FLAP SYSTEMS ON SUPERSONIC TRANSPORT AIRCRAFT

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Abstract

Concorde did not use any flap systems, its trailing-edge elevons being for trim and control purposes only. It relied on vortex flow to reduce incidences but its subsonic performance suffered as a result.

The next generation of supersonic commercial transport aircraft will need to improve this subsonic performance by using flaps. The flaps are envisaged as plain hinged surfaces on both the leading and trailing edges with the aim being to increase lift/drag ratio and not necessarily lift. The leading-edge flaps reduce separation and suppress vortex flow, thus increasing leading-edge suction. Trailing-edge flaps lower incidences to lessen the chance of separation at the leading-edge.

Low speed wind tunnel tests of hinged leading and trailing edge flaps on a typical supersonic transport configuration clearly showed the expected benefits. These improvements in lift/drag values were used to determine the likely benefit of flap systems in reducing take-off noise. Leading-edge flaps were found to reduce flyover noise by 2.5 dB whilst both flaps together could lower it by up to 4.6 dB. Further small reductions of 0.3 dB could be achieved with scheduled flaps.

The proven performance benefit shows the need for flap systems and may be essential for a supersonic transport aircraft to achieve take-off noise targets.

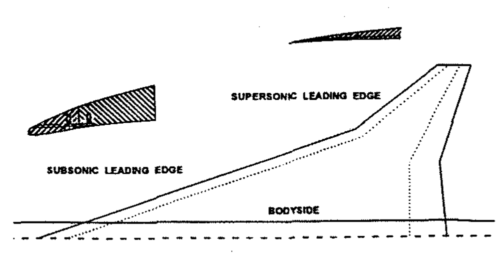
Introduction

The supersonic commercial transport aircraft envisaged for entry into service during the next decade will have a conventional slender arrow wing planform of low aspect ratio. Other alternative configurations such as oblique wings are currently not favoured and will probably only be considered for entry into service at later dates.

The arrow wing will be a compromise between the differing requirements of subsonic and supersonic flight but will be characterised by its high leading-edge sweep and low thickness. For subsonic speeds, these low aspect ratio wings have a poor lift-curve slope and relatively high induced drag which are compensated to some extent by the low wing loading associated with a delta wing.

During supersonic flight, the flow is subsonic over the leading-edge inboard of the kink because of its high sweep angle. This part of the leading-edge will therefore have some roundness although will still be sharp compared to subsonic aircraft standards. On the other hand, the supersonic leading-edge outboard of the kink will be very sharp.

FIG.1 TYPICAL WING PLANFORM FOR AN SCT



Concorde had a similar type of wing, which although had a fairly good supersonic performance, did not perform well at subsonic speeds. Concorde did not use flap systems to improve the subsonic performance. It had no leading-edge devices and the trailing-edge devices called elevons, were primary flight controls used for trim and control purposes only. Instead, Concorde relied on vortex flows to provide extra lift and reduce incidences.

These vortex flows were formed by the fairly sharp leading-edge and high sweep causing separation even at low incidences. The separated flow would form up into vortices which remained attached to the wing giving this extra 'vortex lift'. However, the aerodynamic efficiency of these vortex flows is very poor and so the subsonic performance in terms of lift/drag (L/D) ratio, especially that at low speed, suffered as a result.

The next generation of supersonic commercial transport aircraft will need to have a good subsonic performance for a number of reasons:

- To reduce reserve fuel carried.
- To fly efficiently those routes requiring subsonic cruise.
- To achieve noise limits during take-off and approach.

The first reason was also important for Concorde where the reserve fuel could be equal in weight to total payload. Part of the reserves are calculated to include a subsonic cruise diversion and hold. The better the performance, the less the unproductive fuel carried and with a supersonic transport aircraft, the range is very sensitive to small changes in weight.

Due to sonic boom problems, supersonic flight will be restricted to over water. Routes with a significant proportion of over land flight are becoming important to achieve an acceptable market for a future supersonic aircraft.

The next generation of supersonic aircraft will be designed to meet FAR stage III noise levels. Along with special engine designs and noise suppressers, the aerodynamic performance at low speed will be critical.

Flap systems should improve performance not only at low speed but also during subsonic cruise. The reasons are the same for both speed regimes but the low speed case will be considered in detail here, due to the major importance of the last point above.

Much work was carried out by British Aerospace and Aerospatiale during the late seventies / early eighties in developing Concorde. One of the improvements considered was the introduction of leading-edge flaps. A significant amount of wind tunnel testing and flap mechanism endurance tests were done which verified that L/D ratio could be improved in practice. Along with other changes like increased wing span and acoustically treated jet pipes, it would have been possible[1] to fly with full payload from Rome to New York, flying at subsonic speeds over Europe. In addition the sideline, flyover and approach noise levels could be reduced collectively by about 15 EPNdB in total.

These Concorde 'B' improvements were to be introduced on aircraft production number 19 but it was never built.

Flap Performance

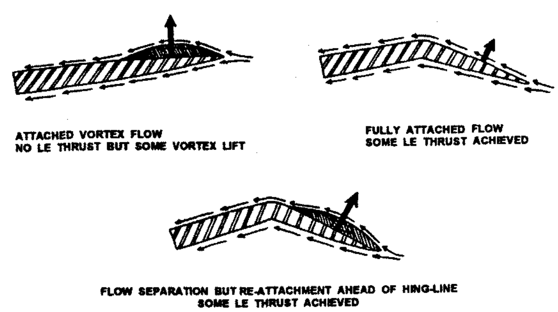
The poor aerodynamic efficiency of attached vortex flow on a delta wing is due to the loss of leading-edge thrust. Usually the high suction pressures acting on the nose of a wing section produce a leading-edge thrust which offsets much of the drag on the rest of the section. When these high suction pressures associated with attached flow cannot be achieved due to the sharp radius, the flow tends to separate forming attached vortices. The suction thrust is not lost but is effectively rotated to become a normal force as Polhamus demonstrated. Thus lift is increased due to this 'vortex lift' but on the other hand so is drag. Overall, the aerodynamic performance in terms of L/D becomes much worse.

To improve the situation, leading-edge flaps can be used in two ways:

- Keeping the flow attached by effectively modifying the leading-edge radius. This gives a distributed leading-edge suction that provides a thrust force.
- By allowing separation but making sure reattachment takes place at or ahead of the hinge-line. Hence, the vortex now sits on the forward pointing surface. This re-orientates the resultant vortex force vector to point forward giving a thrust force.

The former method of using the leading-edge flaps to reduce separation and suppress vortex flow will be concentrated on here. Loss of vortex lift does occur but the aerodynamic performance improves at incidences of interest.

FIG.2 USE OF FLAPS TO ACHIEVE LE THRUST



The use of trailing-edge flaps can also improve the flow conditions at the leading-edge. Their deflection causes the wing loading to increase so that the required lift can be generated at lower incidences. Hence this reduces the chance of separation at the leading-edge. By using the trailing-edge flaps in combination with the leading-edge flaps, the suction force can be preserved even on these inherently sharp nose sections, and this can give large improvements in L/D.

In summary, the flap systems of a supersonic commercial transport aircraft, in common with those on a subsonic aircraft, are there to reduce separation. However, they are not required to attain greater maximum lift because the slender delta wings do not stall in the same sense. They are in fact employed at quite low incidences in order to reduce drag by preserving the suction force or leading-edge thrust. Hence for these thin and sharp, highly swept wings, they improve aerodynamic efficiency in terms of L/D at both low speed and to some extent during subsonic cruise.

Configurational Aspects

The simplest flaps envisaged are plain hinged flaps on both the leading and trailing edges. The trailing-edge flaps will again be used as primary flight controls similarly to those on Concorde and hence necessitate an easy design to allow fast movements. Being used as both controls and flaps will cause many problems but this also indicates the main difficulty of using these large devices as flaps. Namely, they produce large changes in pitching moment which must be trimmed out.

One option is the use of a second control surface such as a tailplane or a foreplane. However, using a second control surface to provide all the pitching moment required to trim would lead to a large surface which may be unacceptable due to weight and supersonic cruise drag problems. Also care must be taken to ensure that the benefit of the trailing-edge flaps in improving the aerodynamic performance at low speed is not counteracted by the losses due to the second surface.

For instance, a tailplane trimming the flaps will produce a downforce which needs to be offset by the wing producing more lift. It has been found that the extra drag from this cancels most if not all the benefit from deploying the flaps. A foreplane on the other hand does not affect total aircraft lift because it has been found that the foreplane lift is counteracted by loss of lift on the main wing due to interference. The resulting pitching moment can still be used to trim but the destabilizing effect of the foreplane can be a problem as mentioned below.

Another option, probably in combination with a second surface, is to move the CG farther aft in order to reduce the pitching moments of the trailing-edge flaps. This however reduces their control effectiveness and the aircraft will become unstable requiring autostabilisation.

The presence of a foreplane destabilizes the aircraft and the CG will have to move forward to achieve the same level of stability. But moving the CG forward means more trimming is required and for a given foreplane actually leads to less allowed flap deflection than if the foreplane was not there at all. Hence the destabilizing effect needs to be removed by automatic scheduling where the foreplane is controlled to be at a fixed local incidence by the use of sensors and fast reacting actuators. If this is possible then the flaps can be trimmed using a foreplane and performance improvements will result.

The above problems may limit the use of the full aerodynamic performance benefit from the trailing-edge flaps. However, the leading-edge flaps do not have these trim problems to the same extent due to their aerodynamic effect and distribution across the wing.

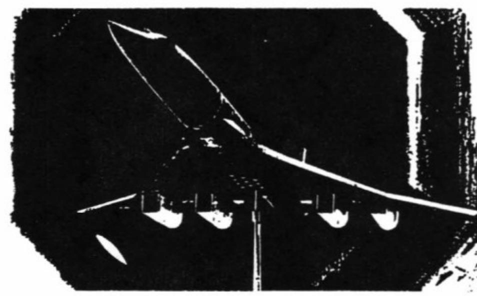
For the next generation supersonic transport aircraft, the size of the flaps will be a compromise between the optimum for performance and the loss in size of the wingbox. Fuel volume is likely to be a critical factor on this type of aircraft.

The flap surfaces are going to be fairly big; in total, probably over 100 m^2 with the leading-edge flap chord about 0.6 m and the trailing-edge chord up to 4 m wide. The jacks need to be fitted within the thin wing and problems will be encountered, especially towards the tip.

Wind Tunnel Tests Results

In 1991/1992, Aerospatiale and British Aerospace co-operated in carrying out low speed wind tunnel tests. The model was supplied by Aerospatiale and force and moment tests took place in the British Aerospace 12' x 10' wind tunnel at Filton, Bristol.

FIG.3 LOW SPEED WIND TUNNEL MODEL



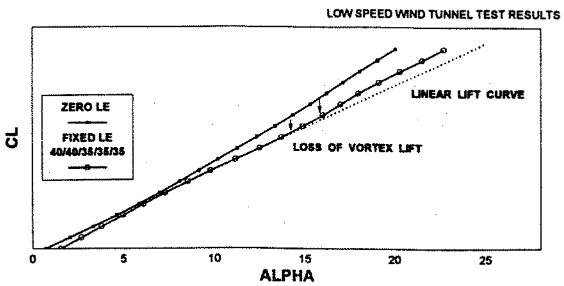
The model had interchangeable wing tips to test the effect of aspect ratio as well as a fuselage plug to vary body length. Some tests were also performed to assess second control surfaces such as a foreplane or a tailplane. One of the main aspects of the test program was the investigation of the effects of leading-edge (LE) flaps and trailing-edge (TE) flaps. The flaps were plain hinged with any hinge-line gaps sealed during the tests.

LE Flap Results

The LE flaps were tested at a number of droop deflection angles both on their own and in combination with TE flaps. There were six LE flap segments per wing including two outboard of the kink. In these tests, the inner two were deflected together at the same angle allowing a droop specification of five deflection angle parameters (degrees measured normal to hinge-line), for example, 40/40/35/35/35.

The typical effect of LE flaps on lift as derived from the test results is shown in Fig.4. With the LE flaps not deflected (Zero LE), the lift slope increases with incidence due to the build up of attached vortex flow. This vortex lift can be clearly seen as the non-linear lift above an arbitrary drawn linear lift curve starting at about 5 degrees incidence. As already described, by deflecting the LE flaps the vortex flow was suppressed and hence this extra lift was lost. It can be seen though that some vortex lift does start to occur at an incidence of 15 degrees. This indicates that above this incidence, the flaps are unable to keep the flow attached and this is probably due to hinge-line separation.

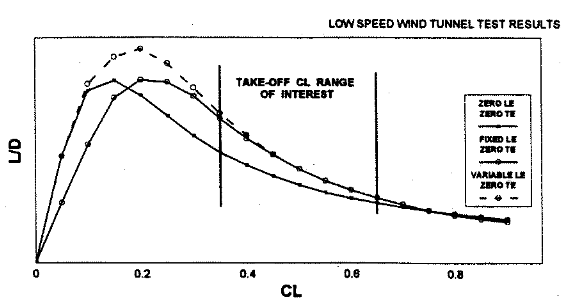
FIG.4 EFFECT OF LE FLAPS ON LIFT



The example given is for a fixed flap setting of 40 degrees inboard changing to 35 degrees outboard. Other deflection angles maybe more suited in attaining LE thrust at the higher incidences and indeed at the lower incidences. Comparisons in the L/D curves are needed to select the best deflection angles that improve the aerodynamic performance at each lift coefficient (CL).

Fig.5 shows a comparison of the aerodynamic efficiency (L/D) of deflecting the LE flaps. A take-off CL range of interest has been defined. The upper end of this range indicates a lift-off CL value and the lower end is typical of the flyover flight condition which is particularly important for take-off noise calculations.

FIG.5 EFFECT OF LE FLAPS ON LIFT / DRAG



Undeflected flaps obviously had the worst performance over this CL range. By using a fixed LE setting of 40/40/35/35/35, the L/D was improved, by up to 30% at flyover CL. However, the disadvantage was the worse performance at the low CL values typically encountered during the take-off run.

At these low incidences, flaps are not required to suppress vortex flow but instead when deflected cause high profile drag and loss of lift. Zero deflection would be best and as incidence increases, the optimum LE flap deflection would gradually increase.

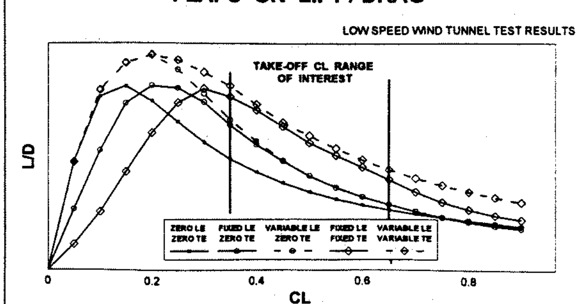
By taking the results for all the LE flap deflections tested, an optimum LE flap schedule was found giving the L/D results (variable LE) as shown. This avoided the problem at low incidences and also gained slightly at the flyover condition where lower LE droop angles of 30/30/30/20/20 degrees were found to be better at attaining LE thrust. At very high incidences (above 18 degrees), LE thrust could not be attained due to hinge-line separation and the best performance was achieved with zero flaps.

The concept of scheduled or variable flaps in practice is that the flap settings will be continuously varied during the take-off run and climb-out so as to achieve optimum performance at each CL. Whereas the TE flaps are used for control and hence are fast moving, this may not be the case for LE flaps and also present certification rules prohibit any changes to the flap configuration during take-off. However, variable flaps are considered here along with fixed flaps to show the possible performance benefits, because in the future, automatically controlled flaps may become acceptable.

TE Flap Results

The TE flaps, when used in combination with the LE flaps, showed a much greater gain in L/D as illustrated in Fig.6. With the flaps fixed (TE at 15 degrees), the aerodynamic efficiency was improved over zero flaps by about 60% throughout the CL range of interest. By using optimum deflection angles at both the leading and trailing edges (Variable LE & TE) this was increased to around a 70% improvement. The optimum schedule for the TE flaps was again a gradual increase with incidence, up to the point where they started to lose their effectiveness at a deflection of 23 degrees.

FIG.6 EFFECT OF BOTH LE AND TE FLAPS ON LIFT / DRAG

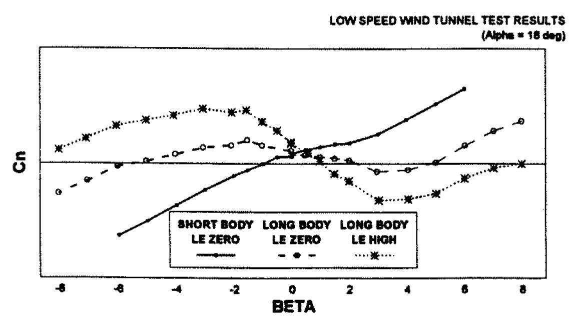


The results from the tests also indicated the relative changes in pitching moment due to LE and TE flap deflections. Whereas LE flaps produced a slight nose down pitching moment, the change due to TE flaps at 15 degrees was over ten times greater. The results proved that the LE flaps will be easily trimmed but problems remain with the TE flaps as discussed before.

Lateral Results

The deflected flaps are also likely to have an effect on the lateral aerodynamics. One interesting result from the tests was the apparent lateral instability at high incidence. Fig.7 shows the instability was present only at the low sideslip angles with a fairly long forebody. The problem was that deflection of the LE flaps made the situation a lot worse. The instability was probably caused by body vortices lying on top of the fuselage and interacting with the fin. The LE flaps by suppressing the vortex flow on the wing may have aided the non-interaction of the body vortices with the wing flow.

FIG.7 HIGH INCIDENCE LATERAL INSTABILITY



Effect On Take-Off Noise

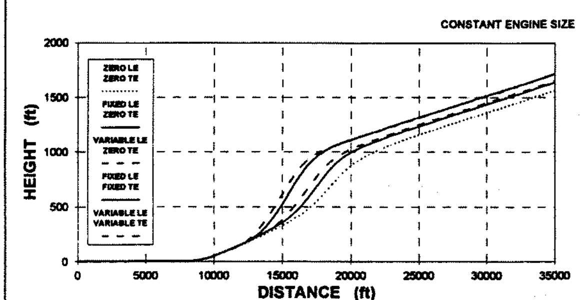
The benefit of flap systems on supersonic commercial transport aircraft in improving the low speed aerodynamic performance can be readily seen by investigating their effects on take-off performance and take-off noise. The calculated L/D curves from the above wind tunnel tests have been used in assessing the take-off noise.

Noise measurements for aircraft certification are taken at three defined points. Flyover noise is measured beneath the flightpath at a distance of 6500m from start of roll. Sideline noise is measured 450m to the side of the take-off path where the maximum level occurs. Finally, approach noise is measured beneath the approach path, 2000m from the threshold although this noise has not been considered in this paper. For certification, noise is measured in terms of the effective perceived noise level (EPNLdB) which takes account of the duration and frequency of any obtrusive tones. It thus measures noise effect of an event rather than the noise at a single instant in time.

For a supersonic transport aircraft, an optimum take-off flightpath in terms of noise can be defined whilst still meeting today's certification rules. In general, this means an initial acceleration to a maximum allowed speed of 250 kts followed by a cutback of the engines to a level which gives the minimum 4% climb gradient whilst still maintaining this speed. The minimum cutback height of 210 m is normally used for these low bypass engines.

Fig.8 gives an indication of how the various flap concepts affect the take-off flightpath. In order to achieve the greatest impact on noise, the benefits of the flaps have not been used to reduce engine size but to increase acceleration. For a slender delta wing aircraft, the minimum drag speed is the fastest speed and noise results showed that this was more important for noise than having smaller engines.

FIG.8 TAKE - OFF FLIGHTPATHS

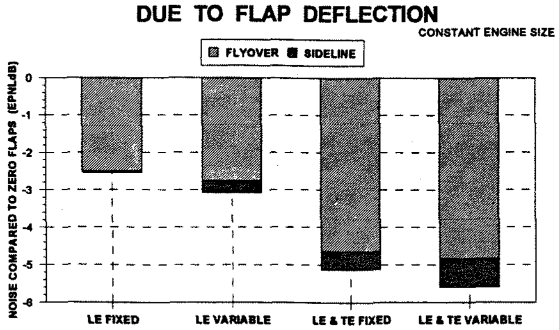


The improvement in aerodynamic performance due to the flap systems improved take-off noise for two main reasons:

- It increased height at flyover as seen by the relative flightpaths in Fig.8. This was due to the better climb performance and the earlier acceleration to minimum drag speed.
- It allowed a greater cutback of the engines whilst still achieving the minimum climb gradient.

Fig.9 shows the calculated noise reductions achieved. It should be noted that a 3 dB decrease in noise can be considered equivalent to a halving of the noise. In general, sideline noise tends to be mainly engine related and so changes were found to be small. However, the aircraft configuration significantly influenced the flyover noise.

FIG.9 EFFECT ON TAKE-OFF NOISE
DUE TO FLAP DEFLECTION



The use of fixed LE flaps caused a decrease in flyover noise of about 2.5 dB whilst the addition of fixed TE flaps decreased it by up to 4.6 dB. Variable flaps as compared to fixed flaps, only decrease flyover noise by a further 0.3 dB but seem to have a similar impact on sideline noise due to the better ground roll performance.

The results showed that LE flaps, by increasing aerodynamic efficiency, bring about significant reductions in take-off noise. The use of TE flaps can reduce noise further but the full benefits may not be achieved unless the problems of trimming can be overcome.

Conclusions

- Flap systems on delta wing, supersonic commercial transport aircraft, will be used to increase the subsonic cruise and low speed aerodynamic performance in terms of lift/drag ratio.
- Leading-edge flaps reduce separation and suppress vortex flow even at low incidences. Trailing-edge flaps reduce incidences to lessen the chance of separation at the leading-edge. These effects reduce drag by preserving the leading-edge thrust hence achieving an overall improvement in aerodynamic efficiency.
- Wind tunnel test results have shown the lift/drag ratio improvements within the take-off CL range of interest, from using both LE flaps on their own and in combination with TE flaps.
- The increased aerodynamic efficiency of flaps has been shown to give significant reductions in take-off noise. The deflection of LE flaps on their own reduced flyover noise by over 2.5 dB.
- The use of TE flaps gave a further reduction of over 2 dB as well as 0.5 dB decrease in sideline noise. However, this may not be achievable in practice due to trim problems.
- The use of variable or scheduled flaps were found to be beneficial especially during the ground roll. Their effort on take-off noise was an addtional reduction of 0.3 dB at each noise measuring point.

References

(1) Concorde Airframe Design and Development D.Collard SAE Technical Paper 912162

FIG.1 TYPICAL WING PLANFORM FOR AN SCT

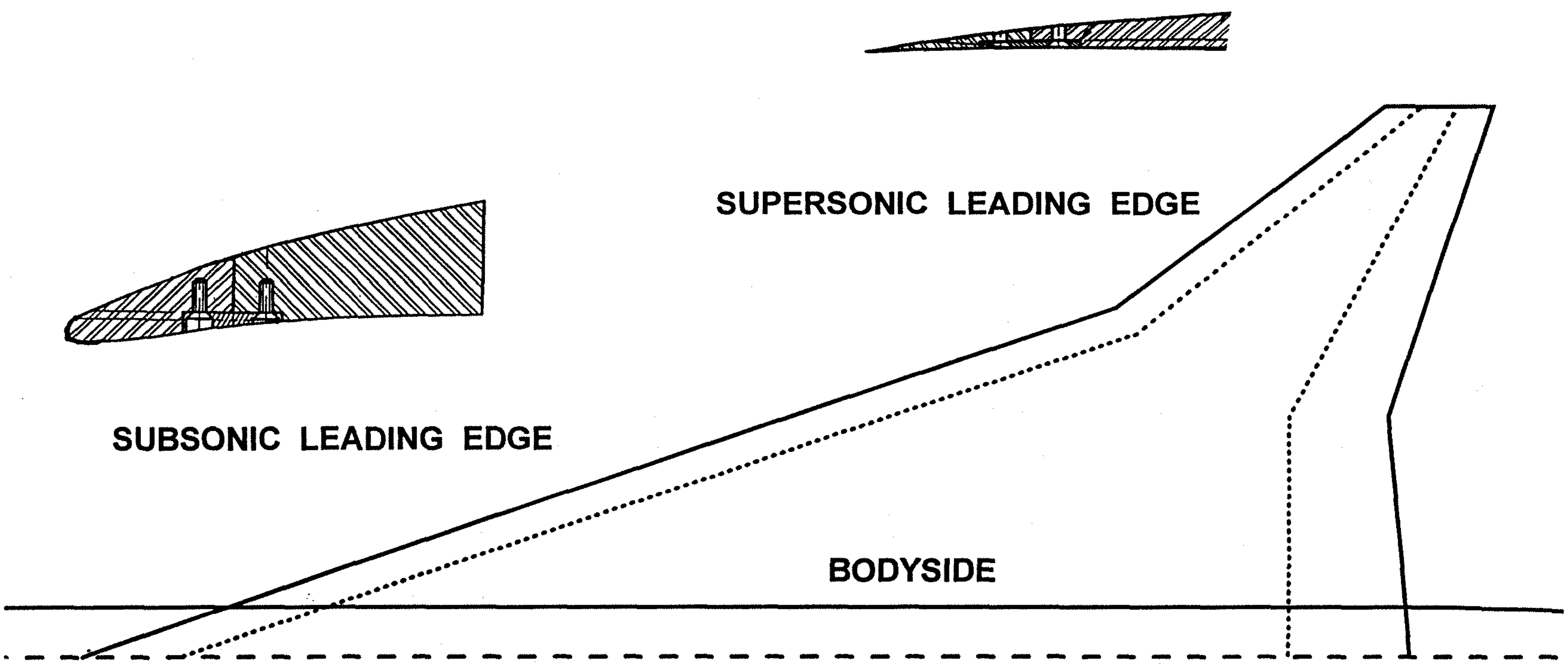
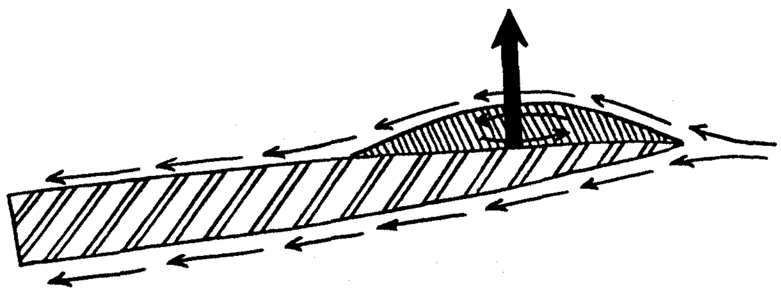
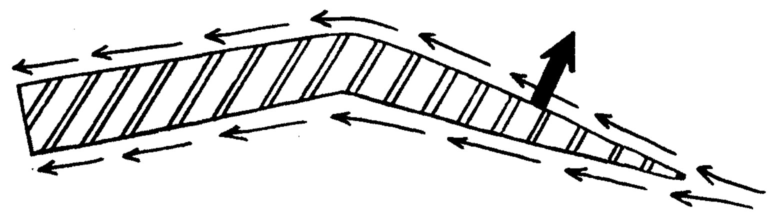


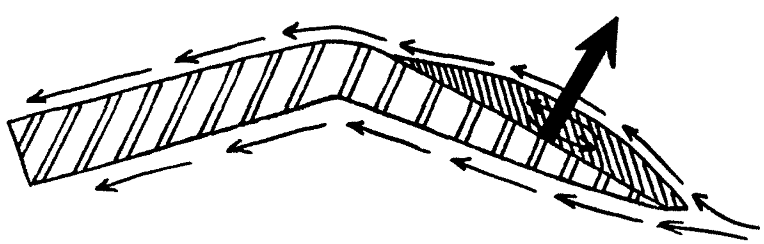
FIG.2 USE OF FLAPS TO ACHIEVE LE THRUST



ATTACHED VORTEX FLOW
NO LE THRUST BUT SOME VORTEX LIFT



FULLY ATTACHED FLOW
SOME LE THRUST ACHIEVED



FLOW SEPARATION BUT RE-ATTACHMENT AHEAD OF HING-LINE
SOME LE THRUST ACHIEVED

FIG.3 LOW SPEED WIND TUNNEL MODEL

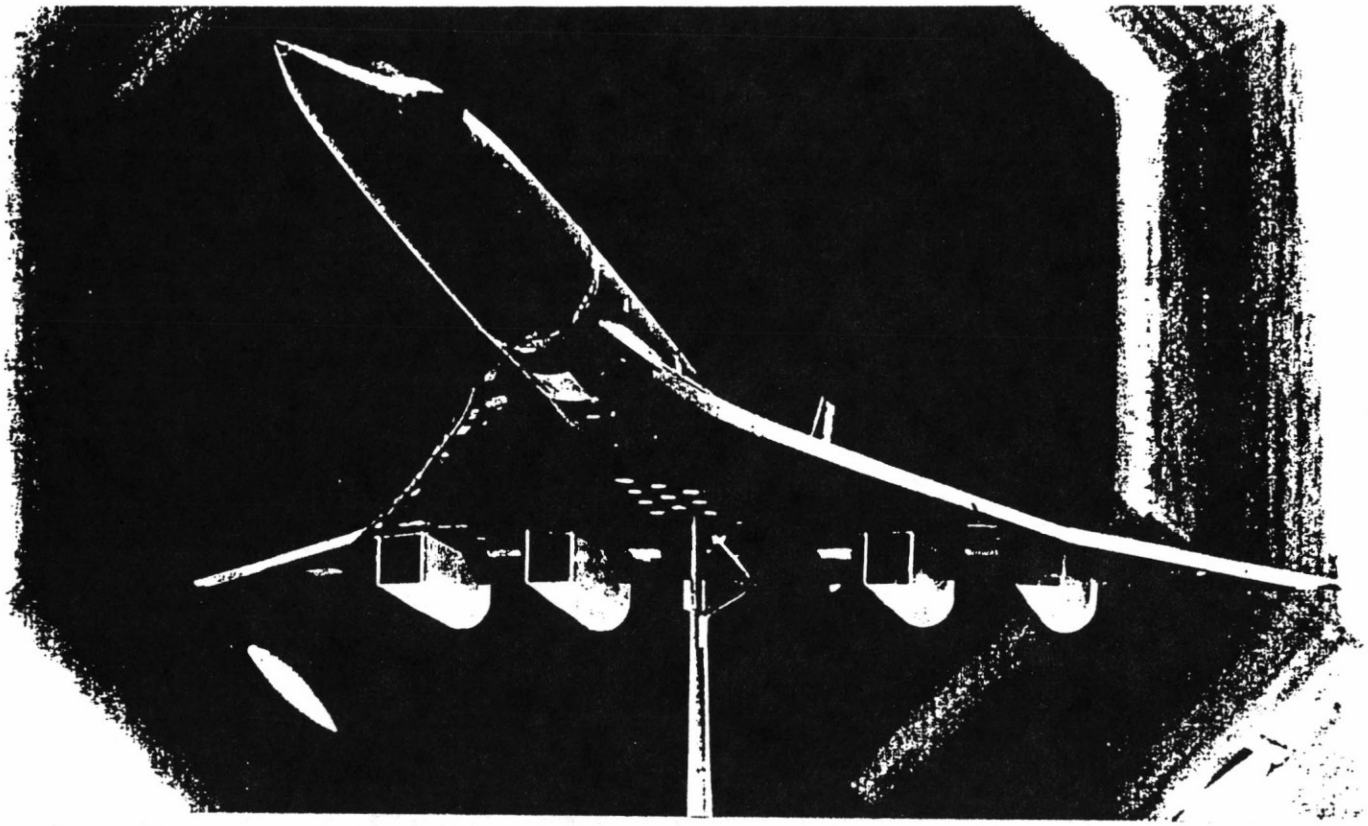


FIG.4 EFFECT OF LE FLAPS ON LIFT

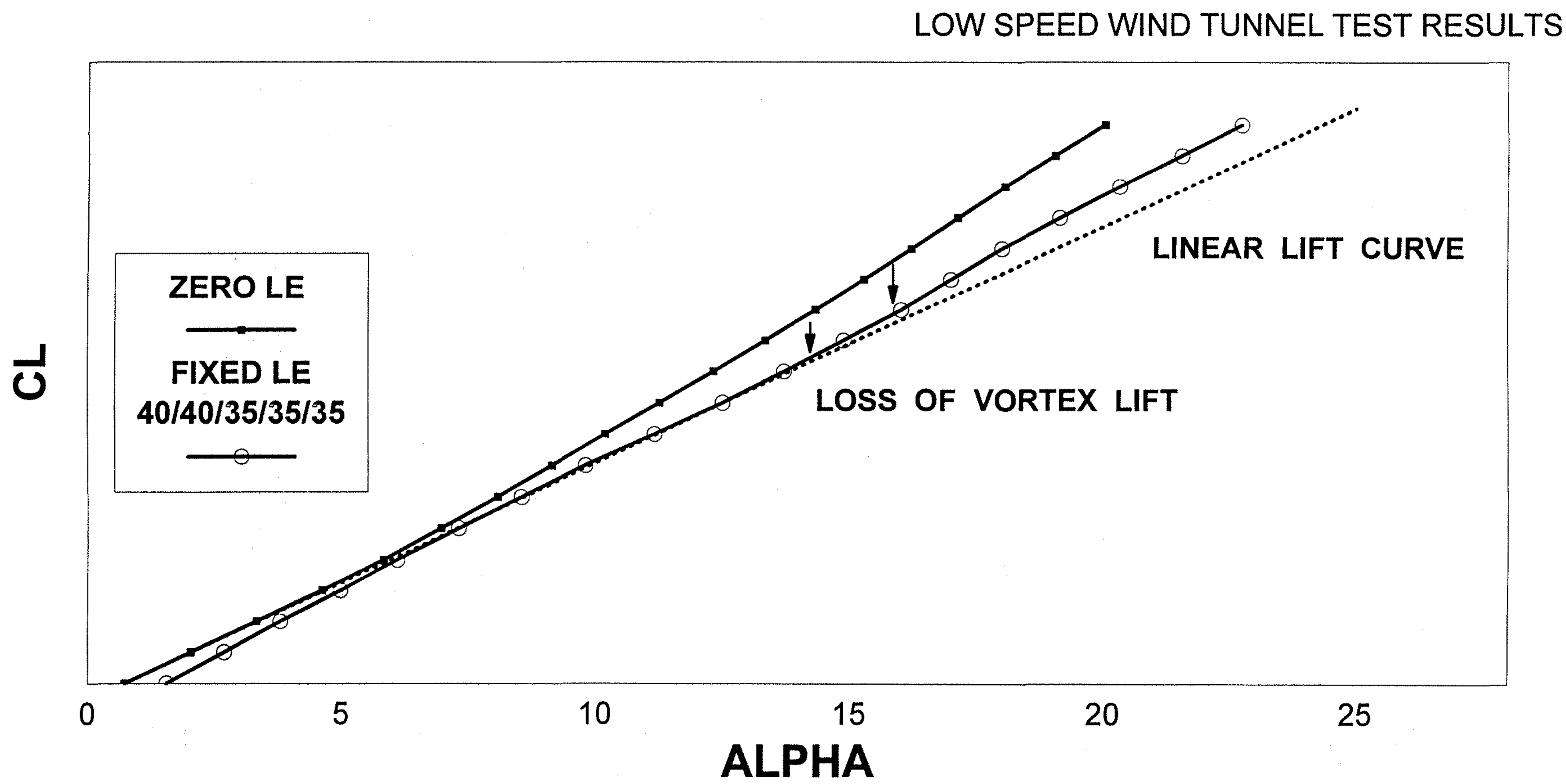


FIG.5 EFFECT OF LE FLAPS ON LIFT / DRAG

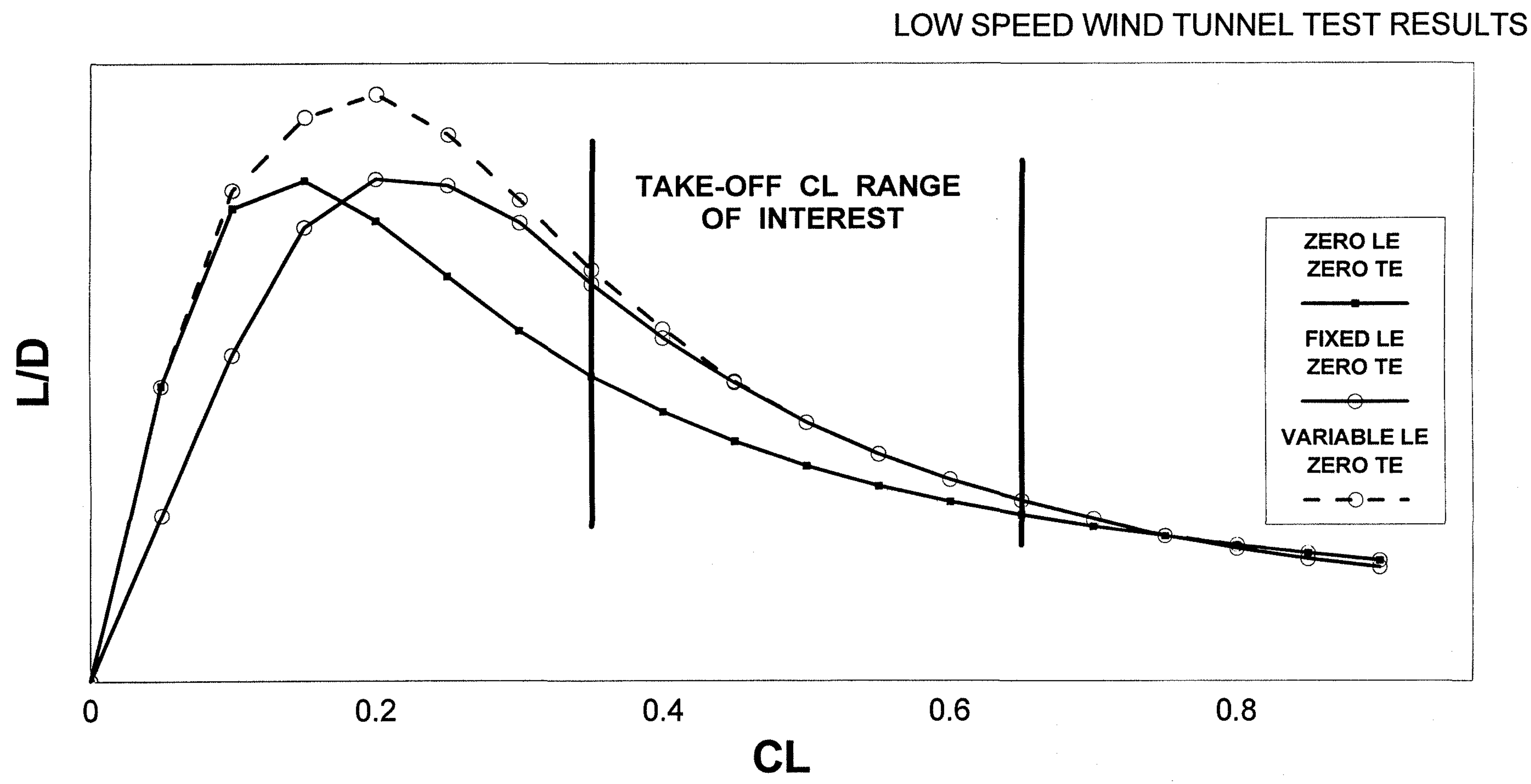


FIG.6 EFFECT OF BOTH LE AND TE FLAPS ON LIFT / DRAG

LOW SPEED WIND TUNNEL TEST RESULTS

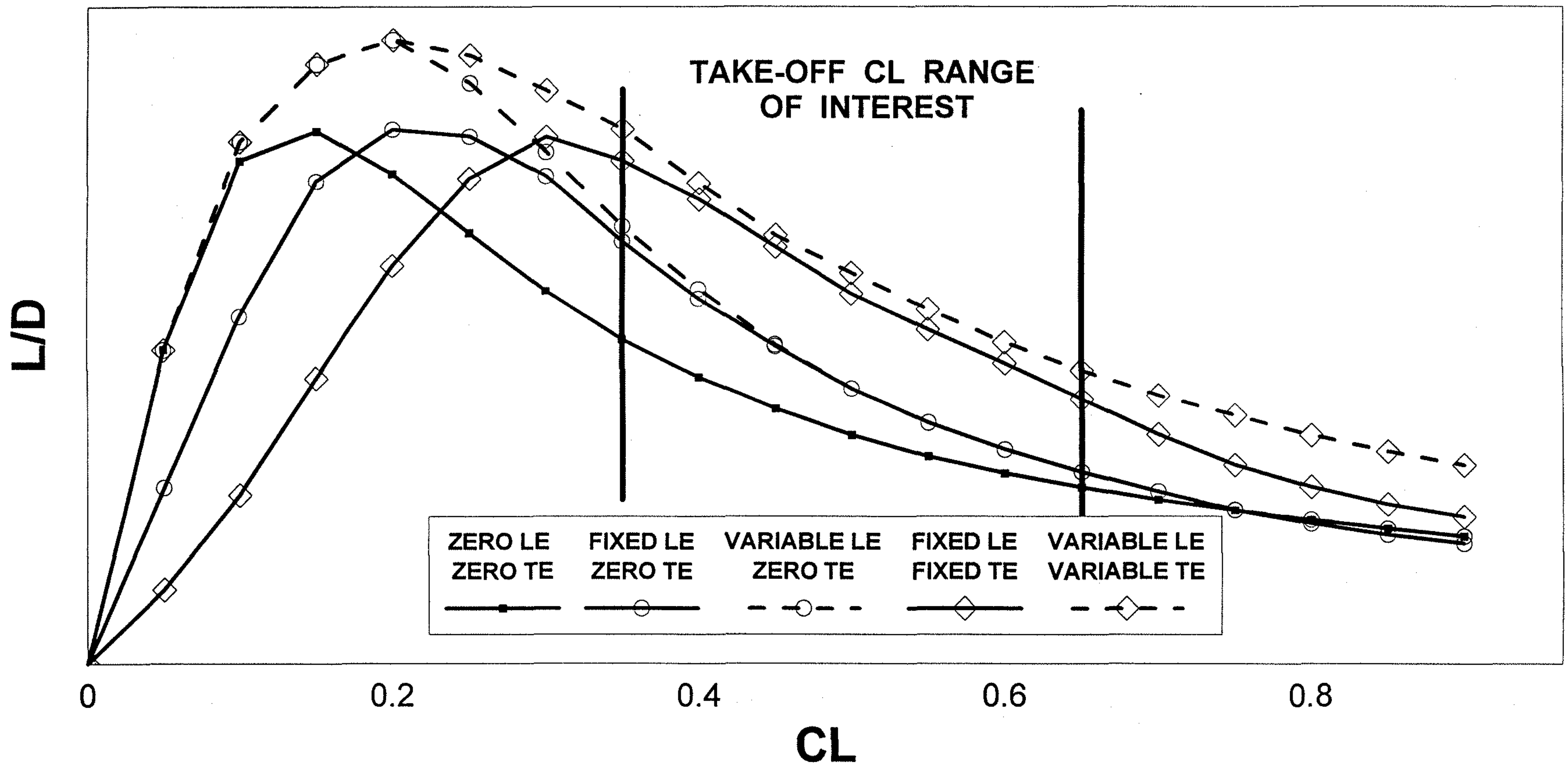


FIG.7 HIGH INCIDENCE LATERAL INSTABILITY

LOW SPEED WIND TUNNEL TEST RESULTS
(Alpha = 18 deg)

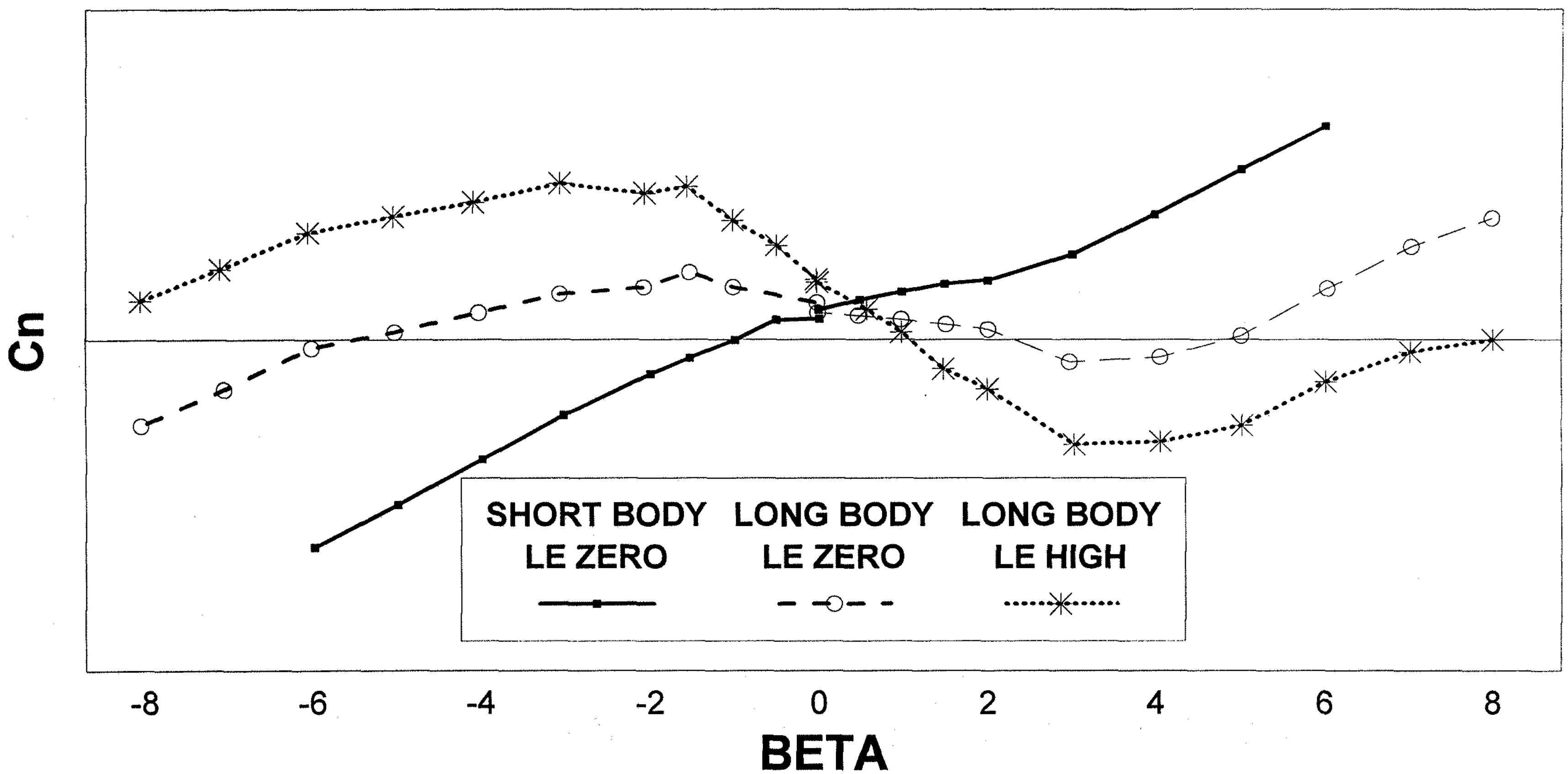


FIG.8 TAKE - OFF FLIGHTPATHS

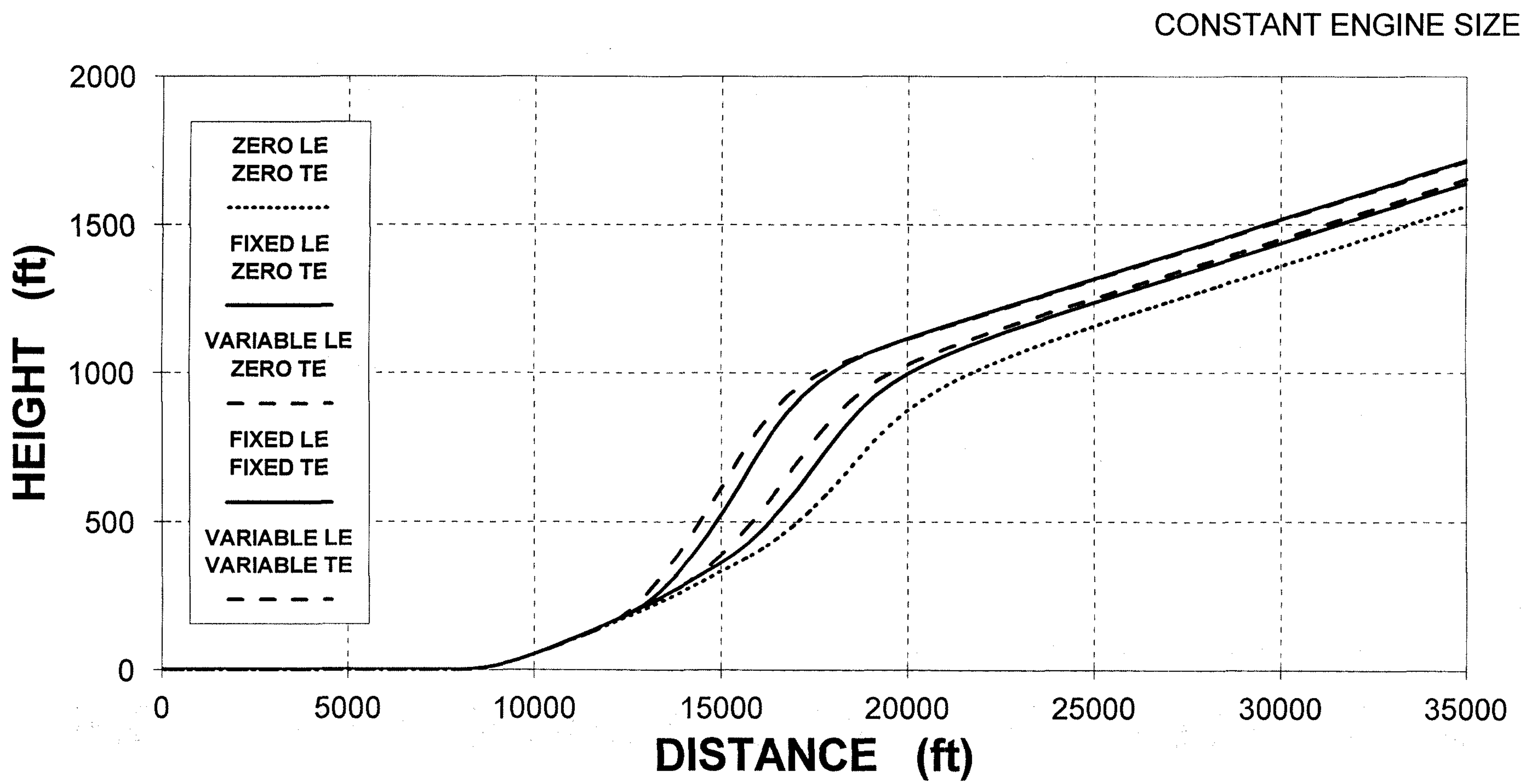


FIG.9 EFFECT ON TAKE-OFF NOISE DUE TO FLAP DEFLECTION