Title: Oscillating 65 Deg. Delta Wing, Experimental

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

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The following component part numbers comprise the compilation report:

ADP010704 thru ADP010735
INTRODUCTION

This data set contains force and pressure data resulting from static and dynamic measurements on a sharp-edged cropped delta wing with a leading edge sweep of 65° oscillating in different modes. Motivation for the experiment were the provision of experimental data for validation of unsteady computational codes and understanding of the flow past an oscillating delta wing.

The model geometry is identical to a geometry used in the Vortex Flow Experiment for Computer Code Validation (VFE), a multinational cooperation which provided experimental data of delta wing configurations in the mid eighties [3], [4]. The geometry of the wing is also used for steady and unsteady calculations within the Western European Armament Group (WEAG, formerly IEPG) TA - 15.

The experiments have been performed in 1994 (force measurements) and 1995 (pressure measurements). They were performed in the German-Dutch wind tunnel DNW-NWB at low speeds, the model undergoing pitching, yawing or rolling motions about wind-fixed axes. The choice of the mean angles of attack was closely related to the expected flow types:

\( \alpha_0 = 0^\circ \): In this case the vortex formation will alternate between the upper and the lower surface of the configuration during the pitching motion.

\( \alpha_0 = 9^\circ \): Vortices will be present over the upper surface of the configuration and no vortex breakdown will occur during the whole cycle of the pitching motion.

\( \alpha_0 = 15^\circ \) and

\( \alpha_0 = 21^\circ \): These conditions are related to mixed cases without vortex breakdown over the configuration at low angles of attack and with vortex breakdown at high angles of attack during the cycle of motion.

\( \alpha_0 = 27^\circ \): Vortices with vortex breakdown are expected to occur over the upper surface of the configuration and this type of flow will be present during the whole cycle of the pitching motion.

\( \alpha_0 = 42^\circ \): During the cycle of the pitching motion the flow is expected to switch between a vortex-type flow with vortex breakdown and a dead-water-type flow.

\( \alpha_0 = 48^\circ \): In this case a deadwater-type flow is expected during the whole cycle of motion.

The mean angles of attack at which no vortex breakdown occurs during the complete cycle of motion are simpler to treat numerically. Therefore the pitching oscillations about \( \alpha_0 = 9^\circ \) was the first case to be included in a WEAG TA-15 common exercise. The other case included in that common exercise is the pitching oscillation about \( \alpha_0 = 21^\circ \), the reduced frequency being 0.56 for all mean angles of attack. Results from unsteady Euler and Navier-Stokes calculations of pitching oscillation about \( \alpha_0 = 9^\circ \) with an amplitude of \( \Delta \alpha = 3^\circ \) by W. Fritz are included in the following chapter 17C.

LIST OF SYMBOLS AND DEFINITIONS

- \( b = 2s \) wing span
- \( c \) chord
- \( c_1 \) root chord
- \( C_{L0}, C_{D0}, C_m \) lift, drag and pitching moment coefficients, reference length for \( C_{L0} \): \( c_0 \), see figs. 1 and 3 for reference point
- \( C_{V0}, C_{V1}, C_{Vn} \) side force, rolling moment and yawing moment coefficients, reference length for \( C_{I1} \) and \( C_{Vn} \): \( s \), see figs. 1 and 3 for reference point
- \( C_p \) static pressure coefficient, \( C_p = (p - p_\infty)/\rho_\infty \)
- \( d \) fuselage diameter, see fig. 3
- \( DNW - NWB \) Deutsch-Niederländischer Windkanal - Niedergeschwindigkeits-Windkanal Braunschweig
- \( f_s \) model oscillation frequency
- \( FS \) full scale
- \( F_x, F_y, F_z \) forces in \( x, y, z \)-direction in balance-fixed coordinate system
- \( LE \) leading edge
- \( m0 \) unsteady mean value of force and pressure values, see fig. 7
- \( m1, m2, m3 \) amplitudes of the first, second and third harmonic of force and pressure values, see fig. 7
- \( M_x, M_y, M_z \) moments about balance-fixed \( x, y, z \)-axis
- \( q_0 \) dynamic pressure
- \( Re \) Reynolds number, \( Re = \frac{V_\infty \cdot c_0}{v} \)
- \( TE \) trailing edge
- \( V_\infty \) free stream velocity
- \( t \) time
- \( x, y, z \) rectangular wing-fixed coordinate system, origin at apex, see fig. 3
- \( \alpha \) angle of attack
- \( \alpha_0 \) mean angle of attack
- \( \Delta \alpha \) amplitude of pitching oscillation
- \( \beta \) angle of sideslip
\[ \beta_{\text{avg}} \] mean angle of sideslip

\[ \Delta \beta \] amplitude of yawing oscillation

\[ \eta \] dimensionless span-wise coordinate, \( \eta = y/s(x) \)

\[ \Delta \Phi \] amplitude of rolling oscillation

\[ \phi_i \] phase angle of the \( i \)th harmonic with respect to the model motion

\[ \omega^* \] reduced frequency, \( \omega^* = 2\pi f_c c / \sqrt{V_o} \) (pitching motion), \( \omega^* = 2\pi f_c s / \sqrt{V_o} \) (yawing and rolling motion)

**FORMULARY**

1. **General description of model**
   1.1 Designation VFE WB1 - SLE
   
   1.2 Type full model
   
   1.3 Derivation NLR 65°-wing, Ref. 1
   
   1.4 Additional remarks none
   
   1.5 References 1

2. **Model geometry**
   
   2.1 Planform cropped delta wing
   
   2.2 Aspect ratio 1.378
   
   2.3 Leading edge sweep 65°
   
   2.4 Trailing edge sweep 0°
   
   2.5 Taper ratio 0.15
   
   2.6 Twist 0°
   
   2.7 Root chord 1200 mm
   
   2.8 Span of model 951 mm
   
   2.9 Area of planform 0.6564 in²
   
   2.10 Definition of profiles symmetrical with sharp leading edge (radius approx. 0.25 mm); 5% rel. thickness; arc segment from leading edge (LE) to \( x/c = 0.4 \); airfoil NACA 64A005 from \( x/c = 0.4 \) to \( x/c = 0.75 \), straight line with 3° inclination from \( x/c = 0.75 \) to trailing edge (TE). A sketch of the airfoil including the coordinates of the NACA airfoil used is presented in fig. 8.

   2.11 Lofting procedure between reference sections N/A
   
   2.12 Form of wing-body junction sharp
   
   2.13 Form of wing tip square cut
   
   2.14 Control surface details N/A
   
   2.15 Additional remarks definition of fuselage: below the wing, the cross section being semicircular at its bottom half and having a constant width at its upper half below the wing. The section of the fuselage protruding above the wing has cylindrical shape again. The fuselage consists basically of three parts: a tapered nose section from \( x/c = 0.0 \) to \( x/c = 0.358 \) (see figs. 2, 3 and 4 for details), a cylindrical section with a width (diameter \( d \)) of 160 mm from \( x/c = 0.358 \) to \( x/c = 1.0 \) and a conical section aft of the TE with a length of 50 mm and a taper angle of 15°. The fuselage centreline is located 50 mm below the wing plane \( (z/c = -0.042) \).

   All dimensions given are nominal dimensions.

   2.16 References 1, 2

3. **Wind tunnel**
   
   3.1 Designation Low Speed Wind Tunnel Braunschweig DNW - NWB
   
   3.2 Type of tunnel continuous, atmospheric pressure
   
   3.3 Test section dimensions height: 2.85 m, width: 3.25 m, Length: 6 m (open) 8 m (closed), open or closed. Open section used.
3.4 Type of roof and floor
3.5 Type of side walls
3.6 Ventilation geometry
3.7 Thickness of side wall boundary layer
3.8 Thickness of boundary layers at roof and floor
3.9 Method of measuring velocity
3.10 Flow angularity
3.11 Uniformity of Mach number over test section
3.12 Sources and levels of noise in empty tunnel
3.13 Tunnel resonances
3.14 Additional remarks
3.15 References on tunnel

4 Model motion
4.1 General description
   4.1.1 Pitching motion
   4.1.2 Yawing motion
   4.1.3 Rolling motion

4.2 Natural frequencies and normal modes of model and support system
4.3 Range of amplitude
4.4 Range of frequency
4.5 Method of applying motion
4.6 Timewise purity of motion
4.7 Actual mode of applied motion including any elastic deformation
4.8 Additional remarks

5 Test conditions
5.1 Model planform area/tunnel area
5.2 Model span/tunnel width
5.3 Blockage
5.4 Position of model in tunnel
5.5 Range of freestream velocity
5.6 Range of tunnel total pressure
5.7 Range of tunnel total temperature
5.8 Range of model incidence
   5.8.1 Range of steady model incidence
5.8.2 Range of mean model incidence

\[ \alpha_p = 0^\circ, 9^\circ, 15^\circ, 21^\circ, 27^\circ, 42^\circ \text{ (pitching)} \]
\[ \alpha_y = 9^\circ, 15^\circ, 27^\circ, 42^\circ \text{ (yawing)} \]
\[ \alpha_r = 0^\circ, 9^\circ, 27^\circ \text{ (rolling)} \]

5.9 Definition of model incidence

model incidence defined relative to the wing plane

5.10 Position of transition, if free

not measured

5.11 Position and type of trip, if transition fixed

no trip used

5.12 Flow instabilities during tests

none encountered

5.13 Changes to mean shape of model due to steady aerodynamic load

not measured, negligible

5.14 Additional remarks

none

5.15 References describing tests

2, 4

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

yes

6.4 Unsteady pressures

yes

6.5 Steady forces for the mean conditions

6.5.1 Steady forces for the mean conditions by integration of pressures

no

6.5.2 Steady forces for the mean conditions by direct measurement

yes

6.6 Steady forces for small changes from the mean conditions by integration

no

6.7 Quasi-steady forces by integration

no

6.8 Unsteady forces

6.8.1 Unsteady forces by integration

no

6.8.2 Unsteady forces by direct measurement

yes

6.9 Measurement of actual motion at points on model properties

no

6.10 Observation or measurement of boundary-layer properties

no

6.11 Visualisation of surface flow

yes

6.12 Visualisation of shock wave movements

N/A

6.13 Additional remarks

steady forces and pressures have been measured with increasing angle of attack, control measurements with increasing and decreasing angle of attack have been performed to ensure the absence of hysteresis effects. Forces and pressures have been measured during different wind tunnel entries.

7 Instrumentation

7.1 Steady pressures

pressures for steady conditions measured with same system used for unsteady measurements with the only difference being that the static measurements have been performed with all 10 psi transducers connected simultaneously whereas the dynamic measurements have been performed with 2 transducers connected simultaneously.

7.1.1 Position of orifices span-wise and chord-wise

see tables 1 and 2.

7.1.2 Diameter of orifices

0.6 mm

7.1.3 Type of measuring system

see 7.2.3

7.2 Unsteady pressures

7.2.1 Position of orifices span-wise and chord-wise

see tables 1 and 2.

7.2.2 Diameter of orifices

see 7.1.2
7.2.3 Type of measuring system

230 pressure orifices connected with short pressure tubes of equal length to 10 PSI pressure transducers, which are located in the wing of the model. 9 of these orifices are also connected to Kulite pressure transducers by means of tubes of approximately 10 cm length.

PSI System 780 B, 16bit ADC.

Sampling frequencies: 74.35 Hz (PSI), 1000 Hz (Kulites)

7.2.4 Type of transducers

PSI modules used: ESP-16 SL, ESP-32 SL and ESP-48 SL, range: 0.35 psi and 1.0 psi.

Kulites used: XCW-062 and XCW 093, range 0.35 bar (= 5.0 psi)

7.2.5 Principle and accuracy of calibration

PSI: 3 calibration pressures (magnitudes adapted to the expected values of the experiment) applied to each module every 30 minutes. Manufacturers claimed accuracy: 0.1% full scale (FS), worst case, 0.07% typical, wind tunnel operators checked accuracy: 0.05% FS

Kulite: static calibration at beginning of tunnel entry, offset measurement every 30 minutes.

7.3 Steady forces

steady and unsteady forces measured with six component strain gauge balance of type "Emmen 196-6"

7.4 Unsteady forces

see 7.3

7.5 Model motion

7.5.1 Method of measurement

spring-loaded foil strain gauges on steel flexures

7.5.2 Accuracy of measured motions

better than 1%

7.6 Processing of unsteady measurements

7.6.1 Method of acquiring and processing measurements

pressure measurements: see fig 6

force measurements: see fig 6

fourier analysis, then analysis of variance

amplitudes and phases up to the 3rd harmonic. Confidence intervals for amplitudes and phases of each harmonic specified in data files

7.6.2 Type of analysis

N/A

7.6.3 Unsteady pressure quantities obtained and accuracies achieved

7.6.4 Method of integration to obtain forces

7.7 Additional remarks

process of calculating the phase angles of the harmonics:
1. calculate position signal \( \alpha(t) \) from raw data
2. calculate Pressure Coefficients \(-Cp(t)\) from raw data:
   \[-Cp = \frac{(p_s - p)}{q_o} \]
3. Set the number of data values to be used for Fourier analysis to cover an integer number of model oscillations
4. Perform Fourier analysis on position signal and calculate phase of its first harmonic according to
   \[\varphi_{\alpha_{\text{new}}} = -\arctan(\text{Im}(\text{Re}_{\alpha_{\text{new}}}))\]
5. Perform Fourier analysis on pressure signals \(-Cp(t)\). Calculate phase angles of the i-th harmonic according to
   \[\varphi_{-Cp_i} = -\arctan(\text{Im}(\text{Re}_{-Cp_i}))\]. Account for the phase of the position signal by subtracting it from the phases of the harmonics according to \(\varphi_{-Cp_i} = \varphi_{-Cp_i} - i\varphi_{\alpha_{\text{new}}}\). This is equivalent with letting the fourier analysis start at an instant where the position signal has a phase angle \(\varphi_{\alpha_{\text{new}}}\) of 0°. The phases are then (if necessary) modified to lie again within the range \(-180° \leq \varphi_{-Cp_i} \leq +180°\)
6. The pressure signal now can be represented by
   \[-Cp(t) = -Cp_0 + \sum_{i=1}^{3} -\hat{Cp}_i \cdot \cos(i\omega t + \varphi_i),\]
   \(-\hat{Cp}_i\) being the amplitude of the i-th harmonic and \(-Cp_0\) the constant offset of the signal as presented in the data files.
7. The procedure above applies also to the force measurements.

It is important to note the negative sign in the definition of the
7.8 References on techniques
7, 8, 9, 10

8 Data presentation

8.1 Test cases for which data could be made available
-6° <= α <= 48° in approximately 1° intervals for β = 0°;
-5° <= β <= +5° in approximately 1° intervals for α = 9°, 15°, 27° and 42°.

8.1.1 Steady pressures
see tables 4, 6 and 8

8.1.2 Unsteady pressures
see tables 4, 6 and 8

8.1.3 Steady forces
-7.5° <= α <= 58.5° in 1.5° intervals at Re = 1.55-10^6, Re = 3.1-10^6 and Re = 3.9-10^6, for β = 0°;
β = -5°, -3°, -3°, 0°, +1°, +3° and +5° for 0° <= α <= 54° in approx. 3° or 6° intervals for Re = 3.1-10^6.

8.1.4 Unsteady forces
see tables 3, 5 and 7

8.2 Test cases for which data are included in this document
α = 0°, 9°, 15°, 21°, 27° and 42° for β = 0°, Re = 1.55-10^6 and/or Re = 3.1-10^6;
β = -5°, 0°, +5° for α = 9°, 15°, 27° and 42° for Re = 3.1-10^6.

8.2.1 Steady pressures
see tables 4, 6 and 8

8.2.2 Unsteady pressures
see tables 4, 6 and 8

8.2.3 Steady forces
-7.5° <= α <= 58.5° in 1.5° intervals at Re = 1.55-10^6, Re = 3.1-10^6 and Re = 3.9-10^6, β = 0°;
β = -5°, 0° and +5° for 0° <= α <= 54° in approx. 3° or 6° intervals for Re = 3.1-10^6.

8.2.4 Unsteady forces
see tables 3, 5 and 7

8.3 Other forms in which data could be made available
none

8.4 References giving other presentation of data
2

8.5 Additional remarks
force coefficients given for steady measurements at β = 0° and
for pitching motion: C_L, C_D and C_m;
force coefficients given for steady measurements at α = 0° and
for yawing and rolling motion: C_L, C_D, C_Y, C_1, C_m, and C_n

9 Comments on data

9.1 Accuracy
9.1.1 Mach number
see 3.14
±0.01°

9.1.2 Steady incidence
±0.1 °

9.1.3 Reduced frequency
see 7.2.5

9.1.4 Steady pressure coefficients
confidence interval is result of Analysis of Variance

9.1.5 Unsteady pressure coefficients
accuracy according to balance manufacturer: 0.1 - 0.3 % of
balance design point values (F_x = 550 N, F_y = 250 N,
F_z = 1200 N, M_x = 100 Nm, M_y = 120 Nm, M_z = 130 Nm)
confidence interval is result of Analysis of Variance

9.1.5 Unsteady force coefficients
no evidence

9.2 Sensitivity to small changes of parameter
no evidence

9.4 Influence of tunnel total pressure
N/A

9.5 Effects on data of uncertainty, or variation, in mode of
model motion

9.6 Wall interference corrections
no corrections applied

9.7 Other relevant tests on same model
none

9.8 Relevant tests on other models of nominally the same
shapes
static tests have been performed within the Vortex Flow
Experiment, see references 1, 5, 6

9.9 Any remarks relevant to comparison between
the presence of the fuselage below the wing is believed to be of
experiment and theory

9.10 Additional remarks

9.11 References on discussion of data

Personal contact for further information
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38108 Braunschweig, Germany
phone: +49 - 531 - 295 - 2454
thomas.loeser@dlr.de

List of references
1 R.H.C.M. Hirdes: US/European Vortex Flow Experiment - Test Report of Wind-Tunnel Measurements on the 65\textdegree Wing in the NLR High Speed Wind Tunnel HST; NLR TR 85046 L
2 T. Loeser: Dynamic Force and Pressure Measurements on an Oscillating Delta Wing at Low Speeds; DLR IB 129-96/9
3 G. Kausche, H. Otto, D. Christ, R. Siebert: The Low-Speed Wind Tunnel at DFVLR in Braunschweig (Status 1988); DFVLR-Mitteilung 88-25, 1988
4 D. Hummel, T. Loeser: Low Speed Wind Tunnel Experiments on a Delta Wing Oscillating in Pitch; ICAS-98-3.9.3, Sept. 1998
5 G. Drouge: The international vortex flow experiment for computer code validation; ICAS-Proc. 1988, Vol. 1, pp. XXXV - XLI

FORMAT OF DATA SET
The static and dynamic pressure and force data are stored in ASCII files. They are located in a directory tree, which is described in the README-file placed in the root directory of this data set. For example, data of dynamic pressure measurements of the pitching motion at 9\textdegree mean angle of attack can be found in the subdirectory pressure/dynamic/pitch/alpha_09. The naming conventions for the files are also described in the README-file. Additional information with respect to the contents of the files is available at the top of the file, comment lines have a # in the first column. The first lines of a data file containing dynamic pressure data is listed below.

```
# Analysis of Variance on constant offset and first 3 Harmonics
# of Magnitudes and Phases of Pressure Coefficients -Cp
# Dimension of Phase Angle : Degrees
# Model : VOMO-model WEAG WB1, SLE, Cl = 1200 mm
# Program : ./2fd.pl -n -a 27 -f1 theta -f2 omega -d 0 -q 980 -no_wildplot -print -eps -30o
# Date of Analysis : Wed Feb 14 00:51:50 MET 1996

# alpha
# mode
# Reynolds Number
# 1. Factor : theta with levels 3.0 6.0
# 2. Factor : omega with levels 0.28 0.56
# Prob. for Confid. Interval: 0.95
# Risk for Significance : 1 %
# location of pressure taps: x/Ci = 0.3, upper side
# Each dim'less spanwise coordinate eta is followed by 7 lines, which contain the following data
# m0: Constant Offset of Signal
# m1: Magnitude of 1. Harmonic
# p1: Phase of 1. Harmonic
# m2: Magnitude of 2. Harmonic
# p2: Phase of 2. Harmonic
# m3: Magnitude of 3. Harmonic
# p3: Phase of 3. Harmonic

# meaning of the columns:
# 1.column: value for theta 3.0 and omega 0.28
# 2.column: value for theta 3.0 and omega 0.56
# 3.column: value for theta 6.0 and omega 0.28
# 4.column: value for theta 6.0 and omega 0.56
# 5.column: Confidence Interval for above mentioned probability
# 6.column: S, if influence of theta is significant. N if not
```
TABLES

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Table 1: Location of the pressure taps, upper side, Kulite locations printed bold

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Table 2: Location of the pressure taps, lower side
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Table 3: Force Measurements, Pitching Motion

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Table 5: Force Measurements, Yawing Motion

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Table 7: Force Measurements, Rolling Motion

All measurements listed in the tables 3 to 8 have been carried out at model oscillation frequencies of $f_0 = 1.5$ Hz and $f_0 = 3.0$ Hz. Measurements, which are included in this document, are printed in bold letters.
FIGURES

Figure 1: Location of the oscillation axes and the moment reference point

Figure 2: Geometry of the fuselage nose
Figure 3: Sketch of the wind tunnel model
Figure 4: Cross sections of the wind tunnel model at the positions of the pressure taps

Figure 5: Schematic view of arbitrary signal with harmonics having phase angles $\varphi_1 = 0$
Figure 6: Schematic view of data acquisition
Figure 7: Typical result of an analysis of variance for the unsteady pressure distribution $C_p(\eta)$ in the section $x/c_1 = 0.6$. Pitching motion with $\alpha_0 = 9^\circ$ and factors $\Delta \alpha$ and $\omega^*$ at $Re = 3.1 \times 10^6$, error bars indicate confidence intervals of 95%. Top to bottom: unsteady mean value, amplitude $m_1$ and phase $\phi_1$ of the first harmonic, amplitude $m_2$ and phase $\phi_2$ of the second harmonic, amplitude $m_3$ and phase $\phi_3$ of the third harmonic.
Figure 8: Definition of the airfoil