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ADP010727

TITLE: Low Speed Straked Delta Wing

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TITLE: Verification and Validation Data for
Computational Unsteady Aerodynamics [Donnees de
verification et de valadation pour
l’aerodynamique instationnaire numerique]

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The following component part numbers comprise the compilation report:

ADP010704 thru ADP010735

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INTRODUCTION

Straked wings have become common features of advanced fighter-type aircraft. The strakes are designed to generate vortices from their highly swept leading edges, which stabilise the flow over the wing and provide additional lift up to high angles of attack. In this way the strakes contribute much to a high manoeuvrability. The vortex lift capability of straked wings has been extensively explored and experimental data concerning aerodynamic loading are available for various planforms and Mach numbers. The knowledge of unsteady loading on straked wings is less developed, both in the cases where the loading is due to wing oscillations - as required for aircraft stability and flutter analysis - and in cases where fluctuations in the flow are induced by vortex burst (or vortex breakdown) - as required for stall and buffet predictions.

Some physical aspects of the unsteady vortex flow are described briefly below.

Vortices are shed from the leading edges of the strake and the wing. The sharp leading edges generate vortex sheets, even at low incidence, which roll up spirally into the strake vortices and flow downstream over the wing. The vortices induce strong lateral velocities at the strake and wing upper surface, giving rise to suction peaks at the position of the vortex cores. When the lateral velocities are large enough, secondary flow separations occur, leading to secondary vortices spiralling opposite to the primary vortices. At moderate incidences vortex sheets start to develop from the wing leading edges, starting at the kinks. At higher incidences vortex burst or vortex breakdown occurs, initially for the wing vortices, followed by the strake vortices. An important consequence of vortex burst is that the corresponding suction peaks become weaker and that the vortices lose their ability to produce additional lift. A normal behaviour of vortex burst is that it will move upstream when the incidence increases. At still higher incidences large-scale boundary layer or stall separation occurs, starting often at the trailing edge.

The explanation of the above vortex flow becomes increasingly complicated in case of interactions of strake and wing vortices, their influence on vortex burst and flow separation and, at high enough speeds their interactions with shock waves.

When the straked delta wing is oscillating, the strength and the position of the wing and strake vortices will oscillate. As the vortices are being fed through the vortex sheets emanating from the leading edges, it is to be expected that the oscillations of vortex strength and position will lag the wing oscillation.

Some phenomena can be distinguished in the results of the steady measurements, shown in figure 1, at some characteristic incidence ranges:

- up to 9° attached ("linear") flow
- 9° to 19° fully developed vortex flow
- 19° to 38° vortex burst extending from trailing edge
- beyond 38° vortex burst penetrating the strake, almost fully stalled flow

For the data selection special interest was placed on incidences which mark transition of flow characteristics, or were typical for the flow characteristics in some incidence range. These incidences were 9°, 19°, 22°, 36° and 42°:

- \( \alpha = 5° \) attached flow
- \( \alpha = 19° \) onset to vortex burst
- \( \alpha = 22° \) burst vortex flow
- \( \alpha = 36° \) maximum CN, change of 180° in phase angle of unsteady pitching
- \( \alpha = 42° \) fully separated flow

The above values are the correct geometric incidences as are included in the database files; in the data point overview adjusted values are indicated. For the above characteristic values of incidence a large number of test conditions was explored. Though there is a full-span model, and conditions for plus and minus 5 degrees side-slip are expected to give the same results, both cases are included, because pressure transducers were situated only in the right half-wing. Both conditions are necessary to understand side-slip effects. This all leads to a selection of test cases as indicated in table 1.

LIST OF SYMBOLS AND DEFINITIONS

Definitions

Figure 2a is included as an example of the CATIA based geometry file, included in the database, with the CATIA body-fixed axis system. The CATIA file provides half of the model geometry. The wind tunnel model was a full model, but because of its symmetry only half of the model had to be designed in CATIA.

- \( x \)-axis: chord-wise co-ordinate in wing reference plane; at apex \( x = 0 \)
- \( y \)-axis: span-wise co-ordinate in wing reference plane; \( y'-axis = rotation \) axis or pitching axis at \( x/cr = 73.27 \% \)
- \( z \)-axis: co-ordinate in plane of symmetry normal to wing reference plane

Figure 2b shows the definitions and sign conventions used for non-dimensionalisation.
Non-dimensionalisation

Mean

steady component

Unsteady
First harmonic component (sometimes also second)
the unsteady component is indicated by the suffix i,
each unsteady component has been decomposed into
a real (in-phase) and an imaginary (out-of-phase) part;
e.g.\((C\#)_i = \text{Re}(C\#) + i * \text{Im}(C\#)\)

Pressures

\((Cp)_m = (p - p_s) / q\)
\((Cp)_i = (p)_i / (Q * d\alpha)\)

Balance loads

\((Cl)_m = 1 / (Q * S * bw)\)
\((Cl)_i = l_i / (Q * S * bw * d\alpha)\)
\((Cm)_m = m / (Q * S * cr)\)
\((Cm)_i = m_i / (Q * S * cr * d\alpha)\)
\((CN)_m = N / (Q * S)\)
\((CN)_i = N_i / (Q * S * d\alpha)\)
\((Cn)_m = n / (Q * S * bw)\)
\((Cn)_i = n_i / (Q * S * bw * d\alpha)\)
\((CT)_m = T / (Q * S)\)
\((CT)_i = T_i / (Q * S * d\alpha)\)
\((CY)_m = Y / (Q * S)\)
\((CY)_i = Y_i / (Q * S * d)\)

Note: Each harmonic component has been non-dimensionalized by the first harmonic of \(d\alpha\) (in radians).

Symbols and abbreviations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALPHA, alpha, (\alpha)</td>
<td>wing incidence</td>
</tr>
<tr>
<td>b</td>
<td>(m) local wing span</td>
</tr>
<tr>
<td>bw</td>
<td>(m) wing span; reference span (bw = 0.8000) m</td>
</tr>
<tr>
<td>BETA, beta, (\beta)</td>
<td>sideslip angle</td>
</tr>
<tr>
<td>c</td>
<td>(m) local chord</td>
</tr>
<tr>
<td>CD</td>
<td>(-) wing drag force coefficient</td>
</tr>
<tr>
<td>CL</td>
<td>(-) wing lift force coefficient</td>
</tr>
<tr>
<td>Cl</td>
<td>(-) wing rolling moment coefficient</td>
</tr>
<tr>
<td>Cm</td>
<td>(-) wing pitching moment coefficient; reference axis = rotation axis (x/cr = 73.27%)</td>
</tr>
<tr>
<td>CN</td>
<td>(-) wing normal force coefficient</td>
</tr>
<tr>
<td>Cn</td>
<td>(-) wing yawing moment coefficient</td>
</tr>
<tr>
<td>Cp</td>
<td>(-) pressure coefficient</td>
</tr>
<tr>
<td>cr</td>
<td>(m) root chord; reference chord (cr = 0.7855) m</td>
</tr>
<tr>
<td>CT</td>
<td>(-) wing tangential force coefficient</td>
</tr>
<tr>
<td>CY</td>
<td>(-) wing side force coefficient</td>
</tr>
<tr>
<td>D</td>
<td>(N) wing drag force</td>
</tr>
<tr>
<td>DALPHA, dalpha, (d\alpha)</td>
<td>(°, rad) harmonic oscillations: amplitude of unsteady wing incidence</td>
</tr>
<tr>
<td>(d)i</td>
<td>(mm/rad) unsteady displacement of accelerometer relative to angular displacement of wing</td>
</tr>
<tr>
<td>DPN</td>
<td>Data point number</td>
</tr>
<tr>
<td>FREQ, freq, (f)</td>
<td>(Hz) frequency, frequency of model oscillation</td>
</tr>
<tr>
<td>HARM, harm, (h)</td>
<td>harmonic component; (harm = 0): mean, (harm = 1): first harmonic</td>
</tr>
<tr>
<td>i</td>
<td>(\forall i)</td>
</tr>
<tr>
<td>L</td>
<td>(N) wing lift force</td>
</tr>
</tbody>
</table>
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LVDT Linear Variable Displacement Transducer
m (Nm) wing pitching moment; rotation axis x/cr = 73.27 %
MACH (-) freestream Mach number
N (N) wing normal force
n (Nm) wing yawing moment
NO number of pressure transducers
p (Pa) pressure at model surface
ps (Pa) freestream static pressure
pt (Pa) total pressure
PHI, φ (°) phase angle
Q (Pa) dynamic pressure
REDFR (-) reduced frequency, REDFR = π * f * cr / V
RUN run number, data point
S (m²) wing area; wing reference area S = 0.2640 m²
T (°C) stagnation temperature in settling chamber
T (N) wing tangential force
T (s) harmonic oscillation: period of oscillation
(1-cos) inputs: duration of a (1-cos) input
t (s) time
V (m/s) freestream velocity
WRP Wing Reference Plane
x (m) chordwise ordinate (see Definitions)
Y (N) wing side force
y (m) spanwise ordinate (see Definitions)
z (m) ordinate (see Definitions)

Subscripts
a, a adjusted
g geometric
m mean
i unsteady
ref reference value

FORMULARY

1 General Description of model
1.1 Designation Low Speed Straked Delta Wing
1.2 Type Full-span model, supported by struts
1.3 Derivation Research fighter-type wing
1.4 Additional remarks
1.5 References Ref. 1, Ref. 2, Ref. 6

2 Model Geometry
2.1 Planform Trapezoidal main wing with simple strake
2.2 Aspect ratio 2.422
### 2.3 Leading edge sweep
Wing: 40°, strake: 76°

### 2.4 Trailing edge sweep
No

### 2.5 Taper ratio
-

### 2.6 Twist
No

### 2.7 Root chord
0.7855 m

### 2.8 Span of model
0.800 m

### 2.9 Area of planform
0.264 m²

### 2.10 Leading-edge flap
Not present

### 2.11 Trailing-edge flap
Not present

### 2.12 Location of reference sections and definition of profiles
Measured upper and lower co-ordinates at 4 chordwise sections (3 on port and starboard side and one at line of symmetry) and at 5 spanwise sections

### 2.13 Form of wing-body or wing-root junction
No fuselage and empennage, middle of main wing thickened to accommodate balance

### 2.14 Form of wing tip
Fairing: geometry included in CATIA file in database

### 2.15 Additional remarks
Outboard wing: NACA 64A005 airfoil, Strake: diamond shaped with sharp LE
Geometry data included as CATIA file in database

### 2.16 References
Ref. 2, Ref. 6 Part I, Appendix A

### 3 Wind Tunnel

#### 3.1 Designation
NLR Low Speed Wind Tunnel LST

#### 3.2 Type of tunnel
Atmospheric, closed-circuit, interchangeable test sections

#### 3.3 Test section dimensions
Width 3 m, height 2.25 m, length 8.75 m (5.75 m forward part for aeronautical testing, aft part for non-aerodynamical (industrial) testing

#### 3.4 Type of roof and floor
Solid

#### 3.5 Type of side walls
Solid

#### 3.6 Ventilation geometry
-

#### 3.7 Displacement thickness of side wall boundary layer
Aeronautical testing (forward part): 10 to 11 mm, nonaeronautical testing (aft part): 15 to 20 mm

#### 3.8 Displacement thickness of boundary layers at roof and floor
About the same as in 3.7

#### 3.9 Method of measuring Mach number in the contraction and a calibration correction
Combination of 4 total pressures in settling chamber, 4 static pressures

#### 3.10 Flow angularity
Well within 0.1%

#### 3.11 Variation in flow velocity across the test section
Less than 0.2%

#### 3.12 Variation in static pressure along length of test section
Less than 0.5% of established dynamic pressure

#### 3.13 Sources and levels of noise or turbulence in empty tunnel
0.02% - 0.03%

#### 3.14 Tunnel resonance
-

#### 3.15 Additional remarks
-

#### 3.16 References on tunnel
-

### 4 Model motion

#### 4.1 General description
Harmonic sinusoidal pitching motion, (1-cos) pitch manoeuvres

#### 4.2 Reference co-ordinate and definition of motion
LVDT between model and support gave correct geometric incidence, which included deformation of balance

#### 4.3 Range of amplitude
1° to 18°

#### 4.4 Range of frequency
1 to 16 Hz
4.5 Method of applying motion
Electro-hydraulic shaker system (Ref. 8)

4.6 Timewise purity of motion
Adequate purity

4.7 Natural frequencies and normal modes of
model and support system
Natural frequencies: 31.97 Hz (yaw), 38.66 Hz (roll), 45.36 Hz (roll + pitch), 53.03 Hz (pitch), also higher frequencies; see Ref. 3

4.8 Actual mode of applied motion including
any elastic deformation
Measured with 9 accelerometers; elastic deformation negligible

4.9 Additional remarks
Position and output included in database files.

5 Test Conditions

5.1 Model planform area/tunnel area
0.0391

5.2 Model span/tunnel height
0.2667

5.3 Blockage
Solid blockage negligible, corrected for wake blockage according standard procedure

5.4 Position of model in tunnel
Supported by struts, Wing reference plane in centre of tunnel

5.5 Range of velocities
80, 55 and 30 m/s (Mach numbers: 0.225, 0.155, 0.085)

5.6 Range of tunnel total pressure
Atmospheric

5.7 Range of tunnel total temperature
Actual total temperature value included in database files

5.8 Range of model steady or mean incidence
and sideslip angles
Adjusted incidences: -10° to 55°
Sideslip angles: -5°, 0°, +5°

5.9 Definition of model incidence
Relative to WRP

5.10 Position of transition, if free
-

5.11 Position and type of trip, if transition fixed
-

5.12 Flow instabilities during tests
-

5.13 Changes to mean shape of model due to steady aerodynamic load
Not measured

5.14 Additional remarks
Correct geometric incidences and amplitudes in data files

5.15 References describing tests
Refs. 5, 6 and 9

6 Measurements and Observations

6.1 Steady pressures for the mean conditions
Yes

6.2 Steady pressures for small changes from the mean conditions
No

6.3 Quasi-steady pressures
No

6.4 Unsteady pressures
Measured directly
- harmonic components Yes
- time histories Yes

6.5 Steady loads for the mean conditions
Measured directly

6.6 Steady loads for small changes from the mean conditions
No

6.7 Quasi-steady loads
No

6.8 Unsteady loads
Measured directly
- harmonic components Yes
- time histories Yes
- Power Spectral Densities Yes
- manoeuvres Yes

6.9 Measurement of actual motion at points on model
Yes

6.10 Observation or measurement of boundary
No
6.11 Visualisation of flow: Yes
6.12 Visualisation of shock wave movements: No
6.13 Additional remarks: -

7 Instrumentation

7.1 Steady pressure
7.1.1 Position of orifices spanwise and chordwise: See Figure 3: positions included in database files of pressures
7.1.2 Type of measuring system: 42 in situ miniature pressure transducers

7.2 Unsteady pressure
7.2.1 Position of orifices spanwise and chordwise: See Figure 3: positions included in database files of pressures
7.2.2 Diameter of orifices: 0.8 mm
7.2.3 Type of measuring system: Processor for measuring harmonic components; see Ref.7
7.2.4 Type of transducers: Endevco 8507-5, Kulite CQL-080-5D, Kulite XCS-093-5D
7.2.5 Principle of calibration: Data acquisition system was calibrated daily, pressure transducers before the wind tunnel test
7.2.6 Accuracy of calibration: ~1%

7.3 Model motion
7.3.1 Method of measuring motion: LVDT: type Sangamo AFG 5.0 S
7.3.2 Method of determining spatial mode of motion: 9 accelerometers: 5 Endevco 2220 C, 4 Kulite GY-155
7.3.3 Accuracy of measured motion: LVDT: better than 0.015 mm

7.4 Processing of unsteady measurements
7.4.1 Method of acquiring and processing measurements: Processor for measuring harmonic components
7.4.2 Type of analysis: Fundamental harmonics: pressures, balance loads
time histories: pressures, balance loads
PSD plots: balance loads
vortex core positions: visualisation
7.4.3 Unsteady pressure quantities obtained and accuracy’s achieved: Fundamental harmonics and time histories, for accuracy see 9.1.6

7.5 Additional remarks: -
7.6 References on techniques: -

8 Data presentation

8.1 Test cases for which data could be made available: see Tables 2 to 5
8.2 Test cases for which data are included in this document: Summarised and motivated in Introduction
8.3 Steady pressures: Mean values; see Low Speed Straked Delta Wing Database
8.4 Quasi-steady or steady perturbation pressures: Mean values and first harmonics; see Low Speed Straked Delta Wing Database
8.5 Unsteady pressures: Mean values; see Low Speed Straked Delta Wing Database
8.6 Steady loads: Mean values; see Low Speed Straked Delta Wing Database
8.7 Quasi-steady or unsteady perturbation forces: Mean values and first harmonic; see Low Speed Straked Delta Wing Database
8.8 Unsteady loads: Mean values; see Low Speed Straked Delta Wing Database
8.9 Other forms in which data could be made: -
available

8.10 Reference giving other representations of data

References 9 to 15

9 Comments on data

9.1 Accuracy

9.1.1 Mach number +/- 0.001
9.1.2 Steady incidence +/- 0.01 at LVDT position
9.1.3 Reduced frequency +/- 0.0005
9.1.4 Steady pressure coefficients +/- 0.5 percent
9.1.5 Steady pressure derivatives -
9.1.6 Unsteady pressure coefficients +/- 0.5 percent

9.2 Spanwise variations Dynamic pressure distribution around model in relation to dynamic pressure, measured by tunnel reference system, measured for zero-lift condition

9.3 Non-linearity's -
9.4 Influence of tunnel total pressure -
9.5 Effects on data of uncertainty, or variation, in mode of model motion -
9.6 Wall interference corrections Not measured
9.7 Other relevant tests on same model Ref. 5
9.8 Relevant tests on other models of nominally the same shapes Ref. 4
9.9 Any remarks relevant to comparison between experiment and theory -
9.10 Additional remarks An example of a database file and its explanation is included in table 6. Structure of file set-up is included in README file in database

9.11 References on discussion of data

References 9 to 15

10 Personal contact for further information

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Fax: +31 20 5113210
Website: http://www.nlr.nl

11 List of references


Cunningham, Jr., A.M., den Boer, R.G., et al., "Unsteady low speed wind tunnel test of a straked delta wing, oscillating in pitch".

Part I General description and discussion of results
Part II Plots of steady and zeroth and first order harmonic unsteady pressure distributions
Part III Plots of zeroth and first order harmonic unsteady pressure distributions (concluded) and plots of steady and zeroth and first order harmonic overall loads
Part IV Plots of time histories of pressures and overall loads
Part V Plots of the overall loads spectra and the response of overall loads to single step (1-cos) inputs
Part VI Presentation of the visualization program
NLR TR 87146 L Parts I through VI. (also "published" in April 1988 as AFWAL-TR-8-3098, Parts I-VI).


<table>
<thead>
<tr>
<th>Incidence [°] (adjusted)</th>
<th>8</th>
<th>22</th>
<th>22</th>
<th>22</th>
<th>22</th>
<th>22</th>
<th>38</th>
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<td>8</td>
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<td>Frequency [Hz]</td>
<td>5</td>
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<td>Side-slip [°]</td>
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<td>0</td>
<td>+5</td>
<td>-5</td>
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<td>Velocity [m/s]</td>
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<td>Steady Pressures (Cp_s)</td>
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<td>Unsteady Pressures (Cp0,Cp1)</td>
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<td>Time histories of pressures</td>
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<td>Time histories of balance loads</td>
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<td>Manoeuvres</td>
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<td>3017</td>
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Table 1: Selected test cases for Low Speed Straked Delta Wing (Values in shaded area indicate data point numbers)
<table>
<thead>
<tr>
<th>Oscillating amplitudes at alpha/frequency combinations</th>
<th>( \beta = 0.0^\circ, \text{V} = 80 \text{m/s} )</th>
<th>( \beta = 5^\circ, \text{V} = 80 \text{m/s} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>frequency</td>
<td>( \alpha_0 )</td>
<td>frequency</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>8</td>
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<tr>
<td>8</td>
<td>4.8, 16</td>
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<td>22</td>
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<td>4.8, 16</td>
<td>4.8, 16</td>
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<tr>
<td>46</td>
<td>4.8</td>
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</table>

Table 2: Steady test program

Table 3a: Unsteady test program (FUNDAMENTAL HARMONICS, BASIC PROGRAM)

Table 3b: Unsteady test program (FUNDAMENTAL HARMONICS, SIDESLIP INFLUENCE)
### Table 3c: Unsteady test program (FUNDAMENTAL HARMONICS, VELOCITY INFLUENCE)

<table>
<thead>
<tr>
<th>Oscillating amplitudes at alpha/frequency combinations</th>
<th>( \alpha = 0^\circ, V = 55 \text{ m/s} )</th>
<th>( \alpha = 0^\circ, V = 30 \text{ m/s} )</th>
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<td>frequency</td>
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<td>( \alpha )</td>
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<tr>
<td>46</td>
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</tbody>
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### Table 4a: Unsteady test program (TIME HISTORIES of PRESSURES)

<table>
<thead>
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<th>Oscillating amplitudes at alpha/frequency combinations</th>
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<tbody>
<tr>
<td>( \beta = 0^\circ, V = 80 \text{ m/s} )</td>
</tr>
<tr>
<td>frequency</td>
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<td>( \alpha )</td>
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<td>18</td>
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<td>20</td>
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<td>38</td>
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<td>46</td>
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</table>

### Table 4b: Unsteady test program (TIME HISTORIES of OVERALL LOADS, PSDs)

<table>
<thead>
<tr>
<th>Oscillating amplitudes at alpha/frequency combinations</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta = 0^\circ, V = 80 \text{ m/s} )</td>
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<td>frequency</td>
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<td>( \alpha )</td>
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Oscillating amplitudes at $\alpha/T$ combinations

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<th>0.330</th>
<th>0.250</th>
<th>0.200</th>
<th>0.125</th>
<th>0.083</th>
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</tr>
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<td>8.16,24,32</td>
<td>8.16,24,32</td>
<td>8.16,24,32</td>
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<td>8.16,24,32</td>
<td>8.16,24,32</td>
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</tbody>
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Table 5: Unsteady test program: (1 - COSINE) INPUTS

File organization of "sel_st" and "sel_uns" (STeady and UNSteady)

<table>
<thead>
<tr>
<th>Description</th>
<th>FORMAT</th>
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</thead>
<tbody>
<tr>
<td>$\phi$, HARM, ALPHA, Re(DALPHA), Im(DALPHA), FREQ, MACH</td>
<td>215, 5f10.5</td>
</tr>
<tr>
<td>VELOCITY, REDFR, Q, ps, T, BETA, S</td>
<td>210.5, f10.2, 4f10.5</td>
</tr>
<tr>
<td>NO, xref, x/xref, yref, y/yref, (Cp)m, Re(Cp), Im(Cp)</td>
<td>44*(12, 7f10.5, /)</td>
</tr>
<tr>
<td>(CN)m, Re(CN), Im(CN), (Ch)m, Re(Ch), Im(Ch)</td>
<td>6f10.5</td>
</tr>
<tr>
<td>(CY)m, Re(CY), Im(CY), (Cp)m, Re(Cp), Im(Cp)</td>
<td>6f10.5</td>
</tr>
<tr>
<td>(CT)m, Re(CT), Im(CT), (CN)m, Re(CN), Im(CN)</td>
<td>6f10.5</td>
</tr>
<tr>
<td>NO, xref, x/xref, yref, y/yref, Re(d), Im(d)</td>
<td>9*(12, 6f10.5, /)</td>
</tr>
</tbody>
</table>

NB. Improper values represented as: 9999.99

Table 6a: Example of explanation of file organisation of pressure data files
Table 6a: Example of an unsteady pressure measurement database file
Figure 1: Low Speed Straked Delta Wing: Steady Normal Force and Pitching Moment vs. alpha.
Figure 2a: CATIA example of NLR Low Speed Staked Delta Wing.
Figure 2b: Definitions and sign conventions
Figure 3: NLR Low Speed Straked Delta Wing, planform and model instrumentation

Dimensions in mm; pitching axis x/cr = 73.27%