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PREDICTION OF LE & TE DEVICES AERODYNAMICS IN HIGH-LIFT CONFIGURATIONS WITH MACH & REYNOLDS NO. EFFECTS

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SUMMARY

The design of an efficient high-lift system on aircraft is effort-intensive. High-lift systems include combinations of "conventional" LE slats and Krueger flaps.

The design process needs to include Mach (M) and Reynolds number (R) effects and implies extensive, costly experimental investigations for selection and optimising. It is therefore prudent to seek theoretical techniques to give satisfactory designs prior to tests.

This paper focuses on results from a technique, incorporating attained thrust principles, capable of addressing M and R effects on high-lift systems of conventional and unconventional wings.

In this paper, wings with LE slats and TE flaps are considered. Initial work focusses on a moderate aspect ratio wing. This is followed by a programme on a generic transport wing. Correlation with experiment is very encouraging. Further, the examples give an understanding of the underlying flow mechanisms for the design of high-lift systems. These also demonstrate the flexibility and potential of the technique and highlight the opening of design space in a logical way. Effects of Reynolds number are particularly strong.

The encouragement provided by the work to-date makes a strong case for continued applications to more realistic and representative geometries.

1. INTRODUCTION & BACKGROUND

Designing an efficient high-lift system (e.g. on A-320, **Fig.1**) is a major effort-intensive challenge. The design process includes Mach (M) and Reynolds number (R) effects implying extensive theoretical and (costly) experimental studies for selection / optimising. The process is complicated by viscous and other effects (nacelle, pylons) and a "large degree" of extrapolation from model to flight scale is usually required. Project designers therefore rely on an evolutionary and largely empirical approach; adapting and developing a related "working" design. This approach, by necessity, proceeds along "narrow" guide-lines.

With existing techniques it is difficult to track the behaviour of a high-lift configuration across the wide range of flight envelope conditions, through experienced "hard" or "soft" flow separation limits. Equally, there is no accepted technique for modifying configurations at wind tunnel conditions to more closely represent flight behaviour with the necessary confidence.

Challenges & Motivations

Fig.2 summarises challenges and motivations for 3-D high-lift (Refs.3-7). A few well-known and practical inferences relate model and flight scale which are relevant to conventional and laminar flow wings:

- At a given M, as R increases, $C_{L max}$ increases. In certain cases, there is evidence of the trend changing at high R when reducing viscous effects may alter the "optimum-balance" between the individual components of a high-lift system. "Hard or soft" flow separation limits may be apparent.
- LE device location optimisation is required on lift and/or drag basis (landing or take-off).
- LE device design is to be within practical manufacturing or structural constraints.
- Understanding of onset of hard and soft flow separation limits.
- Arriving at broader guide-lines for design of more optimum geometry within structural constraints at model or flight scale. More curved LE slats/vented Kruegers are needed for lower R.
- Coping with natural or imposed geometry discontinuities and constraints.

Such aspects have prompted the formulation of theoretical models embodying reliable empiricisms. In view of the large database to be explored, the keynote is efficient CFD. The premise naturally is that large reductions in experimental effort and costs will result. A typical objective would be to conduct confirmatory studies rather than general exploratory ones, prior to flight test.

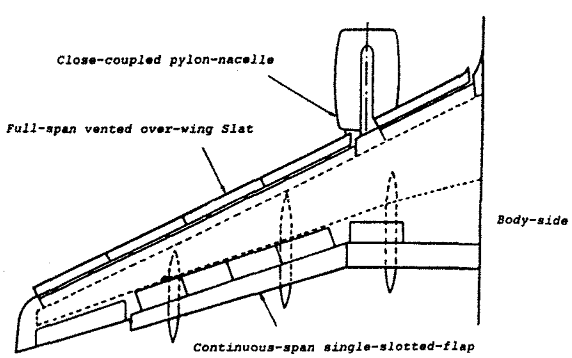
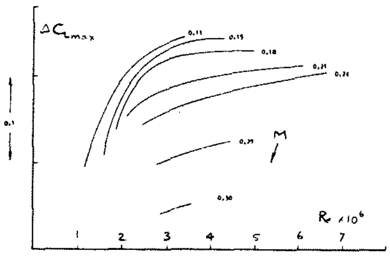
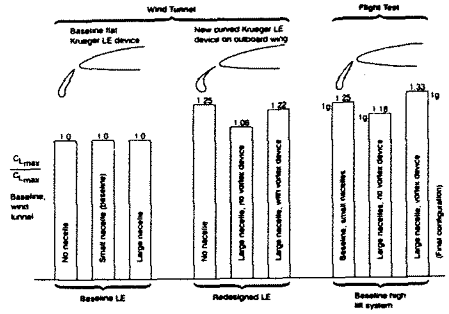


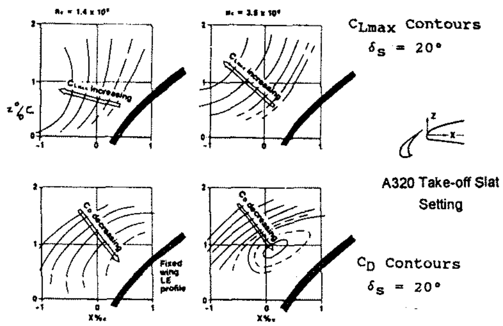
FIG. 1 A320 HIGH LIFT SYSTEM (Wedderspoon, ICAS'86 PAPER)



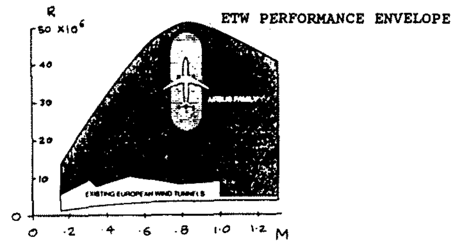
Increase in C_{Lmax} due to R increase at Given Mach



Vented Kruegers - Tunnel & Flight C_{Lmax} (Brune et al)



SLAT location (Wedderspoon et al)



High Lift & Wind Tunnel requirements (Green ARA)

FIG. 2 CHALLENGES & MOTIVATIONS FOR 3-D HIGH LIFT

2. PRESENT TECHNIQUE

The technique developed is capable of addressing the effects of Mach number M, and Reynolds number R, on high-lift systems in a general way. Compared with other approaches available, the capabilities of the technique are different (possibly unique) and more design related. The technique incorporates attained thrust and panel methods (with and without viscous effects). It can also be be applied to high-lift aspects of variable camber wings, conventional as well as unconventional.
According to the attained thrust concept, higher R permits higher proportion of thrust levels to be attained. Increasing M reduces LE suction level attained (**Fig.3**). Thin (or sharper) aerofoils reduce the attained thrust levels. Semi-empirical correlations of LE suction attainment factors have been embodied in a cost-effective approach that can be used on work stations.

Usage has demonstrated the ability to explain rationally why existing methodologies have worked and more importantly sound guidance is offered for improving methodologies which permit flight parameters to be developed and proved with greater confidence in the wind tunnel.

Applications in Ref.7 to Krueger flap systems has given an understanding of why large Krueger deflections are needed and why there are significant variations along the wing-span.

To indicate the important features, broad capabilities and the potential of the technique, it is apt to review selected applications on super-critical section wings (of different aspect ratio) with "conventional" LE slats and TE flaps.

3. HIGH-LIFT APPLICATIONS WITH LE SLAT

With this technique, the estimation of overall performance (C_L & C_D) with varying LE slat and TE flap positions as function of Mach and Reynolds number leads progressively to an optimised location of LE slat. A few runs of the flow solver are usually needed. The geometry changes needed from one stage to next are usually small, and a previous solution can be used as a starting point for the following case.

We next consider applications to two wings of "moderate" and "generic" aspect ratio.

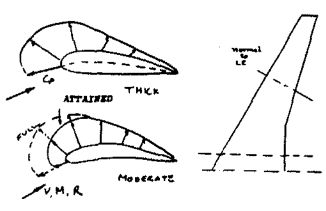


FIG. 3 ATTAINED THRUST PRINCIPLES, 3-D WING

Moderate Aspect Ratio Wing with LE Slat only

For a moderate aspect ratio wing, **Fig.4** shows the C_L - α comparison for the reference case (lap and gap) at $R = 9x10^6$. Theory predicts a "sharp" stall which closely mimics the measured data from 3 test runs.

Fig.5 refers to slat TE location variation with respect to wing LE. Contours of C_L and lift-induced drag C_{De} (= C_{Di}-$0.064C_L^2$ at C_L = 2.0) are shown. Note the "boundary" marking flow separation either at the wing LE or at the slat. The flow separation tendency on the slat increases below this line and the stall behaviour is "hard". These contours bear marked resemblance to the measured ones (Ref.4).

Additionally, the technique offers an ability that experimental data does not easily do, i.e. the spanwise variation of the slat position and component loads. **Fig.6** shows the C_{LL} contours for slat TE variation at different spanwise stations on the wing. Note the position of C_{Lmax} relative to the wing/slat separation line. The slat appears to be heavier loaded than the wing.

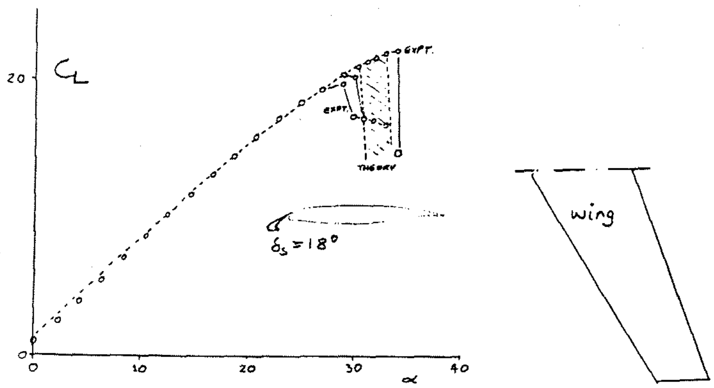


FIG. 4 WING + SLAT 18°, REFERENCE LAP & GAP, MACH = 0.17, Re = 9x10^6, PREDICTION & EXPERIMENT (3 DIFF. RUNS)

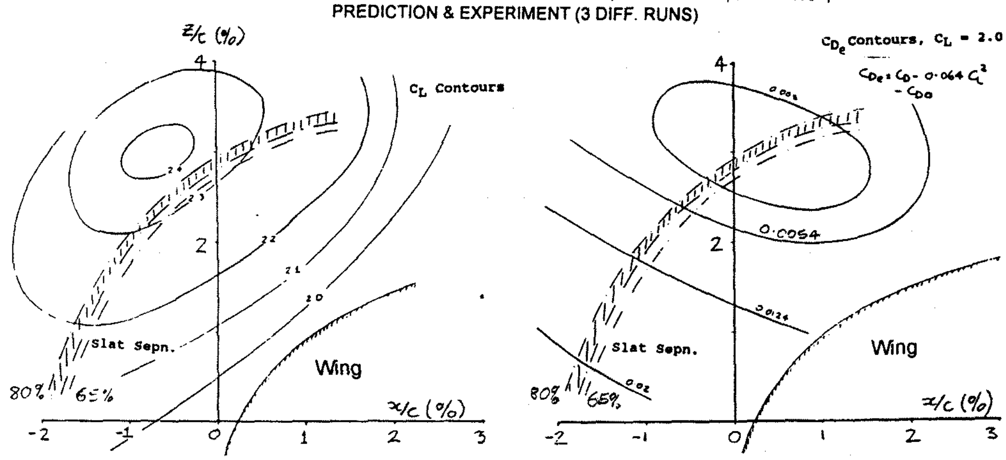


FIG. 5 WING + SLAT 18°, LAP & GAP VARIED, MACH = 0.17, R = 9x10^6

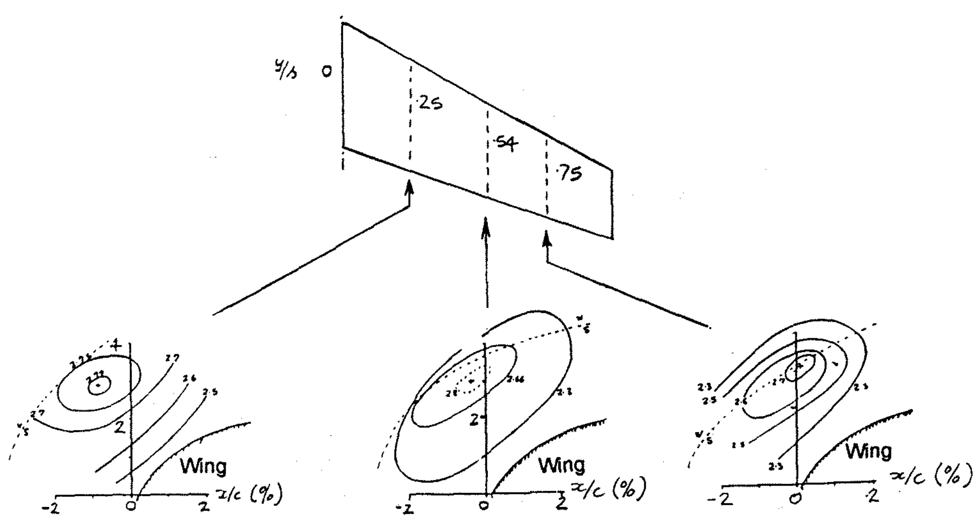
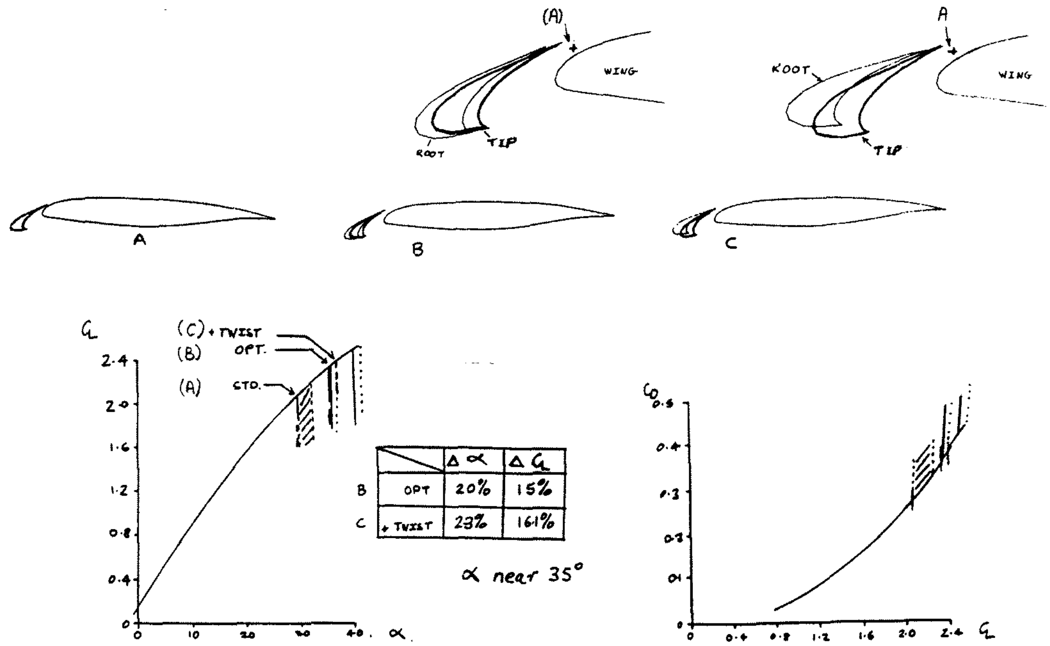


FIG. 6 WING + SLAT 18°, LAP & GAP VARIED, MACH = 0.17, R = 9x10^6, C_{LL} Contours at Different y/s

Fig.7 shows two cases for "narrow" optimising of slat geometry by relating to the C_L contour variations along the wing span. Note the availability of up to 16% increase in lift. The C_D trend follows the attached flow trend.

Fig.8 compares the spanwise variation of peak -Cp for the reference and an optimised case at α = 28°& 36°. For the "optimised" case, the slat suctions have been reduced while those on wing, increased as intended.

This feature enables the "very best" slat location and the slat shape to be determined for highest lift performance (L/D), which cannot be done experimentally. Further the model and flight geometry can be differentiated. Higher camber may be required at model scale.



	Δα	ΔC_L
B OPT	20%	15%
C + TWIST	23%	16.1%

FIG. 7 OPTIMISING WING + SLAT LAP, GAP & TWIST (REFERRED TO 18° SLAT), MACH 0.17, Re = 9x10[6]

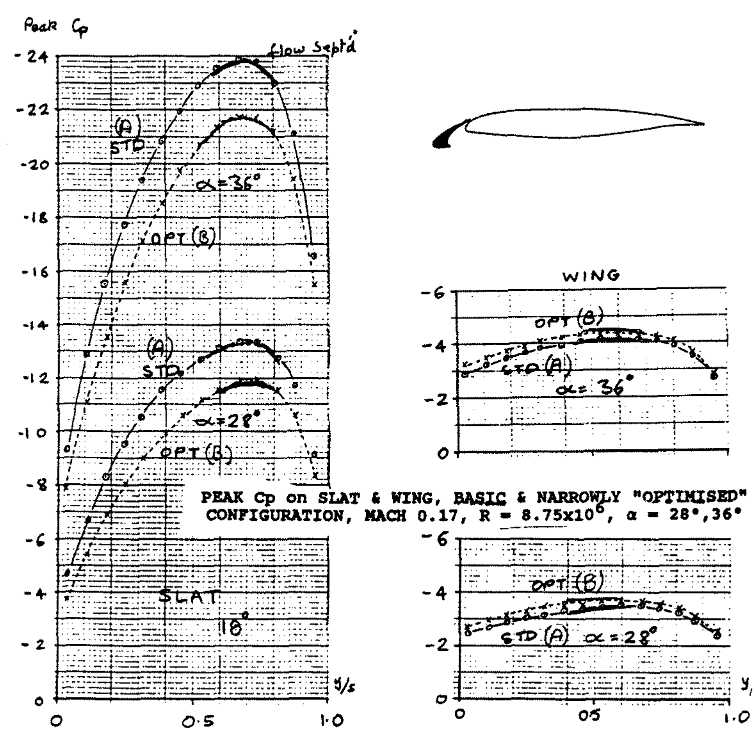


FIG. 8 PEAK Cp on SLAT & WING, BASIC & "NARROWLY OPTIMISED" ARRANGEMENT, MACH = 0.17, Re = 9x10[6], α = 28° & 36°

Moderate Aspect Ratio Wing with LE Slat & TE Flap

Fig.9 shows a C_L - α comparison for R = 3 & 9x10^6. Theory predicts a small range for "stall" which closely mimics the measured behaviour.

Similar procedure as above, used with TE flap (**Fig.10**) led to very significant 8% increase in $C_{L\,max}$.

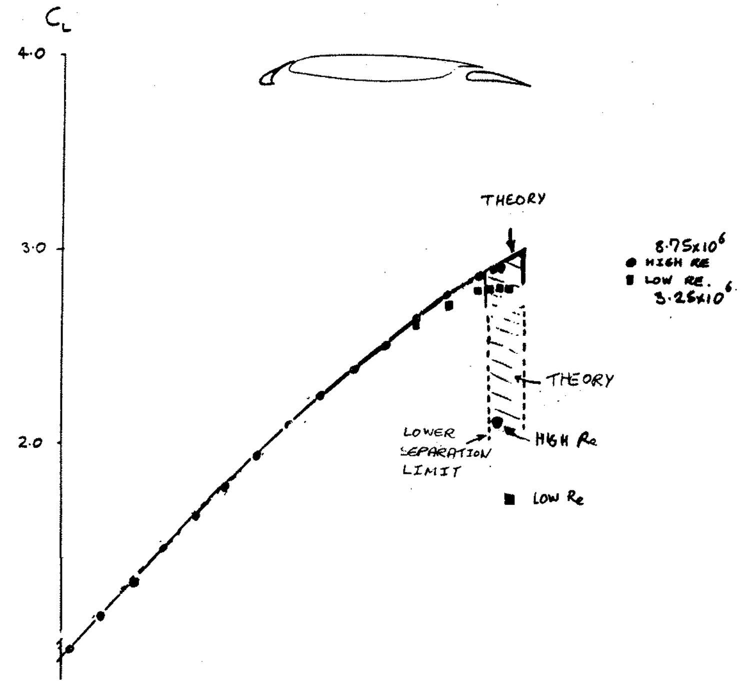
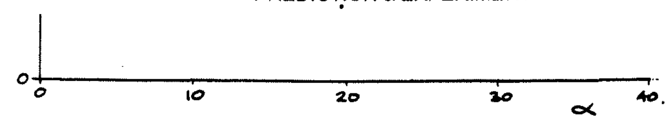


FIG. 9 WING + SLAT 18° + TE FLAP 18°, REFERENCE LAP & GAP, MACH = 0.17, Re = 3 & 9x10^6, PREDICTION & EXPERIMENT



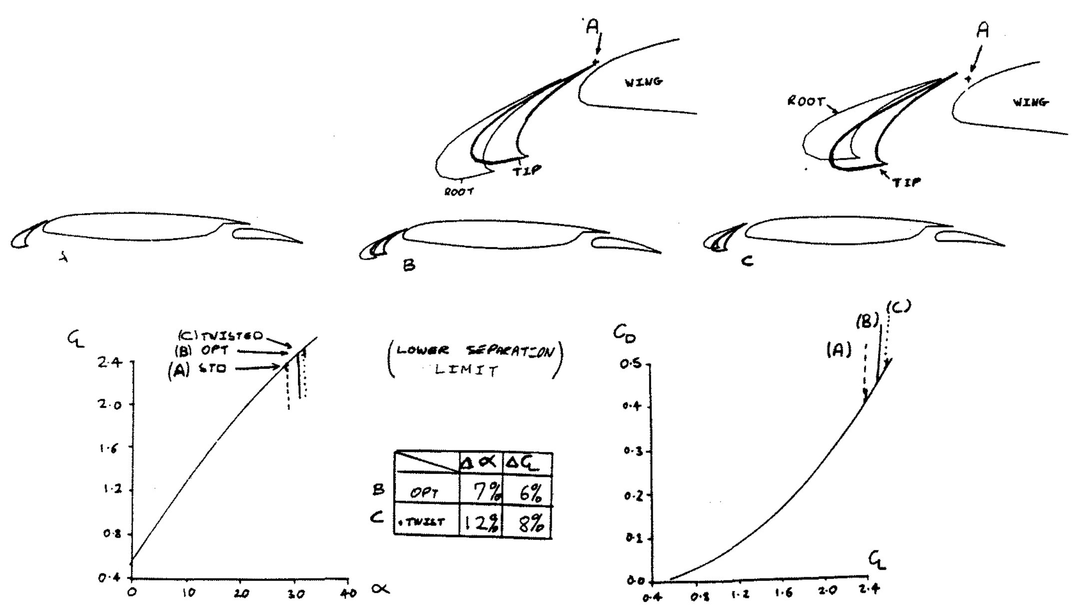


FIG. 10 OPTIMISING WING + SLAT LAP, GAP & TWIST (REFERRED TO 18° SLAT) + TE FLAP 9°, MACH 0.17, Re = 9x10^6

Generic Transport Wing with LE Slat & TE Flap

Studies on a more representative wing (Refs.1 & 7, without nacelle), **Fig.11**, illustrate the effect of R on the "balancing act" between the wing and LE slat loads. The loads are strongly dependent on the slat deflection and location. For a 10° slat, **Fig.12** shows the effect of two R values on C_L limits of wing and slat (in forward-, mid- and aft- locations). Mid-position of the LE slat gave balanced loads at the higher R, whilst the aft-position was more favourable at the lower R. For an 18° slat, **Fig.13**, physical geometry constraints prevent the slat-wing arrangement from being fully "balanced". This does not mean that we should stop at this stage and geometry variations e.g. slat curvature may lead to continued improvements.

For the LE slat configurations, the method has demonstrated the ability to explain rationally why existing methodologies have worked. More importantly it provides sound guidance for developing improved methodologies which permit flight parameters to be developed with greater confidence in more focussed wind tunnel programmes.

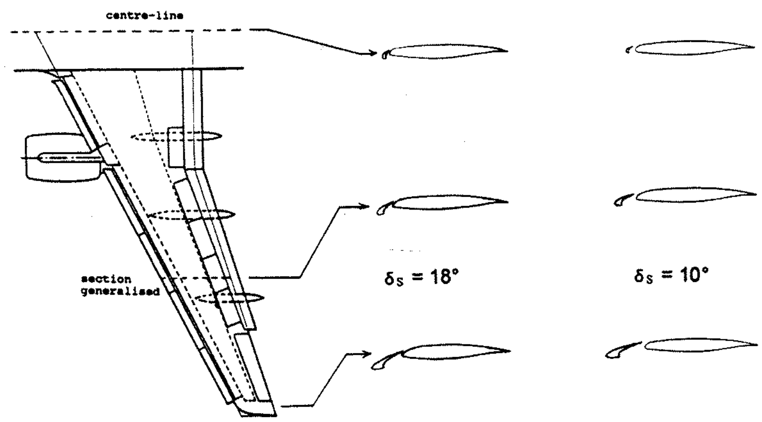


FIG. 11 GENERIC TRANSPORT WING, SLAT 10° & 18°, TE FLAP 0°

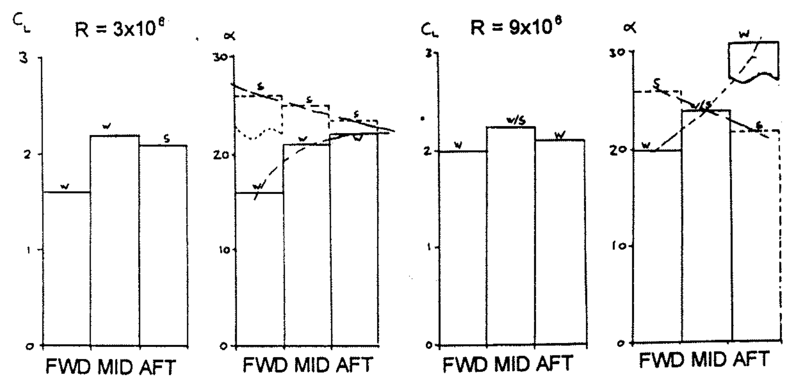


FIG. 12 EFFECT OF FORWARD-, MID- & AFT- SLAT POSITION on TOTAL C_L at FLOW SEPARATION, SLAT 10°, Re = 3 & 9x10⁶

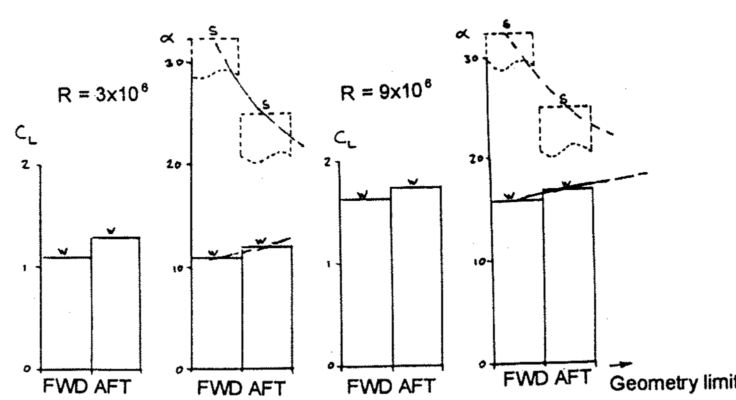


FIG. 13 EFFECT OF FORWARD-, & AFT- SLAT POSITION on TOTAL C_L at FLOW SEPARATION, SLAT 18°, Re = 3 & 9x10⁶

4. CONCLUDING REMARKS & FUTURE WORK

The design of efficient high-lift system on modern transport aircraft is a major and effort-intensive challenge. It can imply extensive theoretical and (costly) experimental investigations for selection and optimising. The process is complicated further by viscous and other effects (nacelle, pylons) and a "large degree" of extrapolation from model to flight scale is usually required. For a new project, designers therefore rely on an evolutionary and largely empirical approach; adapting and developing a related successful design. This approach, by necessity, proceeds along "narrow" guide-lines.

This paper has focussed on results from a relatively new technique for prediction of aerodynamic characteristics of LE and TE devices and applications in high lift configurations. The technique is capable of addressing the effects of Mach and Reynolds number in a general way. Compared with other approaches available, the capabilities of the technique are different (possibly unique) and more design related. The technique "broadens" the guide-lines and leads to an easier optimisation process at model and flight scale. It can be applied also to variable camber wings. The broad capabilities and the potential of the method have been outlined. The premise naturally is that large reductions in experimental effort and costs will result.

The examples have given an understanding of the underlying flow mechanisms for design of LE devices. These have also demonstrated the flexibility and potential of the technique and highlighted the opening of design space in a logical way. R effects are particularly strong. It has been inferred that:

1. In order to arrive at a "balanced" configuration, the LE device geometry needs to be apt for model / flight scale and its performance is very sensitive with respect to the lap and gap from the wing LE.

2. Most of the early predictions can be carried out with an inviscid approach. Viscous effects are needed only on reasonably "workable" configurations on which LE suction levels are realistic and attainable on LE and TE devices.

3. Drag polars at different Reynolds numbers can be predicted. Estimates for the spanwise variation of skin friction drag will allow L/D to be evaluated.

4. It is possible to investigate and compare several candidate devices prior to design selection or testing.

The encouragement provided by the work to-date makes a strong case for continued application to realistic geometries. Further work is seen in the following aspects:

1. Prediction of C_L (attached) on LE devices and wing. This needs to be extended to $C_{L\,max}$ prediction.

2. Investigating "mixed" types of devices. Work is required in estimating workable ranges of LE devices (Flaps, Slats, Kruegers) throughout Mach and Reynolds number ranges (wind tunnel to flight). Prediction of optimum geometry and gaps (in slats). Variable Camber geometry wings are inclusive.

3. Extension to full 3-D configuration capability is possible. Fuselages, pylons can be introduced. Loads on components can be predicted.

These aspects will have a constructive impact on the 3-D high lift systems, conventional and unconventional.

ACKNOWLEDGEMENTS

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The work programme mentioned is a part of in-house Research & Development activities. We are, of course, open to commissions and suggestions for future.

Any opinions expressed are those of the authors.

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LIST OF SYMBOLS & ABBREVIATIONS

b	Wing-span
AR	Wing Aspect Ratio
BL	Boundary Layer
c	local chord
c_{av}	= c, Average chord = c_{ref} (Reference chord)
C_D	= D/(q S), Drag Force Coeff., D is Drag Force
C_{Di}	= Lift-Induced Drag Coeff.
C_L	= L/(q S), Lift Force Coeff., L is Lift force
C_{LL}	Local Lift Force Coefficient
C_p	Pressure Coefficient
HL	Hinge-Line
LE	Leading edge
M	Mach number
q	= 0.5 ρ V^2, Dynamic Pressure
R,R_e	Reynolds Number based on c_{av}
s	Wing semi-span
S	Wing area
t	local thickness (aerofoil or component)
TE	Trailing Edge
V	Airstream Velocity
x,y,z	Orthogonal Co-ordinates,
α	Angle of attack
δ_F	TE flap Deflection
δ_s	LE Slat Deflection
η	= y/s, Non-dimensional spanwise Distance
ρ	Air Density