VORTEX BREAKDOWN STUDY ON A 65° DELTA WING TESTED IN STATIC AND DYNAMIC CONDITIONS

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Abstract

With the aim of giving a contribution to the understanding of the phenomenon of vortex breakdown, a delta wing has been extensively tested in the low speed wind tunnel of the Turin Polytechnic Institute/ Technical University, in static and in dynamic conditions, under forced oscillatory motion.

The model used is a sharp leading edge flat plate delta wing, with 65° sweep angle, which can be tranSformed into a double delta by adding a 80° tip. A fuselage under the wing houses the five component balance and the pressure transducers. Pressure taps are provided on the model upper surface, for pressure measurements in static conditions.

Flow visualizations have been performed using the helium bubble technique, that has a good capability to visualize vortical flows and breakdown phenomena in dynamic conditions.

Both in static and in oscillatory conditions, force measurements are presented, correlated to flow visualizations, for different angles of attack and reduced oscillation frequencies.

Finally, the effect of reduced frequency on roll and pitch damping parameters is discussed.

List of Symbols

A	aspect ratio
b	wing span
c	mean aerodynamic chord
C_L	rolling moment coefficient
$C_{Lp}*$	roll damping parameter $(C_{Lp} + C_{L\dot{\beta}} \sin\alpha)$
C_M	pitching moment coefficient
$C_{Mq}*$	pitch damping parameter $(C_{Mq} + C_{M\dot{\alpha}})$
C_P	pressure coefficient
C_Z	normal force coefficient
DAS	Data Acquisition System
f	oscillation frequency
K	reduced oscillation frequency $(K = 2\pi fl/V)$
l	reference length (b or c)
Re	Reynolds number (based on c)
s	wing semispan
S	wing area
V	airspeed
X	chordwise direction (origin at wing tip)
Y	spanwise direction
α	angle of attack
β	sideslip angle
Δ	increment
μ	phase lag

Introduction

The interest for the study of the vortical flow structures, typical of delta wing planforms, has become relevant, due to the requirement of improving control effectiveness at high angles of attack and of predicting the aerodynamic behaviour and the aircraft performance in these flight conditions.

High-lift flight capability, agility and maneuverability are required - in subsonic regime - in the α-range where separation phenomena are present.

As regards slender wings, at moderate angles of attack the leeward flow field is dominated by highly organized vortical flow structures, that can breakdown, at higher α, into turbulent swirling flow.

These leeward flow structures can be further complicated by non linear interactions with vortical flows emanating from other configuration components (leading edge extensions, forebody, strakes, canards). The flow over double delta planforms (1), although similar to that of simple delta wings, is an interesting example of these interactions. For low angle of attack, two primary vortices are shed on each side of the wing, one from the tip (inner vortex) and one from the leading edge (outer vortex). Increasing α, the two vortical structures merge, following a line parallel to the leading edge, that is the direction of the stronger primary structure (outer vortex).

In dynamic regimes, the analysis of the problem becomes more difficult due to the time dependence of the motion variables and of the aerodynamic reactions.

During oscillatory motions, the wing vortices change their strength and position as a function of aerodynamic angles, which vary their magnitude with time. Consequently, the location of the vortex breakdown is similarly time dependent. Furthermore, the aerodynamic reactions will not occur in phase with the wing oscillation, as a consequence of convective time lag during the dynamic flow field evolution. In these conditions, the behaviour of the aerodynamic coefficients can be dramatically affected by hysterisis.

The sign (2) of the energetic exchanges connected to the cyclic variation of the aerodynamic loads during the motion is directly related to the damping effects, whose reduction or variation may consistently influence the aircraft dynamic stability. A significant example is the wing rock phenomenon, a large amplitude self-sustained oscillation in roll, typical of slender configurations.

When these kind of motions are characterized by large amplitudes, the mathematical modelling based on the classical stability derivatives is not valid and other methods have to be used (3,4,5).

With these preliminary considerations in mind, the Turin Polytechnic Institute/Technical University initiated a wind tunnel experimental research program, in order to investigate some fundamental aspects of the aerodynamic flow field on a delta wing model and their influence on its stability behaviour(6,7).

The following items were considered in detail:

a) Effect of the model configuration on the static aerodynamic coefficients and comparison of the experimental results with theoretical predictions of lifting force.

b) Effect of the model configuration on the breakdown position in static conditions, evaluated by means of flow visualizations and pressure measurements.

c) Effect of the model configuration and of the motion frequency on roll and pitch damping for small amplitude harmonic oscillations.

d) Effect of medium amplitude oscillatory motions on both the vortex breakdown position and the aerodynamic loads.

e) Time lag effect on aerodynamic reactions and breakdown positions.

The Experimental Facilities

The tests were performed in the TPI/TU D3M low speed wind tunnel, that is a closed circuit tunnel with a contraction ratio of 5.44. The test section is circular and its diameter is 3 meters.

The turbulence level is 0.3%, at 50 m/s and the maximum speed is 98 m/s.

The model is a 65° delta wing, with a sharpened edge and removable tip.

The experimental requirements constrained the design of the wing, that has a fuselage with semicircular section and ogival nose shape, in order to fit within the force transducer (five loads are measured) and the devices for the pressure measurements. Two different upper surfaces can be used, one of them being provided with pressure taps located at constant span and root chord percentages.

The dimensions of the 65° model are: wing semispan s=396.5 mm, root chord c= 850 mm, wing area $S=0.337\ m^2$, bevel angle 30°, wing thickness 20 mm, aspect ratio A=1.86. When the 80° tip is adopted, c=1179 mm, $S=0.375\ m^2$ and A=1.67.

A specific servo-mechanical unit (8,9) was designed in order to perform static tests and to generate a harmonic motion on the models in the separate rotational degrees of freedom.

A vertical strut supports the model that is connected to the strain gauge balance by an internal leverage, that links the rear of the fuselage with an oscillating vertical rod.

The harmonic motion of the model is excited by a driving unit, that is placed under the floor of the test section; it is powered by a DC motor and it is linked to the main rod, that supports the wing, by a gearbox connected to an adjustable flywheel.

Setting the flywheel radius, it is possible to modify the oscillation amplitude of the model, within the limit of +/- 3°.

The oscillation frequency of the model (maximum value 5 Hz) is set by the rotation speed of the DC motor.

Two different step-motors are used to move the model: the former, translating vertically the dynamic motion unit, acts on the rod and it changes the main leverage position, that determines the angle of attack of the model (that ranges from -7° to +60°); the latter rotates the vertical strut, modifying the angle of sideslip (ranging from -15° to +15°).

The mechanical apparatus is interfaced to a specific electronic control unit, that acts on the power drivers of the actuators. The control unit is linked to the BUS of the control PC by a digital device and the position of the model and its oscillation is controlled directly by the software operator.

The software control of the generation of the harmonic driving torque is designed in order to correct the distorsions on the sine wave induced by the different geometrical configurations of the support and of the leverage.

The signal outputs of the force transducer were amplified and filtered by a signal conditioning unit.

Two different data acquisition units were used for static and dynamic tests, because of the specific signal elaboration.

For static tests, the amplified signals were multiplexed and measured by a high precision integrating voltmeter, interfaced with the DAS computer by a programmable software language simulation card; on the other hand, in dynamic conditions, a high speed AD converter was adopted in connection with a multisample unit.

The elaboration of the dynamic signals required particular care because of the various electronic and structural interferences on the final results.

The software algorithm is based on the Fourier analysis of the signals, identifying the spectra of the two vectorial components of the driving torque acting on the oscillating model, both in "wind on" and in "wind off" conditions.

Static pressure measurements were performed on the upper surface of the wing at constant values of the parameters x/c and y/s. A PC-based Hyscan pressure measurement system was used for the data acquisition and reduction. A series of rack mounted sensors (ZOC 16) kept at constant temperature, with a range of ±1.0 psi, was interfaced to the A/D conversion unit.

Flow visualizations were obtained with an helium bubble generator, both in static and in dynamic conditions. This methodology allows us to visualize the flow with small soap bubbles - filled by helium - that are injected near to the model apex, with an injection pipe. As the helium specific weight is lower than the air, a correct helium-soap proportion generates a bubble having a neutral behaviour with respect to the gravitational effect.

Static Aerodynamic Coefficients

A large portion of the lift (10) on a delta wing is contributed by the spiraling vortices formed from the separation shear layers which originate at the leading edge. Pressure measurements show that the maximum suction is found just beneath the cores of the vortices.

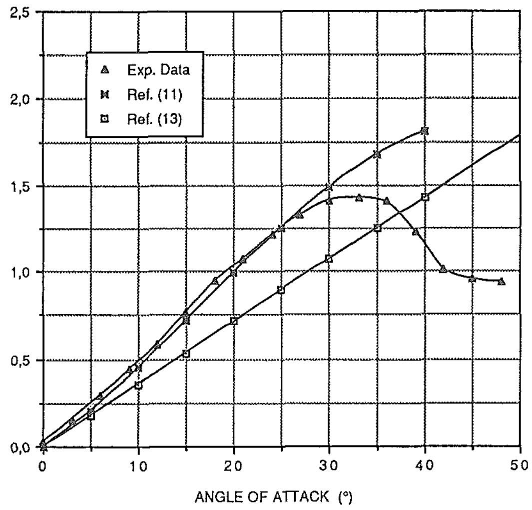

Figure 1. The Normal Force Coefficient for the 65° Delta Wing Model.

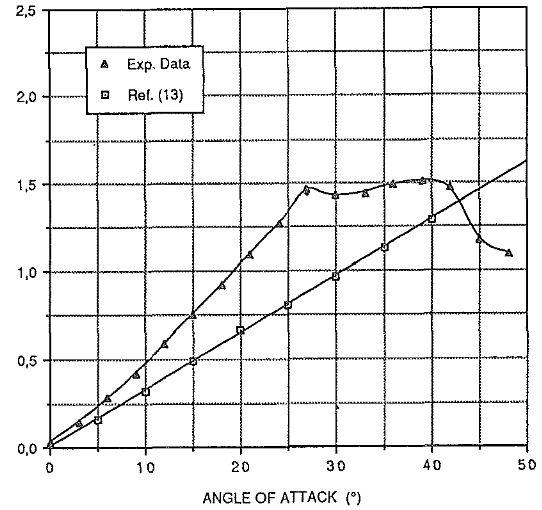

Figure 2. The Normal Force Coefficient for the 65°/80° Delta Wing Model.

At large angle of attack, the vortices will suddenly expand in size, in connection with a sharp increase of dynamic pressure and a decrease of axial velocity. This phenomenon, known as vortex breakdown, becomes a limiting factor for any theoretical method for the prediction of lift on delta wings. One of the simplest and most reliable theory was developed by Polhamus (11,12), and it is based on the leading edge suction analogy. The results of this method are compared with the experimental data obtained on the 65° delta wing model in fig. 1. The theoretical curve fails its prediction in the α-range ($\alpha > 25°$) where the lift decrement due to breakdown becomes relevant. In the same plot, a comparison with the potential lift predicted by the lifting surface theory is presented (13,14,15).

The lift behaviour of the double delta wing model is reported in fig. 2, compared with the linear theory results. The trend is consistently different from the previous case.

Three ranges (16) can be identified, according to the evolution of the wing vortical structures:

a) linear lift
b) vortex lift
c) vortex burst and full separation

A sharp kink is present in the region where the vortices become unstable ($\alpha > 25°$). In the α-range dominated by vortex burst, the increment of the lift coefficient is reduced, reaching a maximum before of full separation.

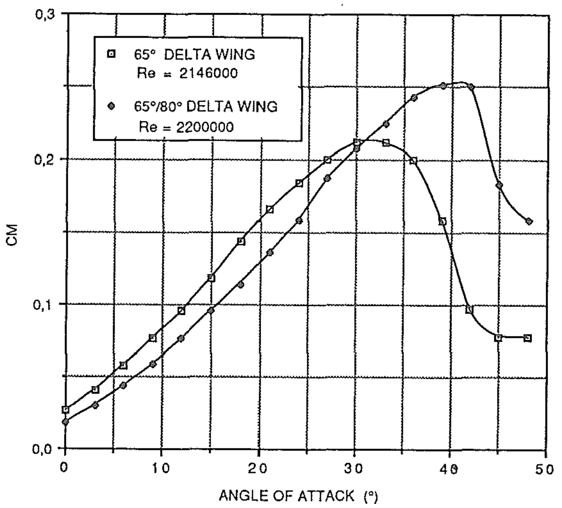

Figure 3. Comparison of the Static Pitching Moment Coefficient.

The variation of Reynolds number had no remarkable effect on the static aerodynamic coefficients of the model, as a consequence of the sharp leading edge shape.

In fig. 3 the trend of pitching moment is compared for the two model configurations. The model was balanced about the centroid of the triangular wing, as the center of pressure is at the two-thirds root chord position if the flow is assumed to be conical (13).

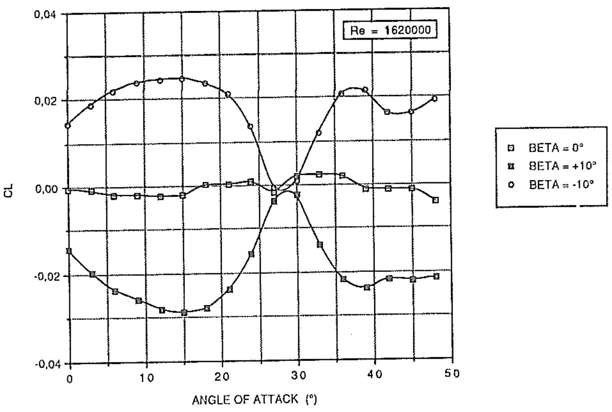

Figure 4. The Rolling Moment Coefficient for the 65° Delta Wing Model.

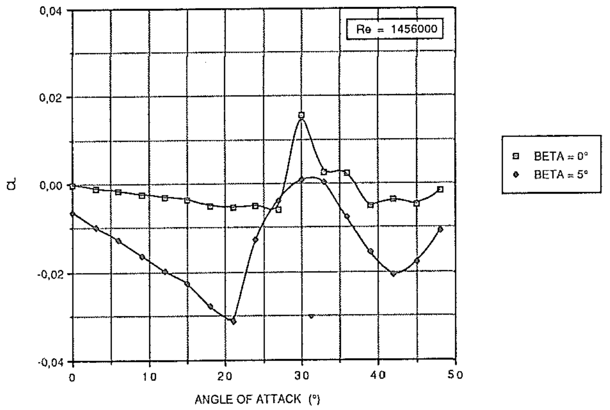

Figure 5. The Rolling Moment Coefficient for the 65°/80° Delta Wing Model.

The variation of the sideslip angle (fig. 4) has an important effect on the rolling moment coefficient for the 65° delta wing model. When the burst reaches the trailing edge of the windward side of the wing, the coefficient changes its slope versus α. As the breakdown moves towards the tip, the asymmetry of the load distribution on the two upper sides of the lifting surface is reduced, becoming very small in the vicinity of complete separation.

The trend of the rolling moment for the second configuration (double delta) is presented in fig. 5. Even for $\beta = 0°$, vortex breakdown occurs in partially asymmetric conditions. This behaviour can be related to the instability of the vortex flow emanating from the 80° tip at high α. For asymmetric flow conditions ($\beta = 5°$), the effect of sideslip on C_L becomes evident, and the positions of the slope changes are shifted at higher angles of attack.

Static Vortex Breakdown Effects

The effect of configuration on the static vortex breakdown position was extensively investigated by means of flow visualizations. The experiments were performed at low speed (Re = 300000), adopting the helium bubble technique.

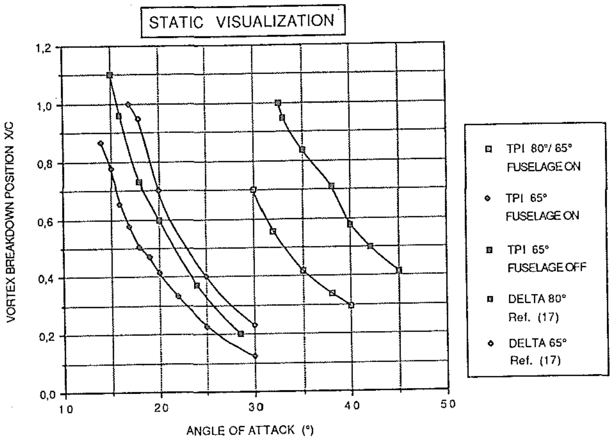

Figure 6. Comparison of the Static Vortex Breakdown Position.

The results are reported in fig. 6, where several experimental data are compared.

The influence of the fuselage (mounted on the lower wing side) on the position of the burst is evaluated comparing the measurements with two series of previous results obtained on flat 65° delta wings at TPI and in another tunnel $^{(17)}$.

The sensitivity of the vortex breakdown position to the change of the wing planform is strong, as the double delta behaviour (80° tip with 65° leading edge) is consistently different from the one of the simple constant 65° sweep model. The burst position is located in an intermediate range between the 65° and the 80° deltas. The angle of attack at which leading edge vortex and tip vortex merge ($\alpha = 8°$) was detected with a series of flow visualizations performed with a smoke generator.

The relation between vortex evolution and suction effect on the upper wing surface was investigated in static conditions, with pressure measurements. The influence of viscosity on the pressure coefficients is not relevant in the considered test conditions, even if some slight difference on the peak values was detected for higher angles of attack.

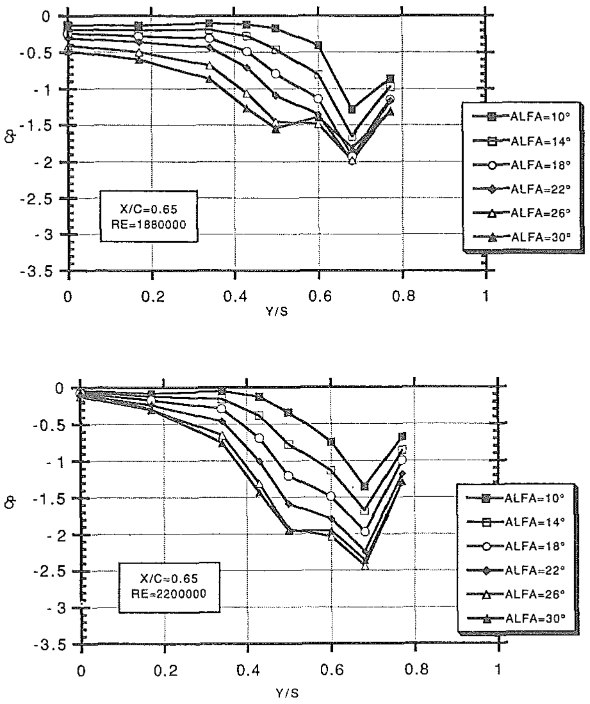

Figure 7. Comparison of the Spanwise Pressure Distribution.

In fig. 7 the effect of configuration is clear: the double delta model presents a higher suction peak under the vortex core, for constant angle of attack.

Furthermore, analyzing the pressure mapping, it is possible to observe that the vortex breakdown on the single delta model reaches the constant x/c location here considered (65% based on the single delta root chord) at α = 17°, while, for the second configuration, the same burst position (75% based on the double delta root chord) is reached at α = 28°. These positions are in accordance with those ones observed during the flow visualization tests (see fig. 6).

In fig. 8 the chordwise pressure distributions are compared, and the increased suction for the double delta wing model is demonstrated.

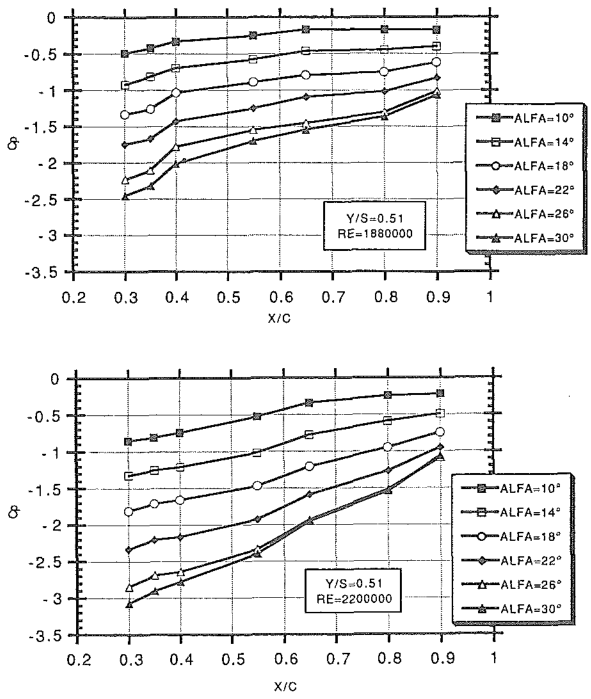

Figure 8. Comparison of the Chordwise Pressure Distribution.

Oscillatory Motions: Roll and Pitch Damping Parameters, Aerodynamic Loads and Time Lag Effects

Oscillatory motions change the position and the strength of the leading edge vortices as a function of aerodynamic angles, which are time dependent.

During roll oscillations, for example, the vortex core of the "upgoing" wing side is displaced outboard, while the other vortex axis is shifted inboard, and no variation of the orthogonal distance from the wing panel is present (2).

The strength of the two vortical structures is affected by this dynamic motion, as the wing side moving upwards experiences an increase of the leading edge sweep angle and a corresponding decrease of vortex strength. The contrary is found for the other wing side.

The delay of the position and of the strength variation of the two vortices with respect to the evolution of the motion variable has a consequence on the pressure distribution of the lifting surface, generating a sensitive time lag effect on the rolling moment coefficient.

Similarly, when the wing oscillates in pitch, the breakdown position moves along the chordwise direction (x). For this condition, the motion frequency and the amplitude may consistently influence the dynamic behaviour of the aerodynamic coefficients. The presence of these unsteady effects may become relevant when maneuvers are performed in post-stall conditions.

Therefore, any oscillatory motion has an important effect on vortex dynamics, and this mechanism seriously affects the aerodynamic damping, that is directly related to the stability of the maneuvering aircraft.

The problem of predicting the damping coefficients is important, and the modelling of the dependence upon vortex evolution cannot be easily solved (18).

The roll damping parameter C_{Lp}^* for the 65° delta wing model, obtained with the small amplitude (+/- 1°) forced oscillation technique, is presented in fig. 9, for two different oscillation frequencies. According to these results, no remarkable effect of this last parameter was found.

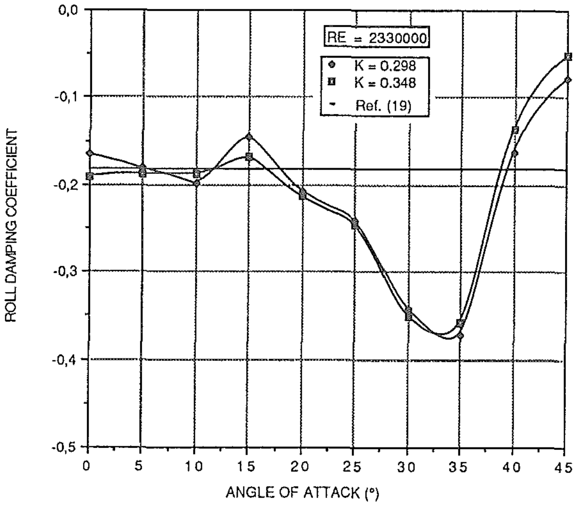

Figure 9. The Roll Damping Coefficient ($C_{Lp} + C_{L\mathring{\beta}}\sin\alpha$) for the 65° Delta Wing Model.

The trend of the experimental data is well approximated by the results (C_{Lp}) of the slender body theory (19) only for low angle of attack, as, for higher α, the contribution of the $C_{L\mathring{\beta}}\sin\alpha$ term cannot be neglected.

The lower damping level is measured at the incidence where the vortex breakdown appears at the wing trailing edge. This is a critical condition for aircraft dynamic stability.in roll.

The vortex burst has an increasing effect on damping, that is maximum when breakdown reaches the wing leading edge.

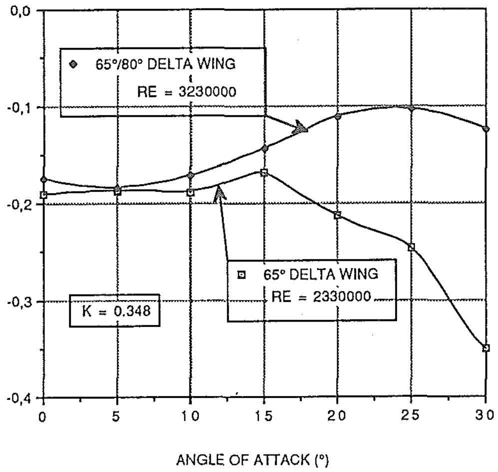

Figure 10. Comparison of the Roll Damping Coefficient ($C_{Lp} + C_{L\mathring{\beta}}\sin\alpha$).

The effect of aspect ratio is reported in fig. 10, where the C_{Lp}^* of the double delta model decreases with respect to the single delta planform. Hence a slender wing exhibits lower roll damping and its mininum value is shifted at higher angle of attack.

A set of experiments was devoted to the check if the oscillation amplitude had any influence on the dynamic behaviour of the rolling moment coefficient C_L. So the harmonic angular displacement was increased to +/- 3°.

The variation of this aerodynamic reaction for the two model configurations is always represented by an anti-clockwise cyclic loop, and the enclosed area - that is related to the energetic dissipation of the oscillating wing - changes its magnitude according to the trend versus α of the aerodynamic damping. In fig. 11, the rolling moment coefficient is plotted at $\alpha = 25°$ as a function of roll angle. In these conditions, the vortex breakdown is reaching the trailing edge of the double delta wing and the C_{Lp}^* coefficient is at a minimum (see fig. 10). The plots confirm that the single 65° delta wing exhibits an higher damping.

The data are compared for two

different oscillation frequencies and a non linear effect on the shape of the cycles is found.

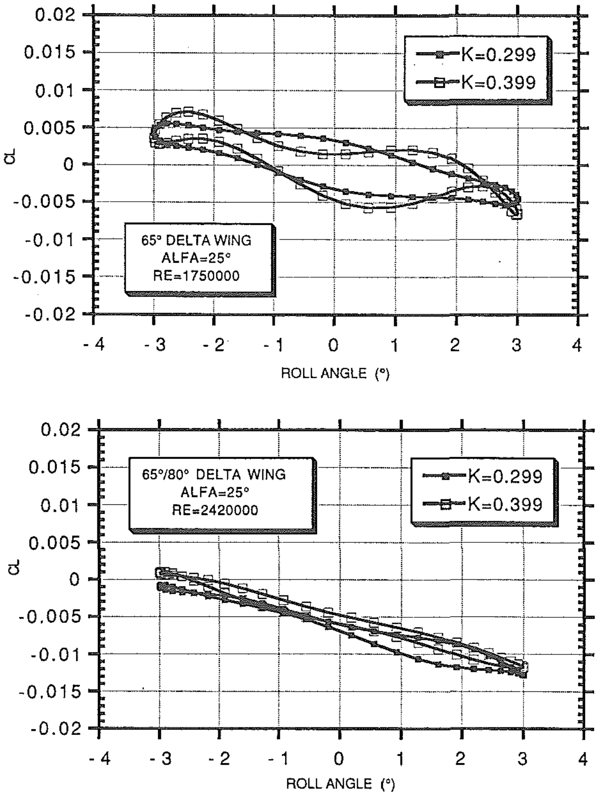

Figure 11. The Rolling Moment Coefficient in Dynamic Conditions.

The pitch damping coefficient C_{Mq}^* has been measured with the same technique adopted for the dynamic roll experiments. The oscillation amplitude was kept constant (+/- 1°) and the influence of the oscillation frequency (see fig. 12) on these results was verified.

At low angle of attack ($\alpha < 15°$), the 65° delta wing model exhibits a stable behaviour and the effect of reduced frequency K is not relevant. Increasing α, the vortex breakdown starts to occur on the wing and a sharp reduction of the pitch damping is detected. The magnitude and the slope versus α of C_{Mq}^* are seriously affected by the reduction of the oscillation frequency (20).

For higher angles of attack, the complete separation on the upper wing surface is reached ($\alpha > 35°$). The wing model becomes less unstable and the magnitude of the positive damping coefficient is consistently reduced.

The behaviour of the double delta planform is similar for the α range tested (see fig. 13), but the positions of the negative and positive damping peaks are shifted at higher incidence, in accordance with the different evolution of the vortex burst positions.

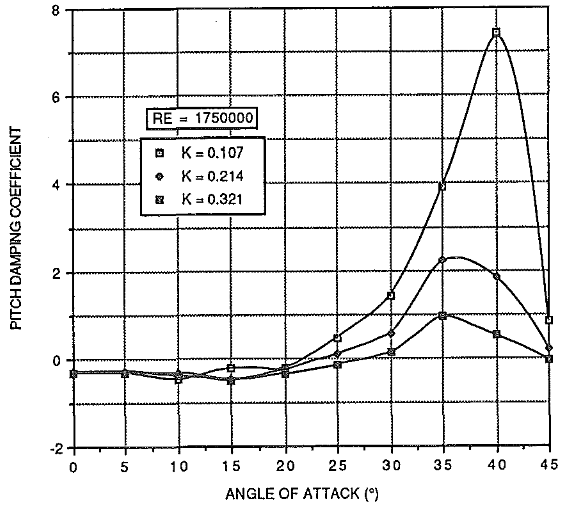

Figure 12 The Pitch Damping Coefficient $(C_{Mq} + C_{M\dot{\alpha}})$ for the 65° Delta Wing Model.

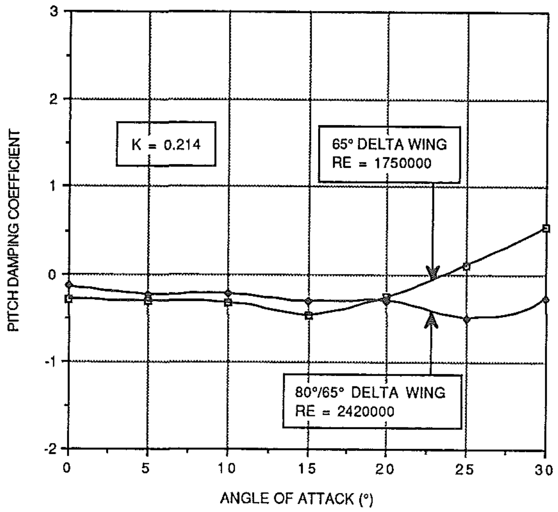

Figure 13 Comparison of the Pitch Damping Coefficient $(C_{Mq} + C_{M\dot{\alpha}})$.

In order to evaluate the phase lag between the vortex breakdown position and the primary motion, a set of dynamic flow visualizations were performed with the helium bubble technique on the 65° delta wing model oscillating in pitch with an amplitude of +/- 3°. During the test the oscillation frequency was modified (K = 0.107 - 1.068), while the wind speed was kept constant (Re = 300000). The direct measurements of the vortex burst displacements, obtained by freezing the video tape images, were compared with a trigger signal that was generated by an encoder. The results have a linear trend versus K (21).

Similarly, the effect of oscillation frequency (K = 0.107 - 0.32) on the phase lag of the aerodynamic coefficients C_Z and C_M was evaluated at higher airspeed (Re = 1620000).

α (°)	$\Delta\mu_X/\Delta K$ (°)	$\Delta\mu_M/\Delta K$ (°)	$\Delta\mu_Z/\Delta K$ (°)
15	46,60	41,61	7,13
17	43,63	40,60	5,48
20	45,65	33,00	1,00

Figure 14 The phase lag effect

The slope versus K of the phase lag of the aerodynamic reactions is compared (see fig. 14) with the dynamic measurements of the vortex breakdown position for different angles of attack. The results for the pitching moment coefficient and the vortex burst displacement in dynamic conditions are comparable. On the contrary, the time lag effect for the normal force is moderate, becoming negligible as the breakdown location moves towards the wing tip (increasing α).

Conclusions

The results confirm that the static aerodynamic loads on slender triangular wings are consistently influenced by the stability of the vortical structures generated on the leeward side of these lifting surfaces. Hence the aerodynamic coefficients and the pressure distributions are strongly affected by the vortex breakdown position.

When oscillatory motions are considered, this dependence becomes even more evident, as the dynamic stability of the wing is affected by the non linear characteristics of the aerodynamic reactions.

Future activity will be concentrated on the measurement of the pressure distributions in oscillatory conditions, with the aim of further investigating the breakdown effects and the post stall regime, where the flow is completely separated.

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