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Oblique Wing: Future Generation Transonic Aircraft

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***Abstract*—**The demand for efficient transonic transport has been growing every day and may turn out to be the most pressed innovation in coming years. Oblique wing configuration was proposed as an alternative to conventional wing configuration for supersonic and transonic passenger aircraft due to its aerodynamic advantages. This paper re-demonstrates the aerodynamic advantages of oblique wing configuration using open source CFD code. The aerodynamic data were generated using Panel Method. Results show that Oblique Wing concept with elliptical wing planform offers a significant reduction in drag at transonic and supersonic speeds and approximately twice the lift distribution compared to conventional operating aircrafts. The paper also presents a preliminary conceptual aircraft sizing which can be used for further experimental analysis.

***Keywords*—**Aerodynamics, asymmetric sweep, oblique wing, swing wing.

NOMENCLATURE

A, B	System matrices
I	Identity matrices
Ixx, Izz, Izx	Moments of inertia, kgm^2
i	√(-1)
K	Feedback gain
L	Lateral moment (at x-axis), Nm
m	Mass of aircraft, kg
N	Directional moment (at z-axis), Nm
p	Roll rate, rad/sec
r	Yaw rate, rad/sec
s	Complex frequency
U_o	Free stream velocity, m/s
u	Input vector
v	Lateral velocity (at y axis), m/s
x	State vector
Y	Lateral force (at y axis), N
ϕ	Bank angle, rad
δa	Aileron input

Subscripts

p,r,v	Derivatives
o	Initial condition

I. INTRODUCTION

DURING the development of the Concorde in 1950s the Oblique Wing was proposed as an alternative to delta-wing configuration by R. T. Jones at NASA Ames Research Centre [1], [10]. In 1958 the Oblique wing design was rejected due to flight control complexity [2]. At the same time, R. T. Jones discovered that the wave drag and induced wave drag reduced by a variable sweep oblique wing with an elliptical distribution. For an equivalent span, sweep and volume; the elliptical wing distributes lift about twice over the span compared to conventional design [3]. However, the predominant issue of stability and control remained for high oblique sweep angles (>40˚) [6], [9].

After grounding the Concorde, there has been a renewed research interest in Oblique wing due to its superior aerodynamic advantages. Over the years, there have been many attempts to improve the stability of the aircraft at high sweep angles such as slewed wing, twin-fuselage configuration and formation flying ideas etc, but none of the ideas have yet provided enough confidence in the concept's stability [4], [7], [8].

In this paper, the first section re-demonstrates the aerodynamic advantage of the conceptually designed elliptical wing swept to different sweep angles. The sizing of the aircraft has been done to compare with Embraer 145 business jet. The wing span of 24m and root chord of 5.2m produce the aspect ratio of 8.8. The aerodynamic analysis was done using Panel Method program Tornado which is a Vortex Lattice Method for linear aerodynamic wing design applications in conceptual aircraft design developed by Royal Institute of Technology, University of Bristol, Linköping University and Redhammer consulting Ltd. The code is implemented in MATLAB and provides wide range of design opportunities. The second section shows the stability and controllability of the system for different sweep angles at Mach 0.9.

The wing was swept from 0˚ to 50˚ for the aerodynamic analysis as shown in Fig. 1.

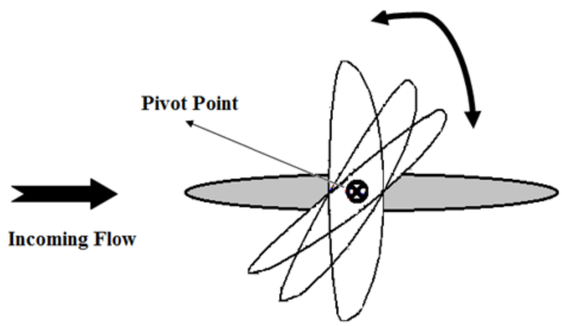

Fig. 1 Variable Oblique sweep about a pivot point from 0˚ to 50˚

II. AERODYNAMIC RESULTS

As mentioned earlier, the aerodynamic analysis was done using Tornado solver. The wing analysis was carried out separately for backward swept semispan and forward semispan, and combined them later. The lift distribution over the wing span for Mach = 0.9 is shown in Fig. 2, where it is seen that lift distribution is better in the forward swept part

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compared to backward swept part, even though the magnitude of lift is lower, the induced drag is reduced due to elliptical lift distribution. From Fig. 2, it can also be seen that asymmetric lift distribution will produce unwanted moments forcing the aircraft to be very unstable. These moments include, the negative rolling moment which also induces negative yawing moment which is highly undesirable.

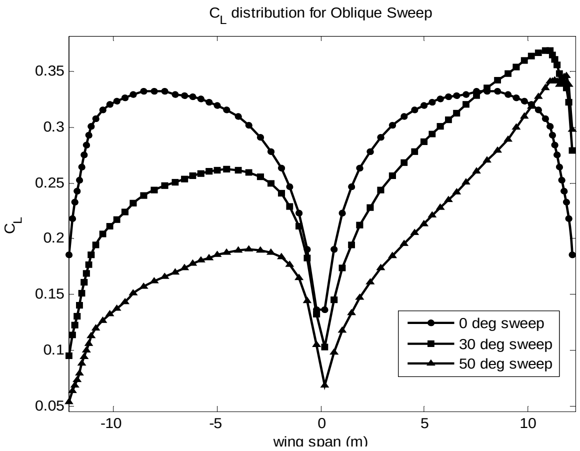

Fig. 2 C_L distribution over span for Mach 0.9 with different sweep angles

This means that, to maintain symmetric lift distribution, the ailerons must be kept deflected throughout the flight which might not be practical in terms of drag, aeroelasticity and flutter etc.

One of the major problems for aircrafts is when approaching Mach 1, after entering the transonic region (Mach = 0.8 to 1) the drag rises rapidly due to shock waves formation on the surface. Therefore the Lift-to-Drag ratio drops to very low value in conventional aircrafts. But it can be seen that Lift-to-Drag ratio could be maintained above certain value by increasing the oblique sweep angle as shown in Fig. 3.

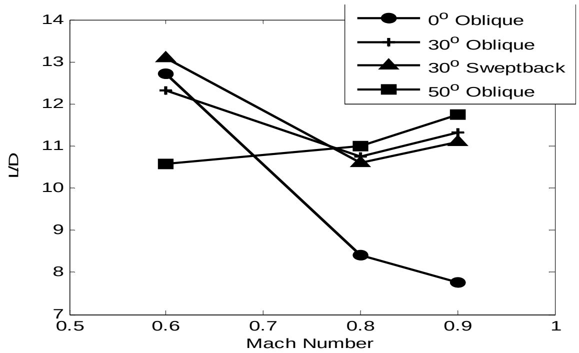

Fig. 3 Lift-to-Drag ratio curve against Mach number

The Lift-to-Drag ratio has increased to 12 at Mach 0.9 for oblique sweep of 50˚ and 11.33 for oblique sweep of 30˚ compared to 7.7 for 0˚ sweep. But the increase in Lift-to-Drag ratio is not considerable when compared to 30˚ sweptback configuration which yields 11.12. The reason is the considerable loss of lift in forward swept wing at high sweep angles.

Therefore, from the above analysis it was clear that sweeping wing to oblique angles reduces drag significantly even though lift is also compensated. The drag analysis was done to visualize the difference in drag for different configurations of wing planforms as shown in Fig. 4.

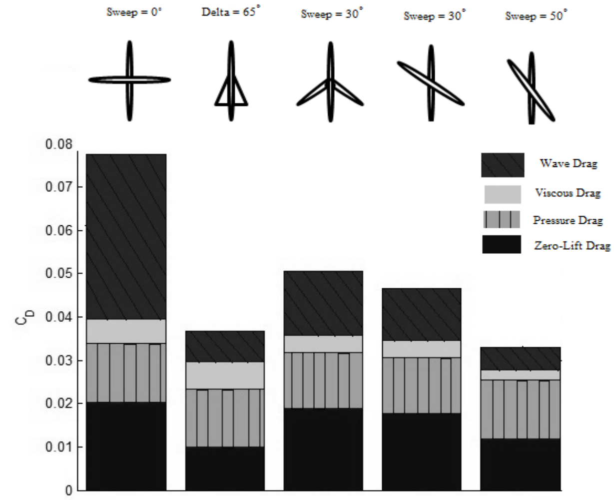

Fig. 4 Drag coefficient at Mach 0.9 for different wing-body combinations

As seen in Fig. 4, the wave drag has been reduced in all the swept wing planforms but the oblique swept wing with 30˚ sweep has 8.95% lower total drag compared to sweptback wing of 30˚ sweep and 40.63% lower total drag compared to 0˚ sweep. The oblique wing with 50˚ sweep has 34.8% lower total drag compared to sweptback wing of 30˚ sweep, 10.17% lower compared to Delta wing of 65˚ sweep and 57.49% lower compared to 0˚ sweep.

III. Lateral Stability

The lateral motion of the oblique wing configuration is unstable primarily due to the asymmetric lift produced in the front swept wing and back swept wing. The instability becomes stronger with the increase in Mach number and sweep angle.

Linearized lateral equations of motion were considered for the analysis purpose and two situations were considered at Mach 0.9 with Sweep 30° and 50°. For the initial lateral stability analysis only the aileron input was considered. The aircraft model can be presented as a linearized state-space model [5].

$$\dot{x} = Ax + Bu \tag{1}$$

$$\dot{x} = \begin{pmatrix} \dot{v} \\ p \\ r \\ \phi \end{pmatrix} \tag{2}$$

$$A = \begin{bmatrix} \frac{Y_v}{m} & \frac{Y_p}{m} & \frac{Y_r}{m} - U_o & g\cos\theta_o \\ (\frac{L_v}{I'_{xx}} + I'_{zx}N_v) & (\frac{L_p}{I'_{xx}} + I'_{zx}N_p) & (\frac{L_r}{I'_{xx}} + I'_{zx}N_r) & 0 \\ (I'_{zx}L_v + \frac{N_v}{I'_{zz}}) & (I'_{zx}L_p + \frac{N_p}{I'_{zz}}) & (I'_{zx}L_r + \frac{N_r}{I'_{zz}}) & 0 \\ 0 & 1 & \tan\theta_o & 0 \end{bmatrix} \quad (3)$$

$$B = \begin{bmatrix} (m^{-1}) & 0 & 0 \\ 0 & (I'_{xx}{}^{-1}) & I'_{zx} \\ 0 & I'_{zx} & (I'_{zz}{}^{-1}) \\ 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} Y_{\delta a} \\ L_{\delta a} \\ N_{\delta a} \end{bmatrix} \quad (4)$$

$$\begin{aligned} I'_{xx} &= (I_{xx}I_{zz} - I_{zz}^2)/I_{zz} \\ I'_{zz} &= (I_{xx}I_{zz} - I_{zx}^2)/I_{xx} \\ I'_{zx} &= I_{zx}/(I_{xx}I_{zz} - I_{zx}^2) \end{aligned} \quad (5)$$

Substituting the aerodynamic data at Mach 0.9 for sweep 30° and 90° into the plant matrix A and input matrix B, the corresponding state equations were calculated.

$$A_{30^o} = \begin{bmatrix} 0.000375 & 39 & -279 & 9.812 \\ -0.00184 & -244 & 9.44 & 0 \\ 2.17e-4 & 2.7 & -0.115 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

$$A_{50^o} = \begin{bmatrix} 5.94e-4 & 49.6 & -279 & 9.812 \\ -9.48e-4 & -126 & 4.82 & 0 \\ 2.1e-5 & -6.57 & -0.115 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

$$B_{30^o} = \begin{pmatrix} -21.66 \\ 55.6 \\ -5.68e12 \\ 0 \end{pmatrix}$$

$$B_{50^o} = \begin{pmatrix} -25.46 \\ 22.7 \\ -1.37e13 \\ 0 \end{pmatrix}$$

The pole zero plot in Fig. 5 of the state equations shows that the plant is marginally stable.

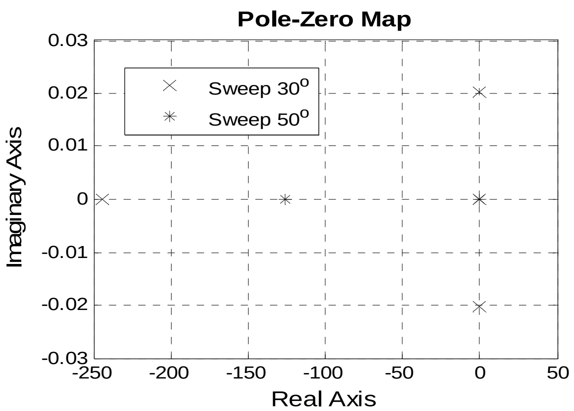

Fig. 5 Eigenvalues for 30˚ and 50˚ sweep at Mach 0.9

TABLE I
EIGEN VALUES AT MACH 0.9

Eigen Values	
Sweep 30°	**Sweep 50°**
-244	-125.7477
$\pm 0.02i$	-0.3020
± 0	-0.0647
	0

IV. CONTROLLABILITY

The controllability matrix of the plane is given by

$$\mathcal{C} = [B, AB, A^2B \dots A^{n-1}B] \quad (6)$$

where n is the rank of plant matrix A. In our case the rank of matrix A in both the cases is 4.

$$\mathcal{C}_{30^o} = \begin{pmatrix} -21.66 & 1.58e15 & -1.84e15 & 4.44e17 \\ 55.60 & -5.36e13 & 1.31e16 & -3.19e18 \\ -5.68e12 & 6.53e11 & -1.45e14 & 3.53e16 \\ 0 & 55.6 & -5.36e13 & 1.31e16 \end{pmatrix}$$

$$\mathcal{C}_{50^o} = \begin{pmatrix} -25.46 & 3.82e15 & -3.71e15 & 2.91e17 \\ 22.70 & -6.60e13 & 8.32e15 & -1.05e18 \\ -1.37e13 & 1.58e12 & 4.34e14 & -5.47e16 \\ 0 & 22.70 & -6.60e13 & 8.32e15 \end{pmatrix}$$

It can be seen that rank of C has the same rank as A.

$$\mathcal{R}\,(\mathcal{C}) = \mathcal{R}\,(A) = 4$$

Therefore matrix C is full rank and the system is fully controllable. Hence simple state-feedback law can be used to stabilize the system by arbitrary assignment of desired closed loop eigenvalues.

V. STATE-FEEDBACK LAW

The linear, time-invariant, state feedback is defined by

$$u = -kx \quad (7)$$

and the state-space model in (1) become

$$\dot{x} = (A - BK)x \quad (8)$$

Hence the desired characteristic equation can be equated with *det (sI-(A-BK))* to find the feedback control gains of the states.

VI. CONCLUSION

Oblique sweep configuration produces lower drag at higher speed compared to symmetrically swept aircraft. This configuration has superior aerodynamic advantages which puts it in a unique position for the next generation supersonic aircraft. The lateral motion of the proposed conceptual aircraft is controllable. The new conceptually designed aircraft is stabilizable with respect to lateral motion. Advanced controller such using state-feedback or LQ (Linear Quadratic) Controller can be used.

Future Investigation will be carried out considering the non-linearized lateral motion with aileron and rudder inputs. Higher Mach will also be considered in the future works.

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