exploit the vortical flows or to control / suppress them (actively or passively) with LE and TE devices. On one hand vortical flows lead to higher lift at the expense of higher drag and possible flow breakdown over the outer wing. On the other hand, controlling them implies reduced lift but higher L/D. The dilemmas are more intense if the configuration is "attitude-limited" (floor angle, tail strike). All this leads to the need for improving the understanding of vortical flows on a given configuration.

This paper focusses on vortex control with different types of LE and TE devices. Several examples are given. The techniques developed can be adapted to more complex configurations including canards, nacelles, etc.

1. INTRODUCTION

Aircraft capable of sustained supersonic flight usually feature low aspect ratio (AR) wings with discontinuous variation of leading edge (LE) sweep, the outer wing sweep being lower, to achieve a compromise for 'adequate' low-speed performance (**Fig.1**, F-16XL, HSCT, ESCT).

Assuming that the wing can be designed 'satisfactorily' for high-speed cruise (low camber), dilemmas arise for flow prediction and control throughout the rest of the operating envelope, e.g. at subsonic and low speeds in high lift or drag dominated situations (take-off, landing and manoeuvring). At low speeds, the first dilemma concerns the type of vortical flow, single or multiple vortex systems. Is the Lift to Drag ratio (L/D) better with or without vortices? Configuration 'hard' limits (tail-strike, cabin floor angle, static margin etc.) further complicate the issue (**Fig.2**).

2. SETTING THE SCENE, QUALITATIVE ASPECTS, DILEMMAS & SOLUTIONS

It is interesting to bear in mind the low-speed vortex breakdown relationships, **Fig.3**, Ref.1.

Consider the flow-fields at high incidence (AoA), **Fig.4**, on a low camber, thin wing design. The inner wing features a rounded LE, whilst the outer wing will have a sharper LE. Note the large variation in local chord (c), root to tip, which implies a corresponding large Reynolds number (Re) variation along the wing-span.

At higher AoA, the 'cranked' wing has two vortex systems, both contributing 'non-linear' lift. The inner vortex introduces 'extra' upwash that encourages another vortex system at the crank. The outer wing being of low sweep is liable to suffer vortex breakdown, possibly near AoA = 10° or so (**Fig.3**). This is unacceptable as L/D is compromised.

Now if we reduce the 'severity' of the 'crank' by rounding, a multiple vortex system becomes more likely, **Fig.4**. L/D will still be compromised as individual vortices breakdown but the overall effects may be less severe.

Coe's Experiments on LE Deflection Optimistion

Coe et al conducted an experimental study of the low speed optimisation of LE deflection on a highly swept arrow-wing configuration (AR = 1.9), **Fig.5**, Ref.2. Optimisation of the LE deflection has a strong bearing on the level of LE suction attained. TE deflections were not included in the study. This work has been re-analysed.

Selected force and moment results for 0°, 30° and 16°-50° LE deflections are presented in **Fig.5**. The 16°-50° case represents an optimised configuration with smooth, continuous deflection across the span. L/D variations, derived from **Fig.5** are shown in **Fig.6**. Ref.2 also provides details of flow visualisation tests and the important features are interpreted in **Fig.5**.

The LEF = 0° case shows attached flow, over the main inboard region of the wing, for 2° < AoA < 4° with a closely wound LE vortex on the outboard panel. Above AoA = 4°, the outboard vortex separates and wing-apex vortices form, leading to pitch up. With the LE deflected 30°, lower surface flow separation occurs at

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14. ABSTRACT

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AoA < 0°. For 0° < AoA < 8°, flow is attached over the majority of the wing surface. Above AoA = 8°, LE vortex separation originates near the mid-semispan. Deflecting the LE 30° reduces the pitch up severity. With the LE optimised (16°-50° deflection), the LE vortex separation is delayed to AoA > 10°.

Corresponding LE suction levels (Suction Parameter S_s) are shown in **Fig.7**. The superior performance of the optimised (smooth), 16°-50° deflected LE is evident. At C_L = 0.3 (subsonic cruise climb), S_s levels of 90% are achieved on the optimised LEF. As C_L increases above 0.3, S_s levels fall significantly in all cases (0°, 30° & 16°-50°). Ref.2 notes that if TEF were also deployed, equivalent C_L could be achieved at much lower AoA with reduced flow separation. With LEF and TEF deployed, the effective increase in wing camber would allow even higher S_s to be achieved over a much wider C_L range.

Improved pitch stability is offered with LEF deflection.

With the 'smoothing fairings' removed from the 16°-50° LEF case there is a marked increase in drag and a corresponding reduction in suction levels, **Fig.7**. Suctions for the unfaired 16°-50° LEF fall well below those of the 30° LEF. These observations highlight the need for smooth, continuous LE geometry to prevent hinge-line separations.

Fig.8 shows the lift and drag characteristics for a wing (AR = 2.1) with and without LE / TE deflection. Curves corresponding to 0% and 100% LE suction are shown.

Without LE devices, using vortex lift at AoA = 12°, the low-speed C_L is adequate but C_D is high. With attached flow, we are attitude limited to lower C_L values (no TE flap). With deflected TEF an extra 15% in C_L may be available but at the expense of increased drag (trim stability). Additional lifting surfaces, e.g. canards, may be required.

With 'simple' LEF deflected, experience has shown that 80%-100% S_s level is attained over a certain C_L range depending on Mach and Re. Higher deflections are required for operation at higher C_L. In general, deflections need to be 'tailored' along the span to control the vortex flow. Chord variations can be included, although the scope of this may be limited because of wing-box constraints.

To improve L/D at high C_L, it was envisaged that LE and TE devices would control (minimise) 'passively' the vortex flows by fixing flow 'attachment' lines at the LE, at the required lift. In this way, we can avoid the need for modelling vortex sheets at the 'design' condition, simplifying the problem considerably. **Fig.9** shows possible LE devices, ranging from simple LE flaps, Kreugers, Slats, Sealed-Slats and Vortex flaps. Which is the best?

A well-known problem with simple LE flaps deflected at large angles on thin wings is the possibility of hinge-line flow separation. Therefore the sealed-slat type devices were proposed to lessen the adverse pressure gradient at the 'knuckle'. An appreciation of the pressure gradients also leads to further flow control possibilities, e.g. introduction of gaps (i.e. unsealed slat), blowing or suction. The task was then to design and evaluate them from, potentially, a large data-set. All this to be achieved within the bounds of practicality. The modelling of sealed slats required thick-wing panel codes. Vortex-flap studies remain to be done (See related work in Ref.3 on F-16XL).

Continual evolutionary progress is anticipated in the assessment and incorporation of these devices.

3. PREDICTION METHODS

Prediction of wing flows with and without LE / TE devices at low subsonic speeds is a continuing challenge. Approaches in order of complexity and cpu usage are: thin-wing and panel codes with attained LE thrust (appropriate Mach & Re), codes with vortex sheet panelling, Full-potential, Euler and ultimately, Navier-stokes. Generally, more flow 'fidelity' is offered as cpu usage increases. Each approach requires assumptions with weak and strong points. CFD methods are very cpu intensive particularly at low-speeds. Drag prediction is still to a large extent very grid-dependent.

The general experience (Carlson & others, NASA Langley, Refs.4 & 5 and the author, Ref.3) is that the thin-wing and/or panel codes with attained LE thrust are capable of predicting design related information (many cases are needed) particularly if the vortex flows are kept 'small'. Mann & Carlson (Ref.5) imply that Euler solvers do not necessarily capture LE thrust adequately on thin wings at supersonic speeds.

Present Approach

Over the past few years, a capability has been developed for 3-D design and evaluation (direct and / or inverse) of conventional and unconventional aircraft wings with and without LE / TE devices (Refs.6-11) and intakes (Refs.12-16). The methods incorporate Mach and Re effects and attained thrust principles, resulting in designs with 'mild / tolerant' deflections. Thin- and thick- wing methods can be used as appropriate. The latter allow more 'fidelity' e.g. inclusion of bodies etc.

Control effects can be assessed. Lift-Drag predictions have been compared with experiment. Correlations have then allowed 'confident' predictions to model or flight scale.

4. THIN-WING LE / TE DEVICES, PREDICTIONS & COMPARISONS WITH EXPERIMENT

Using thin wing theory, with attained LE suction, **Fig.10** (see Ref.3) shows predictions compared with experiment on a MDC-SCT model with LE / TE flaps (Ref.17).

In order to amplify differences, note that the drag scale has been defined as:

$$C_{De} = C_{Di} - k_2\, C_L^2/(pi*AR), \quad k_2=2.15$$

The graphs depict also the curves for 0% and 100% LE suction as well as nacelle effects. The lift curves show that theory predicts a slightly lower incidence for zero lift. Discounting this intercept, the linear and non-linear lift regions are predicted accurately. Further the difference in lift due to the nacelles is relatively small. An estimate for a small reduction in lift due to presence of the fuselage can be inferred.

For a given lift, the non-linear part decreases as the LEF deflection increases.

For the 0° LEF, experimental points on the C_{De} - C_L graph for the wing+body configuration lie close to predictions, up to C_L near 0.6. At higher C_L values, vortex breakdown and flow separation effects would be expected over the outer wing causing loss in non-linear lift and increasing the drag.

With LE deflected, the agreement for C_{De} between theory and experiment is very satisfactory up to C_L near 0.6. The beneficial effects of flap deflection are expected to 'saturate' for high LEF deflections. Flow breakdown effects arising over the outer wing (low Mach and low Re) appear to dominate at high lift.

Estimates for flight scale (Mach 0.2 to 3) and Re based on $c_{av} = 70x10^6$ emphasise the favourable scale effect. Further improvement would be possible by local modifications of the aerofoil shape especially over the inner highly swept portion.

It is significant that the envelope graph (or flap schedules) from theory and experiment are very similar. For large TEF deflections, theoretical prediction is good (within a few drag counts) even at high values of lift. This is not surprising because at given lift, the wing incidence is naturally lower when TEF deflection is high. The flow (vortex) breakdown effects, evident in experiment, do not affect the control schedule. The envelope graph suggests "capture" of nearly 100% LE suction values using appropriate LE deflections.

5. THICK CAMBERED WING PREDICTIONS & COMPARISONS WITH EXPERIMENT

Using thick wing theory with attained LE suction, **Fig.11** shows predictions compared with Mach 0.6 experiment on a half-wing model (Ref.18, two different camber states) at two Re. The correlations are good.

The encouraging predictive capability of the method allows evaluation of possible configuration variations for parametric and exchange rate studies. Differences between model and flight scale can be highlighted.

6. THICK - WING LE / TE DEVICES, HSCT VARIANT

The reference wing was based on a more 'recent' HSCT variant and the fuselage was not included. Several parametric variations of geometry were considered with semi-inverse / manual techniques for each type of LE device. **Fig.12** shows typical LE device hinge-lines. For the sake of brevity, a few results are summarised here.

For the case of 0° LEF, **Fig.13** shows the Cp distributions at AoA = 12° with and without TEF deflection. Note the high LE suctions particularly over the outer wing. These essentially reflect that vortical flow would exist, if the panel code had that capability.

Fig.14 refers to the use of simple LE droop. The Cp distributions show that LE suctions have been controlled (minimised), however there are appreciable suctions at the 'shoulder' line. Deflections required over the outer wing are 'high'.

Fig.15 refers to the use of sealed slat. The Cp distributions show that LE suctions have been (fully) controlled and the suctions at the 'shoulder' line are considerably smaller.

Fig.16 is a composite of the previous two figures. In this somewhat busy illustration, it is not too difficult to infer that the sealed-slat offers very much reduced suction near the 'shoulder' (50% reduction in pressure gradients). In turn, this could help in the specification of additional local flow control e.g. by introducing a gap (unsealing), blowing and suction.

7. CONCLUDING REMARKS, FUTURE

A high-speed "cruise" wing is subject to mixed flows at low-speeds, including strong vortical flows. In order to maximise the low-speed performance (C_L & L/D), dilemmas then arise whether to exploit the vortical flows or to control / suppress them (passively or actively) with LE and TE devices.

Vortex flow needs to be understood well enough to determine whether or not sufficient control can be achieved passively using different types of LE devices.

This paper has focussed on vortex control with different types of LE and TE devices. Several examples have been given.

Results have demonstrated the flexibility and potential of the techniques used through Mach and Re ranges on swept wings prone to vortical flow structures. Thin-wing methods allow good estimation of forces, whilst thick-wing assumptions also allow complex LE / TE devices to be modelled with 'fidelity' provided the flow 'attachment' lines are close to the LE, thus controlling the vortex flows.

As well as assessment of the potential of the LE / TE design in meeting a given design envelope, the limitations of a given design also become apparent which in turn may lead to consideration of more active forms of flow control, blowing or suction.

The approach can guide the detail design of test models and possibly flight demonstrators. An understanding of control laws will arise. Smaller test programmes of a more confirmatory nature should ensure sizeable cost benefits.

Several other types of devices remain to be studied. Further complexities may be introduced e.g. canard, fuselage and nacelle effects. The techniques can be more automated.

Advanced CFD methods need to be employed to confirm the flow characteristics and understanding gained with the techniques of this paper.

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LIST OF SYMBOLS & ABBREVIATIONS

AoA	Ó, Angle of Attack
AR	Aspect Ratio
b	= 2 s, Wing span
c	Local Wing Chord
c_{av}	Wing Mean Chord
C_D	= Drag Force /(q S), Drag Coefficient
C_{D0}	Friction Drag Coefficient
C_{De}	$= C_D - C_{D0} - k_2 C_L^2/(pi*AR)$
C_L	= Lift Force/(q S), Lift Coefficient
C_m	= Pitching Moment/(q S c_{av}), Pitching Moment Coefficient
C_p	Coefficient of Pressure
CP	Centre of Pressure
ΔC_p	Difference in C_p between upper and lower surfaces
k	Lift-Induced drag factor
k_2	A factor
LE	Leading Edge
LEF	Leading Edge Flap
M	Mach Number
q	= 0.5 ρ V^2, Dynamic Pressure
Re	Reynolds Number, based on c_{av}
s	Wing semispan
S	Wing Area
S_s	Suction Parameter = 1 for elliptic loading, = 0 for flat-plate drag
TE	Trailing Edge
TEF	Trailing Edge Flap
V	Velocity
Λ	LE Sweep Angle
η	= y/s, Non-dimensional spanwise Distance
ρ	Air Density

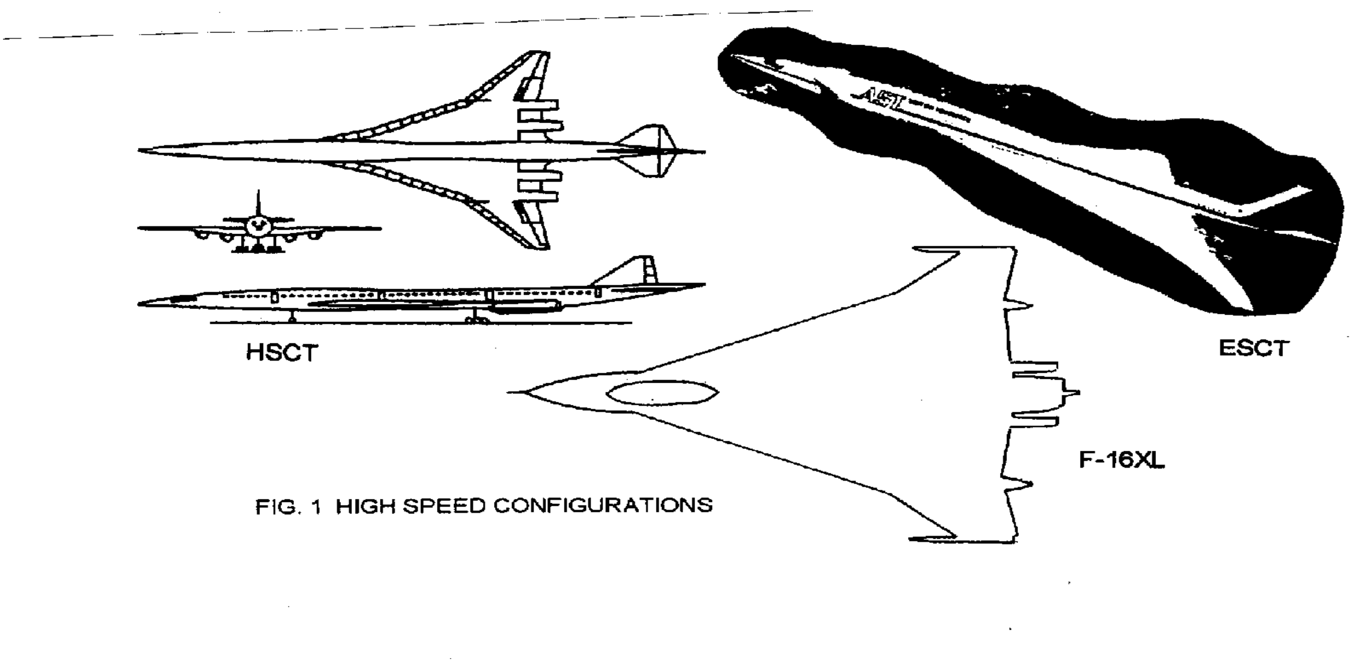


FIG. 1 HIGH SPEED CONFIGURATIONS

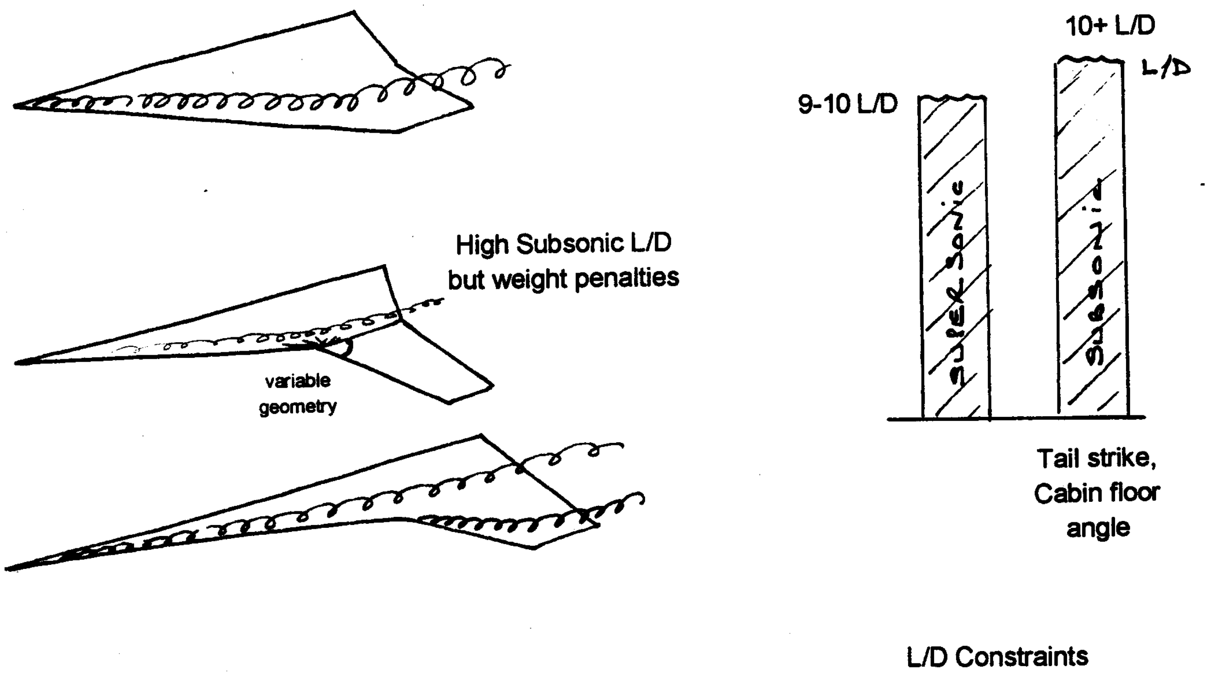


FIG. 2 TYPE OF WINGS & VORTICAL FLOW

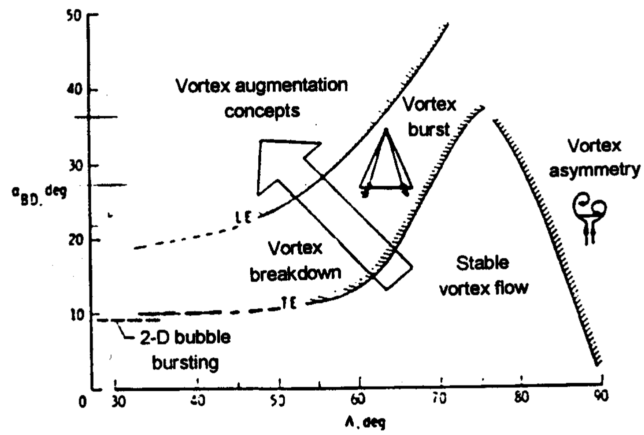


FIG. 3 LE VORTEX BREAKDOWN TRENDS, LOW SPEED, (Lamar)

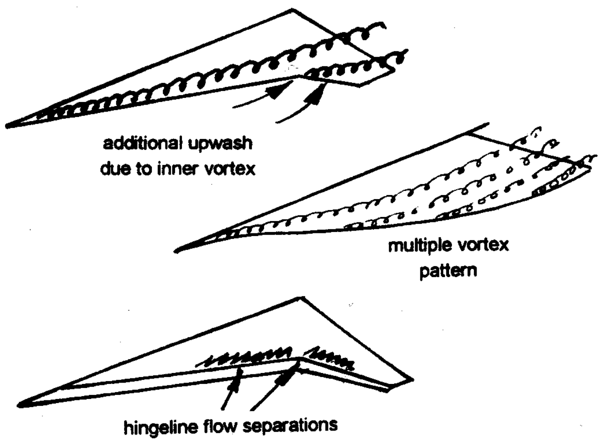


FIG. 4 FLOW-FIELDS

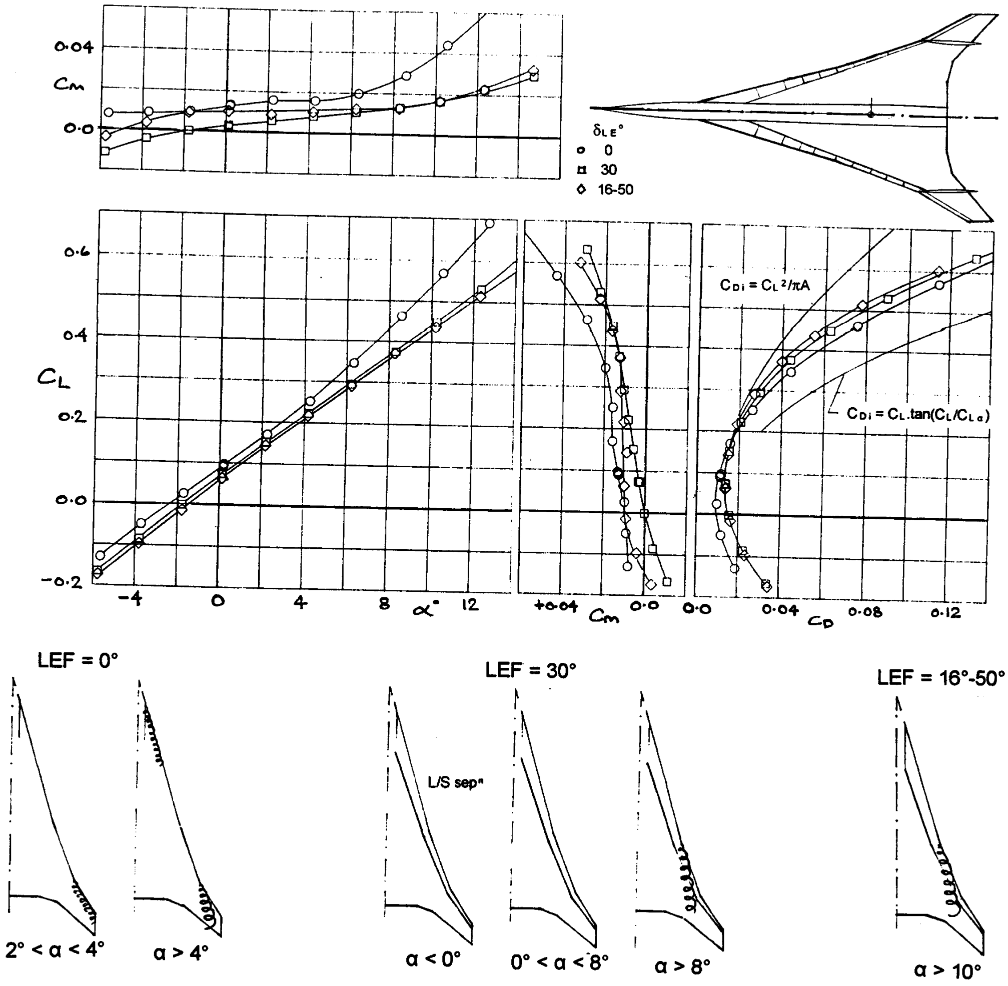


FIG. 5 LIFT, DRAG & PITCHING MOMENT, EFFECT OF LE DEFLECTION, HIGHLY SWEPT ARROW WING CONFIGURATION

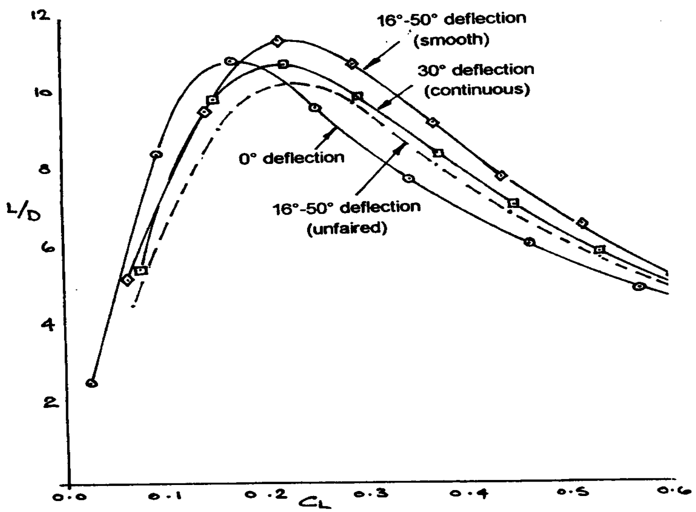


FIG. 6 L/D - C_L, EFFECT OF LE DEFLECTION

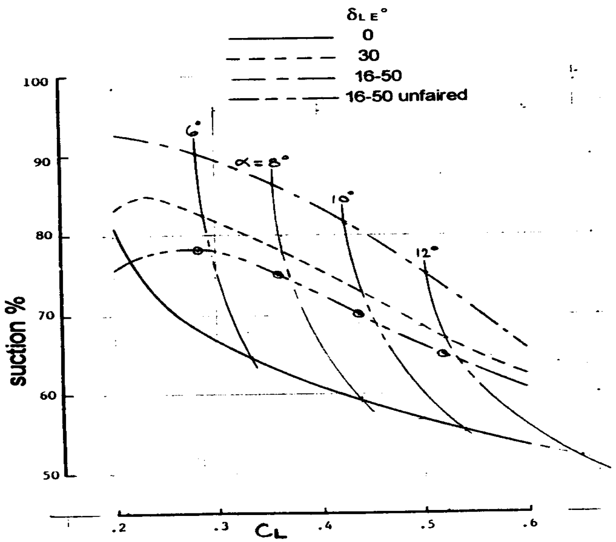


FIG. 7 ATTAINED SUCTION LEVELS, EFFECT OF LE DEFLECTION

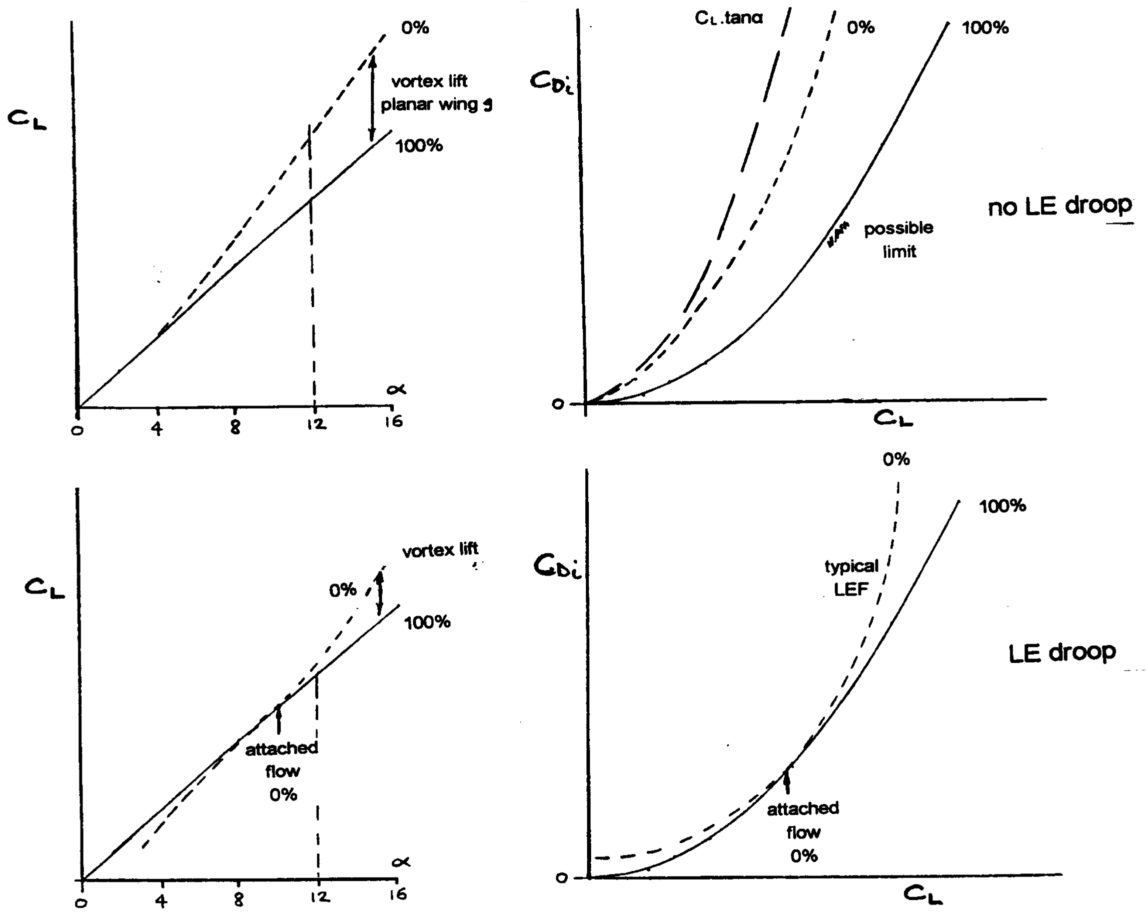


FIG. 8 LIFT, DRAG, WING WITH & WITHOUT LE / TE DROOP

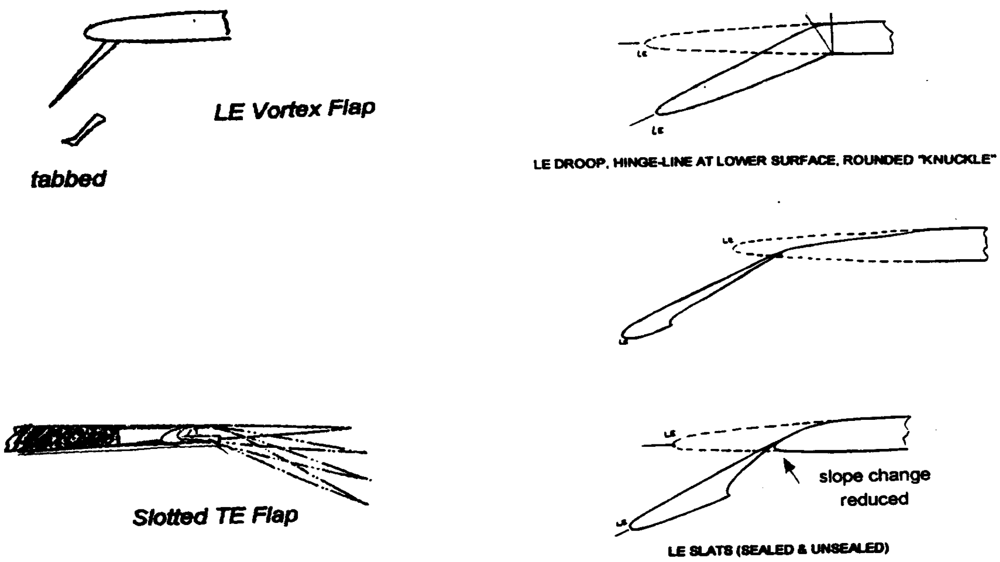


FIG. 9 TYPES OF LE DEVICES

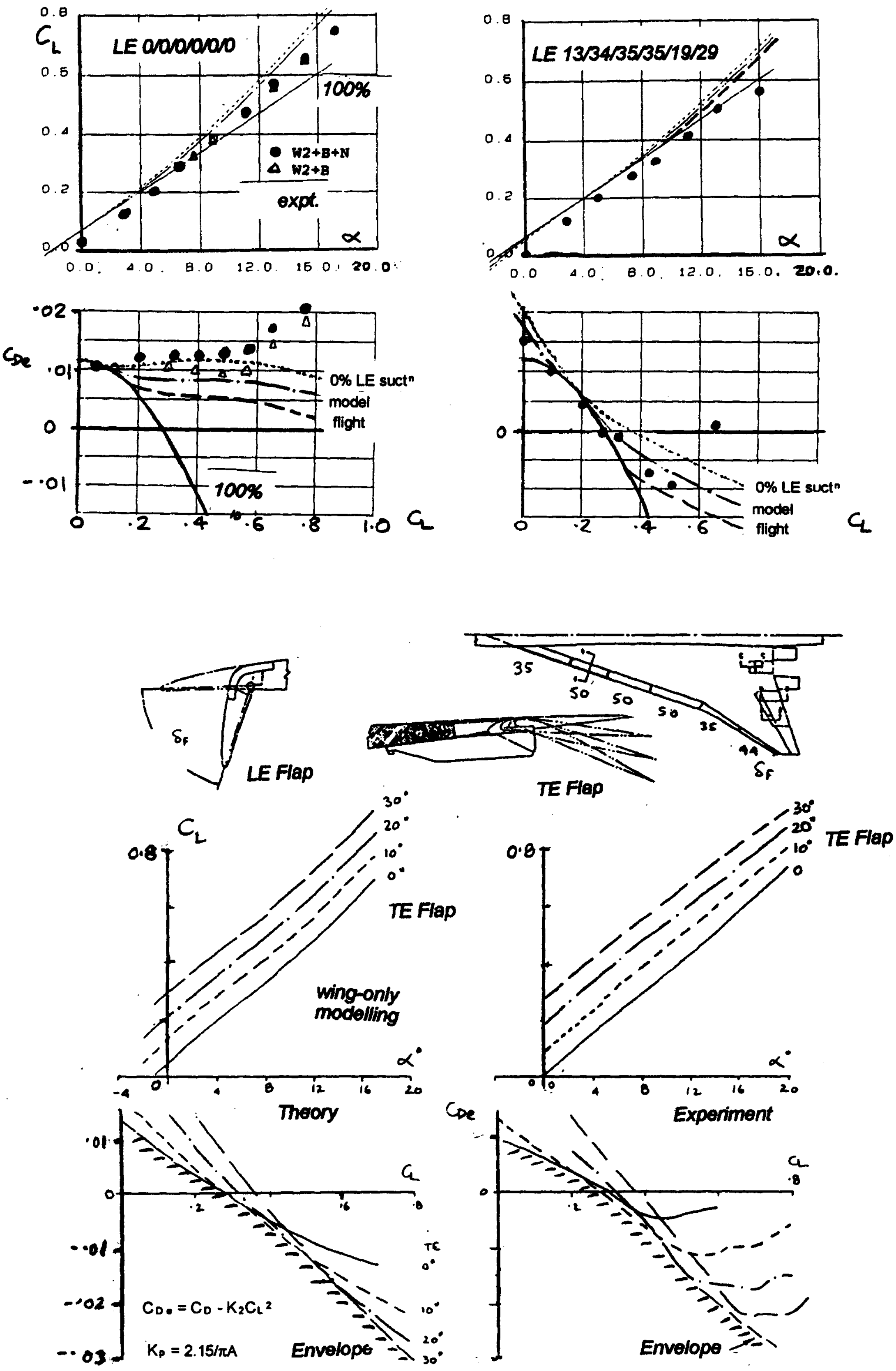
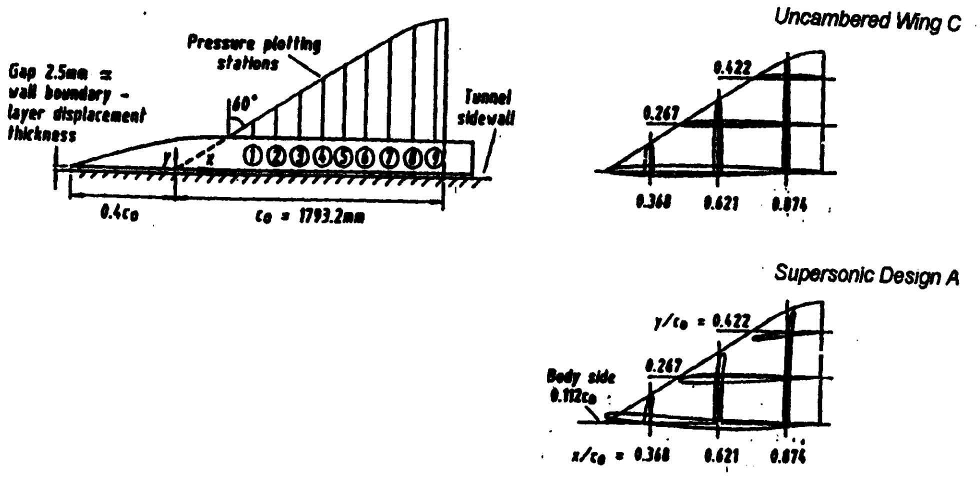


FIG. 10 THEORY (THIN-WING) & EXPERIMENT, LE & TE FLAP DEFLECTIONS
Re = 4.76x10^6, Mach 0.09, MDC MODEL



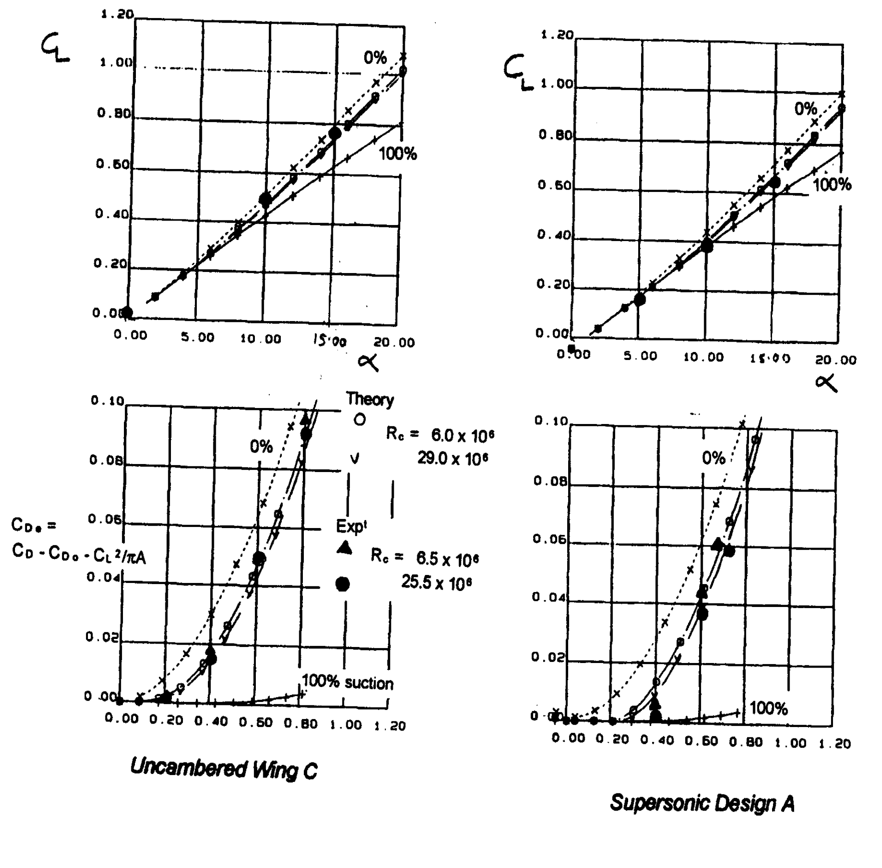


FIG. 11 THEORY (THICK-WING) & EXPERIMENT, LIFT-DRAG, Re EFFECTS AT MACH 0.6
(Experiments of Ashill et al)

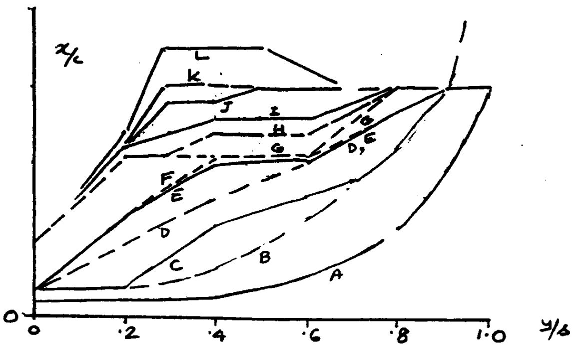


FIG. 12 TYPICAL HINGE-LINES

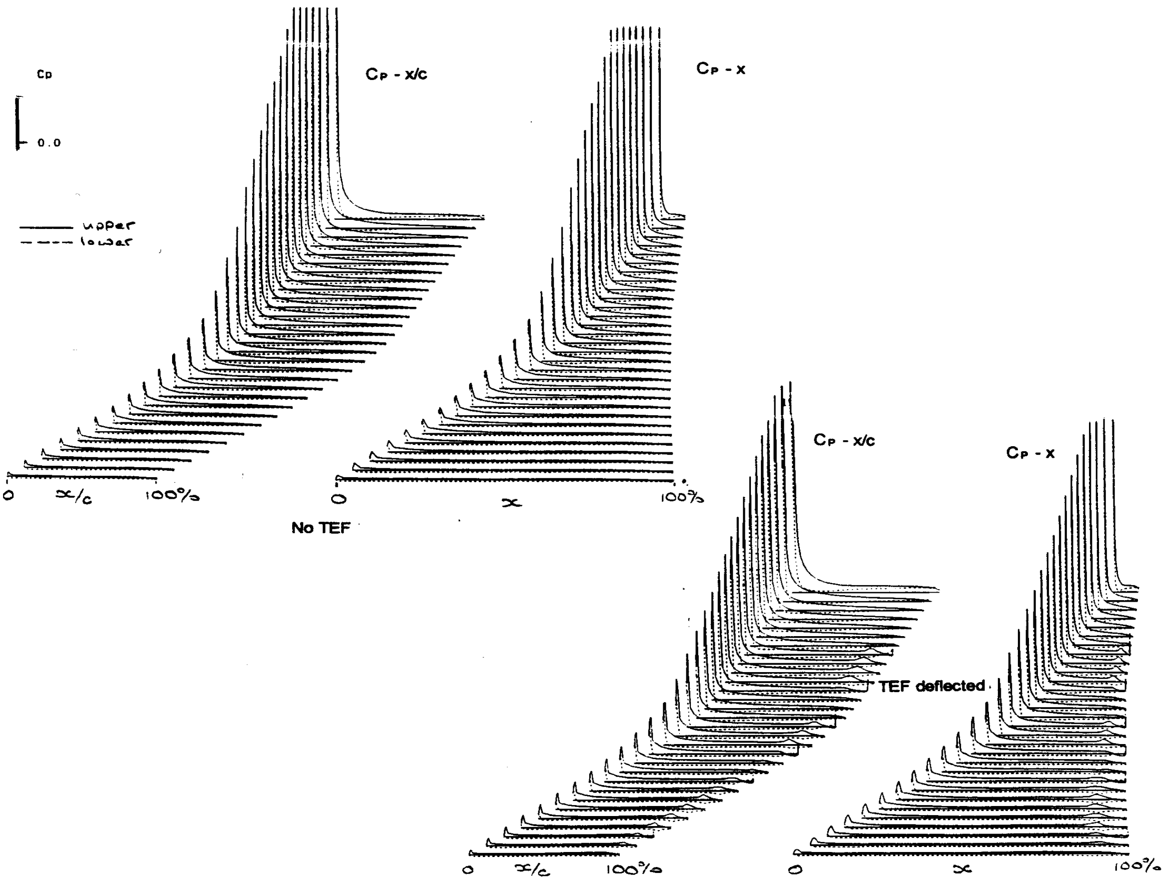


FIG. 13 DATUM WING, Cp DISTRIBUTIONS AT α = 12°, WITH & WITHOUT TEF DEFLECTED

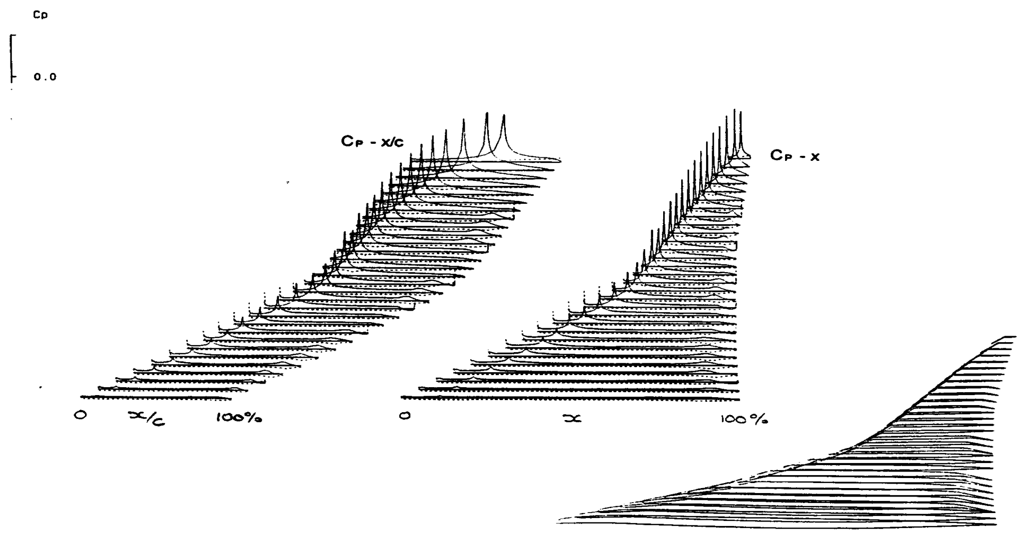


FIG. 14 WING WITH LE FLAP, Cp DISTRIBUTIONS AT α = 12°, TEF DEFLECTED

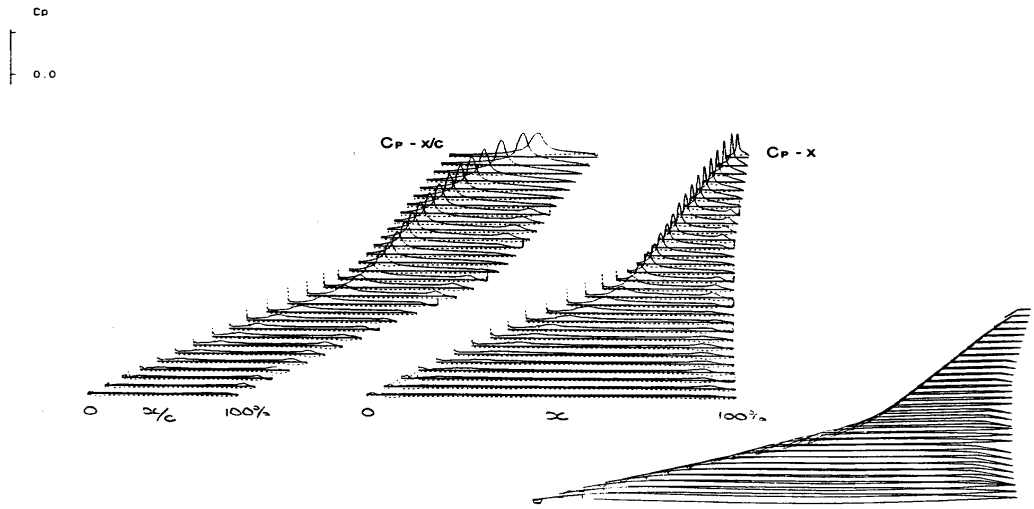


FIG. 15 WING WITH LE SEALED-SLAT Cp DISTRIBUTIONS AT α = 12°, TEF DEFLECTED

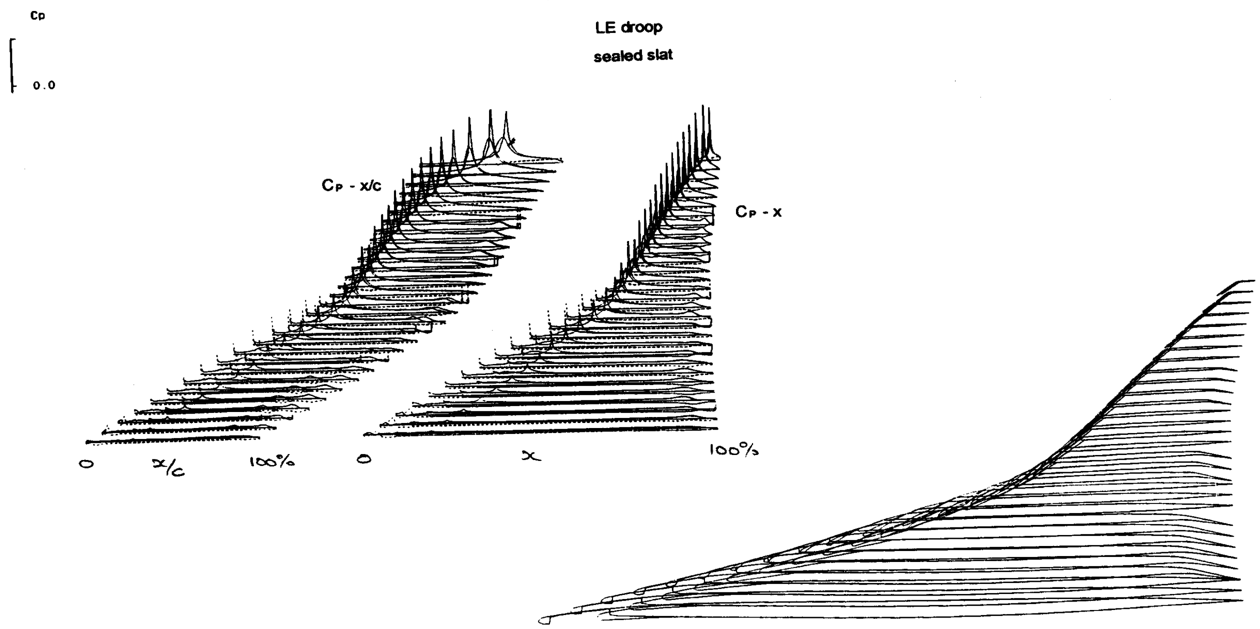


FIG. 16 A COMPOSITE OF LE FLAP & LE SEALED-SLAT Cp DISTRIBUTIONS AT α = 12°, TEF DEFLECTED

Paper: 9
Author: Dr. Nangia

<u>Question by Dr. Khalid</u>: You say that you had good agreement between theory and experiment. Getting good agreement is a little more than just getting good C_L/C_D trends. Did you carry out any other pressure distribution or flow field comparisons to be able to make such claim?

<u>Answer</u>: Here "good agreement" is in the context of forces and moments. The work is aimed at applications more from project/design viewpoint. Good L/D estimates, etc. are extremely significant. With leading-edge devices designed for attached flow, the pressure predictions are more comparable with experiment.