SUPERSONIC AIRCRAFT FORMATION FLYING TO INCREASE FLIGHT EFFICIENCY

Dr. R. K. Nangia* Dr. M. E. Palmer* Mr. W. Blake Dr. C. P. Tilmann****

***Nangia Aero Research Associates, WestPoint, 78-Queens Road, Clifton, BRISTOL, BS8 1QX, UK**

****US-AFRL, Wright Patterson Air Force Base, OHIO, USA**

Keywords: *Supersonics, Oblique Flying Wings, Formations, Aircraft Efficiency*

ABSTRACT

Flying aircraft in Close Formation Flight (CFF) to reduce fuel usage, is well appreciated. Results are available for conventional aircraft using idealized approaches e.g. vortex lattice formulations in subsonic regime with reductions in lift induced Drag (C_{Di}) of 30-50% predicted.

With greater importance of Oblique Flying Wing aircraft (OFW) and the research programme (e.g. the supersonic DARPA & USAF "SwitchBlade"), a need has arisen to evaluate the possible advantages and disadvantages of OFW in CFF. Compared with conventional symmetric aircraft flying in formation, asymmetric OFW present different and "handed" geometric relationships. Earlier work, in the transonic regime, showed reductions of more than 35% C_{Di} for trailing OFW in CFF, after redesign to eliminate lift and roll increments. However, there is little background on the Supersonic regime, hence prompting this paper.

Typical spacing parameters have been considered for OFW at 60^o sweep. Formations with single Trail aircraft to the right (Core 1) and also to the left (Core 2) of the Lead aircraft are assessed. Multi-Formations are also considered. Lift increments on trail OFW in favourable CFF geometries are trimmed out by reducing AoA. Benefits of up to 35% or more in C_{Di} reduction occur for the trimmed (1-DoF) trail aircraft. An accurate modelling the Lead aircraft trailing wakeis needed.

Brief assessment of Trailing edge flap deflections required to trim trail OFW in CFF, eliminating induced pitch roll and lift is shown. The use of camber design methods to re-design the trail wings to eliminate CFF induced forces and moments has been outlined.

The geometry changes for control are of course immediately applicable to morphing wing technology. Several avenues of further work and development have arisen.

1. GENERAL INTRODUCTION

Flying aircraft in formation to reduce fuel usage, has been appreciated. With importance of environmental aspects, need has arisen to evaluate the possible advantages /disadvantages of Close Formation Flight (CFF) and the means for implementing it practically. Aircraft formations, **Fig.1** occur for several reasons e.g. in displays or air-to-air refuelling but they are not maintained for any great length of time from the fuel reduction perspective. The background work is essentially for subsonic / transonic flight.

USAF work on T-38 formations is shown in **Fig.2**. Recently NASA has conducted tests on formations of two F/A-18 aircraft to establish possible benefits (Refs.1-4 & **Fig.2**). Benefits occur at certain geometry relationships in the formation. For example the trail aircraft overlaps the wake of the lead aircraft by 10-15% semi-span.

In the civil scene, Jenkinson (Ref.5, 1995) proposed a CFF of large aircraft as being more efficient than flying one very large aircraft. Aircraft could take off from different sites, then fly in formation over large distances, peeling away to land.

Many results are available using idealized approaches e.g. vortex lattice formulations e.g. Ref.6 (with a useful bibliography). Aircraft formations can comprise large and small aircraft. Each aircraft in a formation is likely to experience off-design forces and moments. It will be pre-requisite to ensure that these off-design effects can be adequately and efficiently modelled/controlled. Simply using ailerons, to control induced roll on a trail wing, may increase drag and compromise CFF advantage.

Refs.7-8 presented the induced effects and control aspects of conventional wings in CFF, addressing also the relative size effects (**Fig.3**). For the Subsonic regime, several papers mention up to 30-50% reduction in lift-induced drag.

1.1. Recent Interest in OFW

As a result of DARPA activities on the Supersonic SwitchBlade project, there is revived interest in

Oblique Flying Wings (OFW), **Fig.4**, Refs.9-10. OFW have been considered as design options in the past with considerable advantages over conventional wing, fuselage, tail configurations, Ref.11. However stability issues have usually limited their use. Swept, OFW may now be a viable option for UAV's.

1.2. Some Claimed Advantages & Capabilities

Fig.5 summarises the perceived advantages for the OFW (based on descriptions of Kroo, www.Desktop Aeronautics). These are with regard to Wave drag, Lift-induced drag (higher Aspect Ratio) and Structure. The OFW planform naturally avoids the difficulties induced by the sweep discontinuities at the centre-line of a conventional swept wing, **Fig.5(a)**. At high speed, the attached shocks can be tailored to have constant sweep across the span leading to low wave drag. The Aspect Ratio can be much higher for oblique wings. These ideas will potentially lead to higher L/D..

The wing box can be straight (no centre-line kink), **Fig.5(b)**. This should result in a lighter, more efficient structure. However, other issues e.g. bending / twisting are relevant.

There are advantages for variable sweep wings. In a conventional layout, as the wings sweep back progressively for high speeds, **Fig.5(c)** the neutral point shifts rearwards. This property implies significant design problems for the longitudinal stability of conventional layouts. Such effects are significantly reduced in the case of the variable sweep OFW. However, OFW asymmetric flight leads to several complexities especially if the sweep varies, e.g. thrust pivoting etc.

Because of lower wave drag, the L/D of the OFW is higher than that for a corresponding swept-back wing, **Fig.5(d)**. The OFW layout with 30 degree sweep can approach L/D of 20 or more and this could amount to a 20% advantage over an equivalent conventional wing. The more simple, lighter structure ensures a relatively low OEW (Operating Empty Weight). These factors lead to a much more efficient and capable aircraft, affording greater payload capacity or range or endurance.

For "natural stealth", planform parameters (LE and TE sweep) need to be chosen appropriately.

The possibility of combining the advantages of OFW and CFF led to the work in Ref.12. This studied a planform based on Switchblade (public domain). The work focused on transonics and, after redesign of the trail wing to trim lift/roll increments, reductions of more than 35% C_{Di} were noted. There is little background in CFF and Supersonics.

2. OBLIQUE FLYING WING FORMATIONS

Compared with conventional symmetric aircraft flying in formation, asymmetric flying wing aircraft present different, "handed" geometric relationships, **Fig.6**. Regions where the trail wings may incur single or double improvements are identified. Note the different core formations 1-4 highlighted in **Fig.7**. Cores 1 and 2 are handed "cascade" CFF and Cores 3 and 4 are skewed "echelon" CFF. We also get regions of mutual interference depending on the relative separations of the neighbouring wings. Formations of mixed aircraft types (conventional, delta and flying wing) may yield additional advantages. Multiple aircraft "Swarms" will, no doubt, provide yaw and sideslip challenges. Further formation options and challenges arise with future Long Range Supersonic Strike (LRS) aircraft.

3. OBLIQUE WINGS, PLANAR & DESIGN, SUPERSONIC FLIGHT

Before studying at formations, we need to focus on design parameters for an OFW. Possible supersonic flight parameters and a planform selected are shown in **Figs.8** & **9** respectively. Note the trailing edge flap (TEF) in 8 segments (A to H). The emphasis of the work is on a 60 deg. sweep wing, Aspect Ratio (AR) = 3.21 at Mach 1.4 for design C_L near 0.245. The OFW planform origin lies at x=0, y=0, with span=1.0. The OFW apex is at x=0.0, y=0.1. The wing is initially assessed in its planar, uncambered state. At this stage, simple aerofoil sections have been used. Supersonic Panel Method results predict that Centre of Pressure (CoP) at M1.4, lies at x=0.885, y=0.556, **Fig.9**.

3.1. Oblique Wing, Mach 1.4, C_L= 0.24 Designs

A Modal Linear Theory technique (Refs.13-17) was used to define the camber surface required for design C_L and C_m constraints at the design Mach number. A constant thickness distribution (t/c = 7.5%) was applied across the span. The geometry was then evaluated using a supersonic panel method (PANAIR). A simple calibration was required to match the Linear Theory and Panel methods.

Fig.10 compares planar and designed wings (Wing-1 and Wing-2). Spanwise distributions of Lift from the supersonic panel method and Cp contours from an Euler method, Ref.18, (C_L = 0.244) are also shown. For the planar wing, C_L = 0.245 at AoA = 4.83^o and $C_{L\alpha}$ = 0.0509. Wing-1 was designed with C_m constraint of –0.01 about M1.4 CoP. This design gave a triangular loading very similar to the planar case, C_L = 0.24 at AoA = 5.09^o. Wing-1 twist / camber are in **Fig.10**.

Wing-2 was designed with C_m constraint of –0.01 about the chordwise CoP location and the centreline (y=0.5). This design gave a less triangular, approaching elliptic loading, $C_L = 0.21$ at AoA = 4.83°. Wing-2 twist is also shown in **Fig.10**. The LE pressures have been controlled in the designed cases. Considering suitable estimates of C_{Di} and C_{Do}, we touch L/D of 12 at the design C_L for the isolated OFW.

4. FORMATION EXAMPLES

With reference to formation core geometries defined in **Fig.7**, we present selected typical cases. These will cover two and three wing formations of identical, planar or designed OFW. At this stage, we assume that the aerodynamic performance of the Lead OFW (C_L=0.24, L/D=12) is unaffected by the presence of one or more trail OFW in CFF. We have avoided CFF geometries in which Mach lines generated by one wing interfere with other wings.

Depending upon the formation geometry, the trail wing is affected by either upwash or downwash from the Lead wing. In the most favourable locations, the trail wing may experience an increase in C_L and a reduction in C_{Di}. Unfavourable locations may result in a reduction in C_L / an increase in C_{Di}.

In this early work, we establish formation geometries where the effects are favourable and simply trim out the interference lift arising on the trail OFW by reducing its AoA (α), one degree of freedom (1-DoF). The reduction in C_{Di} on the Trail wing can also be evaluated from Trefftz plane analysis or surface pressure integration. The latter method is very dependent upon panel descretisation for absolute drag estimation but in general is adequate for predicting changes in drag. Following Blake & Multhopp (Ref.19), a simple formulation for lift induced drag estimation on the trail wing in formation flight has also been used, **Fig.11**. The lift vector on the trail wing is tilted forward in the upwash field of the lead wing and this contributes largely to the lift-induced drag reduction ($\Delta C_{Di} = C_L \tan(\Delta\alpha)$). For the CFF cases here, both planar and designed OFW, the three methods show very close agreement. The overall reduction in C_{Di} on the trail OFW contributes to an increase in L/D.

4.1. Core 1 Formations

Fig.12 shows the geometry relationships between Lead and Trail wing. The Trail wing is placed at the Cartesian origin (x,y,z = 0,0,0). We assess changes in the aerodynamic performance of the Trail wing due to one or more Lead wings located upstream. The streamwise, lateral and vertical Lead wing displacements (dx, dy, dz) are non-dimensionalised by OFW span (b=1.0) and are referenced to the origin. For Core 1 formations, the Lead wing is upstream (dx negative) and to the left (dy negative) of the Trail wing. For Lead wing below Trail wing, dz is negative.

Fig.13 refers to a CFF of **two** identical planar wings, dx = -2, dy = -1, dz = -0.03. Spanwise lift loadings are for the Lead (isolated) and Trail (untrimmed) wings in **Fig.13(a)**. The increase in C_L on the Trail wing is trimmed out by reducing the Trail wing incidence by 1.18°. The resulting spanwise lift loadings are shown in **Fig.13(b)**. It is evident that there is an induced rolling moment on the Trail wing after trimming for C_L (1-DoF). This, and other induced moments (pitch and yaw), will require a combination of control surface deflections (camber modification), and possibly thrust vectoring, to fully trim.

Results for L/D improvement on the trail wing as a function of dy and dz for dx of 1.6 and 2.0 are shown in **Fig.14**. The curves optimize (35% improvement in L/D) when the wings are nearly in one plane lying close to dy = -0.9. The benefits will "carry-over" to subsequent aircraft in multi-CFF.

Fig.15 shows the spanwise loadings in a CFF of **three** planar wings, before and after trimming in C_L. The wings are equi-spaced in cascade CFF. Before trimming, the spanwise distributions on the second and Trail wings are less triangular than the Lead and an increase in C_L is evident. The second and Trail wings require 1.18° and 1.19° reductions in AoA for C_L trim condition. In this case the spanwise distributions on the second and Trail wings are now similar and less triangular (cf the Lead).

We consider one case for determining the TEF deflections required to trim the Trail OFW for C_m, C_l and C_L (3-DoF). Trim in yaw is not attempted, at this stage. The effectiveness (control power) of the TEF arrangement shown in **Fig.9** was evaluated on the isolated planar OFW. For Core 1 CFF (dx = -2.0, dy = -0.9, dz = -0.05), changes in C_m, C_l and C_L on the Trail OFW were determined. To establish the principles and feasibility we have determined TEF deflection angles for TEF A and H only (ε_A and ε_H) and the change in AoA required to trim, to a first order. The values are $\varepsilon_A = -0.73$, $\varepsilon_H = 4.82$ and $\Delta\alpha = -1.118°$. The CFF induced C_l has been reduced by two-thirds and induced C_m by three-quarters. The desired C_L has been achieved with a notable reduction in C_{Di}. Deflection of TEF A and H only to correct for C_L, C_m and C_l (3-Dof) has had a favourable effect in reducing C_n. This preliminary solution has been obtained with simultaneous equations, using only two of the eight available TEF. A full optimisation process using Lagrange multipliers will be needed to trim the OFW in CFF whilst minimising drag.

4.2. Core 2 Formations

Fig.16 refers to Core-2 formation geometry. As for Core 1, dx, dy, dz are defined in terms of OFW span (b) and are referenced to the OFW apex locations. For Core 2, the Lead wing is to the right of the Trail wing (dy positive).

Fig.17 shows the spanwise loadings in a formation of **two** planar wings, before and after trimming in C_L (dx =-2, dy = +1.0, dz = -0.03). Although the magnitudes of the dx, dy, dz displacements are equivalent to the Core 1 CFF, **Fig.13**, the asymmetry of the OFW results in different interferences in this Core 2 case. The triangular nature of the spanwise lift loading of the isolated OFW has been enhanced on the Trail OFW in CFF. After trimming to the same C_L the loadings on the Trail and Lead wings are almost identical, implying little or no induced rolling moment.

Results for L/D improvement on the Trail wing as a function of dz for dx of 2.0 and dy = +1.0, are shown in **Fig.18** for CFF with planar wings and also CFF with designed Wing-2. Note that the curves show 20% improvement in L/D with the wings nearly in one plane. The designed wing geometries experience consistent L/D improvements over a greater dz range than the planar wings. As is the case for Core 1, the benefits will “carry-over” to subsequent aircraft in CFF of more than two aircraft.

Fig.19 shows the spanwise loadings in an equi-spaced CFF of **three** planar wings, before and after trimming in C_L. Note the “triangular“ of loadings on all three wings. After trimming to the same C_L, the loadings on the second and Trail wings are identical and very close to that of the Lead wing, again, implying little or no induced rolling moment for this Core 2 CFF.

4.3. Core 1 Formations of Wing-1 design OFW

Fig.20 refers to Core 1 CFF, (dx = -2, dy = -1.1, dz = -0.01) of design Wing-1 OFW. It shows the Trail OFW spanwise lift loadings before and after trimming in C_L. The designed Wing-1 behaves in an identical fashion to the planar case. Note that the loadings become less triangular when trimmed, effectively inducing a rolling moment.

4.4. Cross-Flow Plane Analysis

Provided there is adequate coverage in the y-z plane, contours of significant variables (C_L, L/D, C_l/C_n, etc) arising on the Trail wing can be produced. From these, CFF geometries providing benefits (increased L/D), and those that need to be avoided (stability and control problems), can be assessed. The y and z dimensions in **Figs.21** & **22**, refer to the displacement of the Lead wing relative to the Trail wing (see **Fig.12**, Core 1 and **17**, Core 2). **Fig.21** shows contour plots of C_l/C_n arising on the planar Trail wing (untrimmed case). These will be useful during the design and CFF evaluation stages.

Fig.22 shows L/D contours arising on the planar Trail wing (trimmed). Immediately it can be seen that there are regions where L/D increments, based on isolated OFW L/D = 12, readily exceed 20% near y = -1.0 and +1.0. We note the near circular region (radius = 0.15b about the Lead right tip) defining Trail left tip location for which L/D rises above 14.5 (approaching 15.5 to 16.0). This gives rise to the 30%-35% increments seen in **Fig.14**. At y = 0.0 the wings are in line and L/D on the Trail wing drops to less than 8. The L/D gains will reflect directly in range improvements, on the basis of the Breguet Range Equation.

5. SUPERSONIC DELTA WING FORMATION

Another “out of the box” item is analysis of conventional supersonic layouts (e.g. LRS type) in formation, **Fig.23**. Note straight LE & Cranked LE planforms at Mach 1.6 and 2.0. **Fig.24** shows the spanwise loads and geometry of planar and designed Wings at Mach 1.6.

Formation flying. allows very encouraging results (up to 25% L/D improvement on Trail aircraft) as illustrated in **Fig.25**. Such numbers should have a favourable effect on range determination of supersonic aircraft.

Based on Ref.2, for Mach 1.6 aircraft of different payload capacity, we see substantial benefits in range and hence Payload Range Efficiency Parameters, **Figs.26 & 27**.

6. GENERAL INFERENCES, CONCLUSIONS

The idea of flying aircraft in formation to reduce fuel usage, has been appreciated for some time. Many theoretical and experimental results are available for conventional winged aircraft in the subsonic regime. Efficiency, environmental and economic issues and renewed interest in OFW configurations and their suitability to supersonic flight has led to the work in this paper.

The design of a supersonic, 60^o sweep, AR = 3.21, OFW and its integration into supersonic CFF have been studied. Building upon previous work that predicted 30-50% reductions in C_{Di} for conventional wings in subsonic CFF and similar advantages for OFW in subsonic CFF, we show benefits of the same order for a simple OFW in supersonic CFF.

A wide range of CFF layouts have been evaluated (planar and designed OFW, typical spacing parameters). Formations with single trail aircraft to the right (Core 1) and also to the left (Core 2) of the Lead OFW have been assessed. CFF with multiple trail OFW have also been studied. For each case, using a supersonic panel method (PANAIR), we have derived C_{Di} reductions and L/D increments for the trail OFW at trimmed C_L,.

The off-design forces and moments induced by CFF can be adequately and efficiently modelled and controlled using a simple array of TEF.

The Trail aircraft benefits for multiple aircraft in formation are, to a first order, cumulative.

In certain CFF situations the lead wing may be affected by the trail wing, especially where more than one trail wing is present (Core 4) and these are in relatively close proximity. The interaction effects are likely to be complex and the benefits may not be simple summations. In all cases, the streamwise spacing of the aircraft will also have a strong effect.

The implications of accurately modelling the Lead aircraft trailing wake have been highlighted.

The work so far has been very interesting and challenging. Large benefits (25 - 30% L/D increments on Trail OFW in CFF) in supersonic flow are noted. Substantial Range enhancement will result. We can see the need for a suitable series of experiments at subsonic and supersonic speeds.

The need for efficient control in the modern context implies morphing, exploiting variable camber, winglets, span extension or other ideas. Recently, we have developed a design method for subsonic / transonic regime, Refs.20-21, applicable to wings with or without winglets. This approach starts with wake shape and spanwise loading constraints and then produces appropriate wing camber and twist shapes. Any solvers e.g. panel, Euler or Navier-Stokes types can be implemented. The method has been adapted to the evaluation of aircraft flying in formation (Refs 6, 7 & 12). This approach could be extended to Supersonics.

Aircraft formations comprise large and small aircraft and many combinations arise. Each aircraft in CFF is subject to off-design forces and moments. It will be pre-requisite to ensure that off-design forces and moments can be adequately and efficiently modelled and controlled. Sideslip cases need to be included.

We can see the need for a suitable series of experiments at subsonic and supersonic speeds.

ACKNOWLEDGEMENTS

Part of the work has been funded by AFRL EOARD. Opportunities for collaboration are warmly invited. Opinions expressed are due to the authors.

REFERENCES

1. HAGENAUER, B. "NASA Studies Wingtip Vortices." Aerospace Engineering Online: Technology Update, Jan/Feb 02, http://www.sae.org/aeromag/techupdate/02-2002/page5.htm.
2. IANNOTTA, B. "Vortex Draws Flight Research Forward." Aerospace America, Mar 02, 26-30.
3. RAY, R. J., et al. "Flight Test Techniques Used to Evaluate Performance Benefits During Formation Flight." AIAA paper 2002-4492, Monterey CA, August 2002.
4. WAGNER, G., et al. "Flight Test Results of Close Formation Flight for Fuel Savings." AIAA paper 2002-4490, Monterey CA, August 2002.
5. JENKINSON, L.R., CAVES, R.E & RHODES, D.R., “A Preliminary Investigation into the Application of Formation flying to civil operation”, AIAA Paper –95-3898, 1995.
6. IGLESIAS, S., “Optimum Spanloads Incorporating Wing Structural Considerations & Formation Flying”, Virginia Polytechnic, 2000 Thesis.
7. NANGIA, R.K., PALMER, M.E., “Formation Flying of Commercial Aircraft – Assessment using a New Approach - Wing Span Load & Camber Control”, AIAA Paper 2007-0250, 2007.
8. NANGIA, R.K., PALMER, M.E., “Formation Flying of Commercial Aircraft, Variations in Relative Size / Spacing – Induced Effects & Control”, AIAA Paper 2007-4163, 2007.
9. “DARPA sponsored Oblique Wings” Flight International, 13-19 September, 2005.
10. NANGIA, R.K. & GREENWELL, D.I., "Wing Design of Oblique Wing Combat Aircraft", ICAS 2000-1.6.1, 2000.
11. SOBIECZKY, H., “Manual Aerodynamic Optimisation of Oblique flying Wing, ICAS-98-1.1.3, 1998.
12. NANGIA, R.K., PALMER, M.E., “Oblique Flying Wing for Increased Capability UAV’s, Design & Formation Flying”, 22nd International Unmanned Air Vehicle Systems Conference, Bristol, April 2007.
13. NANGIA, R.K., PALMER, M.E., & DOE, R.H., "A Study of Supersonic Aircraft With Thin Wings of Low Sweep", Paper AIAA Paper 2002-0709, AIAA Aerospace Sciences Meeting & Exhibit, Reno, USA.
14. NANGIA, R.K., PALMER, M.E. "Unconventional Joined-Wing Concept for Supersonic Aircraft", Paper 24, RTO-AVT-99 Conference, Brussels, April 2003.
15. NANGIA, R.K., PALMER, M.E. & IWANSKI, K.P. (AFRL), “Towards Design of Long-range Supersonic Military Aircraft”, AIAA Paper, 2004-5071, Providence Rhode Island, USA, 2004.
16. NANGIA, R.K., PALMER, M.E. & DOE, R.H., “Towards Design of Mach 1.6+ Cruise Aircraft”, AIAA Paper, 2004-5070, Providence, RI, USA, 2004.
17. NANGIA, R.K., PALMER, M.E. & IWANSKI, K.P. (AFRL), “Towards Design of Long-range Supersonic "Large" Military Aircraft”, RAeS Paper 16, Sept. 2004, London, UK.
18. GUPTA, K.K. & MEEK, J.L., "Finite Element Multi-

Discliplinary Analysis”, AIAA, 2000.

19. BLAKE, W.B. & MULTHOPP, D., “Design, Performance and Modeling Considerations for Close Formation Flight”, AIAA 98-4343, August 1998.
20. NANGIA, R.K., PALMER, M.E. & DOE, R.H., “Aerodynamic Design Studies of Conventional & Unconventional Wings with winglets”, AIAA-2006-3460. 25th Applied Aero Conference, San Francisco, June 2006.
21. NANGIA, R.K., PALMER, M.E., “Morphing UCAV wings, Incorporating in-Plane & Fold-Tip Types – Aerodynamic Design Studies”, AIAA-2006-2835. 25th Applied Aero Conference, San Francisco, June 2006.

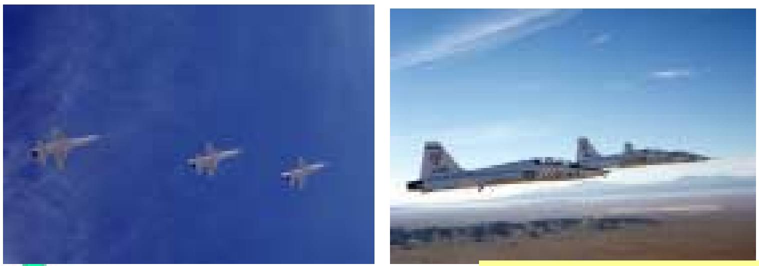
NOMENCLATURE

y_{CP} Spanwise location of Centre of Pressure
α AR Aspect Ratio
b = 2 s, Wing span
c Local Wing Chord
c_{av} = c_{ref} = S/b, Mean Geometric Chord
C_A = Axial force/(q S), Axial Force Coefficient
C_{AL} Local Axial Force Coefficient
C_D Drag Force /(q S), Drag Coefficient (C_{Di}+ C_{D0})
C_{Di} Lift Induced Drag Coefficient
C_{DL} Local Drag Coefficient
CG Centre of Gravity
C_L = Lift Force/(q S), Lift Coefficient
C_{LL} Local Lift Coefficient
C_l = l/(q S b), Rolling Moment Coefficient
C_m = m/(q S c_{av}), Pitching Moment Coefficient
C_{mL} Local Pitching Moment Coefficient
C_n = n/(q S b), Yawing Moment Coefficient
C_P Coefficient of Pressure
ΔC_L Difference in C_L
ΔC_{Di} Difference in C_{Di}
ΔC_D Difference in C_D
dx, dy, dz for specifying formation relative distances
LE, TE Leading Edge, Trailing Edge
LEF, TEF Leading Edge Flap, Trailing Edge Flap
L/D Lift to Drag ratio
l Rolling moment (positive right tip up)
m Pitching moment (+ve nose up)
n Yawing moment (+ve nose to right)
M Mach Number
q = 0.5 ρ V^2, Dynamic Pressure
Re Reynolds Number, based on c_{av}
s, S semi-span, Wing Area
S_L Lead aircraft Wing Area
S_T Trail Aircraft Wing Area
V Free-stream Velocity
x, y, z Axes system of an aircraft
x_{AC} Chordwise position of Aerodynamic Centre
x_{CP} Chordwise location of Centre of Pressure
AoA, Angle of Attack
$\Delta\alpha$ Change in local AoA for C_L trim
ß $\sqrt{(1-M^2)}$
λ Taper Ratio, c_t/c_r
Λ LE Sweep Angle
η = y/s, Non-dimensional spanwise distance
ρ Air Density

COPYRIGHT STATEMENT

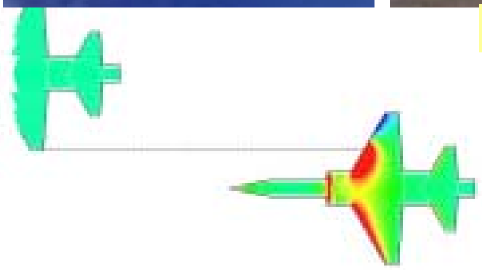
Fig. 1 DISPLAY FORMATION IN-FLIGHT REFUELLING

F/A-18 FORMATIONS, NASA



T-38* FORMATIONS, *USAF

Fig. 2 F/A-18 & T-38 FORMATIONS



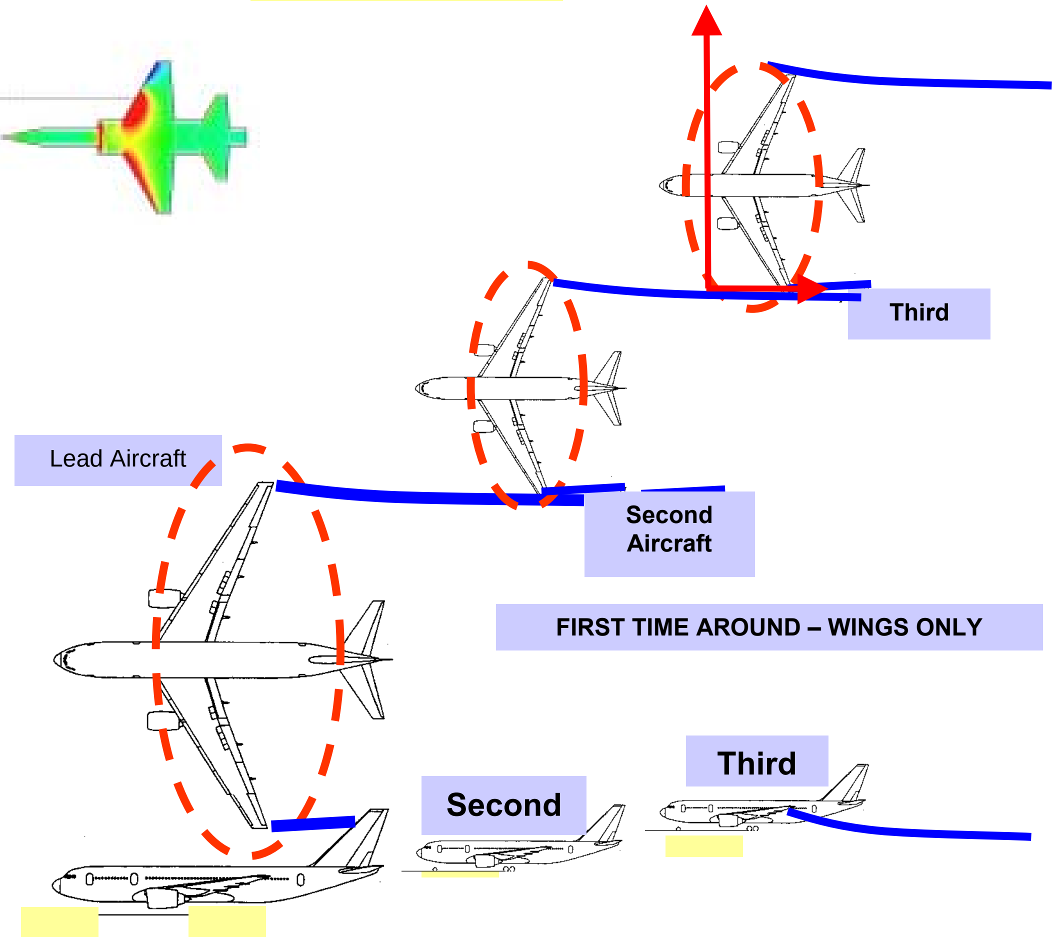
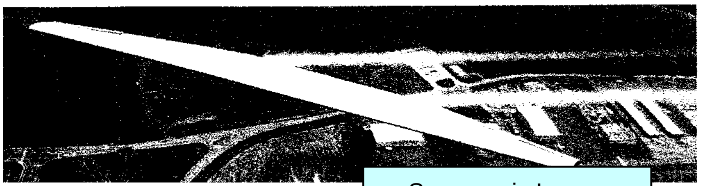


Fig. 3 BASIC FORMATION, CONVENTIONAL UNEQUAL SIZE AIRCRAFT

Low-Speed

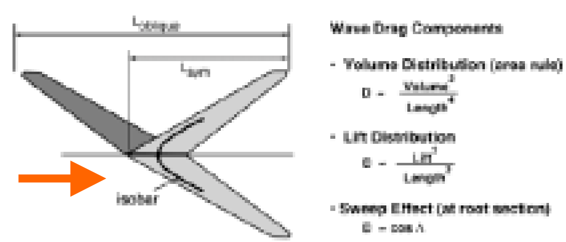
Supersonic



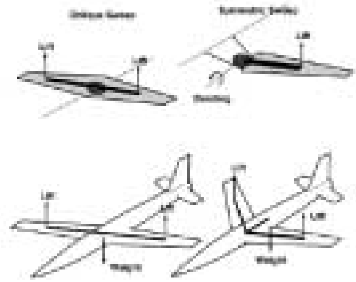
Supersonic Large-scale OFW, "Buried" Propulsion

Supersonic Demonstrator, Twin Pivoted Engines

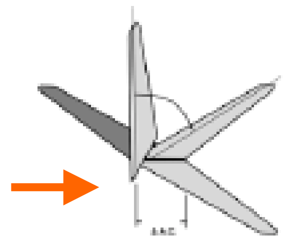
Fig. 4 OBLIQUE FLYING WINGS, OFW (DARPA)



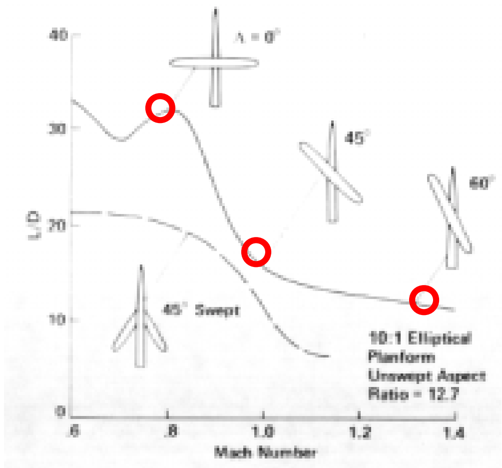
(a) Drag Reduction Aspects



(b) Structural Advantages



(c) Relief from Symmetric Variable Sweep Structural, stability & control difficulties



(d) OFW – L/D vs M compared with Fixed Geometry Symmetric Design, Idealized Wing-Body

Fig. 5 OBLIQUE FLYING WINGS, SOME POSSIBLE PERCEIVED ADVANTAGES

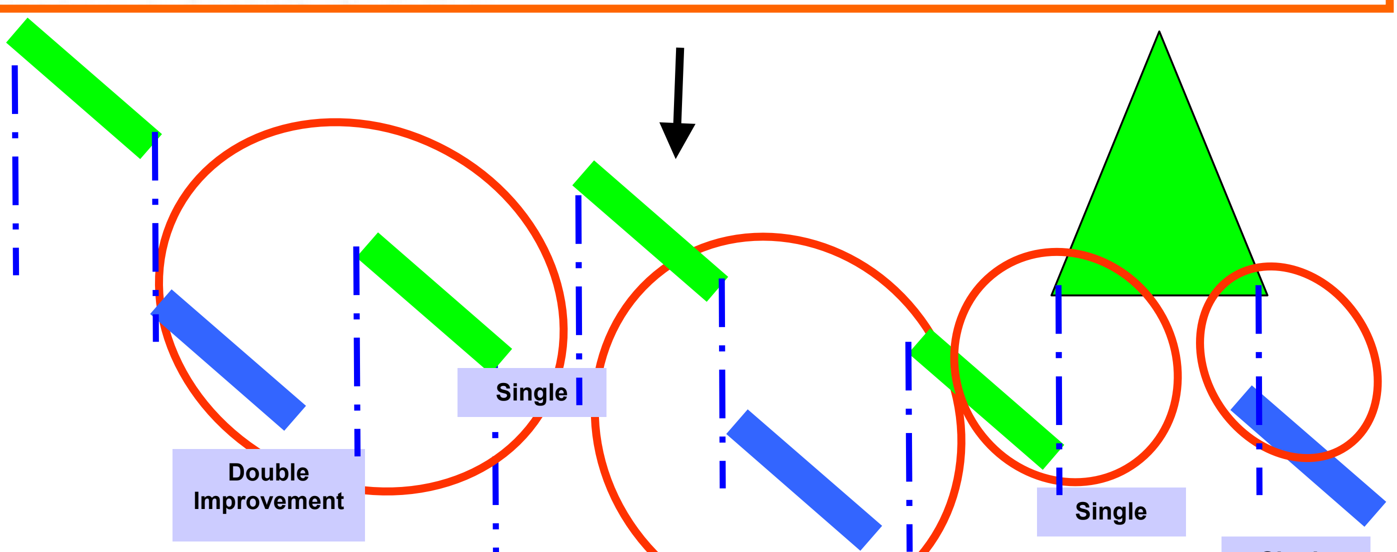


Fig. 6 OBLIQUE FLYING WINGS, SWARM, Single & Double Improvements

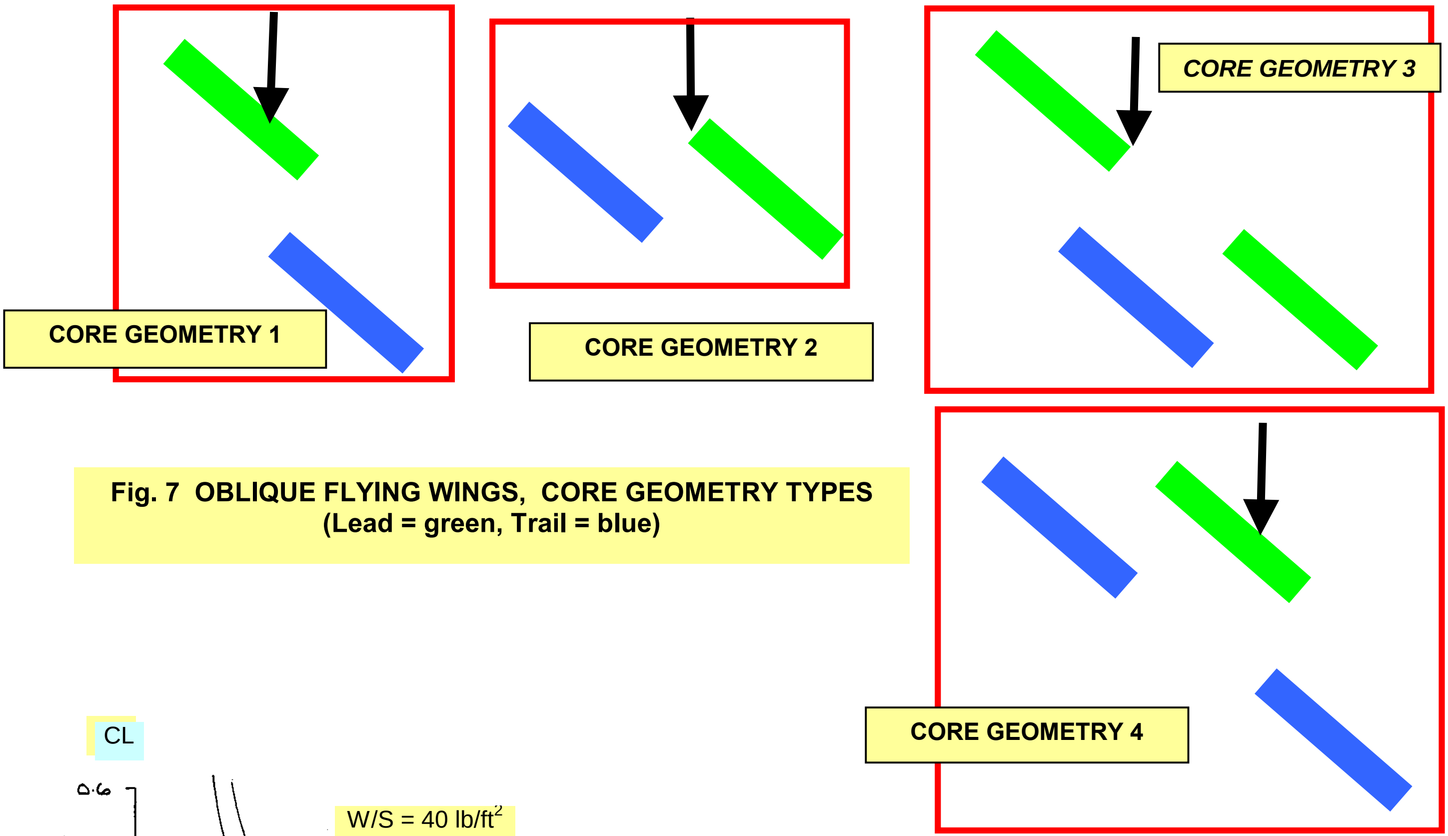


Fig. 7 OBLIQUE FLYING WINGS, CORE GEOMETRY TYPES
(Lead = green, Trail = blue)

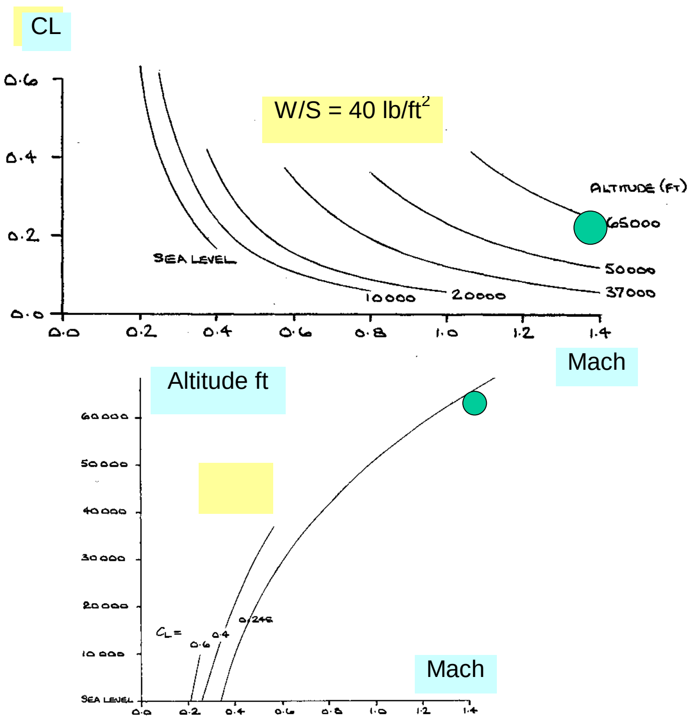


FIG. 8 SELECTION OF DESIGN POINT for a 60 deg OFW, CL & MACH No. RELATIONSHIPS

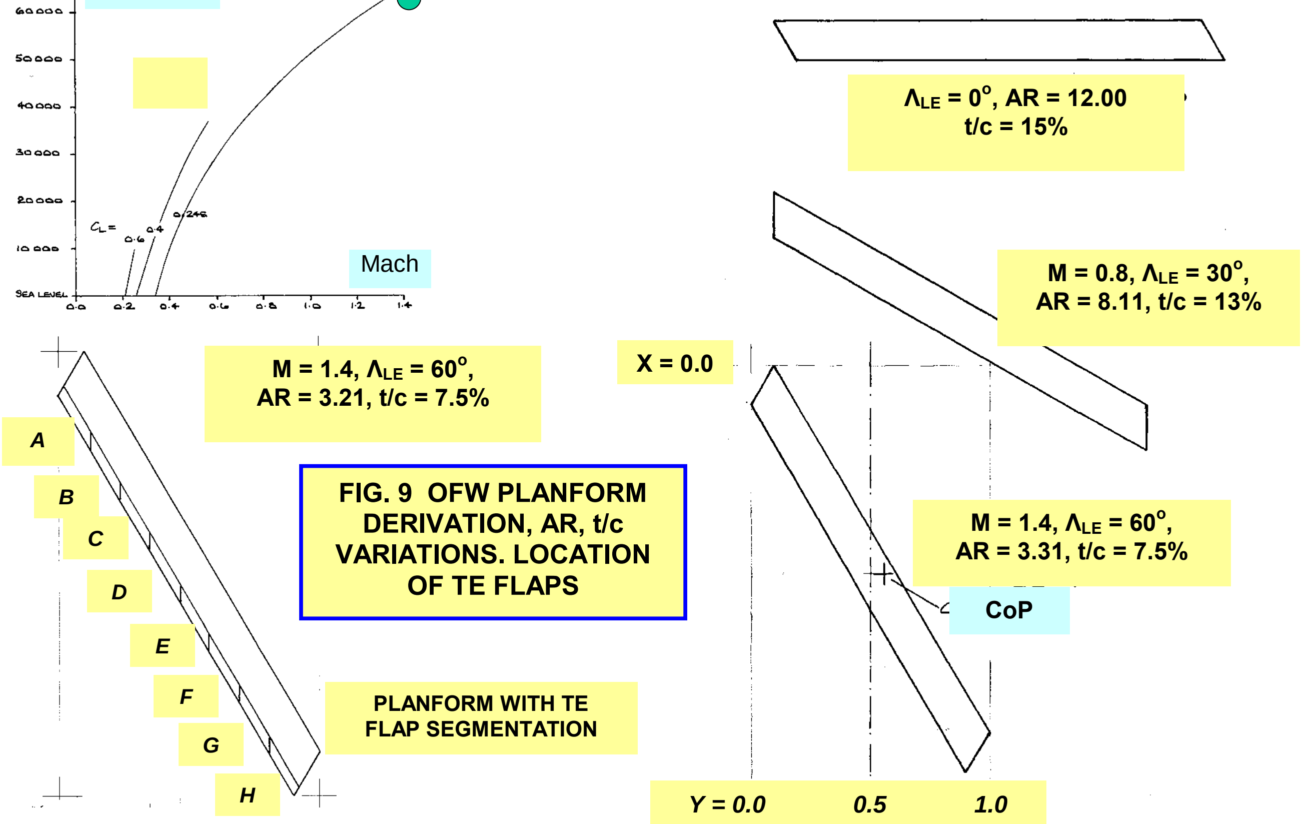
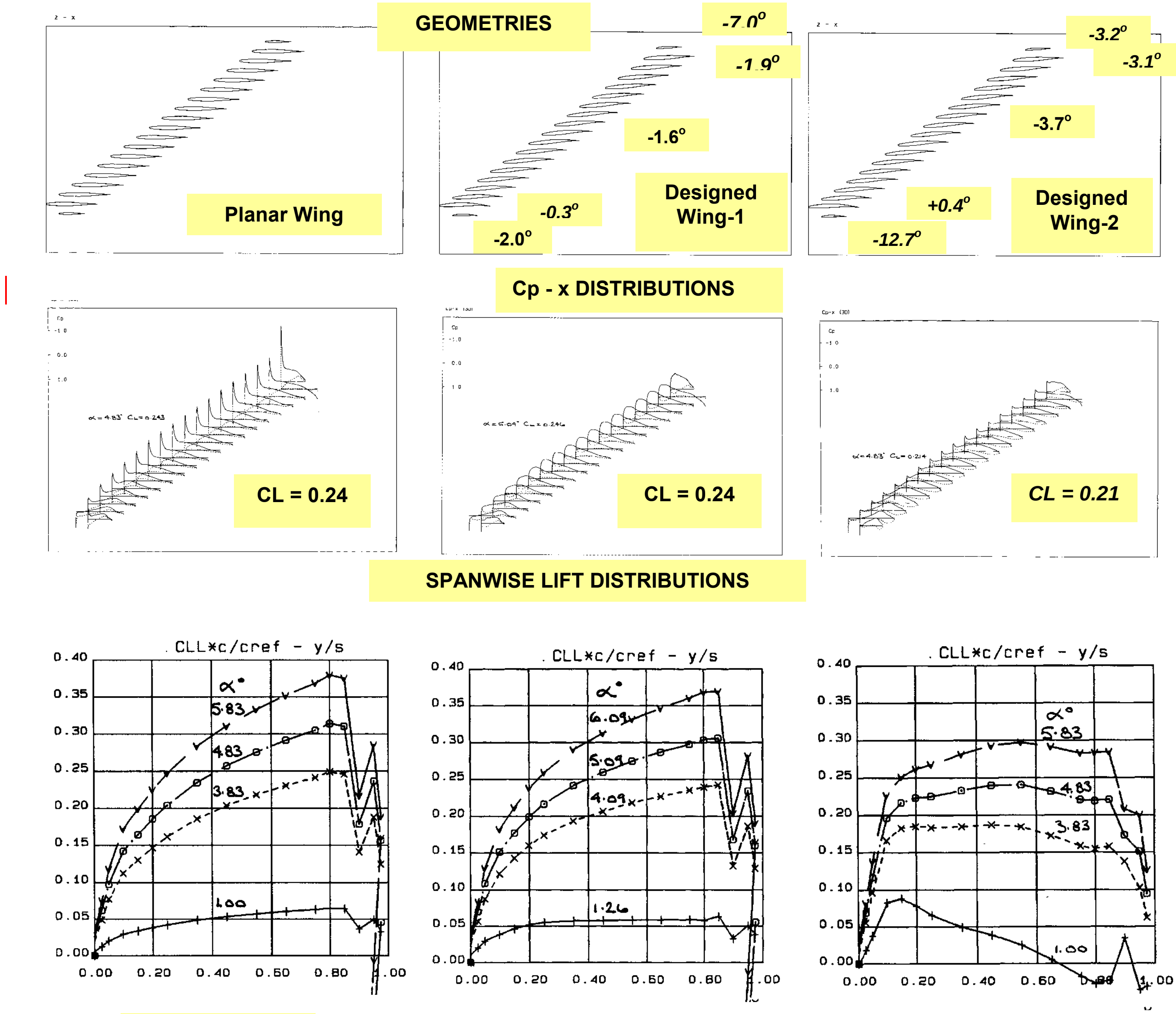


FIG. 9 OFW PLANFORM DERIVATION, AR, t/c VARIATIONS. LOCATION OF TE FLAPS



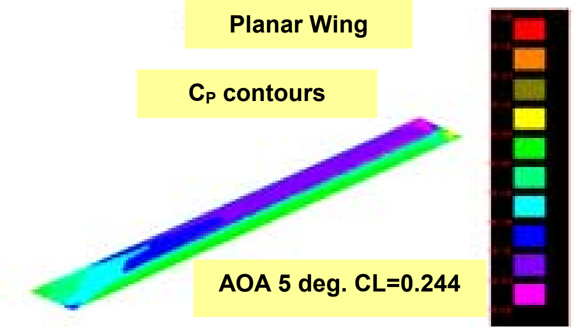
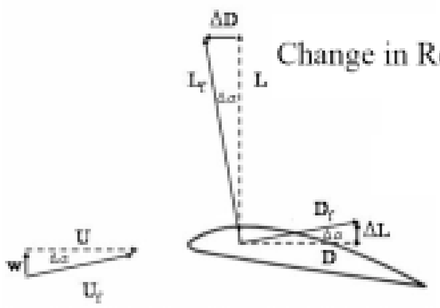


Fig. 10 COMPARING UNCAMBERED and DESIGNED WINGS, CHORDWISE & SPANWISE LOADINGS



Change in Relative Angle of Attack $\Delta\alpha = \tan\left(\frac{w}{U}\right) \approx \frac{w}{U}$

$$L = L_f\cos(\Delta\alpha) + D_f\sin(\Delta\alpha) \approx L_f + D_f\Delta\alpha \approx L_f + D_f\frac{w}{U} \approx L_f$$

$$D = D_f\cos(\Delta\alpha) - L_f\sin(\Delta\alpha) \approx D_f - L_f\Delta\alpha \approx D_f - L_f\frac{w}{U}$$

Or the difference in drag can be expressed as: $\Delta D \approx -L_f\frac{w}{U} \approx -L\frac{w}{U}$

Fig. 11 DRAG ESTIMATION

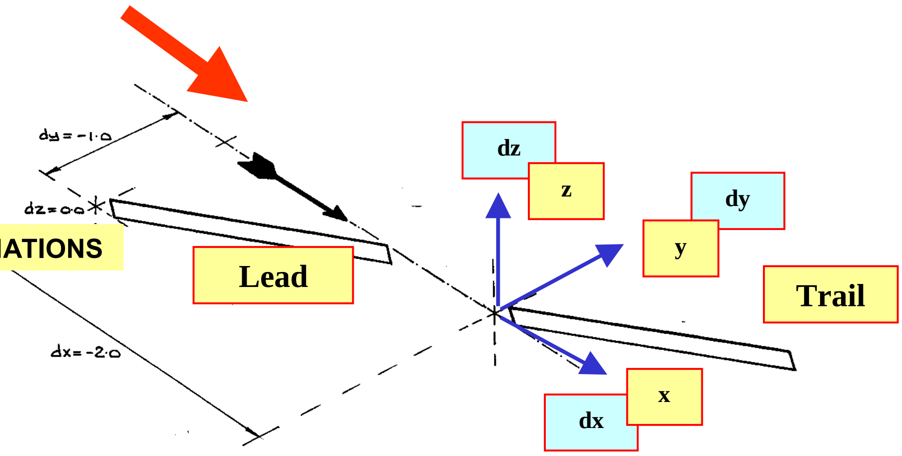
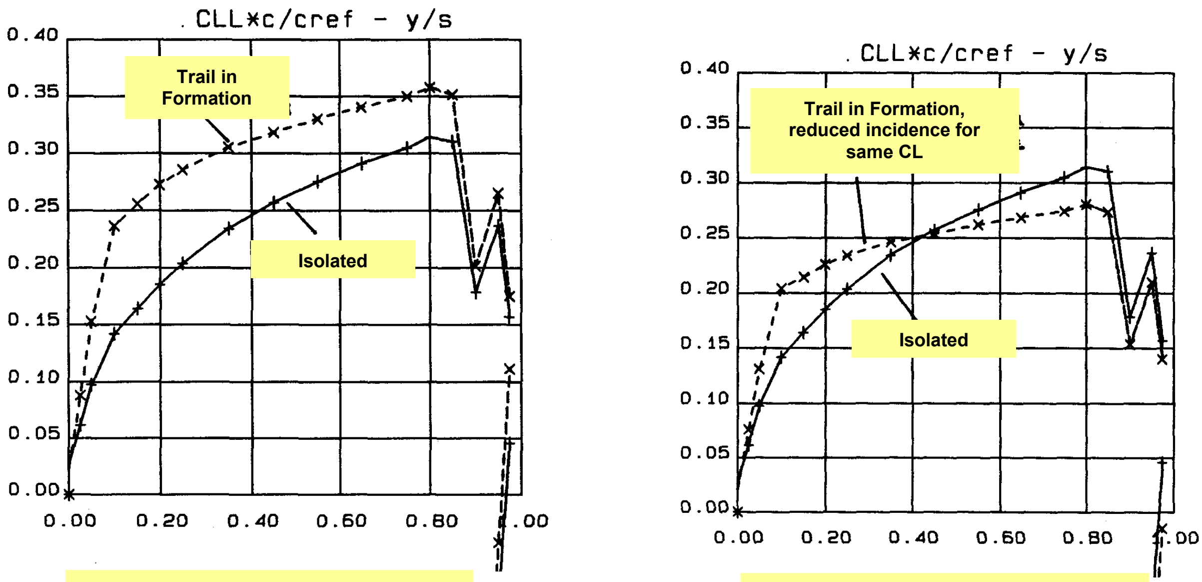


Fig. 12 CORE 1, OFW FORMATIONS



(a) at same AoA, Start

(b) Both at same C_L

FIG. 13 TWO PLANAR WINGS IN FORMATION, SAME AOA and SAME C_L
CORE 1, dx=-2, dy=-1.0, dz=-0.03

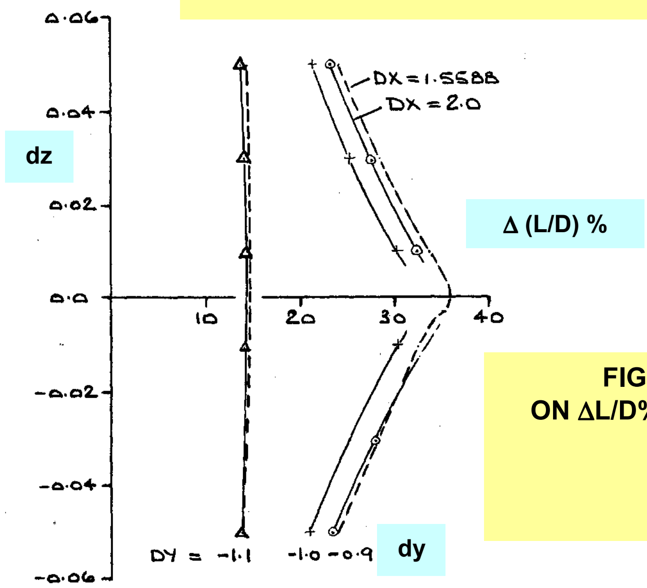


FIG. 14 EFFECT OF VERTICAL DISPLACEMENT ON ΔL/D% OF TRAIL OFW IN TWO AIRCRAFT FORMATION, BOTH AT SAME C_L

PLANAR, CORE 1, dx=-2, dy=-1.0

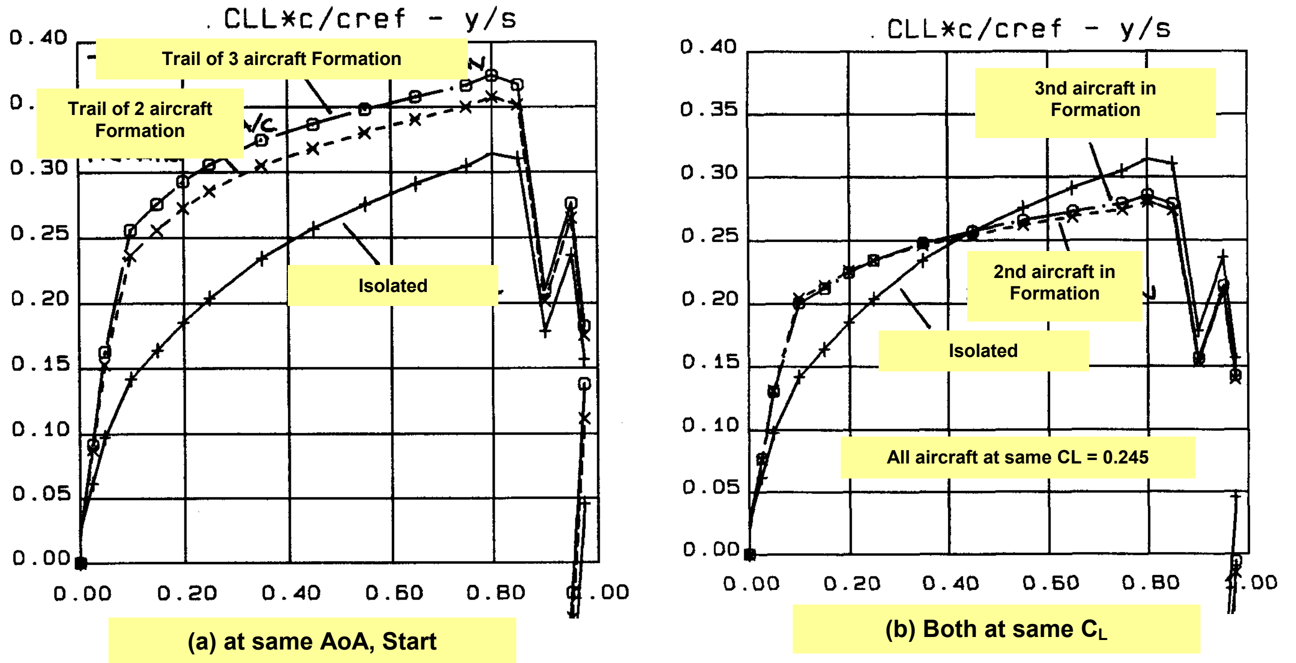


FIG. 15 THREE UNCAMBERED WINGS IN FORMATION, SAME AoA and SAME C_L
CORE 1, dx=-2, dy=-1.0, dz=-0.03, dx=-4, dy=-2.0, dz=-0.06,

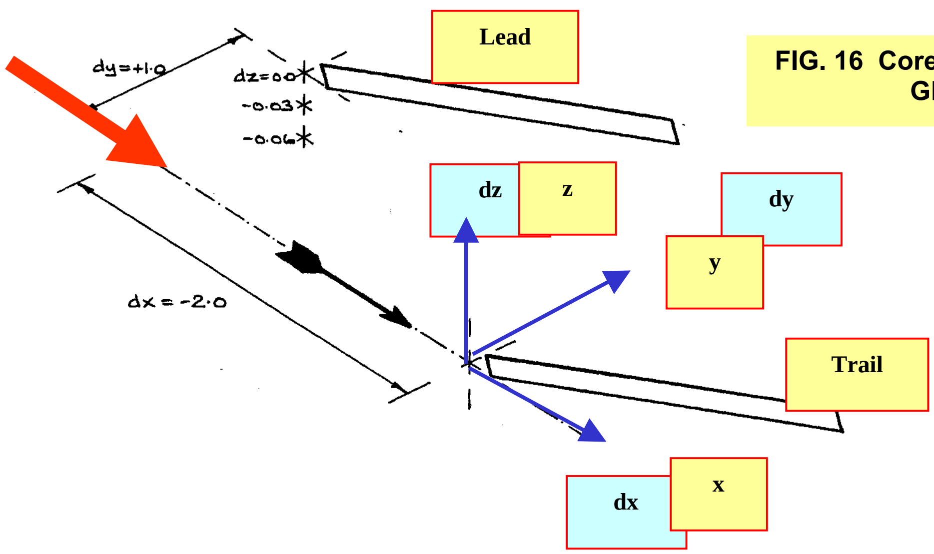


FIG. 16 Core 2 OFW FORMATION GEOMETRY

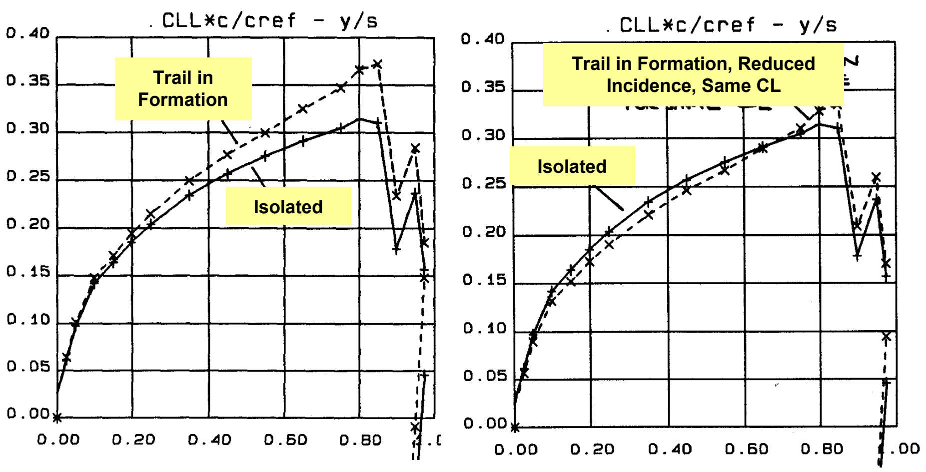


FIG. 17 TWO UNCAMBERED WINGS IN FORMATION, SAME AoA & SAME CL
CORE 2, dx=-2, dy=+1.0, dz= -0.03

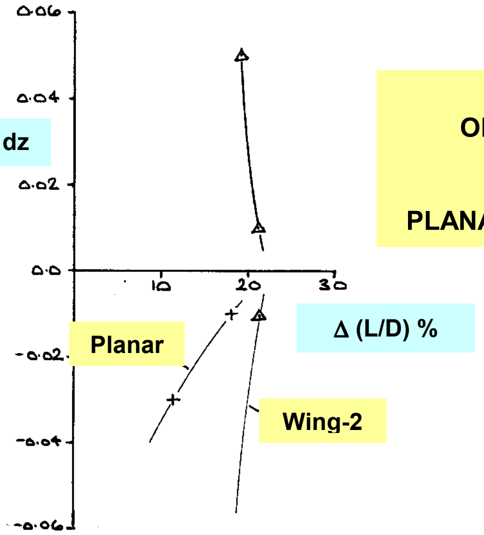
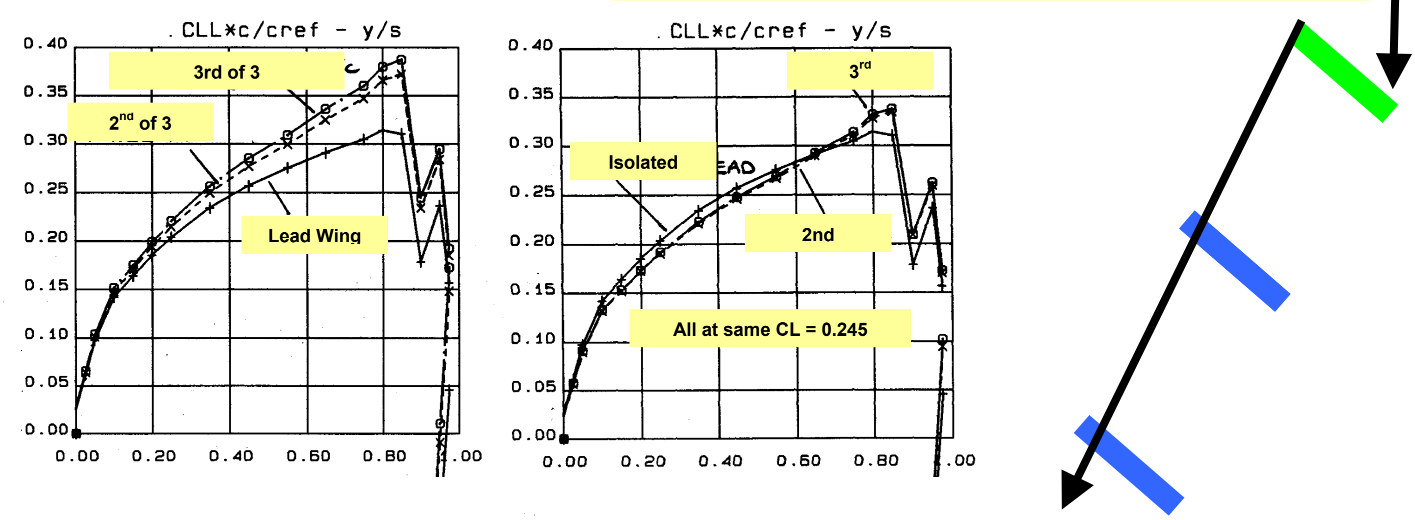


FIG. 18 EFFECT OF VERTICAL DISPLACEMENT ON ΔL/D% OF TRAIL OFW IN TWO AIRCRAFT FORMATION, BOTH AT SAME C_L

PLANAR AND DESIGN WING-2 COMPARED, CORE 2, dx=-2, dy=+1.0

FIG.19 THREE PLANAR WINGS IN FORMATION, SAME AoA and SAME C_L, CORE 2, dx=-2, dy=+1.0, dz= -0.03, dx=-4, dy=+2.0, dz= -0.06



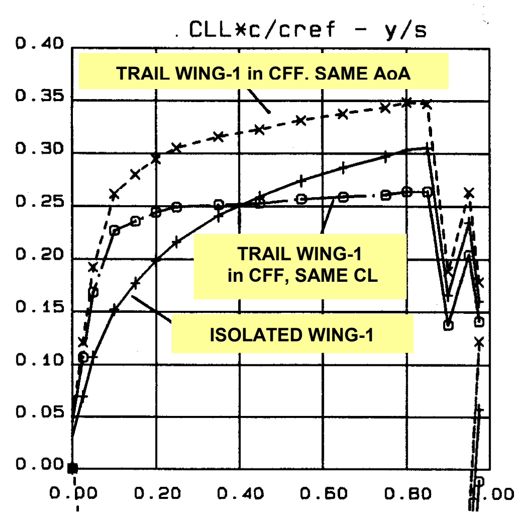


FIG. 20 WING-1 IN FORMATION, SAME AoA and SAME C_L CORE 1, dx=-2, dy=-1.1, dz=-0.01

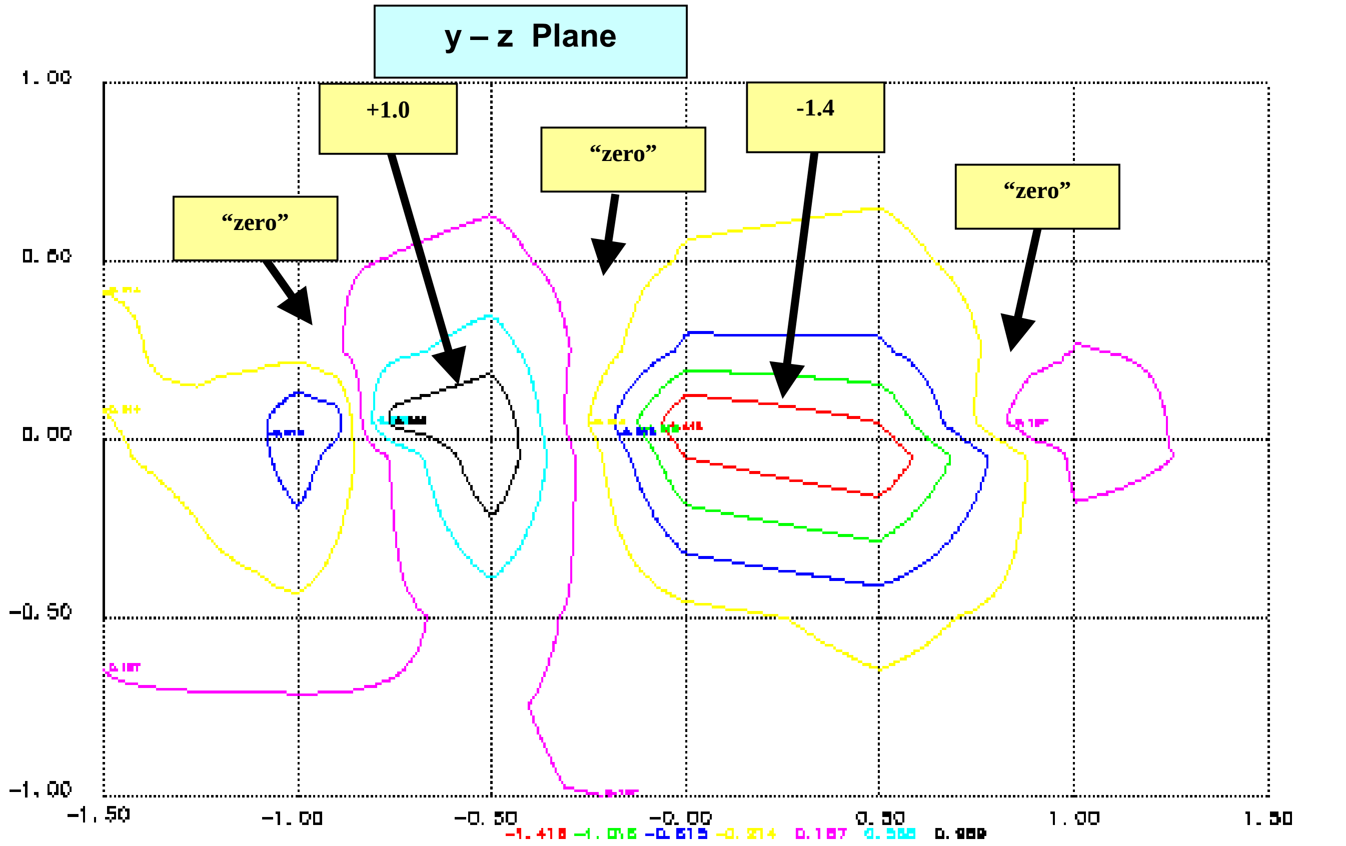


Fig. 21 Croll / Cyaw arising on Trail Wing, UNCAMBERED WINGS, dx = -2.0

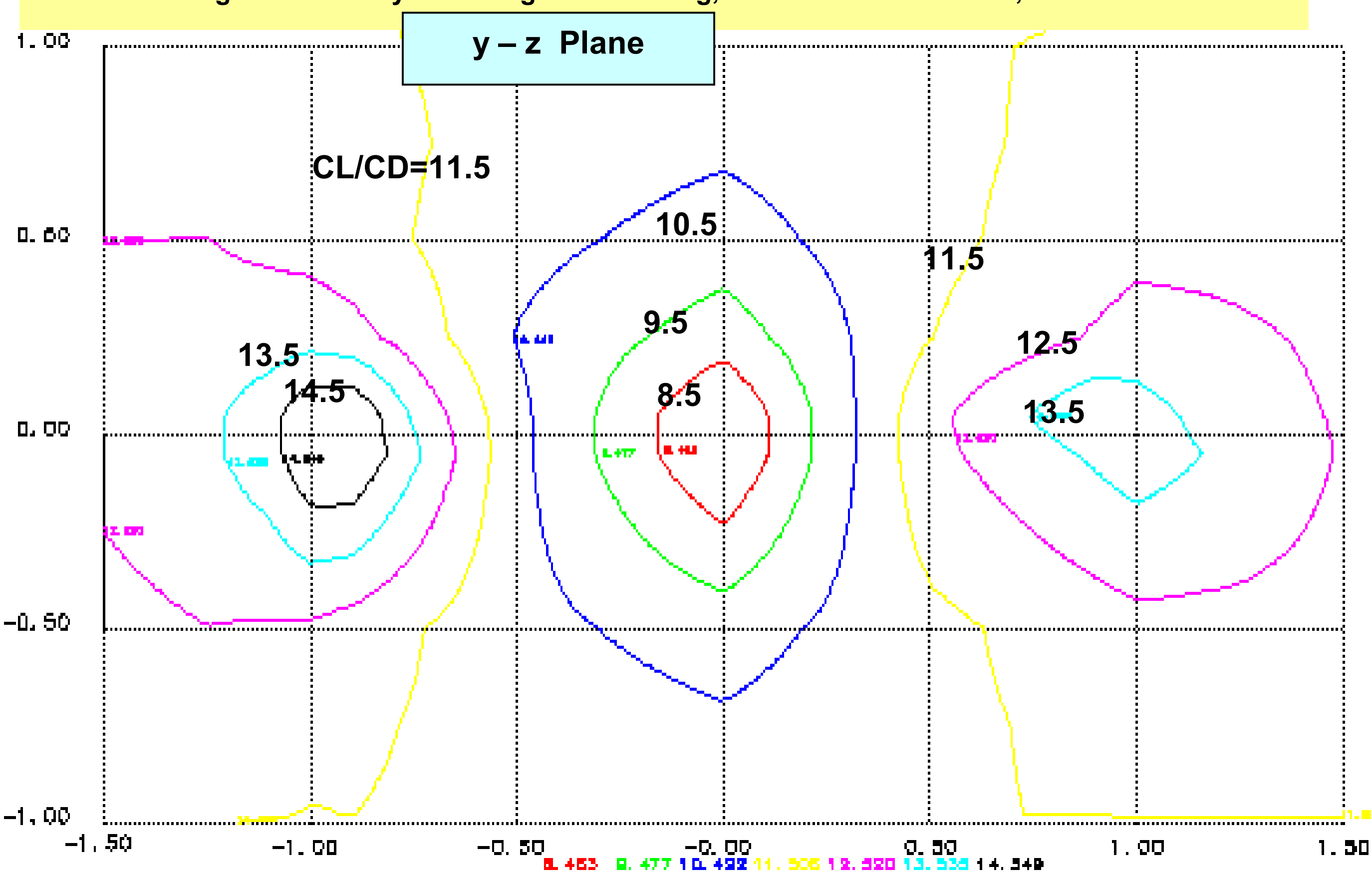


FIG. 22 C_L/C_D ARISING, UNCAMBERED WINGS, WITH Trimmed CL, dx=-2.0

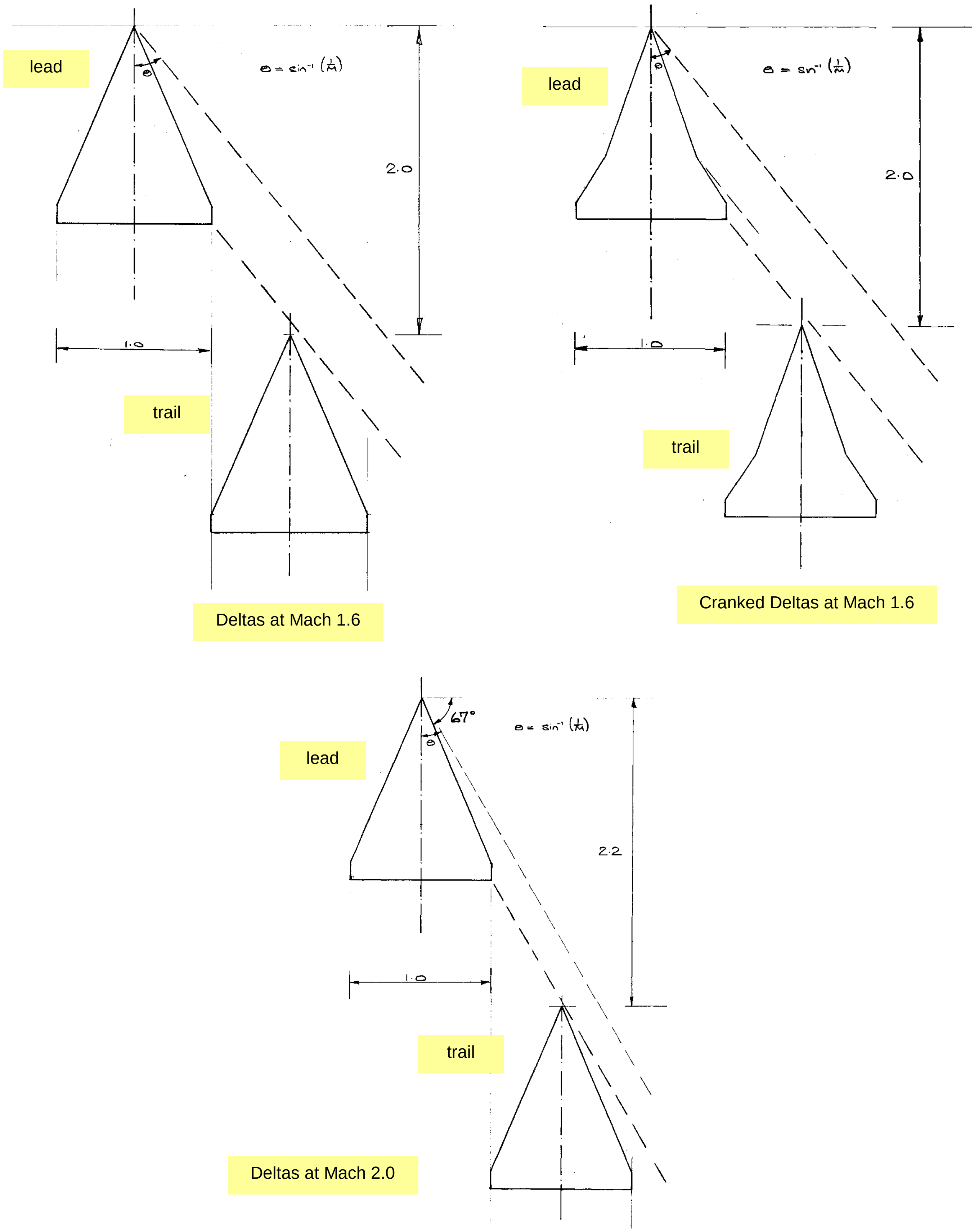
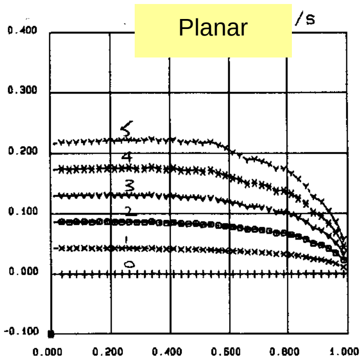
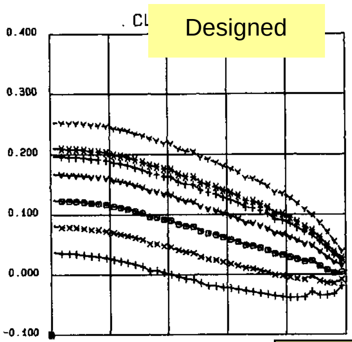


FIG. 23 Formations Envisaged at Mach 1,6 & 2.0





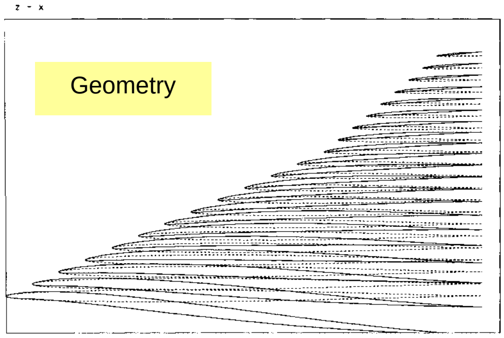
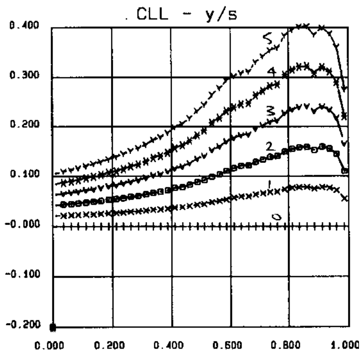
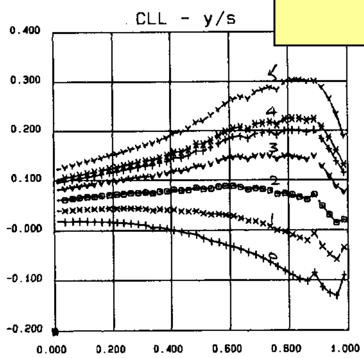


FIG. 24 Spanwise Loadings, Planar & Designed Wing1(CL=0.14)





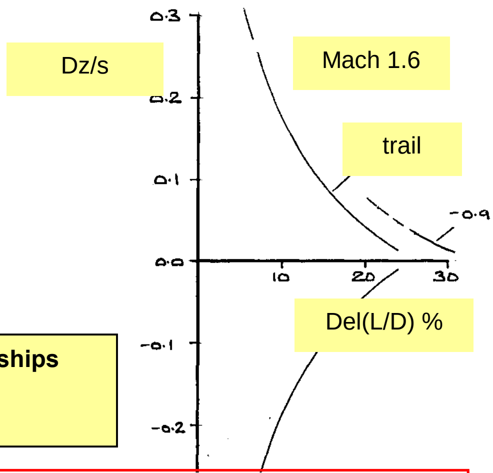


FIG. 25 Typical L/D gains as function of geometry relationships between Lead & Trail wings
Trail wing Trimmed AoA to give same CL

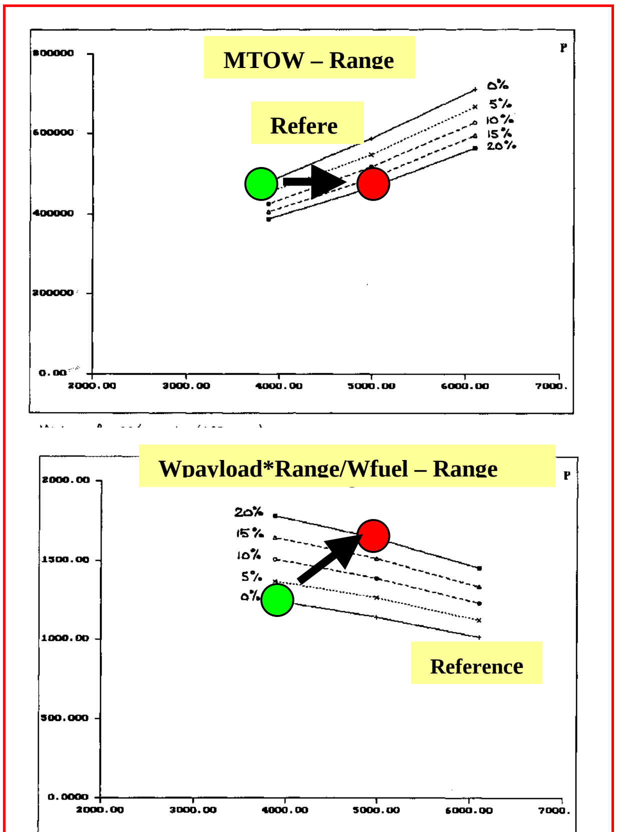


FIG. 26 ESTIMATES, MACH 1.6, 52500 lb Payload AIRCRAFT, PARAMETERS FROM BREGUET Eqn. PLOTTED AGAINST RANGE, IMPROVING REFERENCE TECHNOLOGY IN 5% STEPS

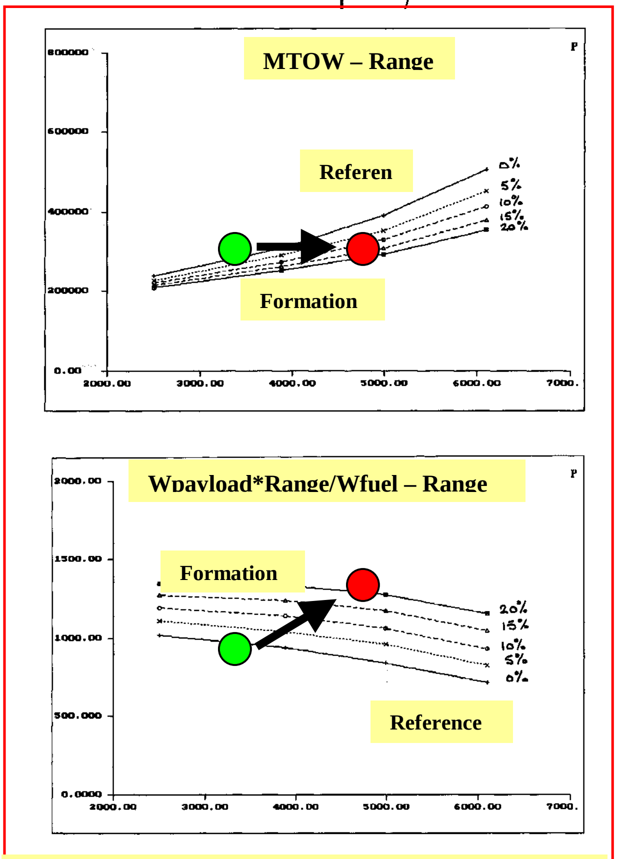


FIG. 27 ESTIMATES, MACH 1.6, 21000 lb Payload AIRCRAFT, PARAMETERS FROM BREGUET Eqn. PLOTTED AGAINST RANGE, IMPROVING REFERENCE TECHNOLOGY IN 5% STEPS