THE CHARACTERISTIC TIME CONSTANT APPROACH FOR MATHEMATICAL MODELLING OF HIGH ANGLE OF ATTACK AERODYNAMICS

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Abstract

Experimental and modelling results for nonlinear unsteady aerodynamics of 65, 70 *degree delta wings and* 80/60 *degree double delta wing at high angles of attack are discussed, considering the characteristic time constants approach. The research is done in the framework of a joint collaborative programme between DERA Bedford, UK and TsAGI, Russia. In this paper the current state of the work is presented.*

Introduction

The fact that the standard method for aerodynamic coefficients representation based on the aerodynamic derivatives concept at high angles of attack should be improved is now generally acknowledged [1-9]. The main stumbling block in the application of the aerodynamic derivatives is their strong dependency on the amplitude and frequency of motion, arising due to internal dynamics of flow separation and vortex breakdown and associated changes in the flow structure.

Interest in unsteady nonlinear aerodynamics modelling is growing as aircraft manoeuvring capabilities expand to high angles of attack. Unfortunately, CFD methods still cannot provide the necessary database for unsteady mathematical modelling and cannot be used by themselves in real time for solving flight dynamics problems. That is why mainly experimental methods are used, which require for this purpose special wind tunnel experimental techniques and facilities [3].

The fundamental problem in such experimental tests is that wind tunnel measurements at high angles of attack are extremely sensitive to experimental conditions (eg rig and tunnel interference effects, freestream turbulence, aeroelastic vibrations, micro-asymmetries in model geometry, etc.). A physical analysis of flow structure and dynamics is therefore essential in understanding the artificial effects due to wind tunnel conditions, and finally in developing an appropriate mathematical model structure for unsteady nonlinear aerodynamics. In turn an identification of mathematical model parameters may give valuable feedback for the physical understanding of the flow dynamics.

In the authors' opinion, the most reasonable approach to the mathematical modelling in this case is one based on characteristic time constants which can be related to the flow adjustment processes. These parameters can be considered as good indicators of changes in the flow structure and flow dynamics, thus providing the feedback to the physical analysis referred to above. It should be mentioned that the well-known generic methodology [4] based on the application of nonlinear indicial response functions in practical cases is also reduced to simple characteristic time constant models [5, 11].

This paper presents experimental results and physical analysis of high angle of attack unsteady aerodynamics for a number of simple planforms (65, 70 degree delta wings and 80/60 degree double-delta wing) from a current collaborative programme between TsAGI and DERA Bedford. The physical aspects of wind tunnel tests at high angles of attack are discussed using results obtained in TsAGI and DERA Bedford for the same shapes at similar test conditions.

Mathematical modelling of the frequency effects for linear aerodynamic derivatives is discussed and the characteristic time constants identified for the 65^o wing are analysed. Nonlinear mathematical modelling results for the normal force and the rolling moment coefficients due to large amplitude non-planar motions in pitch and yaw are presented for the 70^o degree delta wing. The structure of the mathematical model for unsteady nonlinear aerodynamics in this case permits the reconciliation of characteristic time constants for different motion modes, over a wide range of angles of attack and sideslip.

Collaborative Programme between DERA Bedford and TsAGI

The representation of aerodynamic forces and moments in flight dynamics, especially at high angles of attack, relies mostly on wind tunnel experimental data.

The standard methods such as rotary balance and oscillatory tests, which have been in long use from thirties years for spin investigation and for dynamic tests at low angles of attack, have encountered a lot of basic problems when the tests for modern manouevring aircraft have been intensified at high incidences.

A special cooperative experimental programme was set up in 1991, which involved 10 wind tunnel facilities in 7 countries in Europe and North America, to assess the reliability of dynamic test methodology at high angle of attack conditions [1]. The experiments, which were carried out over a period of several years, produced a comprehensive dynamic data base for a schematic fighter configuration.

During the last decade a significant effort from the USA Air Force Research Laboratory and the Canadian Institute for Aerospace Research has been put into an in-depth study of the 65 degree delta wing at high angles of attack. This work, partially outlined in [11-14], produced a large set of high-quality unsteady aerodynamic data for this particular delta wing from oscillatory and ramp motions in pitch and roll.

The current collaborative work initiated in 1998 between DERA Bedford and TsAGI is a logical continuation of the previous efforts undertaken in this area. It is focused on a systematic experimental study of high angle of attack unsteady aerodynamics of several simple planforms (70, 65 degree delta wings and 80/60 degree double delta wing), and the mathematical prediction of their aerodynamic loads by means of relatively simple aerodynamic models.

Most experiments have been conducted in the TsAGI low speed wind tunnel T-102 using the recently modified angular oscillatory rig OVP-102 capable of performing oscillatory motions with small and large amplitudes in pitch, roll and yaw, and oscillatory coning motion. Some small-amplitude experiments have been repeated in the DERA Bedford 13ft x 9ft low speed wind tunnel, where in addition the tests for heave motion have been performed (see Fig.1).

The main attention in the work is given to the dynamic properties of the vortical flow with vortex breakdown at high angles of attack. Interference effects are significant in any wind tunnel experimental test at high angle of attack, and their elimination is of great importance in the formulation of adequate mathematical model structure and its parameters identification.

Characteristic time scales reflecting the flow adjustment properties at different incidences are supposed as more invariant characteristics than particular static dependencies of aerodynamic coefficients affected by different interference effects. The development of physically adequate and at the same time practical mathematical formulation for nonlinear and unsteady aerodynamic loads at high angles of attack with arbitrary non-planar angular motions is the ultimate objective in the project. In this paper the current state of the work with some experimental and modelling results are presented.

TsAGI low speed wind tunnel and oscillatory rig

The experimental investigations have been conducted in the TsAGI low speed wind tunnel T-102. This closed circuit tunnel has an elliptical open jet test section 2.33×4.0 m with a flow speed range of $5 \div 70$ m/s. Dynamic tests are usually performed at $25 \div 50$ m/s ($Re = \dfrac{V\bar{c}}{\nu} \approx 1 \times 10^6$).

The experimental facility OVP-102 used in this work was designed in the sixties as a conventional angular-oscillation rig for static and dynamic tests with small amplitudes in pitch, yaw and roll. In the beginning of eighties this rig was modified for large amplitude oscillations in pitch, roll and yaw. Now it can vary the frequency and amplitude of pitch, roll and yaw oscillations in the ranges - $0.2 \div 2.5$ Hz, $\Delta\alpha(\Delta\beta) = 3^o \div 26^o$. The rig is mounted on the rotating floor of the wind tunnel test section, which provides sideslip angle in the range $-90 \div 20$ deg (see Fig.2). To perform yaw oscillations the wing model is mounted in a vertical plane with 90^o bank angle, and in this case angle of attack is changed using the rotating floor.

The aerodynamic loads acting on the model are measured with a 5 component internal strain gage balance (axial force excepted), which is integral with the sting mounted on the vertical and L-shaped rotated struts of the rig. Oscillatory motion of the model is excited by the oscillating vertical rod driven by the electric motor/gearbox unit placed on the rotating floor of the wind tunnel test section (see Fig.2).

In 1999 the rig was modified for oscillatory coning tests. The rotating sting with integral strain gage balance is installed on the main vertical strut and driven by means of belt link with the electric motor/gearbox unit (see Fig.3).

Five simple planforms - three 70^o delta wings (two with rounded leading edges having $\bar{c} = 727$ mm and 494 mm, and one with sharp leading edges having $\bar{c} = 494$ mm), one 65^o delta wing ($\bar{c} = 437$ mm) and one $80^o/60^o$ ($\bar{c} = 860$ mm) double delta wing have been tested in the programme. Three of the delta wings with sharp leading edges are shown in Fig.4. The tests were conducted at speed $V = 40$ m/s.

The rig OVP-102 has a very thin sting ($\emptyset = 33$ mm) giving a very small size for the docking adapter for the strain gage balance. To compare the results for the 65^o delta tested in this programme with the Canadian-American 65^o delta wing a special simulation of the large center body on the latter has been used.

The signals from the strain gage balance were measured with a high speed analog-to-digital converter. Aerodynamic response during eight periods of oscillations were collected in small amplitude tests and the Fast Fourier Transformation (FFT) was used for data processing. Measurements from sixteen periods of oscillations were collected and averaged in high amplitude tests.

Experimental results

The 70^o, 65^o delta wings and $80^o/60^o$ double delta wing have been investigated using a wide range of pitch, roll and yaw motions including static tests, slow sweep motions, small and large amplitude oscillations, oscillatory-coning tests and pure heave/plunging motions. The programme for experimental work is not yet complete and the current paper presents only some of the available results.

Interference effects inevitably arise in the wind tunnel investigation at high angles of attack and it is important to understand their level. Different wing mounting for testing in pitch, roll and yaw oscillations on the rig OVP-102 may generate changes in the aerodynamic loads both in static and dynamic tests. The vortex breakdown is highly sensitive to minor factors changing the pressure gradient above the wing (so called blockage effect). As a result the interaction of the vortices with the sting or the rig struts may lead to significant variations in the aerodynamic loads due to changes in location of vortex burst points. To assess the possible changes in the aerodynamic loads special tests have been performed for two different wing mounting with bank angles $\phi = 90^0$ and $\phi = -90^0$ (see Fig.5).

In the oscillatory-coning tests the wing is mounted on the top sting having different attitude to the wing (see Fig.3). It was found that this sting induces strong effects on the vortex bursts at high angles of attack leading to significant changes in the aerodynamic loads. For this purpose the aft sting mounting with special imitator for the top sting have been used to identify the level of interference effects in the oscillatory-coning tests. The variety of the tested wings permitted also to analyze the influence of the wing size, leading edges shape, size of center body housing the sting.

Fig.6 shows the general view of the static normal force and the rolling moment coefficients for the 70^o delta wing obtained by 2D spline approximation of their experimental dependencies on angle of attack and sideslip. The non-linearities of these surfaces in the range of $\alpha \approx 30 \div 50$ degrees reflect the level of the vortex breakdown effects.

The small and large 70^o delta wings at the same test conditions have differences in the aerodynamic loads, which can be ascribed to the sting housing (small wing has a relatively larger center body) and different wings weight (the weight of the wing influences the natural frequencies of aeroelastic rig/model vibrations). The comparison of the static test results for the normal force, the pitching and the rolling moment coefficients for large and small 70^o delta wings shows that the most significant changes arise in the rolling moment (see Fig.7,a) mainly due to different onset of aerodynamic asymmetry.

The dynamic aerodynamic responses in C_N, C_m and C_l during large amplitude yaw oscillations of the small 70^o delta wing mounted at $\alpha = 30^o$ with different orientation to the rig struts ($\phi = \pm 90^o$) look practically identical (see Fig.7,b), while in the static tests equidistant shifts in C_N, C_m are obtained. A possible explanation may be the decreasing of interference effects due to dynamic averaging of blockage effects.

Motion frequency/amplitude effects in the aerodynamic derivatives are directly connected with internal vortical flow dynamics. The "in-phase" and the "in-quadrature" components of the aerodynamic derivatives (so called "static" and "dynamic" derivatives) are presented in Figs.8,9 and 10 for 65^o, 70^o and $80/60^o$ delta wings respectively. These derivatives were obtained by standard harmonic analysis of experimentally measured aerodynamic loads during small amplitude oscillations in pitch, roll and yaw with amplitude $\Delta\theta = 3^o$.

One can see that due to frequency effects these aerodynamic derivatives may change not only in magnitude but even in sign. From the other side the appearance of significant dependence in these aerodynamic derivatives on frequency of oscillations corresponds to the range of angle of attack and sideslip with vortex breakdown onset. The comparison of the "static" and the "dynamic" derivatives for the 70^o delta wings with rounded and sharp leading edges given in Fig.9 shows that the sharp leading edges (generating stronger vortices) shift the start of vortex breakdown to smaller angles of attack.

The 70^o delta wing ($\overline{c} = 727$ mm) with the rounded leading edges and beveled trailing edge has been tested in TsAGI and in DERA Bedford wind tunnels. The comparison of the normal force coefficient aerodynamic "in-phase" and "in-quadrature" derivatives for this wing obtained in different wind tunnels (see Figs.11 and 12) shows very good agreement in both the location and the level of the frequency dependence.

Oscillatory-coning tests data can be used to obtain the pure aerodynamic derivatives due to vertical and lateral acceleration (i.e. due to $\dot{\alpha}$ and $\dot{\beta}$). An example of such oscillatory-coning data processing is shown in Fig.13 for 70^o delta wing with rounded leading edges. The comparison with the conventional composite derivatives from the oscillatory tests, which include a combination of pure rotation derivatives (i.e. p,q and r) and vertical/lateral acceleration derivatives, demonstrates a very good quantitative and qualitative agreement. The composite derivatives $C_{l_p} + C_{l_{\dot\beta}} \sin\alpha$ and the pure unsteady derivative $C_{l_{\dot\beta}}$ (see Fig.13) have similar frequency dependence, so one can conclude that at high angles of attack the $\dot\alpha$ and $\dot\beta$ derivatives constitute the dominant part of the composite derivatives.

Slow sweep motions with variations in angle of attack and sideslip ($\dot\theta = \pm 2$ deg/s) in a wide range of attitudes permit to detect the critical states crossings, reflecting changes in the flow structure. Such critical crossings are usually accompanied by hysteresis loops in the dependencies corresponding to up and down attitude variations. The flow with vortex breakdown is characterized by hysteresis loops on the border of the vortex breakdown region and some level of irregularities in the aerodynamic loads inside this region. Conversely, the attached flow and fully separated flow are free from hysteresis type dependencies (see Figs.14 and 15). The experimental dependencies have been smoothed by eliminating the high frequency noise using a cut-off digital filter. Note, that the fluctuations in the raw aerodynamic responses were higher in the region with vortex breakdown.

The slow sweep aerodynamic responses presented in Figs.14 and 15 allow an approximate evaluation of the region in the plane of angle of attack and sideslip, where the vortex burst points are above the wing. This estimated region is in good agreement with the region presented in [9], which was obtained from the mathematical model parameter identification using large amplitude yaw oscillations data (see Fig.17). The characteristic time constant identified in [9] (see Fig.21) are much higher in the region with vortex breakdown.

Large amplitude oscillatory motions in pitch, roll and yaw covering the attitudes with different flow structures (see shadowed region in Fig.17) have been widely investigated for two 70^o delta wings. Similar tests later will be performed for the other wings.

The aerodynamic loads on a wing undergoing such large amplitude oscillations reveal complicated nonlinear behavior, which can be linked both with the nonlinear static dependencies and the time lag effects.

An example of aerodynamic responses during large amplitude oscillations in pitch at non zero sideslip $\beta = -10$ deg is given in Fig.16. At low frequency $\overline{\omega} = 0.0194$ the aerodynamic responses in the normal force coefficient C_N and the pitching moment coefficient C_m bear a resemblance to the shape of the static dependencies, while at the higher frequencies $\overline{\omega} = 0.0388, 0.0466$ they lose this memory. The local nonlinearities in static aerodynamic loads reflect the vortex breakdown processes, which are very sensitive to any interference effects and can vary in some critical parts in different tests. The aerodynamic responses at fast and large amplitude motions look to be less dependent on the interference effects due to time lag effects and averaging of the blockage effects.

Mathematical modelling

Relatively slow development of vortex burst points produces considerable time lags in aerodynamic loads, which are much bigger than the convective time scale (of the order of 15 times if normalized by chord length). The contribution to aerodynamic loads from vortex breakdown ΔC_{vb} therefore should be described by some dynamical model explicitly representing characteristic time scales defining the adjustment processes. Based on physical consideration the state space form for unsteady nonlinear aerodynamics has been introduced in [7]. The simple linear dynamic equation rather accurately described the internal variable dynamics and allowed to model available frequency effects in the aerodynamic derivatives. The characteristic time constant is directly connected with the level of this frequency dependence and may vary at different attitudes.

A modified version of mathematical model was introduced in [9] with generalized nonlinear dynamic equation for inertial aerodynamic contribution from vortical or separated flow. This nonlinear equation allows the representation of the time lag effects at large amplitude oscillations and during crossing the critical states by including a static hysteresis in the model. The characteristic time scales are local characteristics and in this case they coincide with the eigenvalues of nonlinear equation.

In comparison with the more strict methodology based on the application of nonlinear indicial response approach [4] it should be noted that in practical cases the problem is finally also reduced to very simple characteristic time constant models [5, 11].

Aerodynamic loads partitioning can be helpful in the assessment of the unsteady aerodynamic effects. In Fig.18 the experimental dependency for the normal force coefficient on angle of attack is given along with the approximate dependencies computed using simple flow models such as attached flow ((1)-vortex lattice method), unburst vortical flow ((2)-vortex suction analogy of Polhamus) and fully stalled flow ((3)-conical approximation of Kirchgoff mathematical model with the region of constant pressure above the wing). The vortices generated on the leading edges of the delta wing produce a significant increase in the normal force ΔC_{N_v} with respect to the attached flow case (1). The onset at $\alpha \approx 30^o$ and further development of vortex breakdown lead to the loss of the normal force $\Delta C_{N_{vb}}$ with respect to unburst vortices (2). Finally, after the vortex burst locations reach the apex of the wing ($\alpha \approx 45$ deg) the aerodynamic load approaches the curve defined by the fully stalled flow (3). Such simple analysis reveals the possible variations in the aerodynamic loads due to flow structure changes. As long as the vortex breakdown and flow separation processes display big delays in a flow adjustment the unsteady aerodynamic responses will be essentially non-linear and amplitude/frequency dependant.

Motion frequency effects for linear derivatives. The normal force coefficient, as well as any other ones, can be represented in the following form:

$$C_N = C_{N_{att}}(\alpha) + C_{N_{\dot\alpha att}} \frac{\dot\alpha c}{V} + C_{N_{vb}}(\alpha), \qquad (1)$$

where dynamic contribution $C_{N_{vb}}$ is governed by linear dynamic equation:

$$\tau_1 \frac{dC_{N_{vb}}}{dt'} + C_{N_{vb}} = C_{N_{vbst}}(\alpha), \qquad (2)$$

where $t' = \frac{Vt}{c}$ is nondimensional time, τ_1 is the characteristic time constant. The following linearized transfer function for aerodynamic derivatives can be derived from (1) and (2):

$$C_{N_\alpha}(s) = C_{N_{\alpha att}} + \frac{C_{N_{\alpha_{vb}}}}{1+\tau_1 s} \qquad (3)$$

The "in-phase" and the "in-quadrature" derivative components have the following form:

$$\begin{aligned} C_{N_\alpha}(\omega) &= C_{N_{\alpha att}} + C_{N_{\alpha_{vb}}} \frac{1}{1+\tau_1^2\omega^2} \\ C_{N_{\dot\alpha}}(\omega) &= C_{N_{\dot\alpha att}} - C_{N_{\alpha_{vb}}} \frac{\tau_1}{1+\tau_1^2\omega^2} \end{aligned} \qquad (4)$$

Eliminating the explicit dependence on frequency from equations (4) can be derived the following relation:

$$C_{N_{\dot\alpha}}(\omega) = C_{N_{\dot\alpha att}} - \tau_1 [C_{N_\alpha}(\omega) - C_{N_{\alpha att}}] \qquad (5)$$

The linear relation in (5) between the "in-phase" and the "in-quadrature" aerodynamic derivatives valid for different frequencies of oscillations can be used for direct estimation of the characteristic time scale τ_1 using the linear regression method. After that the linear regression method can be applied for two equations in (4) and unknown derivatives $C_{N_{\dot\alpha att}}$, $C_{N_{\alpha att}}$ and $C_{N_{\alpha_{vb}}}$ will be also estimated.

The characteristic time constants τ_1 have been identified for the 65^o delta wing at different angles of attack using above outlined procedure. Fig.19 shows results for the wing with the center body, imitating the Canadian-American 65^o delta wing. Fig.20 shows results for the wing without the center body.

The frequency effects in the aerodynamic derivatives obtained in roll and yaw oscillations mainly occur in the range $\alpha \approx 25^o \div 35^o$, while the frequency effects in pitch oscillations occur at higher angles of attack $\alpha \approx 30^o \div 50^o$. In the case of wing without the center body (see Fig.20) all three time constants (normalized to the semi-span $b/2V$), obtained from pitch, roll and yaw oscillations are practically identical in the range $\alpha \approx 25^o \div 35^o$. In the case of wing with the center body there is clear difference between the characteristic time constant for roll motion and the characteristic time constants for yaw and pitch motions. For example, at $\alpha = 35^o$ the time constants for pitching and yawing motions (squares and diamonds) are about one-half the time constant for body-axis rolling motion (circles).

This difference in time scales are in good agreement with the conclusions made in [12, 13] for Canadian-American 65^o delta wing concerning the dependence of characteristic time constant on the type of wing motion. Based on the results obtained (Fig.19 and Fig.20), one can conclude that this dependence on motion form is specific only to the wing with a center body. The possible explanation of the obtained fact may be connected with the center body effect on the flow structure around the wing, for example through the formation of additional secondary vortices interacting with the main ones [14].

Decomposition on static and dynamic contributions in nonlinear case has been applied in [9] for modelling aerodynamic responses at large amplitude pitch and yaw oscillations covering a wide range of incidences with different flow structures. The representation of the normal force and the rolling moment coefficients was in the form (1). However, instead of linear dynamic equation (2) the following nonlinear dynamic equation was used for the dynamic contribution C_{vb}:

$$\frac{dC_{vb}}{dt'} = \sum_{n=0}^{m} k_n(\alpha)[C_{vb_0}(\alpha,\beta) - C_{vb}]^n \qquad (6)$$

where $t' = \frac{tV}{c}$ is nondimensional time, $k_1^{-1} = \tau_1$ is characteristic time constant.

The mathematical model (6) and (1) has been identified in [9] for the large 70^o delta wing model. The obtained characteristic time constant (see Fig.21) is the same for the normal force coefficient and the rolling moment coefficient at large amplitude pitch and yaw motions. Fig.22 shows the comparison of the mathematical model results with the experimental results obtained for the small 70^o delta wing (computed by N.Abramov). The lower wing scale and the higher test speed $V = 40$ m/s keep the same *Re* number, but the reduced frequencies were different. Despite these differences and other interference effects the mathematical model fits in well with experimental data.

Concluding remarks

1) A collaborative research programme between DERA Bedford and TsAGI has been presented and the current state of experimental and math modelling work are summarised. Main attention is given to a systematic study of several simple planforms (70^o, 65^o, $80^o/60^o$ delta wings) with different scales, leading edges in two wind tunnels for a wide range of motions, and an assessment of the importance of interference effects. The broad aerodynamic data base being collected is being used for math model development using the characteristic time scales approach, and will permit comparisons with published data.

2) The results obtained for small amplitude oscillations in pitch and roll for the same wing geometry in TsAGI and DERA Bedford wind tunnels on different rigs show good agreement. So the whole experimental programme can be shared between these two facilities with confidence.

3) The characteristic time constant approach is based on a physical understanding of the

flow processes, leading to a formal split of attached and separated flow contributions in mathematical representation of aerodynamic coefficients (where the first one depends only on instantaneous motion states and the second one depends also on motion history and is governed by dynamic equations). This approach is shown to be applicable to the representation of frequency dependence of linear derivatives for small-amplitude oscillations, and to the modelling of nonlinear aerodynamic responses for large-amplitude non-planar motions.

Acknowledgments

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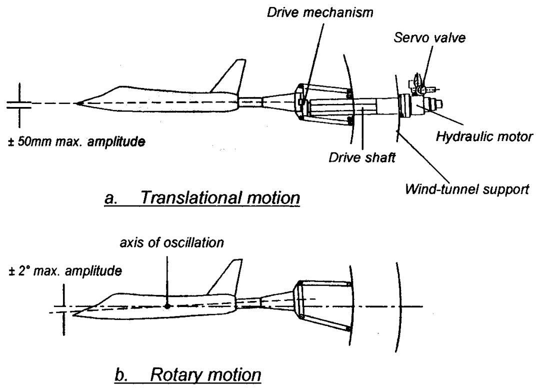

Fig. 1 General arrangement of DERA Bedford Inexorable Drive Rig [1]

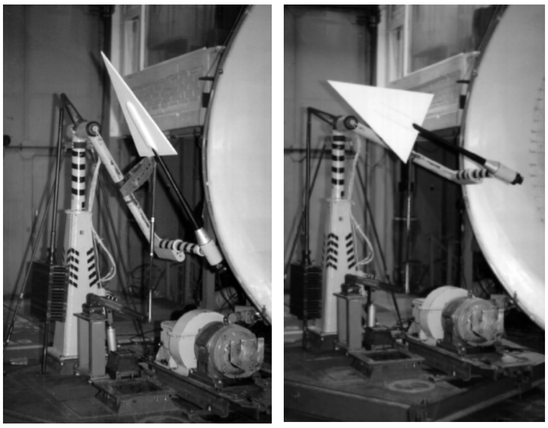

Fig. 2 General view of TsAGI oscillatory rig OVP-102. Wing mounting for large amplitude oscillations in pitch, roll (left), and yaw (right).

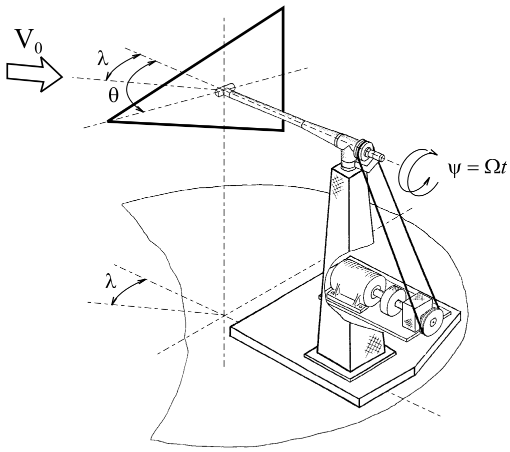

Fig. 3 TsAGI rig modification for oscillatory coning tests.

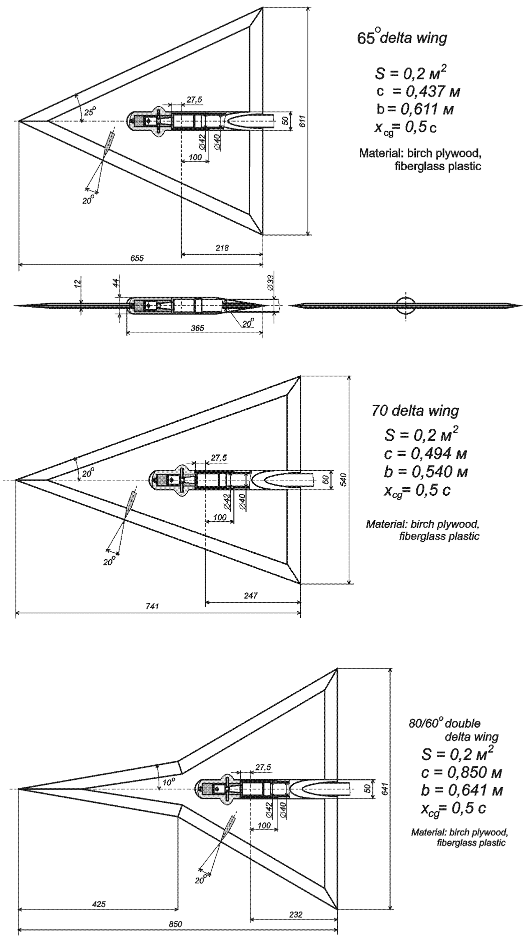

Fig. 4 Investigated 65^o,70^o and $80^o/60^o$ delta wings.

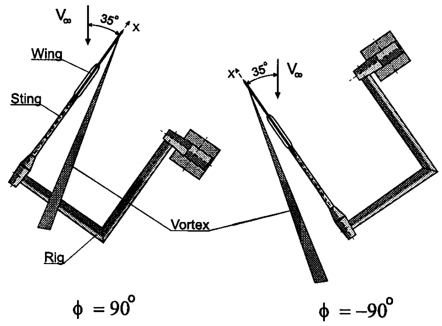

Fig. 5 Blockage effects due to proximity of the rig struts.

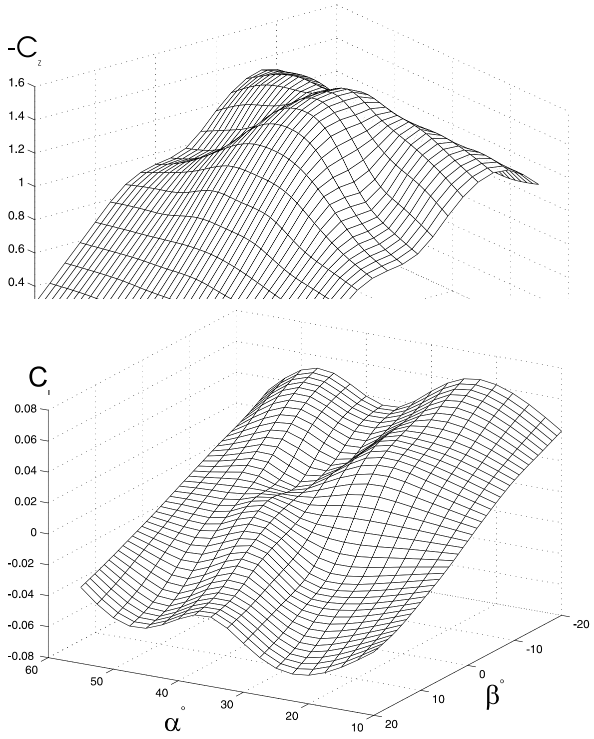

Fig. 6 The normal force and the rolling moment coefficient dependencies on angle of attack and sideslip for the 70^o delta wing (2D spline approximation of experimental results)

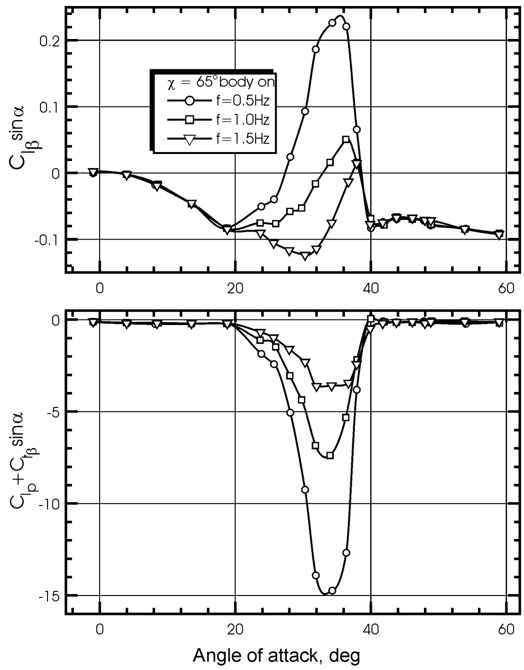

Fig. 8 The 65^o delta wing with a center body: the "in-phase" and the "in-quadrature" derivatives of the rolling moment coefficient in roll motion.

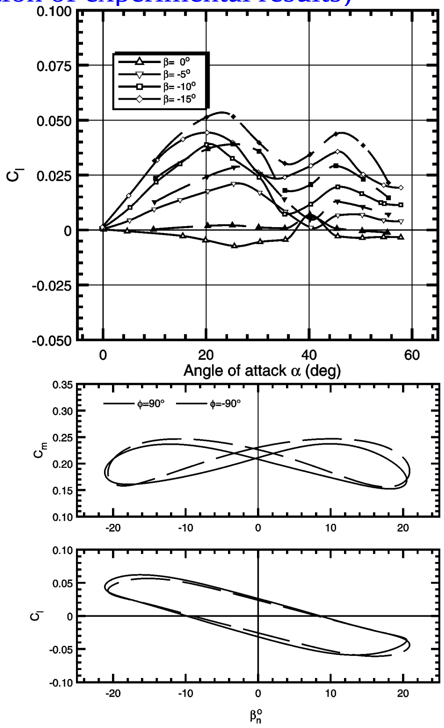

Fig. 7 Scale and interference effects in static (small 70^o delta wing - emty markers, large 70^o delta wing - black markers) and dynamic ($\phi = \pm 90^o$) tests.

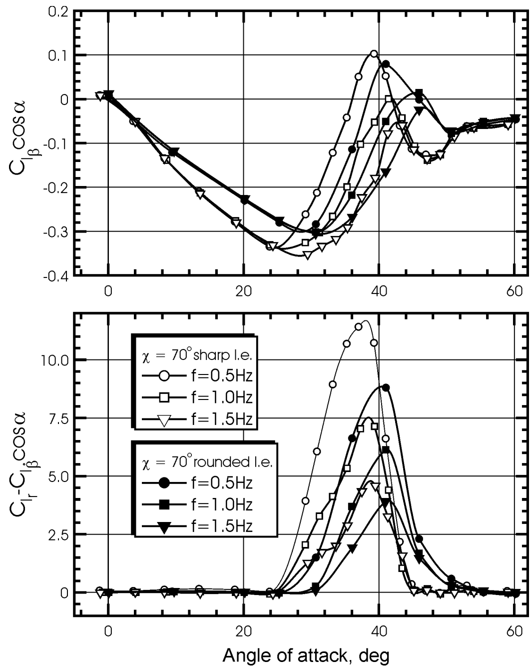

Fig. 9 The 70^o delta wings: the "in-phase" and the "in-quadrature" derivatives of the rolling moment coefficient in yaw motion.

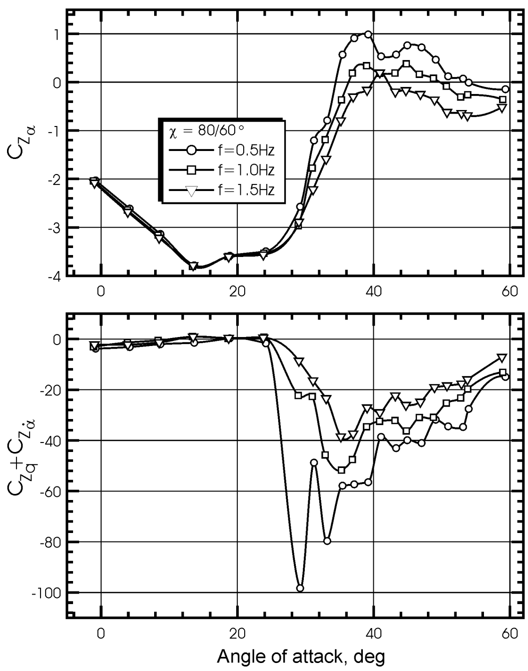

Fig. 10 The $80^o/60^o$ double delta wing: the "in-phase" and the "in-quadrature" derivatives of the normal force coefficient in pitch motion.

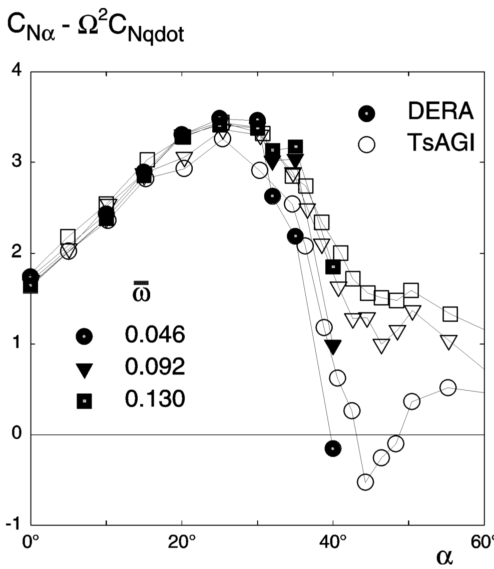

Fig. 11 Comparison of experimental results obtained in DERA Bedford and TsAGI for the 70^o delta wing.

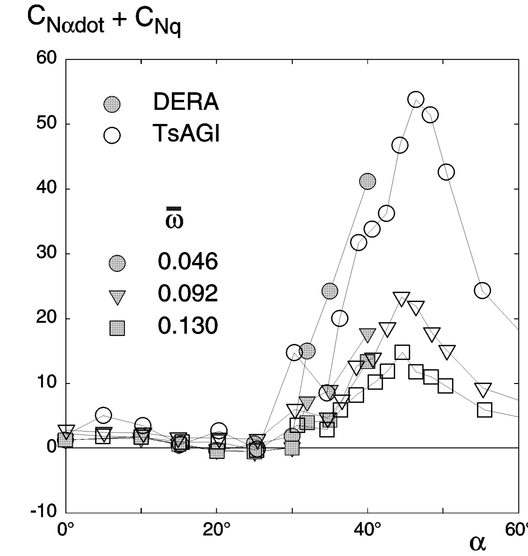

Fig. 12 Comparison of experimental results obtained in DERA Bedford and TsAGI for the 70^o delta wing.

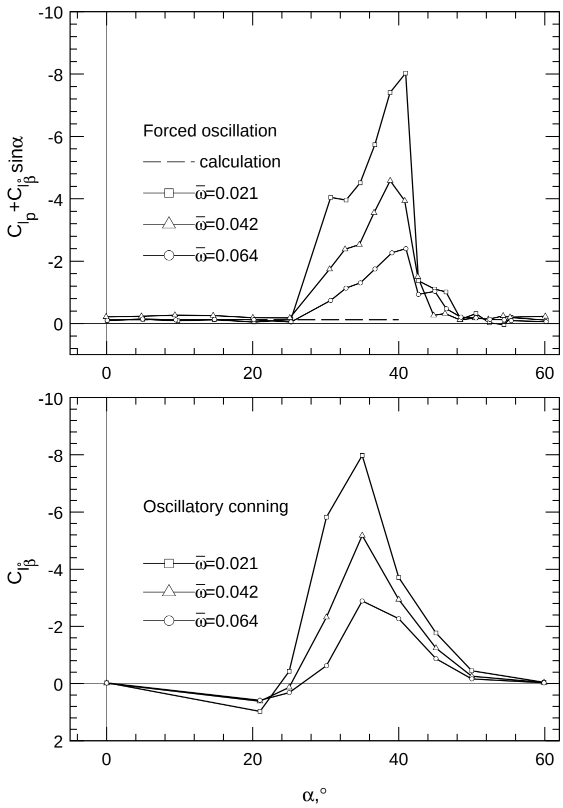

Fig. 13 The 70^o delta wing: composed aerodynamic derivative $C_{l_p}+C_{l_{\dot\beta}}\sin\alpha$ and pure unsteady derivative $C_{l_{\dot\beta}}$ from oscillatory-coning tests.

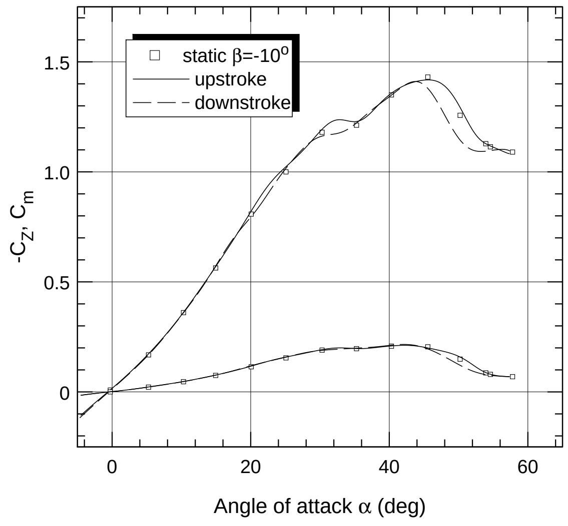

Fig. 14 Slow sweep pitch motions ($\dot{\alpha} = \pm 2$ deg/s, $\beta = -10$ deg, the 70^o delta wing).

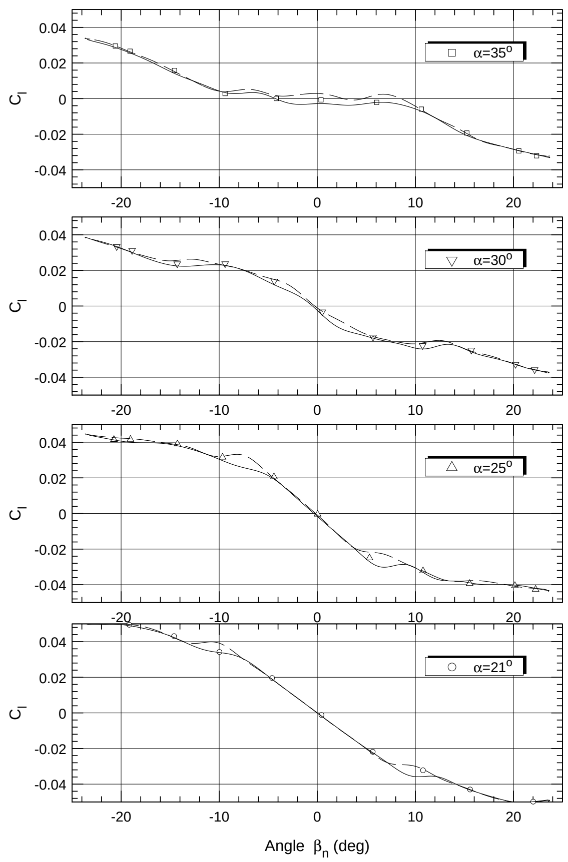

Fig. 15 Slow sweep sideslip motions ($\dot{\beta} = \pm 2$ deg/s, the 70^o delta wing).

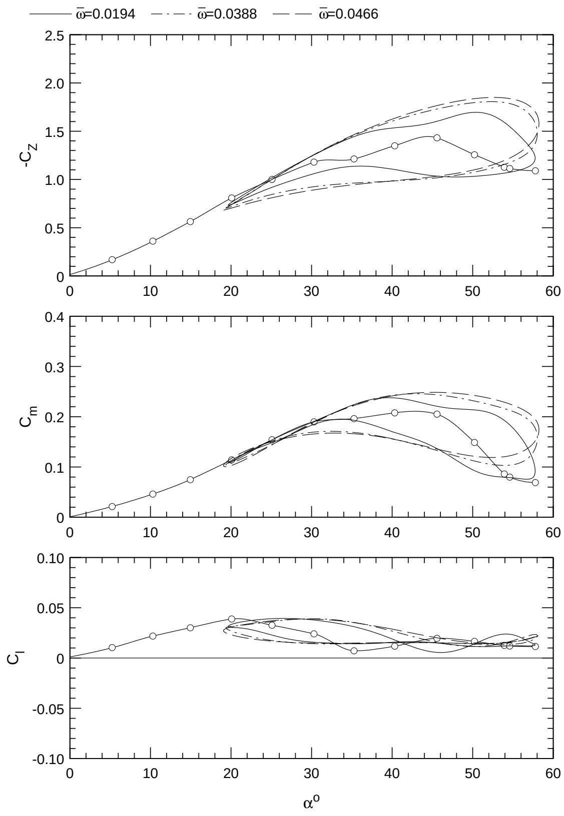

Fig. 16 Aerodynamic responses to large amplitude pitch oscillations with nonzero sideslip ($\beta = -10$ deg, the 70^o delta wing).

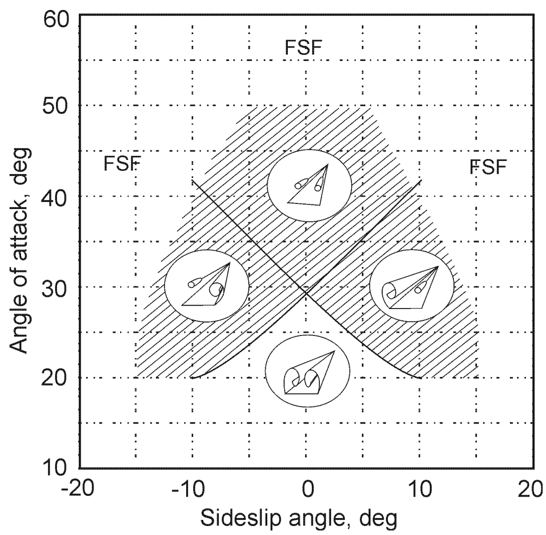

Fig. 17 Regions with different flow structures for the 70^o delta wing [9].

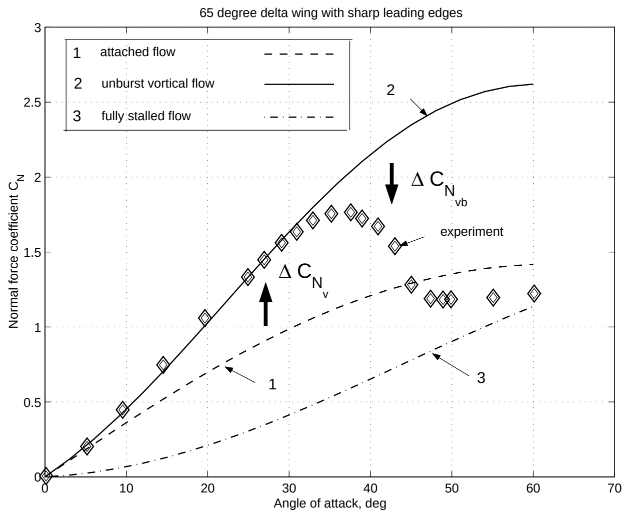

Fig. 18 Aerodynamic loads at different flow structures (the normal force coefficient for the 65^o delta wing): (1) - attached flow, (2) - unburst vortical flow, (3) - fully separated flow, " diamonds" - experimental data.

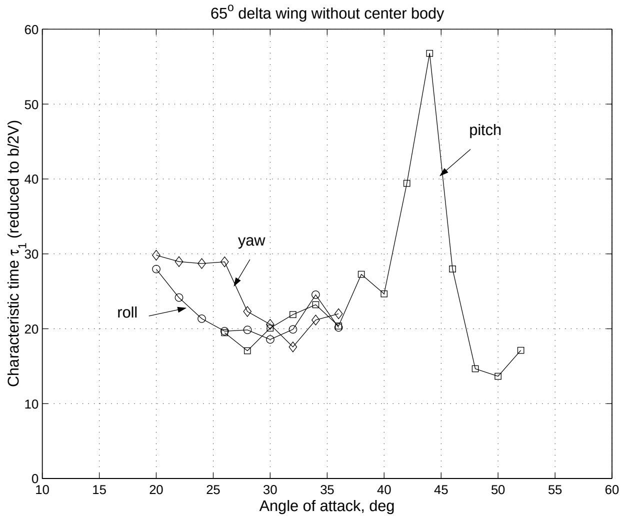

Fig. 20 Characteristic time constants τ_1 for the 65^o delta wing without a center body (square - pitch, diamond - yaw, circle - roll, normalized by semi-span b/2V)

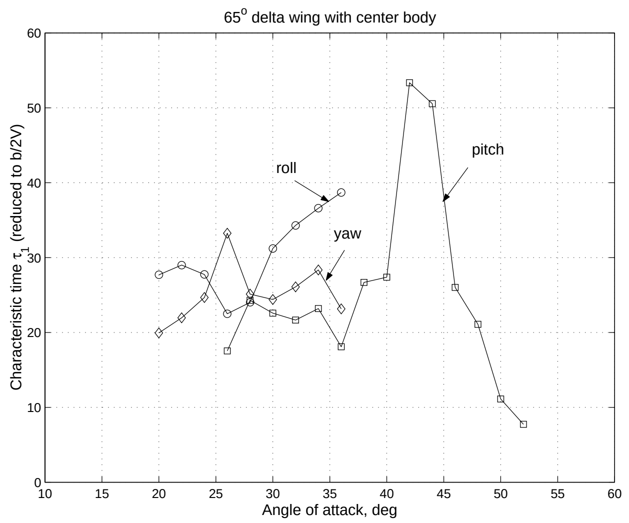

Fig. 19 Characteristic time constants τ_1 for the 65^o delta wing with a center body (square - pitch, diamond - yaw, circle - roll, normalized by semi-span b/2V)

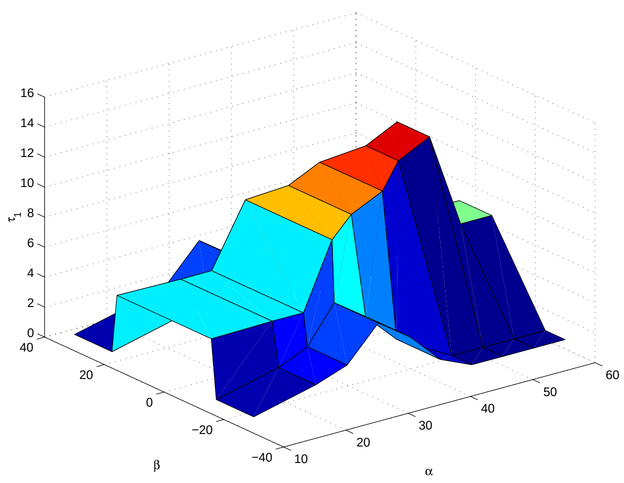

Fig. 21 Characteristic time constant $\tau_1(\alpha,\beta)$ for the 70^o delta wing identified from large amplitude pitch and yaw oscillations.

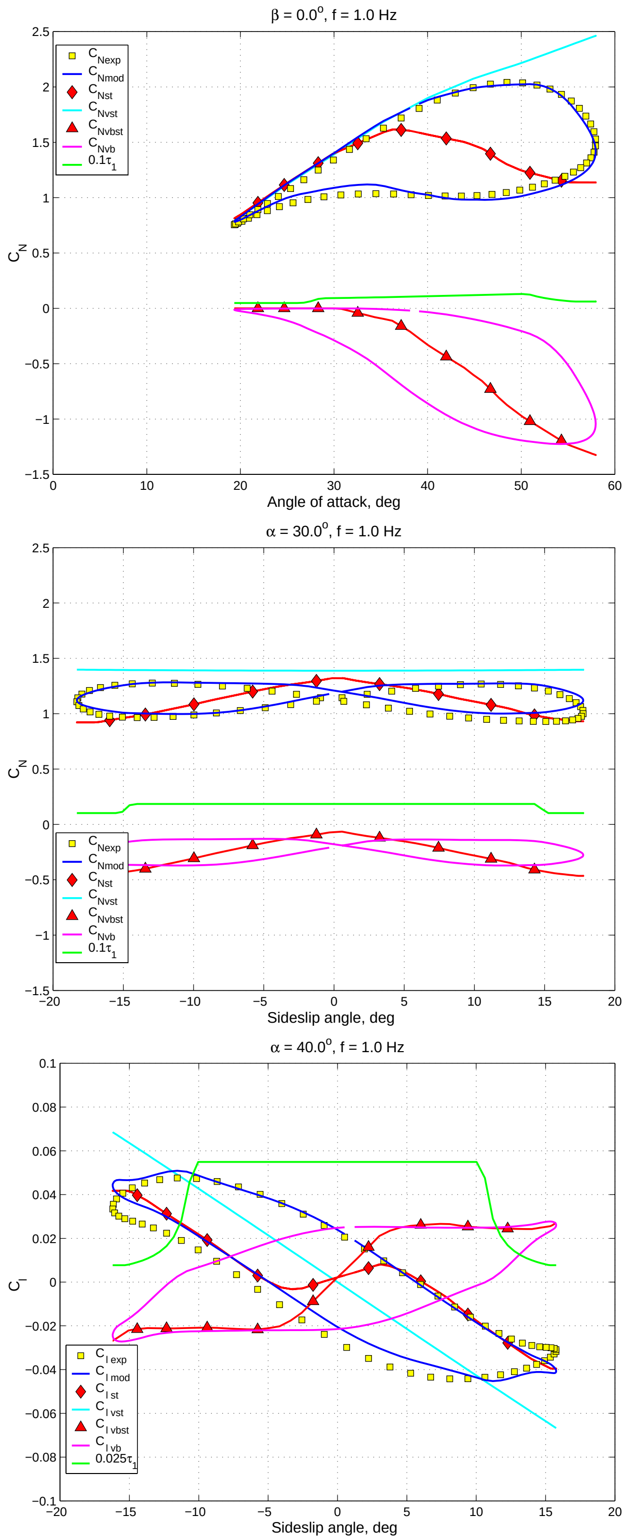

Fig. 22 Aerodynamic responses for the normal force and the rolling moment coefficients at large amplitude pitch and yaw oscillations: experimental and modelling results for small 70^o delta wing.