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SOME DESIGN CONSIDERATIONS & PROSPECTS OF APPLYING LEADING-EDGE VORTEX FLAPS TO COMBAT AIRCRAFT WINGS

R.K.Nangia (Bristol) & G.E.Lockley (BAe, MAL, Kingston), U.K.

Abstract

The evolution of combat aircraft is towards higher manoeuvrability and agility. The need has arisen for integrated design for operation over wide range of flight conditions that encompasses attached flow, vortex flow at subsonic, transonic and supersonic speeds. A promising device is the Leading Edge Vortex Flap (LEVF) for fully utilising the vortex flows on the complete span of the typically moderate aspect ratio (AR) wings.

Some results from wind tunnel tests comparing data on variable camber devices, strakes (LERX) and LEVF have been presented to show performance, stability, control and high α characteristics. The results highlight the differences in LEVF application on wings of different sweep. Comparisons are also made against conventional LE flaps and TE flaps (LEVF and TEF).

Several avenues for further theoretical and experimental work have been identified.

1. Introduction & Background

The evolution of combat aircraft is towards higher manoeuvrability and agility. The need has arisen for integrated design for operation over a wide range of flight conditions that includes attached flow, vortex flow at subsonic, transonic and supersonic speeds. The evolution also implies a close integration of systems for flight control, propulsion, combat and weapon delivery in order to maximise combat effectiveness and contain pilot workload to ensure effective management of combat operations.

The aerodynamic development required is then to extend the range of speed and manoeuvre envelopes to the required levels of agility compatible with future weapon systems and required levels of performance and handling standards.

With classical attached flow designs, limits on the design envelope are imposed by the onset of buffet. The limits may be alleviated partially by the use of flow control devices and deployable surfaces that maintain attached flow. The next stage is to allow an amount of controlled separation which can then permit a small but appreciable level of buffet penetration and lift gain. However, this process is still likely to be limited by larger buffet levels arising from major flow separations.

Demands for further increased performance has stimulated research on separated flows with the objectives of establishing stable vortex flows. Exploitation of these vortex flows through favourable location of vortex forces and interaction with attached flow, then becomes a possible means for improving wing aerodynamic performance. A promising device is the Leading Edge Vortex Flap (LEVF) that has the potential of utilising the vortex flow over the complete span of a typically moderate aspect ratio (AR) wing.

The LEVF is a deflectable device (Figs.1 and 2) that reduces the drag of manoeuvering swept wings by recovering the LE suction normally lost under those conditions (because of LE flow separation) in the form of a vortex "trapped" above the flap itself. Additional drag reduction at high C_L is obtained due to suction pressure gradients being less adverse on the the curved LE of the aerofoil and therefore less prone to separation. Several types of LEVF can be visualised.

Whereas initial studies were on higher LE sweep (Λ_{LE}) wings that easily established the LE vortex flow (Refs.1-5), recent work has shown that the LE vortex flow can be successfully established at the sharp edges of the LEVF down to moderate values of LE sweep and LEVF applications are therefore feasible on this class of wing.

The development of LEVF application is timely and appropriate for typical future optimised combat aircraft configuration as determined by technology developments and future operation needs. In this context, analysed results from recent F106B flight trials with simple LEVF would be of interest.

In considering design applications, vortex flow control devices need to be evaluated against devices designed to maintain attached flow. The fundamental change in aerodynamic design technique, to promote separation in a controlled way to obtain ordered vortex flow requires, apart from performance assessment, an appreciation of the broader aerodynamic characteristics and the impact on flying qualities pertinent to combat aircraft.

In this paper, some results on typical combat aircraft configurations are discussed with particular comment on design applications and further developments.

2. Vortex Flow Control Applications

The objective is to permit controlled vortex flows to exist over the forward face of the wing swept LE. At moderate wing angle of attack, the sharp LE is at a moderate incidence to the local flow (and hence at a large downward angle to line-of-flight) will cause a vortex to form on its upper surface. Because of the sharp edge, the actual local incidence of the LEVF is not critical, and because of sweep, the vortex tends to remain "trapped" over a range of conditions. As shown in Fig.2, the flow development over the LEVF from points (a) to (e) can be related to the drag polar for 0% and 100% LE suction. The maximum benefits occur near point (d) when the drag polar with LEVF approaches 100% suction line. Even at point (e), although the vortex may lift clear of the wing ,the flow over the wing LE may remain attached, at a higher α than would be possible with the plain wing.

As the mechanism is dependent on flow separation it is less sensitive to Reynolds number than LE droop and as long as the LEVF is at a positive incidence to the local flow, it will produce the desired effect independent of aircraft incidence, and is less demanding of fine "tuning" either at a particular station or along the span. The only requirement is that to maintain the growing vortex on the forward surface there should ideally be no spanwise discontinuities and the droop angle should be approximately correct.

The vortex flow along the forward face of the LEVF gives rise to suction force on the LEVF, which due to its extreme deflection has a significant forward or thrust component coupled with lift component. With the LEVF placed under the LE, the suction caused around the LE also has a forward component, although this suction is less intense than without LEVF and therefore makes the flow less likely to separate. This as for simple LE flaps, enables higher α to be achieved, increasing the potential C_{Lmax} of the wing. Fig.3 illustrates schematically the effect, with a lower suction force on the wing LE with LEVF present, but with additional suction force present on the LEVF.

Fig.4 shows the domains of vortex flow as derived by Lamar (Ref.3) for planar sharp-edged delta wings. The boundary of stable vortex flow decreases as sweep decreases. On wings with rounded LE, it is often difficult to distinguish between the spiral and "controlled" vortex flow at low LE sweeps. On the other hand generally, a sharp LE encourages vortex flow to develop. This is obviously of interest for LEVF application. Fig.4 suggests that vortex augmentation and vortex control devices may be used with advantage to increase the stable vortex flow region ie. shifting the boundaries upwards for α above 10° for moderate wing LE sweep.

3. Test Programme & Results

Awareness of these possible qualities of LEVF has led to a major research programme at BAe (MAL), Kingston. Several wings (Fig.5) of varying planform (with and without LERX), LE sweep (from 36° to 59°), varying t/c have been tested in different cambered states at low and transonic speeds

Longitudinal and lateral data has been obtained. The LEVF chordwise size was between 7 and 10% of the wing mean chord c_{av}. The location of the LEVF was in general either at the LE or set-back 3 to 4% chord under the LE. The deflection of the LEVF varied beween 20° and 50°.

To assess the experiments, theory is needed. However, the full treatment of LEVF within existing state of art is difficult (Refs.6 and 7). Analyses that exist are mainly for simple configurations (Refs.8 and 9) or for simplified conical flow framework (Ref.10).

Therefore, to aid the interpretation of experimental data, recourse has been made to theory with empirical description of "attained" LE thrust based on methods pioneered by Carlson and others of NASA. This has enabled determining the limits of zero LE thrust, full LE thrust and the likely "attained" thrust at a given Mach and Reynolds number combination for a wing.

Some results from wind tunnel tests comparing data on variable camber devices, strakes (LERX) and LEVF have been presented to show performance, stability, control and high Ç characteristics. The results highlight the differences in LEVF application on wings of different sweep. Comparisons are also made against conventional LE flaps.

In the first instance, emphasis is on C_A and L/D and envelopes of these characteristics with respect to LEVF deflection are presented.

Fig.6 shows the C_A - C_L relationships for the 36° wing. Curves for LERX off and on with different TEF are compared against estimated full LE suction curves.

Fig.7 refers to the 48° wing. Comparisons are offered for effect of LEVF with and without LERX against scheduled LEF+TEF case.

For the 59°/55° wing, Fig.8 shows the effect of LEVF on the basic planar wing and a wing with 10° LE droop through transonic speeds. Examples of effect on C_A, of VF,TEF,LEF, LERX are given.

These verify the gains in forward axial force due to LEVF. The gains in LE thrust markedly affect the L/D and C_{Lmax} relationships.

For the $\Lambda_{LE}=36°$ wing, Fig.9 is an example of gain in C_L for given value of L/D with LEVF, with and without LERX, and different TEF referred to the basic wing without LEVF.

Fig.10 shows the ratio $C_{Lmax}/C_{Lmax(ref)}$ for configurations with and without LERX and different TEF. LEVF configurations with small TEF offers the possibility of appreciable gains over the basic configuration with large TEF deflection.

Fig.11 compares the L/D - C_L relationships for scheduled LEF and LEVF on moderately cambered 59°/55° wing.

Fig.12 shows the comparison of L/D for LEVF against LE and TE flaps with and without strake on the 48° wing.

Fig.13 shows the L/D - C_L relationships for a wing with LEVF at transonic Mach numbers from 0.6 to 1.2.

We note advantages for the configurations with LEVF.

Fig.14 illustrates the effect of LEVF on typical high α behaviour (C_n - α, C_l - α, $C_{n\beta}$(dynamic) - α and $C_{l\xi}$ - C_L). Comparisons have been made with scheduled LEF. Note that with LEVF, stability is maintained to higher C_L than for LEF. This indicates that LEVF offers the possibility of higher useable α and less departure tendency with roll power maintained.

Another important high α parameter is the cross-coupling term $C_{m\beta}$ which should indicate that nose-drop tendency is to be preferred as sideslip occurs. This tendency was generally associated with LEVF configurations.

Fig.15 for the derivative n_v through transonic speeds shows the improvements with LEVF.

Fig.16 depicts the effect of LEVF on buffet coefficient C_B variation with C_L on the 59°/55° wing. Buffet response levels at high C_L are substantially lower with LEVF.

4. Agility & Performance Considerations

In considering the impact of improved lift and drag performance available from LEVF, the effect on agility is examined for a hypothetical aircraft with typically representative parameters W/S and T/W.

The significant advance in air combat is due to the introduction of all aspect IR missiles which is changing the emphasis on agility parameters towards better attained turn rate (ATR) and rolling manoeuvres at high g, α with lower priority for sustained turn rate (STR). Requirements for high P_S at 1g remain dominant to ensure short response times.

We take a hypothetical example to give a feel for the likely manoeuver implications with the following assumed parameters:

$W/S = 84\ lb/ft^2$, $T/W = 0.99$, Mach 0.55, Altitude 10,000 ft.

Fig.17 shows four drag polars and L/D curves (A1, A2, A3 and A4) selected on basis of typical variations with and without LEVF from the low speed tests on the 48° wing.

A1: Theoretical 0% LE suction
A2: Theoretical 100% LE suction
A3: Experiment, Wing with LEVF
A4: Experiment, Basic (No LEVF)

Fig.18 shows the Specific Excess Power P_S relationships plotted to bases of g, C_L, Rate of Turn (ROT) and Radius of turn (RAD). The improvements obtained with LEVF are evident:

- STR (level flight, $P_S = 0$) improves from 3.2g to 4.7g (47%).
- Instantaneous Turn at $P_S = 200$ improves from 3.4g to 5.2g (53%).
- Sustained Rate of Turn improves from 9.2 to 14.2°/sec (54%).
- Sustained Radius of Turn improves from 3750 to 1900 ft (97%).
- Maximum Instantaneous Turn improves from 3.5g ($C_L = 0.95$) to 5.3g ($C_L = 1.45$) ie 51%.

Based on equal P_S values, exchange rates may be derived with the objective of reducing the total size and weight of aircraft with LEVF installed. An obvious first attempt is to reduce the area of the wing with LEVF. The process becomes iterative as reducing wing area leads to reductions in structure weight and profile drag. The P_S relationships need to be assessed during every iterative stage. Some early work has suggested that LEVF incorporation may lead to 10-20% reduction in the aircraft weight.

This preliminary excursion into manoeuvre implications merely indicates the potential of the LEVF applications. Further work with more realistic values at transonic Mach numbers and full-scale Reynolds number is required. Exchange rates will be needed to relate the aircraft configuration LE devices parameters with manoeuvre performance for example in terms of ROT, P_S variation with speed.

5. Design Applications

The LEVF offers a convenient way of integrating an aircraft configuration with multiple design points. The emerging principle is to design the basic wing for high speed flight (C_L below 0.4) and aim to reduce the profile drag C_{D0}. The LEVF needs to be deployed at C_L above 0.5 or 0.6, at subsonic or transonic speeds.

By virtue of exploiting the natural tendency of the swept LE flow ie to separate, the LEVF offers a stable and tolerant flow field. In contrast a conventional LE device such as a slat or LEF emphasises postponing of the flow separation to higher α and the flow is generally prone to rapid deterioriation at off-design points. Flow separations often result at hinge lines on highly drooped LE flaps which imply loss in thrust. The gaps in LE slats on transonic swept wings demand an extra variable to be investigated. The sideslip behaviour of attached flow devices poses a complication often.

For a given aircraft configuration depending on the wing LE sweep, the various types of LE devices may be developed to high levels of effectiveness. It is felt however that the LEVF offers the virtue of relative simplicity for application to wings of moderate aspect ratio and moderate sweep.

6. Future Work

Several avenues for further work have been identified:

(1). Tests are required on various wings particularly at high speeds, high α, to generate the design data base.

(2). High Reynolds number testing is required to correlate with theoretical results and support any envisaged flight tests.

(3). Studies are required to assess the vortex breakdown characteristics to define limiting characteristics with and without LEVF or other devices.

(4). Detail LEVF design studies are required to identify optimum geometry and relative position along LE.

(5). Development of theoretical and empirical framework for design evaluation of general configurations is required.

(6). Agility and performance aspects need to be further developed.

7. Concluding Remarks

It has been shown that the LEVF is a "tolerant" device which exploits the natural tendency of the flow i.e. separation at high Mach-C_L conditions, in a favourable manner. By controlling flow separation, the "bluff-body" type behaviour can be postponed to still higher angles of attack. The aerodynamic envelope of a given aircraft can therefore be enhanced substantially. Some of the features are:

- Gains in L/D at high C_L and gain in C_{Lmax}.
- Gains in L/D broadly additive to those from wing camber.
- Maximum L/D is lower than tuned LEF/TEF.
- LEVF effective down to wing LE Sweep of 36° or less.
- LEVF effective on thicker wings both for C_{Lmax} and L/D.
- LEVF gains maintained at high speeds.
- Lateral/directional stability maintained to higher α , β.
- With LEVF, Buffet levels at higher C_L substantially lower than for LEF.

Several avenues for further theoretical and experimental work have been identified. Application to full-scale aircraft should be envisaged.

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Any opinions expressed are those of the authors.

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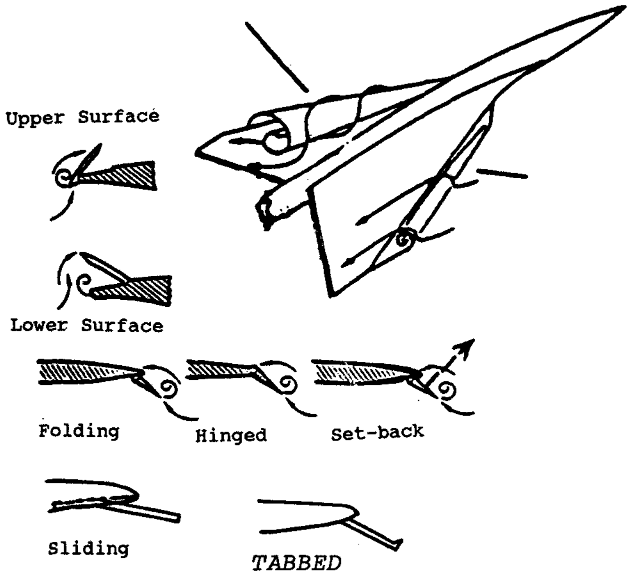

FIG.1 DIFFERENT TYPES OF LEVF

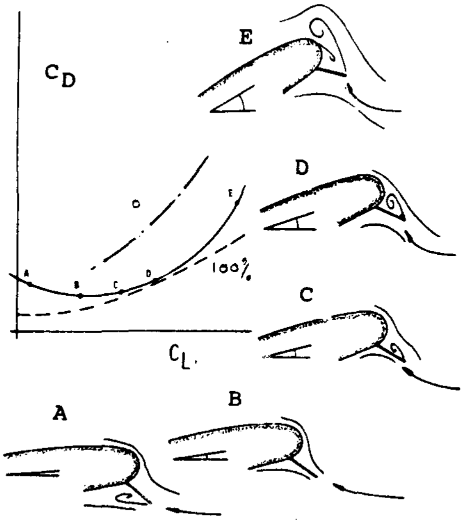

FIG.2 FLOW DEVELOPMENT OVER A LEVF & EFFECT ON A DRAG POLAR

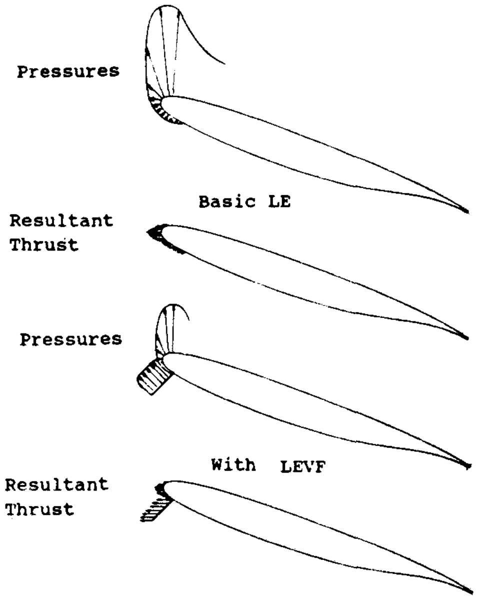

FIG.3 SCHEMATIC EFFECT OF LEVF ON LE SUCTION & AXIAL FORCE

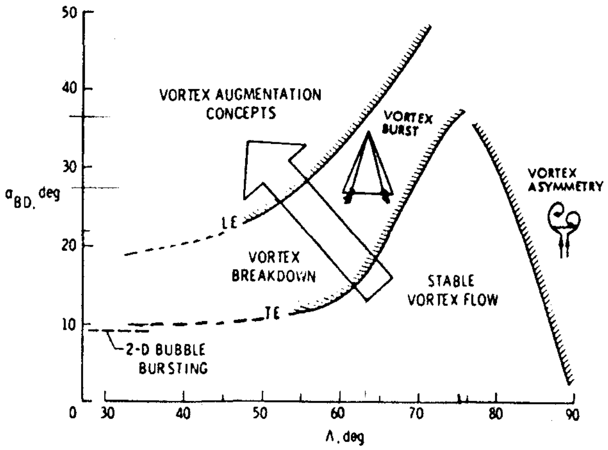

FIG.4 LE VORTEX BREAKDOWN TRENDS FOR PLANAR SHARP-LE DELTAS, LOW SPEED

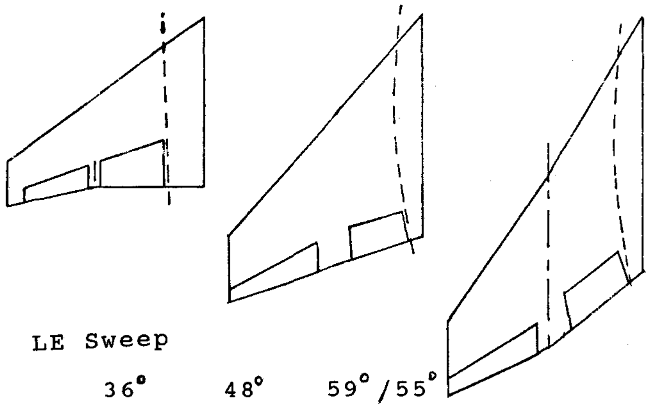

FIG.5 TEST PLANFORMS

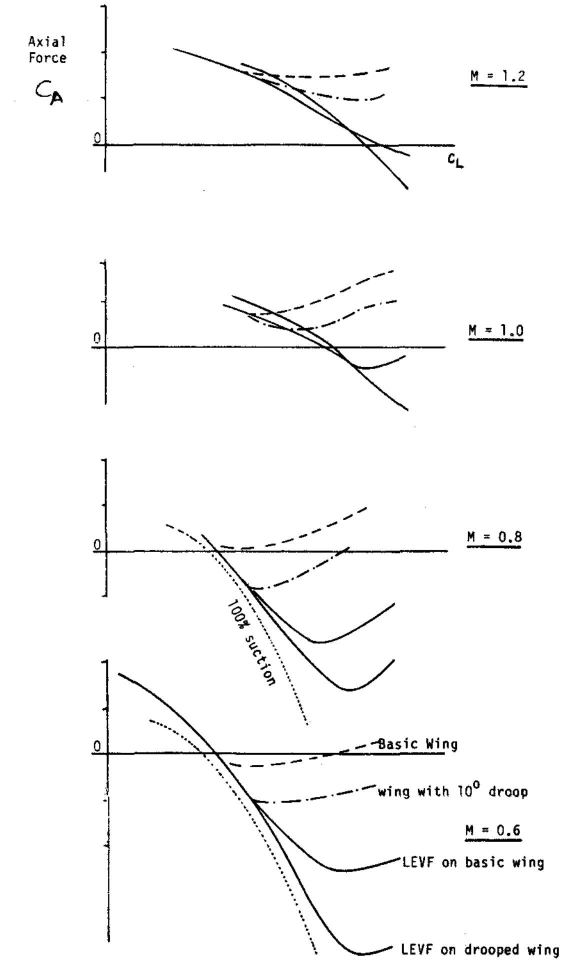

FIG.8 AXIAL FORCE - C_L , TRANSONIC SPEEDS, 59°/55° WING

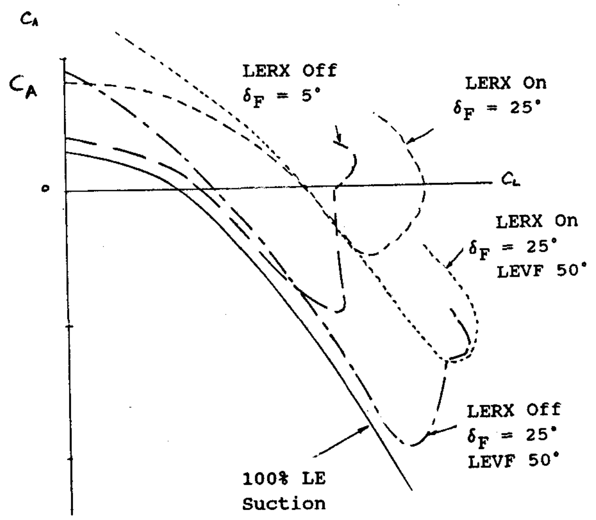

FIG.6 AXIAL FORCE - C_L , LOW SPEED, 36° WING

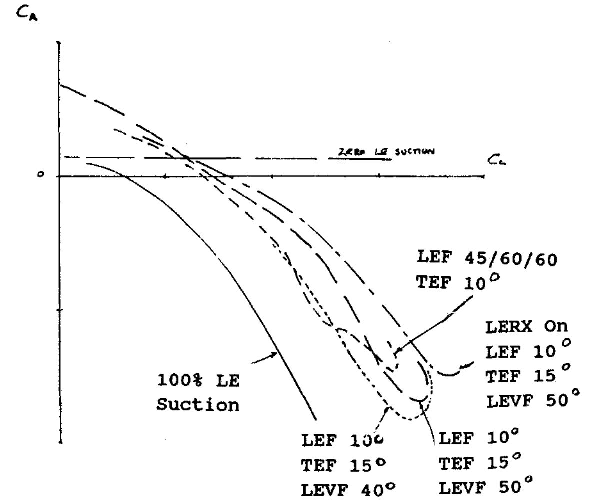

FIG.7 AXIAL FORCE - C_L , LOW SPEED, 48° WING

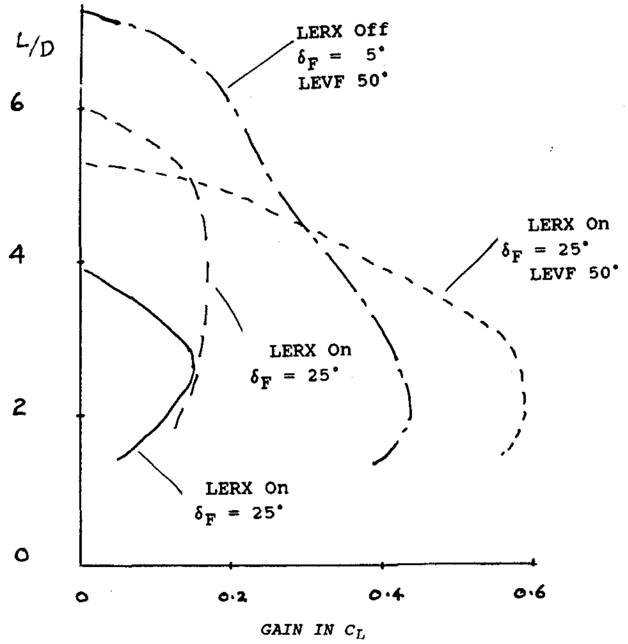

FIG.9 GAIN IN CL FOR GIVEN VALUES OF L/D, 36° WING

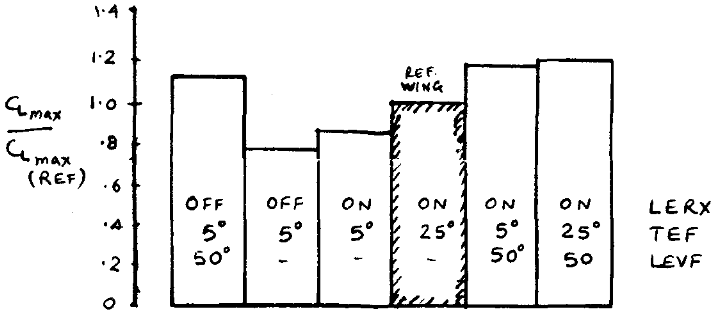

FIG.10 $C_{L\max}/C_{L\max(\text{ref})}$ for LERX, TEF, LOW SPEED, 36° WING

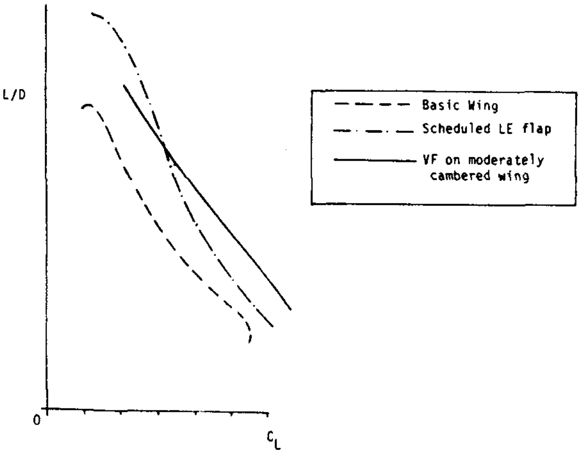

FIG.11 L/D - CL RELATIONSHIPS, COMPARISON OF SCHEDULED LEF & TEF, LOW SPEED, 59°/55° WING

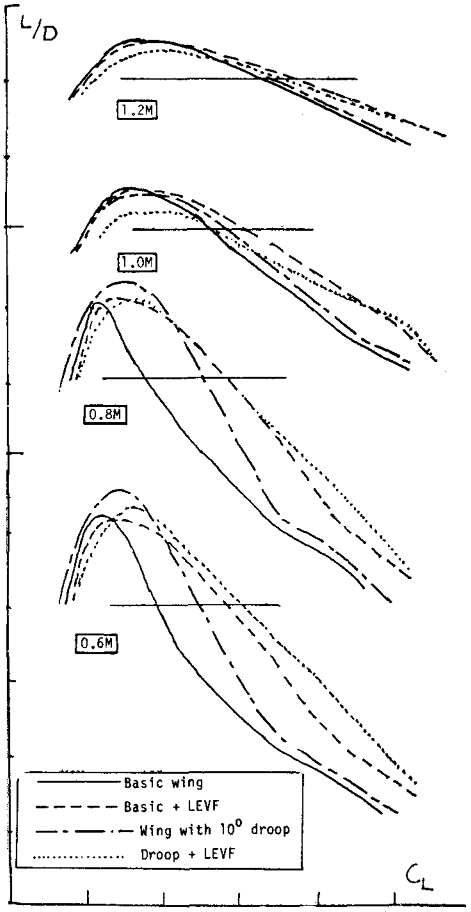

FIG.13 L/D - C_L RELATIONSHIPS, TRANSONIC SPEEDS, 59°/55° WING

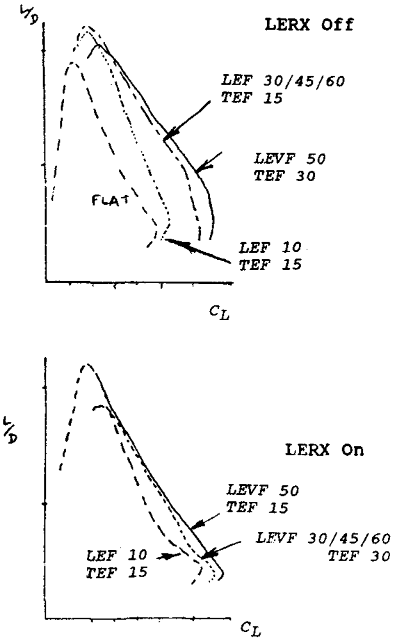

FIG.12 L/D - C_L RELATIONSHIPS, COMPARISON OF LEF, LERX & LEVF, LOW SPEED, 48° WING

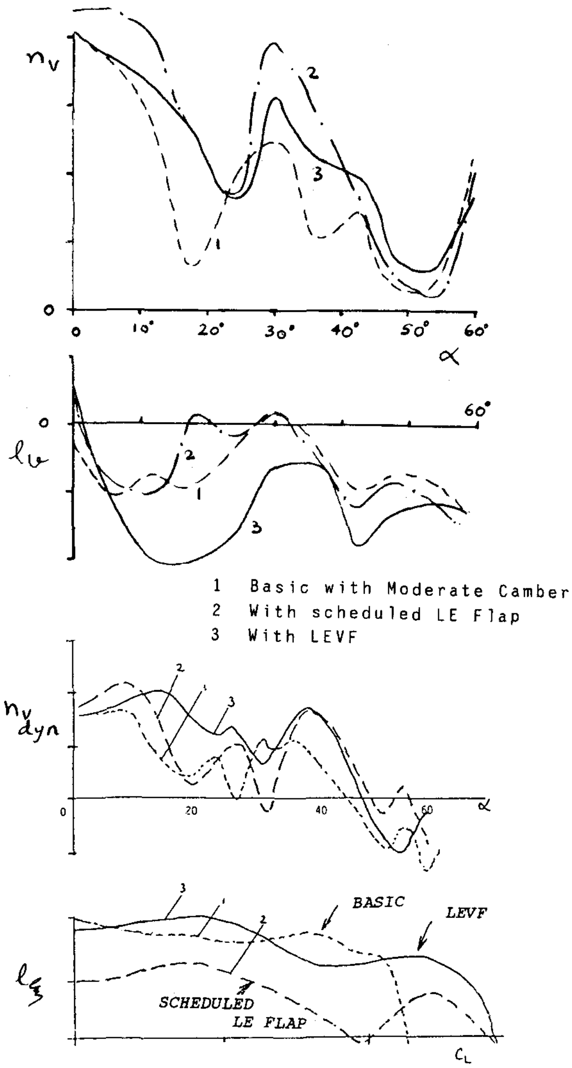

FIG.14 LATERAL, DIRECTIONAL, Cnβ(dynamic), Clξ CHARACTERISTICS, HIGH α, LOW SPEED, 48° WING

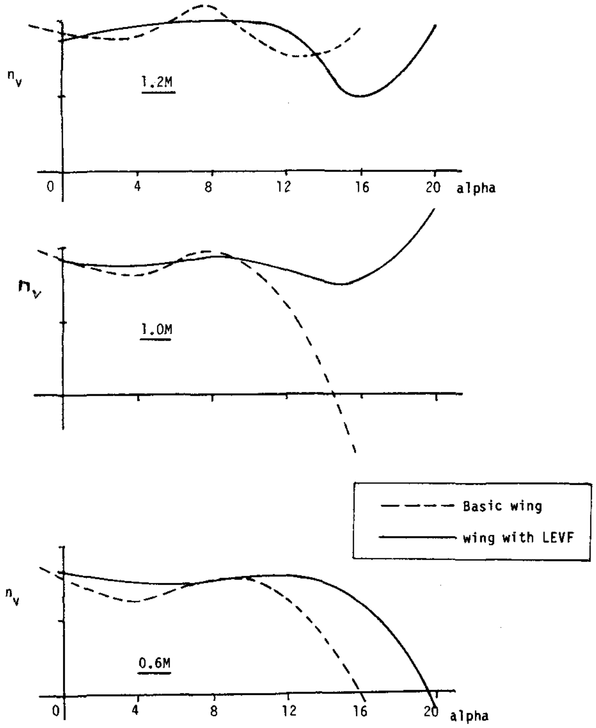

FIG.15 DIRECTIONAL DERIVATIVES, TRANSONIC SPEEDS, 59°/55° WING

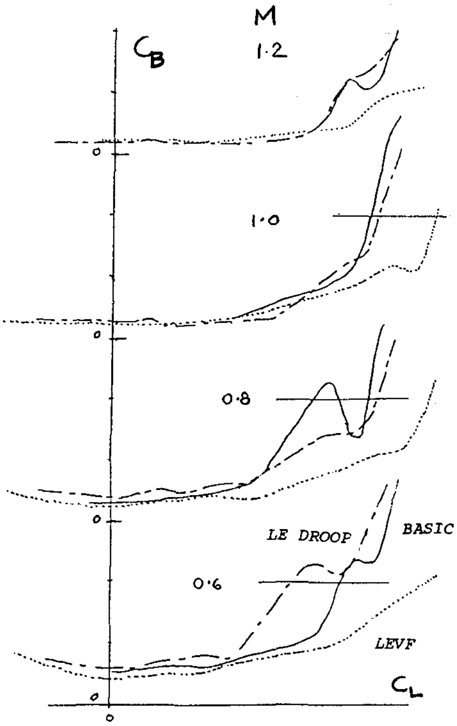

FIG.16 BUFFET RESPONSE, TRANSONIC SPEEDS, 59°/55° WING

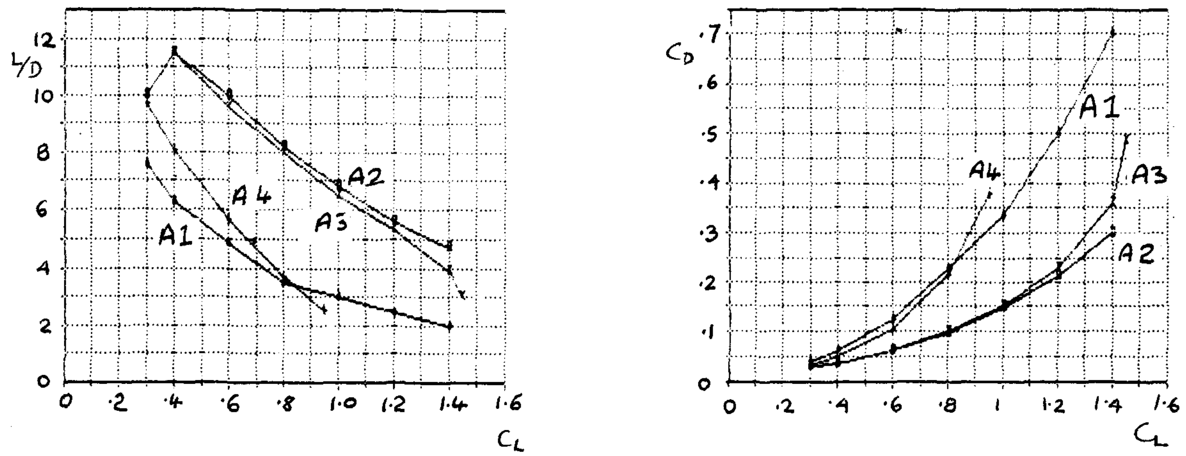

FIG.17 ASSUMED DRAG - LIFT FOR P_S ESTIMATES

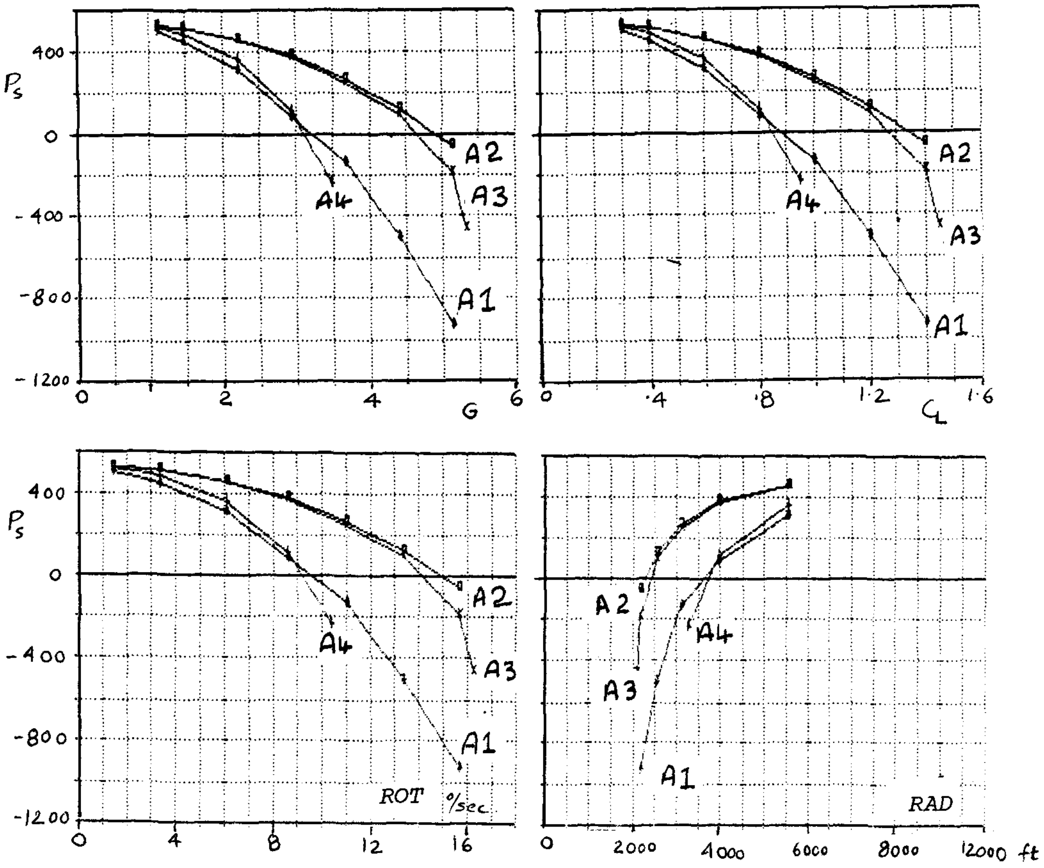

FIG.18 P_S VALUES, M=0.55, 10000 ft, W/S = 84 lb/ft^2, T/W = 0.99