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DESIGN OF MANOEUVRABLE SIMPLE & COMPLEX PLANFORM TRANSONIC WINGS WITH ATTAINED THRUST-, PANEL- & EULER- METHODS

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ABSTRACT

New generation of aircraft will require increased performance from the wing throughout the flight envelope. The wing design will be a compromise between the requirements of efficient cruise, high speed dash (low C_L) and transonic manoeuvrability (high C_L). Practical project requirements may lead to complex planforms incorporating Leading-Edge strakes (LERX) with sharp leading edges.

The general design practice is to use linear theory panel methods for sub-critical flow conditions and full potential or Euler methods for transonic conditions. Sharp leading edges with consequent flow separations and the formation of vortices can sometimes pose problems.

The method of this paper is based on the incorporation of a LE "attained thrust" method into a linear theory programme. This enables an optimum camber surface to be generated with near-elliptical spanwise loading at the design point with a broad off-design capability. Empirical Mach number and Reynolds number effects on "attained thrust" can be introduced. The "attained thrust" depends also on wing aerofoil parameters which may be varied. The present method differs from conventional methods which imply a near elliptical spanwise lift loading at the design point and which can in certain situations lead to LE suctions which may not be "attainable" in practice.

Euler methods, which are both more capable and more expensive than linear methods, are used to verify the design at transonic design points where strong shocks may be present which require a modification to the initial conditions. A few iterations of this design cycle are normally required.

The examples chosen illustrate the applications to simple planforms and to complex wings with LERX strakes. The cambered designs have been verified against multi-block Euler methods. This aspect is particularly encouraging as isobars on upper surface are well behaved. The design process can be biased towards efficient high speed or high manoeuvrability or a suitable combination.

The work has proved encouraging and it underlines a logical and relatively inexpensive design technique for low-camber transonic aircraft wings with tolerant off-design behaviour. Several aspects for further work including experimental verification have been proposed e.g. work with LE and TE devices to increase the manoeuvrability.

1. INTRODUCTION

New generation of aircraft will require increased performance from the wing throughout the flight envelope. The wing design will be a compromise between, for example, the requirements of efficient cruise, high speed dash (low C_L) and transonic manoeuvrability (high C_L). Practical project requirements may lead to complex planforms incorporating Leading-Edge Root Extensions (LERX) or strakes with sharp leading edges (LE) (Fig.1).

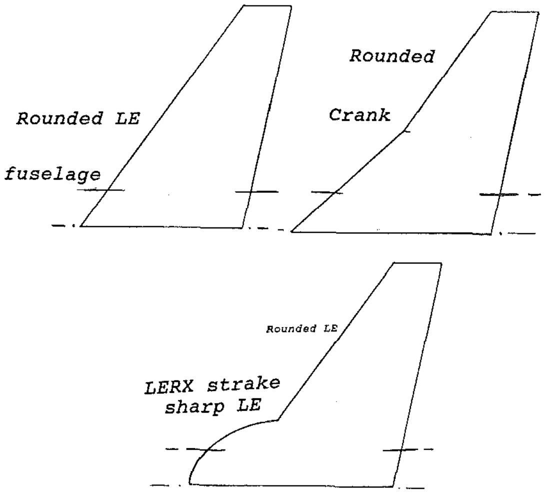

FIG. 1 POSSIBLE CHOICE OF PLANFORMS AT OUTSET

General Design Practice

The underlying philosophy is to design the wing for efficient high speed cruise (low camber, weak shocks on upper and lower surfaces). High C_L conditions are then catered for, with minimum sized LE and TE controls.

In the general design methodology, linear theory panel methods are used for sub-critical conditions and full potential or Euler methods for transonic conditions. Inverse transonic (iterative) design methods can, in general, allow the shock location and strength to be tailored, but the optimum operational lift range can often become "narrow". In certain cases, because upper and lower surfaces are treated independently, the effective mean-surface camber can show inflexions and this may lead to possible off-design penalties.

Sharp leading edges with associated flow separations and the formation of vortices frequently cause problems. Difficulties are also found when a portion of the LE is discontinuous and sharp as in LERX. In such a case, a difficult mixed flow problem arises due to interaction between the flow separations (vortical flow) over the inner region which has a "sharper" aerofoil section and the nearly attached flow over the outer wing.

On the other hand, linear theory using mean camber surfaces, may be formulated to account for the mixed flow problem (LE in part sharp, and in part, round). An extra advantage is that the Mach and Reynolds number effects can be empirically introduced in terms of "attained thrust" so that the high lift capability and "tolerant" design range can be validated.

2. PRESENT APPROACH, BRIEF DETAILS

2.1. Main Features

At the outset of a wing design task, there is a choice of several typical planforms: simple or complex. For dealing with such planforms, a "hybrid" approach (Fig.2) has been devised. This method is based on the incorporation of a LE "attained thrust" method into a linear theory programme. This enables an optimum cambered (and twisted) surface to be generated with near-elliptical spanwise loading at the design point with a broad off-design capability. If required, the aerofoil parameters can be varied. In general, thicker sections lead to higher "attained suction" and therefore low camber designs. Empirical Mach number and Reynolds number effects on "attained thrust" can be introduced. Euler methods, which are both more capable and more expensive than linear methods, are used to verify the design at transonic design points where strong shocks may be present which require a modification to the initial conditions. A few iterations of this design cycle are normally required.

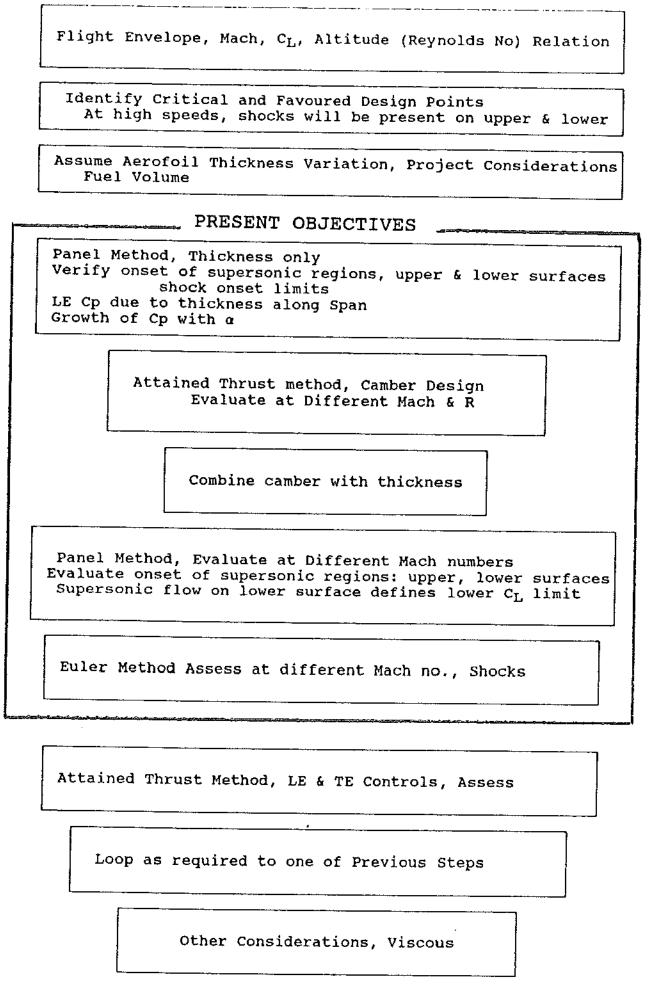

FIG. 2 DESIGN APPROACH

The present design method differs from conventional methods which imply a near elliptical spanwise lift loading at the design point. The elliptical loading can lead to high LE suctions particularly on highly tapered wings and these suctions which may not be attainable in practice. Shock tailoring methods (Refs. 1-3) go partly and indirectly towards the objective of limiting the LE suction.

The examples chosen for this paper depict the applications to moderately swept simple and complex (LERX strake) planforms. These studies demonstrate the salient points of the present approach.

3. CONSIDERATION OF TYPICAL DESIGN, MANOEUVRE ENVELOPE FOR TRANSONIC AIRCRAFT

Fig.3 shows the 1g C_L - Mach relationships at different altitudes (Sea level, 10k, 30k ft), for two wing loadings of a typical aircraft: low $(W/S)_1$ and high $(W/S)_2$. For high speed, generally, low C_L values are required.

For efficient manoeuvre (without excessive flow separations) at moderate high speed, an average of 1.5 to 2g flight would be anticipated. This will imply that LE and TE devices are likely to be needed for high lift conditions.

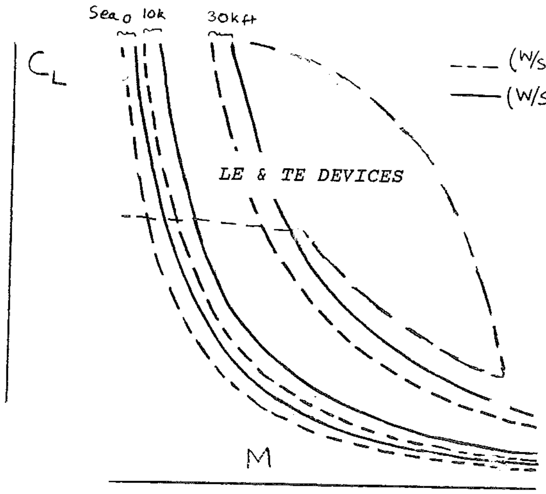

FIG. 3 C_L - M RELATIONSHIPS AT Sea Level, 10k & 30k ft, $(W/S)_1$ & $(W/S)_2$, 1g FLIGHT & TYPICAL MANOEUVRE ENVELOPE

Reynolds numbers at high speed condition vary from 18 to 50×10^6 (based on g.m.c.) depending on the altitude. For loiter and manoeuvre, the comparable range is 10 to 35×10^6.

It follows that optimisation is required over a wide range of Mach, C_L and Reynolds number combinations. The demanding and critical conditions from the viewpoint of manoeuvrability are those at high altitude: high C_L and low values of R. Low altitude and high speed can also be critical.

An interesting point relating to scale model tests is apparent from the foregoing considerations. For a typical 10% model in an un-pressurised wind tunnel (at sea level), Reynolds numbers of the order of 3 - 5 x 10^6 can be achieved which are still much lower than those required to simulate full-scale flight at 30k ft. This raises the possibility of designing the model in its own environment. Subsequent to verification of theory and experiment, the design can be aimed at the full-scale environment.

4. BASIC WING (STRAIGHT LE)

We begin with an uncambered wing with straight and rounded LE. This lays the foundations for the comparisons. The tapered wing selected is of moderate sweep and moderate aspect ratio. The average wing aerofoil t/c is 9.5%.

Evaluating Uncambered Rounded LE Wing (A)

Using the attained thrust method, longitudinal characteristics of the wing (A) were predicted. The performance of the wing is displayed in terms of the induced drag factor k, defined from the well known relationship:

$$k = \pi A (C_D - C_{DO}) / C_L^2 .$$

Fig.4 shows the iso - k lines on C_L - Mach basis at 30k ft. Note that the attached flow regime range (k = 1.03) decreases as the Mach number increases.

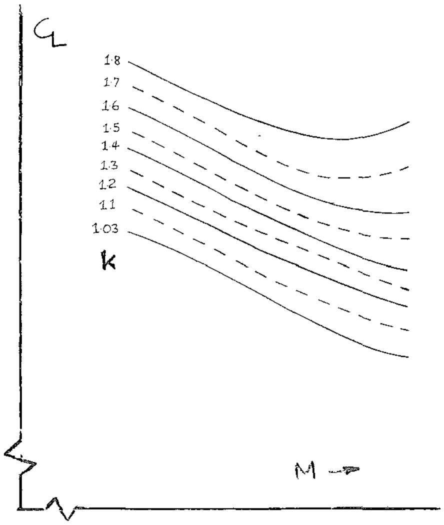

FIG. 4 BASIC UNCAMBERED WING (A), CONSTANT k LINES ON C_L - M BASIS, 30k ft.

On C_L - Mach basis, Fig.5 and 6 show the various boundaries (shock onset on upper surface, attained thrust limits for 0% and 7% drag penalty). These boundaries (see also Fig.2) have been supported by selected pressure distributions. Note the high *suction peaks near the wing tip.* The attained thrust limits (0 and 7% drag penalty) are higher than the shock onset limit at high speeds. The achievements of the wing with regard to the 1g flight envelope are evident from Fig.5. Note the deficiency for high C_L at moderate Mach numbers.

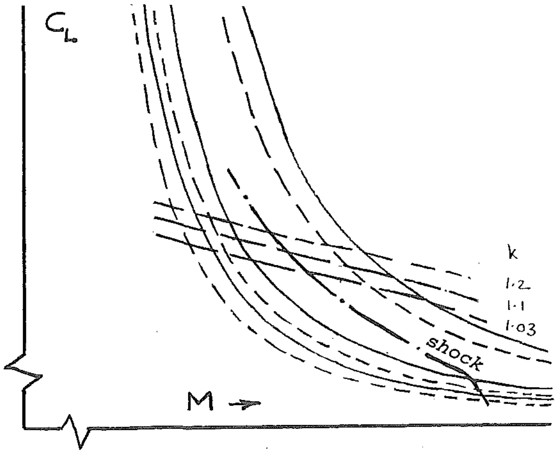

FIG. 5 C_L - M RELATIONSHIPS AT Sea Level, 10k & 30k ft, $(W/S)_1$ & $(W/S)_2$, 1g FLIGHT & BOUNDARIES OF UNCAMBERED WING (A)

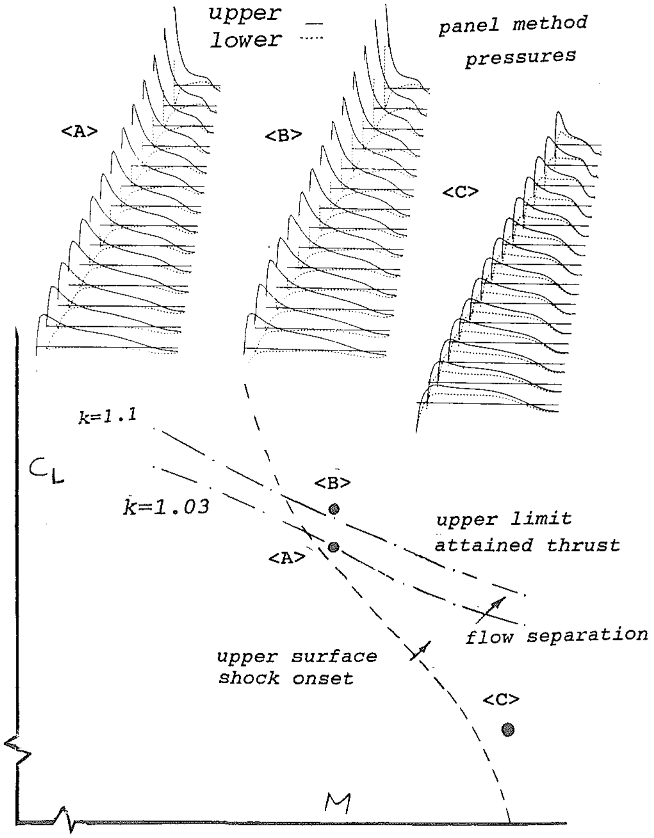

FIG. 6 ROUNDED LE, UNCAMBERED WING (A), VARIOUS BOUNDARIES (C_L - M BASIS) WITH SELECTED PRESSURE DISTRIBUTIONS

Wing (B) Designed For High Manoeuvrability at Moderate Speed

Fig.7 refers to a rounded straight LE wing (B) with its camber and twist designed for high manoeuvrability at moderate speed at high altitude. It shows the iso - k lines on C_L - Mach basis at 30k ft. Note that attached flow region (k = 1.03) is bounded with a lower and a higher C_L value. The factor k is acceptable for low to moderate Mach numbers but rather large for high speed cruise.

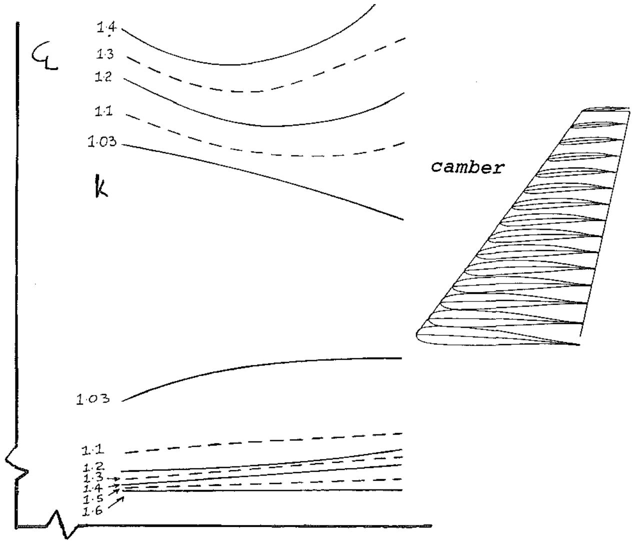

FIG. 7 CAMBERED WING (B), CONSTANT k LINES ON C_L - M BASIS, 30k ft.

Fig.8 summarises the various boundaries supported by selected pressure distributions and isobars. Fig.9 relates these boundaries to 1g envelope curves from Fig.3. The pressure distributions (Fig.8) have verified the design capability. High transonic speed capability at low lift is limited by the appearance of the lower surface shock as predicted. Note that suction peaks over the whole wing at moderate Mach number (points <A> and <B>) remain low. The attained thrust limits (k=1.03 and 1.1, 0 and 7% drag penalty) are higher than the shock onset limit at high speeds.

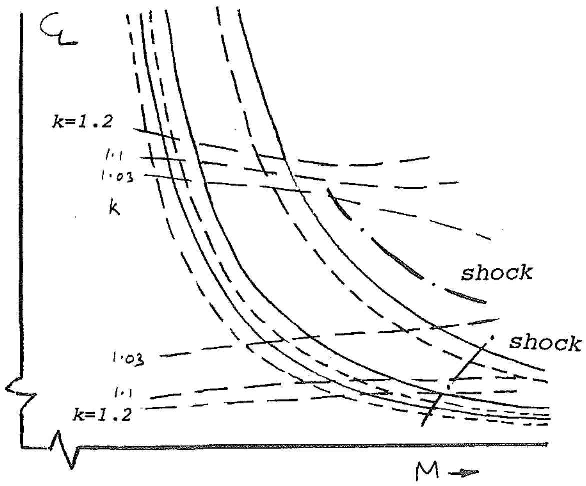

FIG. 9 C_L - M RELATIONSHIPS AT Sea Level, 10k & 30k ft, $(W/S)_1$ & $(W/S)_2$, 1g FLIGHT, Cambered Wing (B)

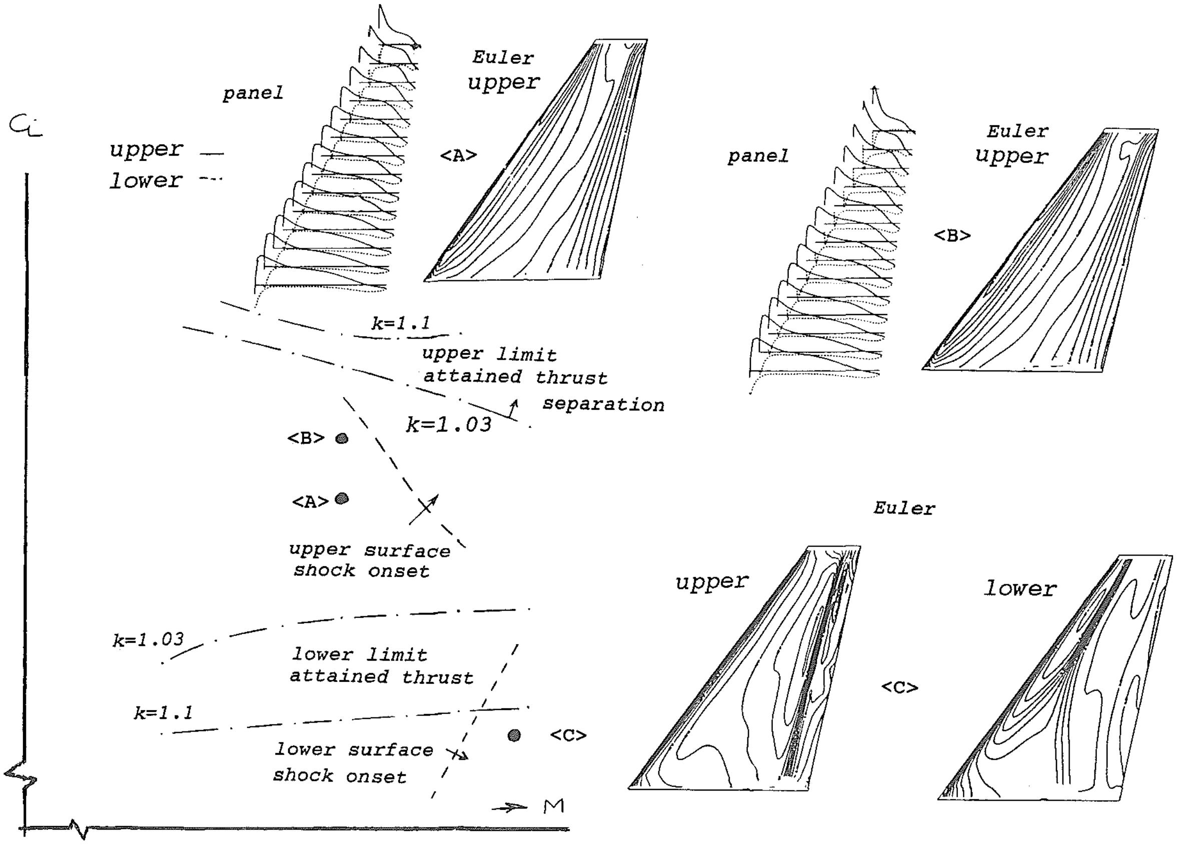

FIG. 8 CAMBERED WING (B), VARIOUS BOUNDARIES (C_L - M BASIS) WITH SELECTED PRESSURE DISTRIBUTIONS & ISOBARS

High Speed Wing (C) Design

Fig.10 refers to the same wing planform (as for wing A) with camber and twist designed for high speed (C). It shows the iso - k lines on C_L - Mach basis at 30k ft. Note that k values for low to moderate Mach numbers are somewhat lower than the comparable values from the previous cases.

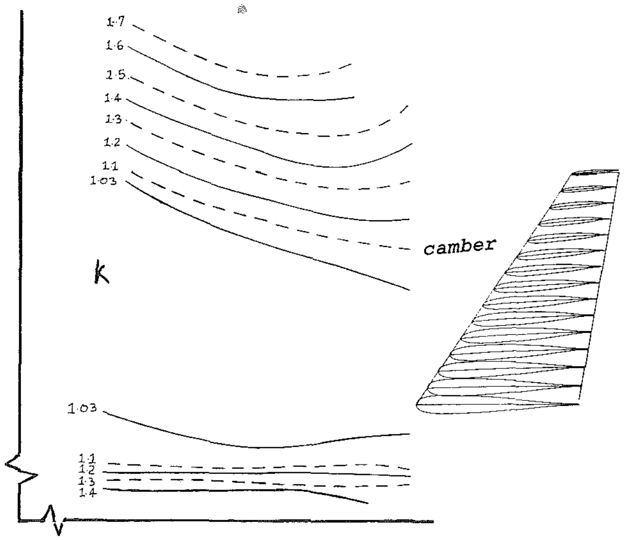

FIG. 10 CAMBERED WING (C), CONSTANT k LINES ON C_L - M BASIS, 30k ft.

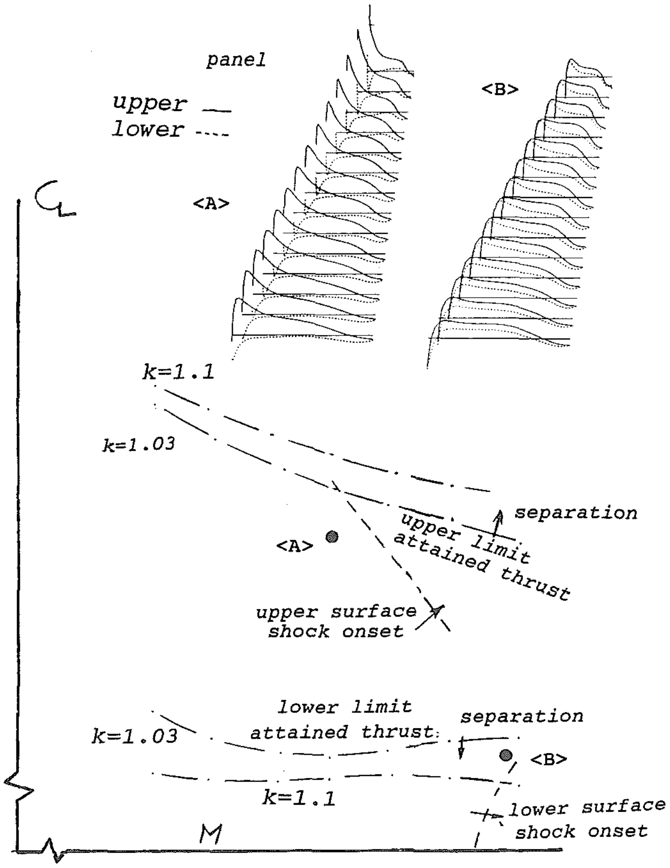

FIG. 11 CAMBERED WING (C), VARIOUS BOUNDARIES (C_L - M BASIS) WITH SELECTED PRESSURE DISTRIBUTIONS

Fig.11 summarises the various boundaries supported by selected pressure distributions. High transonic speed capability at low lift is significantly improved compared with the previous cases.

Fig.12 shows the achievement of the cambered wing on the 1g C_L - Mach relationships at different altitudes (Sea level, 10k, 30k ft), for two wing loadings of aircraft: $(W/S)_1$ and $(W/S)_2$ (taken from Fig.3). This confirms that the wing apparently has an adequate high speed capability. The lift capability at lower Mach numbers is slightly short of the performance for the previous design.

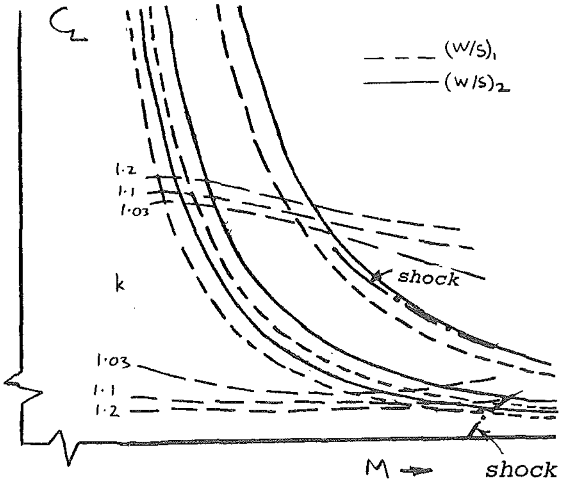

FIG. 12 C_L - M RELATIONSHIPS AT Sea Level, 10k & 30k ft, $(W/S)_1$ & $(W/S)_2$, 1g FLIGHT, Cambered Wing (C)

The technique has shown that because of low camber and twist overall, the lower surface shock tendency at small α can be considerably weakened.

We can now summarise some general inferences that arise from studies on wings with straight LE:

- The technique offers low camber, tolerant off-design with therefore the possibility of well-behaved pitching moment characteristics.
- An envelope of the attached flow regime is predicted. The approach shows how the drag rises beyond the onset of flow separation or vortical flow. Estimating performance at different g levels can be attempted.
- The panel method is used within its capability: essentially for sub-critical flows. Euler methods which are both capable and expensive need to be run for verification of flows with shocks.
- For high lift capability throughout the envelope and Mach number range, the various boundaries may need to be extended using LE and TE controls.

5. WING WITH LEADING-EDGE ROOT EXTENSION

We begin with an uncambered wing with LERX.

Evaluation of Uncambered Wing+LERX (Wing D)

Fig.13 refers to an uncambered wing + sharp LERX. It shows the iso - k lines on C_L - Mach basis at 30k ft. The variation of k is from 1.1 to 1.8 which corresponds to 70% increase in drag for given speed.

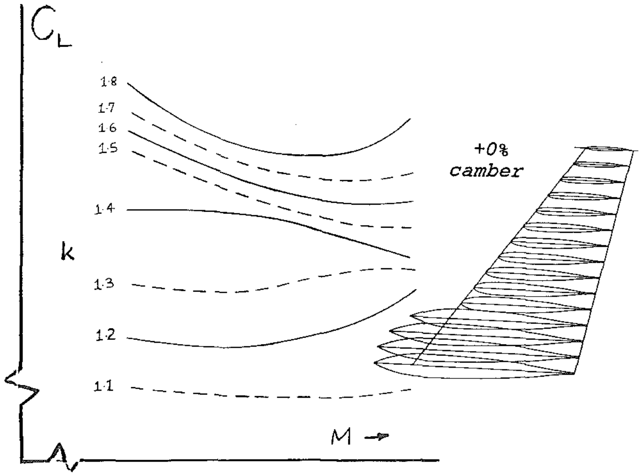

FIG. 13 UNCAMBERED WING + LERX (WING D), CONSTANT k LINES ON C_L - M BASIS, 30k ft.

Fig.14 summarises the various boundaries supported by selected pressure distributions. Note the high suction peaks near the wing tip. The LERX carries positive loading. The attained thrust limits (k = 1.1 and 1.2) are generally lower than the shock onset limit except at high speeds. Note also the comparatively high drag levels for moderate Mach number and moderate lift. The drag at high speeds is however very much lower.

Fig.15 shows the achievement of the uncambered wing + LERX on the 1g C_L - Mach relationships at different altitudes (Sea level, 10k, 30k ft), for the two wing loadings of aircraft: $(W/S)_1$ and $(W/S)_2$ (taken from Fig.3). Shock onset boundary and curves for k = 1.1 and 1.2 have been shown. The boundaries obviously need to be "adjusted" using camber and twist.

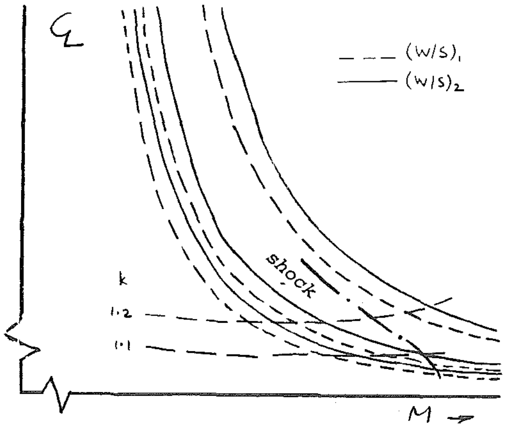

FIG. 15 C_L - MACH RELATIONSHIPS AT Sea Level, 10k & 30k ft, $(W/S)_1$ & $(W/S)_2$, 1g FLIGHT, BOUNDARIES OF UNCAMBERED WING + LERX (D)

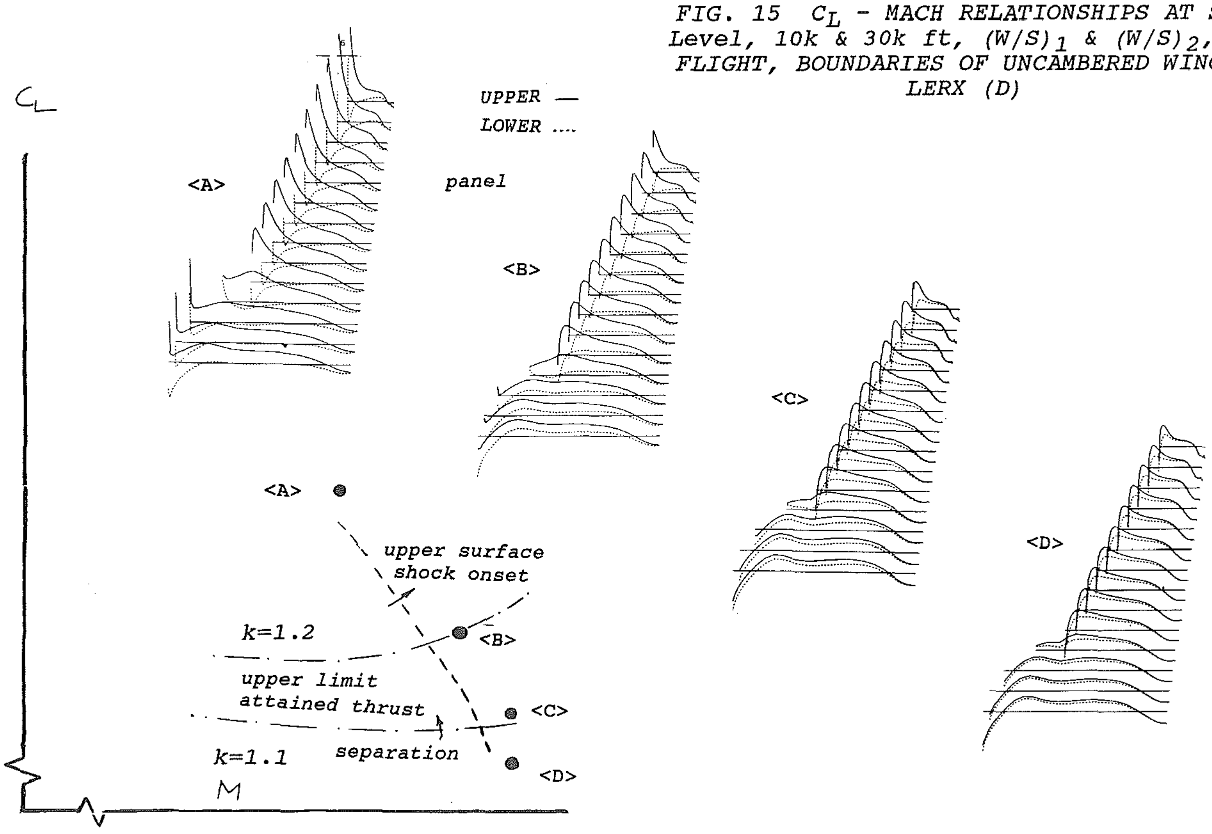

FIG. 14 UNCAMBERED WING + LERX (D), VARIOUS BOUNDARIES (C_L - M BASIS) WITH SELECTED PRESSURE DISTRIBUTIONS

Wing + LERX designed for High Manoeuvrability, Moderate Speed at High Altitude (Wing E)

Fig.16 shows the iso - k lines on C_L - Mach basis at 30k ft. The attached flow region (approximately k = 1.1) is bounded with a lower and a higher C_L value. The factor k is acceptable for low to moderate Mach numbers but rather large for high speed or cruise conditions.

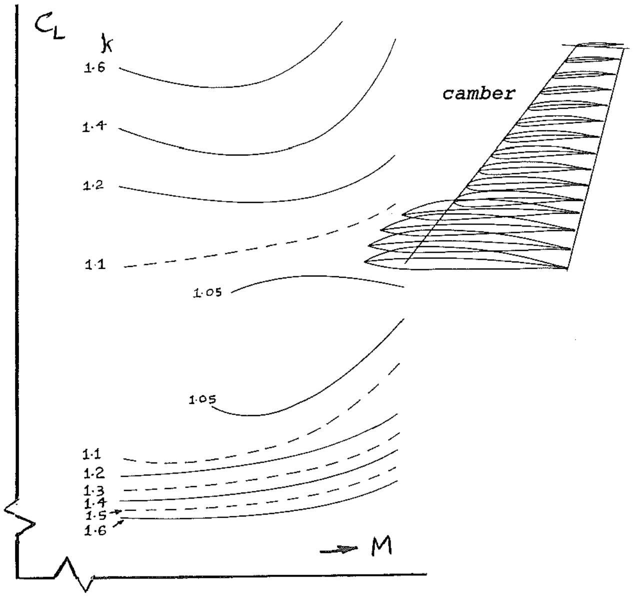

FIG. 16 CAMBERED WING + LERX (WING E), CONSTANT k LINES ON C_L - M BASIS, 30k ft.

Fig.17 summarises the various boundaries supported by selected pressure distributions and isobars. Fig.18 relates these boundaries to 1g envelope curves from Fig.3. The pressure distributions (Fig.17) have verified the design capability. High transonic speed capability at low lift is limited by the appearance of the lower surface shock as predicted. Note that suction peaks over the whole wing at moderate Mach numbers remain low. The attained thrust limits (k = 1.1 and 1.2) are lower than the shock onset limit to fairly high Mach numbers.

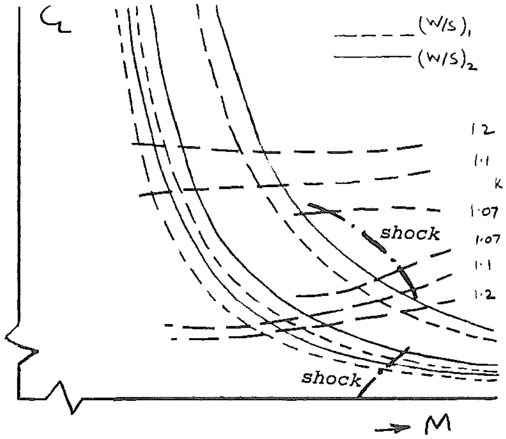

FIG. 18 C_L - MACH RELATIONSHIPS AT Sea Level, 10k & 30k ft, $(W/S)_1$ & $(W/S)_2$, 1g FLIGHT, Cambered Wing + LERX (E)

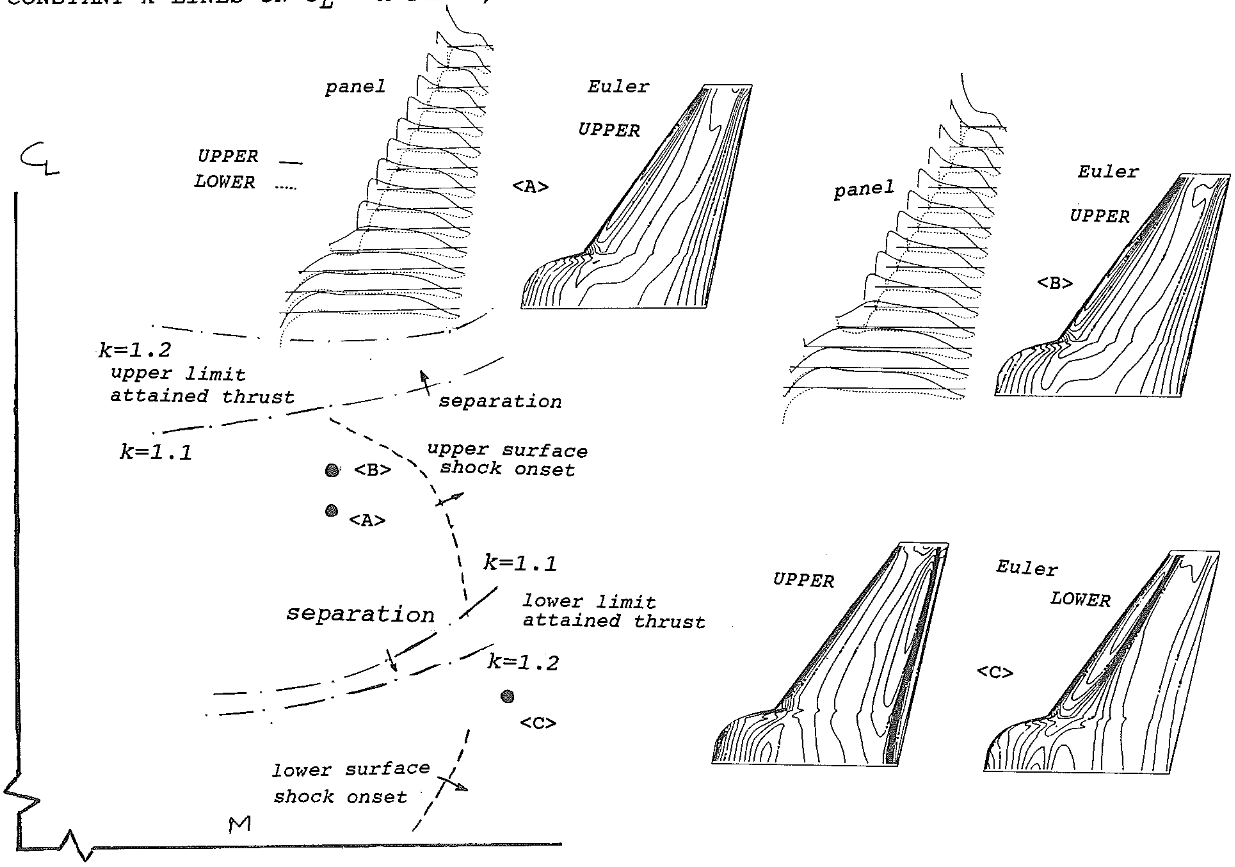

FIG. 17 CAMBERED WING + LERX (E), VARIOUS BOUNDARIES (C_L - M BASIS) WITH SELECTED PRESSURE DISTRIBUTIONS & ISOBARS

Comparing Fig.17 with Fig.14 for the uncambered wing, we note the upward movement of the upper surface shock boundary for the cambered wing and the appearance of a lower surface shock boundary. Boundaries from attained thrust method for planar and cambered wing are shown. All these suggest that this camber design is suitable for flight at moderate speed and high manoeuvrability. For high speed dash application, the wing is possibly over-cambered.

This exercise with LERX has been instructive in demonstration of the principles involved for the demanding high manoeuvrability case. We examine a high speed case next.

<u>High Speed Wing+LERX Design (Wing F)</u>

Fig.19 shows the iso - k lines on C_L - Mach basis at 30k ft. Note that k levels are shifted upwards compared with those for the planar wing (Fig.13). The factor k is generally acceptable for low to moderate Mach numbers and slightly on the high side for cruise conditions.

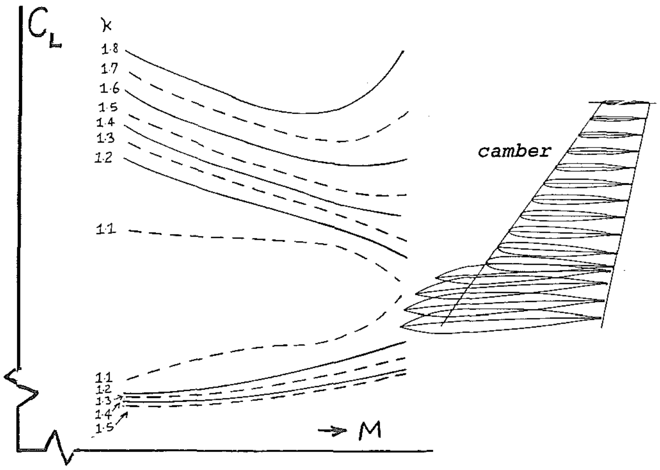

FIG. 19 CAMBERED WING + LERX (WING F), CONSTANT k LINES ON C_L - M BASIS, 30k ft.

Fig.20 summarises the various boundaries supported by selected pressure distributions. High transonic speed capability at low lift is affected by the appearance of the lower surface shock. Compared with the previous case, the high speed capability is very significantly improved.

Fig.21 shows the achievement of the cambered wing + LERX on the 1g C_L - Mach relationships at different altitudes (Sea level, 10k, 30k ft), for two wing loadings of aircraft: $(W/S)_1$ and $(W/S)_2$. Shock onset boundary and curves for k = 1.1 and 1.2 have been shown. Note the improved drag levels for high Mach number and moderate lift when compared with the previous case).

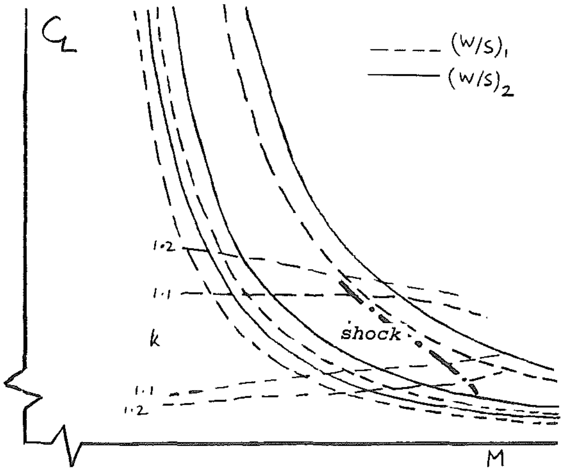

FIG. 21 C_L - MACH RELATIONSHIPS AT Sea Level, 10k & 30k ft, $(W/S)_1$ & $(W/S)_2$, 1g FLIGHT, Cambered Wing + LERX (F)

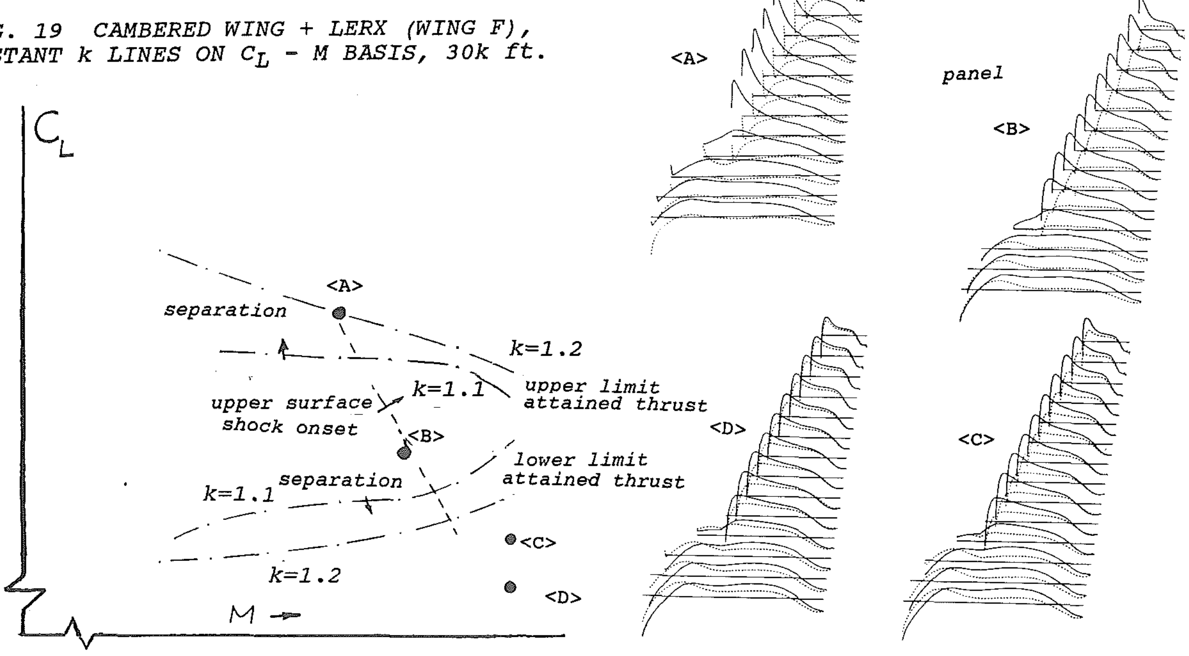

FIG. 20 CAMBERED WING + LERX (F), VARIOUS BOUNDARIES (C_L - M BASIS) WITH SELECTED PRESSURE DISTRIBUTIONS

Fig.14, 17 and 20, all for wings with sharp LERX, exemplify the control over the loadings by comparing the pressures on uncambered and designed wings at the same lift. Note that for the designed wing, the tip loading has been markedly reduced and the lower surface shock tendency has been reduced. The loading over the LERX LE is slightly negative. Further design cases need to be set up to help in limiting this negative loading on the LERX.

Inferences

In addition to general inferences (Section 4) for the straight LE wing, the LERX studies indicate several further aspects:

- The cambers designed with the LERX are different from the LERX off case. This may preclude the possibility of using a multi-purpose wing without and with LERX to reduce the model and testing costs.
- For wings with LERX, the drag levels are generally higher at low lift.
- Over the outer wing, the camber required is apparently smaller for the LERX on case.
- The technique may be used to assess the "pros and cons" of "adding" a LERX to a given wing design.
- High speed capability can be improved by allowing a slightly round-edged LERX. This aspect needs to be assessed.

6. FURTHER WORK POSSIBILITIES

The theoretical work so far, although essentially on wing-alone configurations has proved encouraging and demonstrates a logical and relatively inexpensive design approach for transonic flight with tolerant off-design.

We need to consider and incorporate related topics that exert strong influence on the practical wing design. The first aspect concerns experimental validation.

(1). Experimental Validation of Cambers

We need to verify the selected designs experimentally. Because the wind tunnel test Reynolds numbers are likely to be an order less than those in flight, the present technique may be exploited to design the wings for the test conditions. Alternatively, for a model with camber designed for full-scale, we can assess the performance at lower Reynolds numbers. These aspects need to be followed.

It will be prudent to include at least the first-order viscous effects e.g. subtraction of the boundary layer displacement thickness from the designed shapes. These will be different for model tests and full-scale.

(2). Incorporation of Bodies (Fuselage / Tanks)

The presence of fuselage and/or tanks will modify the flow-field over the wing. The physical length of the wing LE for suction attainment is less with the body present. The design is therefore compromised. Further, the setting angles of the bodies with respect to the wing can have a strong influence. In principle, technique extensions can be envisaged that will enable the wing to be designed in presence of the flowfield of a given body.

A simple way to assess the effect of a body is to assume that LE suction over the wing area occupied by the fuselage is turned into normal force. This assumption goes partly towards reducing the overall suction and allowance of normal force over the fuselage. It does not, however, cater adequately for a cambered body, body incidence or its contribution to pitching moment. Experience with this technique implies a 15 to 20% increase in induced drag factor k at low lift. The penalty decreased at higher lift values.

We need now to include the interference effects in the technique in such a way so as to minimise them. In the first stage, body-induced upwash/downwash effects can be imposed and camber determined in the presence of these induced effects. The longer term solution would be to achieve body shaping that minimise the interference. Both of these aspects need to be addressed.

(3). LE & TE Controls & Devices

For manoeuvrability at high lift conditions, efficient flight is needed beyond the 1g boundaries exemplified. The LE suction attainment can be favourably altered with LE and TE flaps (or using LE vortex flaps). Assessments are needed within the geometry constraints (wing-box, actuator limits etc.). The objective will be to design for minimum-sized controls deflected through small angles. Trimmed flight estimates need to be included.

Energy Manoeuvrability Studies need to be undertaken to assess the gains due to the Control deflections.

(4). Wing Geometry Considerations

Aircraft balance and flight envelope requirements can lead to options of "multi-role planforms" with cranked LE. These wings can be studied with the present approach and compared with other existing approaches.

A logical approach is to advance a selection of three planforms to their full aerodynamic capability. This process can then enable reasoned judgement of the planform selection within the flight envelope constraints.

On LERX configurations, with a slight rounding of the LERX, gains in transonic performance may be possible. This needs to be assessed.

It appears that the optimised camber designs for a wing without or with LERX are fairly different.

7. CONCLUSIONS

Future advanced projects will require increased performance from the wing throughout the flight envelope. The wing design will be a compromise between, for example, the requirements of efficient cruise, high speed dash (low C_L) and transonic manoeuvrability (high C_L). Project requirements may lead to complex planforms incorporating Leading-Edge strakes (LERX) with sharp leading edges.

This paper has demonstrated the design of wing camber and twist according to the attained thrust linear theory method. The method optimises the wing camber with respect to estimated realised LE thrust on wings with given aerofoil parameters and flow conditions. In this respect, the present design method differs from conventional methods which imply a near elliptical spanwise lift loading at the design point and which can in certain situations lead to LE suctions which may not be attainable in practice.

Wings with or without LERX have been considered with linear theory methods to predict camber and twist. The cambered designs have been verified against multi-block Euler methods. This aspect is particularly encouraging as isobars on upper surface are well-behaved.

The designed wings have been evaluated through the critical portions of the Mach - C_L and Reynolds number range using Panel and Euler methods. The Panel methods are used within their validity for sub-critical flows. These methods signify the boundaries of the onset of shock tendency. With shocks present, Euler methods are used for verification.

An envelope of the attached flow regime is predicted. The approach shows how the drag rises beyond the onset of flow separation and vortical flow. Estimating manoeuvre performance therefore at different g levels can be attempted.

The design process can be biased towards efficient high speed or high manoeuvrability or a suitable combination.

The work has proved encouraging and underlines a logical and relatively inexpensive design technique for transonic combat aircraft wings with tolerant off-design behaviour.

Several avenues for further work including experimental verification have been proposed e.g. incorporating fuselage effects and design of LE and TE devices to increase manoeuvrability.

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Any opinions expressed are those of the author.

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