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Experimental benchmark of a free plunging wing with imposed flap oscillations

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ABSTRACT

The validation of fluid–structure interaction solvers is difficult since there is a lack of experimental data. Therefore, in this work an aeroelastic experiment is presented. The focus is on the temporal coupling between fluid and structure dynamics. Issues in the spatial coupling are eliminated by using a rigid wing. The wing, with a harmonically actuated 0.2*c* trailing edge flap, has a degree of freedom in the plunge (vertical) direction. The wing has a chord of 0.5 m and is suspended with springs. The wing motion is constrained by a vertical rail system.

For simplicity attached flow is desired and therefore the set angle of attack is $\alpha=0^\circ$. The Reynolds number is approximately Re = 700 000 and the flap deflects over a range of about $\pm 2^\circ$. The damped natural frequency of the structure expressed as a reduced frequency is about $k=0.194$ and measurements are performed for reduced flap frequencies ranging from $k=0.1$ to $k=0.3$. Displacements and time dependent aerodynamic forces are measured and for $k=0.198$ 2-D PIV measurements are performed. The planar PIV measurements are used to intrinsically determine the unsteady loads using Noca's method.

As expected the aeroelastic problem shows similarities with a viscously damped mass–damper–spring, meaning the maximum excursion of the wing is found near the system eigenfrequency. The lift is dominated by the flap motion and the effective angle of attack due to the motion introduces phase shifts of the lift signal with respect to the flap phase angle.

The experiment has been set up and executed with the necessary precision, but small ambiguities are found in the lift and drag disqualifying the data for validation. Nevertheless the data set provides a clear insight into typical loads and motions and can be used for comparative studies. It can also be used to (re)design future experiments to improve the quality of the data to the desired level of accuracy for validation.

1. Introduction

In many applications the interaction between fluid and structures is important to consider. Examples are deformations of aircraft, buildings, bridges and wind turbines due to air loads. Fluid–structure interactions (FSI) can be investigated by performing field measurements, a numerical assessment or experiments.

Abbreviation: DAQ, data acquisition; DOF, degrees of freedom; FOV, field of view; FSI, fluid structure interaction; OJF, open jet facility; PIV, particle image velocimetry; RMS, root-mean-square; URANS, unsteady Reynolds averaged Navier–Stokes

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Nomenclature

Symbols

α	angle of attack (deg), (rad)
Δ	change of quantity
δ	flap deflection, positive downward (deg), (rad)
$\dot{\delta}$	flap angular velocity, positive downward (rad/s)
$\ddot{\delta}$	flap angular acceleration, positive downward (rad/s^2)
θ	phase (deg), (rad)
ρ	density (kg/m^3)
ϕ	flap phase angle (deg), (rad)
ω	vorticity (1/s)
ω	radial frequency (rad/s)
c	chord (m)
c	damping coefficient (kg/s)
c_{D}	3-D drag coefficient
c_{d}	2-D drag coefficient
c_{L}	3-D lift coefficient
c_{l}	2-D lift coefficient
c_{M}	3-D moment coefficient ($1/4c$)
c_{m}	2-D moment coefficient ($1/4c$)
D	drag (N)
F	force (N)
f	frequency (Hz)
$F0$	forcing amplitude (N)
k	reduced frequency
k	spring stiffness (N/m)
L	lift (N)
m	mass (kg)
p	pressure (Pa)
T	temperature (K), (°C)
t	time (s)
U	flow velocity (m/s)
u	undisturbed flow velocity (m/s)
x	horizontal displacement (m)
$\dot{x}$	horizontal velocity (m/s)
$\ddot{x}$	horizontal acceleration (m/s^2)
Y	displacement amplitude (m)
y	vertical displacement (m)
$\dot{y}$	vertical velocity (m/s)
$\ddot{y}$	vertical acceleration (m/s^2)

Subscripts

amp	amplitude
cg	center of gravity
d	damping
eq	equivalent
f	flap
l	left side
l	low
LC	load cells
mean	mean value
ms	mini step
n	natural
n	normal
p	plates
r	right side
s	springs
SG	strain gauges
t	tangential
u	up
w	wing

Aeroelastic field measurements are performed for different applications. Burner et al. (2005) measured the inflight deflection and torsion of the wing of an aircraft together with the aerodynamic loads. With a relatively standard and low cost videogrammetry technique useful data could be obtained, although improvements are necessary for accurate measurements. Larose et al. (1998) performed aeroelastic measurements on a concrete bridge pylon and compared the findings with the results of scaled experiments. Except for mismatches in the Reynolds number and uncertainties in the measurement conditions of the field test, a satisfying match between the experiment and the full-scale measurement was found. However, this latter example reveals one of the disadvantages of field measurements: measurement conditions are difficult to measure accurately and are not fully controllable.

A numerical approach for solving FSI problems is commonly used, see, e.g. Garcia (2005), Gardner et al. (2008) or Riziotis et al. (2004). Numerical assessments are relatively cheap, but the problem with FSI solvers is that the validation with measurement data is relatively unexplored. In general the validation of FSI solvers focuses on the coupling of the fluid and the structure code and the temporal and spatial discretizations. Comparison of numerical results with experimental data is difficult due to a lack of good experimental data for most combinations of Reynolds and Mach numbers and types of structures. Examples of the latter are heavy wind turbine blades or lightweight insect wings. Validation is crucial in the development of solvers, since it enables one to make sure that the equations that are solved represent the real situation and are solved correctly. As long as a validation has not been performed, there is always an uncertainty about the correctness of the solution.

Experiments are also widely performed to assess FSI problems. Although costs and efforts of experimental work are most likely more than that for numerical work, experiments are performed to check numerical results or directly assess FSI cases. Experiments are case specific in the sense that, e.g. a limited Reynolds range is covered in combination with a certain type of structure. Examples of such experiments are the work of Stijnen et al. (2004) on the dynamic response of heart valves (low Reynolds numbers) and the work of Gerontakos and Lee (2008) who assessed the unsteady aerodynamics around a prescribed oscillatory airfoil with trailing edge flap. Rivera et al. (1991) performed aeroelastic flutter experiments with the aim to obtain experimental data for validation purposes. Hereto, for a large range of Mach numbers from low subsonic to

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