

Force Measurements of the Aerodynamic Characteristics of Micro Aerial Vehicles in Motion

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Abstract

An experimental test environment to investigate the unsteady aerodynamic properties (i.e. forces, moments and flow field) of micro air vehicles (MAV) is introduced. This test rig is designed for wind tunnel testing of 1:1 scale MAVs. The development of such small vehicles needs investigations of their behaviour under realistic but also clearly defined, repeatable flow conditions simulating dynamic flight. The new setup is capable to measure the unsteady aerodynamic forces whilst performing freely defined motions with 3 degrees of freedom in the upright $Y=0$ plane. These include typical flapping wing motions like plunging, pitching and their combinations as well as transients to simulate sudden gusts. Dynamic force measurements for plunge and pitch motion of a moving MAV wing model were performed and a solid method to separate aerodynamic and inertial force is introduced.

Nomenclature

AR	aspect ratio= s^2/A	$\bar{x}$	mean value
A	wing area	$\hat{x}$	amplitude value
C_D	drag coefficient	$\dot{x}_{(t)}$	time variant speed
C_L	lift coefficient		
C_M	pitch coefficient		
c	chord length		
f	frequency		
h	plunge amplitude		
k	reduced frequency = $\frac{\pi f c}{U_\infty}$		
l_μ	reference length		
M_y	pitch moment		
q_∞	stagnation pressure		
U_∞	free stream velocity		
s	wing span		
z_1	amplitude of plunge motion		
α	angle of attack		
$\bar{\alpha}$	mean angle of attack		
α_1	pitch amplitude		
α_{eff}	amplitude effective angle of attack = $2k \frac{z_1}{l_\mu}$		
ρ	density		

Introduction

The aerodynamic of MAVs in the low speed regime differ considerably from the aerodynamics of larger vehicles, e.g. Unmanned Air Vehicle (UAV). To improve the understanding of the flow phenomena occurring in the low Reynolds number regime, it is useful to conduct experiments under realistic flight conditions and to provide experimental data for comparisons with CFD results. For recently developed MAVs, Reynolds numbers of $Re = 5 \cdot 10^4 - 2 \cdot 10^5$ characterise the typical regime [1]. Additionally, the wings of MAVs usually have low aspect ratios, so that the wing tip vortices influence the overall wing behaviour significantly which results in non-linear characteristics.

Typical MAV geometries are presented by Lian et al. [2]. They use a flexible wing and present a numerical method to optimize the performance of the wing. They determine the optimum from mean aerodynamic coefficients. Grasmeyer et al. [3] present a MAV with rigid wing. Flows in low Reynolds number regime are analysed applying numerical methods by Ekaterinaris et al. [4]. Their focus is on the simulation of the transitional flow features of the flow over a NACA 0012 airfoil. Ramamurti et al. [5] present a simulation of several realised MAV configurations. They report on the effect of geometry and angle of attack on the steady aerodynamic coefficients. Swanson and Issac [6] present numerical results on the aerodynamics of wings for MAVs for high angles of attack. Torres and Mueller [7] experimentally investigated different types of wing plan form with aspect ratios in a range of 0.5 – 2 and found larger nonlinearities in the measured lift data. The application of flapping wing principles used by birds could be a more efficient way to produce lift and thrust for MAVs.

Jones et al. [8] give an overview over flapping wing propulsion techniques and the kinematics.

Another aspect related to the design of MAVs is to introduce some kind of wing flexibility in order to improve the aerodynamic stability (gust response) by damping unsteady forces [9].

Sunada et al. [10] report on the unsteady forces on a 2d wing in pitch and plunge motion but give no unsteady aerodynamics coefficients for the investigated configuration. Particle Image Velocimetry (PIV) and dye visualisation have been used in [11] to investigate the effect of aspect ratio on the flow field of flat plate wings in pitch and plunge motion. Hart and Ukeiley [12] investigate the aerodynamics of flat plates in combined pitching plunging motion. They used PIV and force measurements to determine the effect of the phase lag between pitch and plunge motion.

The effect of Strouhal-Number and reduced frequency k on airfoils in pitching and plunging motion are discussed by Baik et al. [13]. They applied PIV to observe the formation of leading and trailing edge vortices. It is found k influences the formation phase of the leading edge vortex.

The validation of numerical results at such low Reynolds numbers and especially for the unsteady aerodynamics is very difficult due to the low resulting forces. Therefore a specially built test facility for this flow regime is applied in the present work. The experimental facility presented here is designed to allow for a broad range of static and dynamic flow investigations for 3D MAV shapes and to fulfill many needs for experimental data of both research and industrial MAV activities. Dynamic derivatives of pure pitch and plunge motions have been determined [14], [15]. First applications of optical measurement techniques to determine instantaneously model position, orientation and flow velocity is presented by Konrath et al. [16].

Another low speed test facility for low Reynolds numbers for the investigation of unsteady aerodynamic is presented by Albertani et al. [17].

In this paper results of dynamic force measurements of a combined pitch and plunge motion and a pure plunge motion are presented. Furthermore a method to separate inertial and aerodynamic forces is presented.

Experimental set up

The test section of the Low Noise Windtunnel (LNB) for testing of 1:1 scale MAV is used for the presented investigations. The test rig was tailored to conduct studies on MAV under realistic but also clearly defined, repeatable situations. Therefore the test rig is capable of measuring the aerodynamic forces and moments whilst performing a controlled motion with three degrees of freedom in the upright $y=0$ plane including flapping wing motions like plunging, pitching and their combinations and transients simulating sudden gusts or crosswinds.

1.1. Wind tunnel

The LNB is a continuous atmospheric Eiffel-type wind tunnel with a closed test section. The settling chamber with nozzle, the diffuser and the motor mounting are made of glass fibre reinforced epoxy and the test section is transparent for using optical measurement techniques (s. Fig. 1). A 3 kW motor drives the tunnel in suction mode,

which gives a maximum flow velocity of 19 m/s. The wind tunnel is installed in a 8.2 m long room, which allows circulation of the flow. The ceiling of the room is covered with open-cell acoustic foam to damp noise. To minimize vibrations, the wind tunnel is mounted on rubber absorbers that are fastened on a steel construction. Motor and fan are decoupled from the rest of the tunnel. The turbulence level within the test section is $Tu < 0.1\%$ at 10 m/s. The velocity varies less than 1% over the cross section.

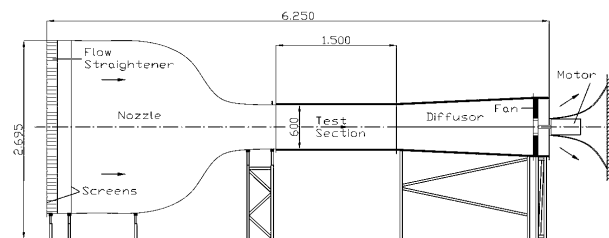


Fig. 1. Sketch of wind tunnel LNB

1.2. Model support

The model support is designed for the measurement of 3D aerodynamic models during high dynamic and high precision movements with 3 degrees of freedom in the upright plane.

The model support is driven by linear synchronous direct drives; each consuming a maximum of 1950 W transferred into a maximum force of 700 N or a speed of 5.3 m/s, during high dynamic and high precision movements. The design was made for a plunging motion up to ± 150 mm @ 3 Hz and a pitching motion with max. $\pm 20^\circ$ @ 3 Hz. The repetitive accuracy of both types of motion is ± 0.05 mm or $\pm 0.1^\circ$.

A sketch of the actuation principle is shown in Fig 2. The two actuators denoted with a are used to create pitch and plunge motion of the model. The established set up generally causes a small longitudinal motion in x -direction. To remove this problem an additional actuator named b will be added in a next step to optimise the test rig.

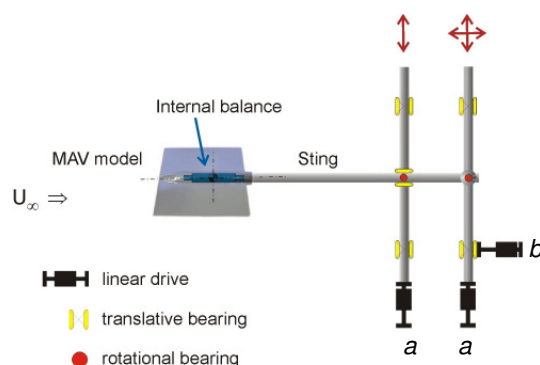


Fig 2. Sketch of actuation principle of model support

To prescribe the movement of the linear drives the planned model motion is created by using a CAD tool. With this tool the motion of the model is simulated and the coordinates of the resulting movement of the motors are

exported as an ASCII file. This file is converted by a specially designed program to the format of the programmable logic controller (PLC) of the linear motors. This method allows a precise and flexible setting of the model motion.

While moving, the sting has a natural bending mode of a typical frequency of around 37 Hertz. This frequency is found in the balance signal. Therefore this component of the balance signal has to be removed by data processing during the data evaluation.

To assure the wind tunnel model and hence the wind tunnel balance will not contact the walls of the test section different precautionary measures are implemented to prevent this kind of accident. In a first step the real time logic controller will stop all motors immediately in case of deviations from the programmed motion. Light barriers are installed to stop instantly the motion of the motors if the model moves below a certain defined distance to the wall.

1.3. Wind tunnel balance and measurement system

A very small, specially designed six component internal strain gauge balance is used to determine the aerodynamic forces. The dimensions of the balance are 107 mm in length and 11.2 mm in diameter with a weight of 35g. The specifications are given in Tab 1. Fig. 4 shows a picture of the balance.

The balance and a Hottinger Baldwin Messtechnik MGCplus strain amplifier were used to measure the dynamic forces and moments on the MAV wings. The overall accuracy of the balance is better than 0.025% FS.

$F_x : \pm 7 \text{ N}$	$M_x : \pm 0.750 \text{ Nm}$
$F_y : \pm 20 \text{ N}$	$M_y : \pm 0.750 \text{ Nm}$
$F_z : \pm 20 \text{ N}$	$M_z : \pm 0.374 \text{ Nm}$

Tab 1: Wind tunnel balance measurement range

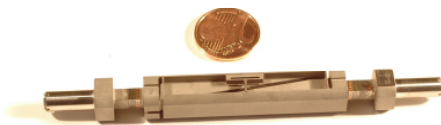


Fig. 4. Wind tunnel balance

1.4. Wind tunnel model

A flat plate wing with aspect ratio $AR=2$ (s. Fig. 5) is used here to investigate different types of motions. It has a chord length $c=117 \text{ mm}$ and span $s=234 \text{ mm}$ and its thickness is 2.7 mm while all edges are rounded with $r=1.35 \text{ mm}$. Except for the aluminum balance clutch, the model is made of stiff carbon fiber reinforced plastic. The fuselage to hold the internal balance has a diameter of 18 mm . The moments are measured at 70% chord and

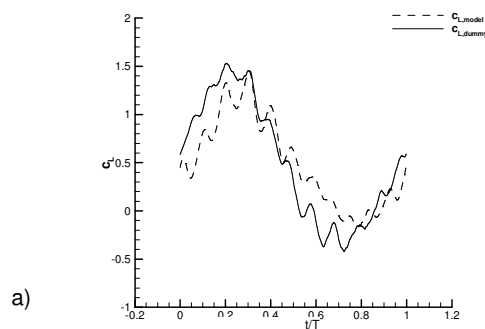
during the post processing referenced to the $1/4$ -chord point. With a reference area of 273.8 cm^2 the model weight is 65 g .



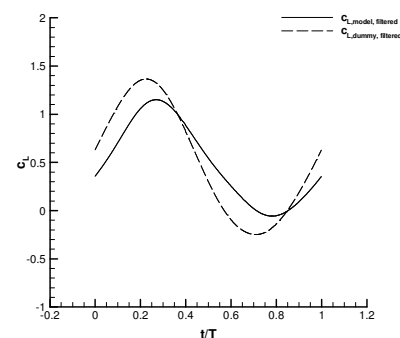
Fig. 5. Flat plate MAV wing with aspect ratio $AR=2$ and dummy model for flat plate MAV wing with aspect ratio $AR=2$

1.5 Data evaluation

The wind tunnel model is assumed to be ideally stiff, hence no elasticity effects are considered under this assumption.



a)



b)

Fig. 6. a) Example c_L as a function of time (averaged data)
b) Example c_L as a function of time (low pass Bessel filter)

To eliminate added mass and inertial forces measurements with wind-off conditions are performed with exactly the same conditions than in the wind-on

conditions. Two different models have been used for these measurements. The first is the flat plate model. Furthermore a dummy model with the same mass, centre of gravity and moment of inertia as the flat plate wing has been applied for the wind off measurements.

The wind-on and wind-off balance data are then subtracted, after averaging the raw data (s. Fig. 6a) over 80 periods. After the averaging over 80 cycles still high frequency perturbations caused by the harmonics of the natural vibration of the actuator mechanism can be seen on the signal. To remove this perturbation from the signal a low pass Bessel filter is applied (s. fig 6b). The amplitude of the signal is changed. This could be caused by the flow induced by the flat plate model. Furthermore a phase lag occurs between the different tare methods. The reason for this might be an additional bending of the model sting when using the flat plate model.

EXPERIMENTAL RESULTS

Dynamic measurements for pure plunge and combined pitch and plunge motion were performed to determine the dynamic aerodynamic coefficients of the flat plate wing. In this paper the results for two motion types and for flow with $Re=36000$ are presented.

2.1 Dynamic measurements

A harmonic motion in the dimension x , either of translative or rotative kind can be formulated as follows.

$$x(t) = \bar{x} + \hat{x} \cos\left(2\pi \frac{t}{T}\right) \text{ with } f = \frac{1}{T}$$

The reduced frequency k relates this motion to the free stream fluid velocity and the object size.

$$k = \frac{\pi \cdot f \cdot c}{U_{\infty}}$$

From the range of dynamic measurements performed so far, the results of two specific motions are investigated together with the dummy body to examine the new method to separate aerodynamic and inertial forces.

The first motion is a harmonic plunging motion with an amplitude of $h=60mm$ and with a mean angle of attack $\alpha_0=8^\circ$. The second motion is a combined pitch and plunge motion with a plunge amplitude $h=60mm$, a pitch amplitude of $\hat{\alpha}=8.815^\circ$ and a mean angle of attack

$\bar{\alpha}=8^\circ$. The characteristic value of the motions is summarized in tab. 2. All motions share the same mean angle of attack and are carried out at the same frequency $f=3.14Hz$ at a wind tunnel velocity of $4.52m/s$ ($Re=36000$).

2.1.1 Results of pure plunge motion

The plunging motion about the mean value α_0 with amplitude of h generates a hysteresis loop in the aerodynamic response. Figures 7-9 show the aerodynamic coefficients c_L , c_D and c_M , respectively. It can be seen the using the wind off balance data of the dummy body gives results which differ considerably from the data which using the flat plate wing. The slope for the increase of lift based on static measurements is also shown in Fig. 7. Furthermore, the static slope indicates the new tare method provides more plausible data than using the wind tunnel model to separate aerodynamic forces from the inertial forces, because the slope of the new method is similar to the static slope.

The result in Fig. 8 show thrust can be generated with this plunging motion. Furthermore it can be seen the magnitude of the thrust is decreased by using the dummy model for the tare procedure.

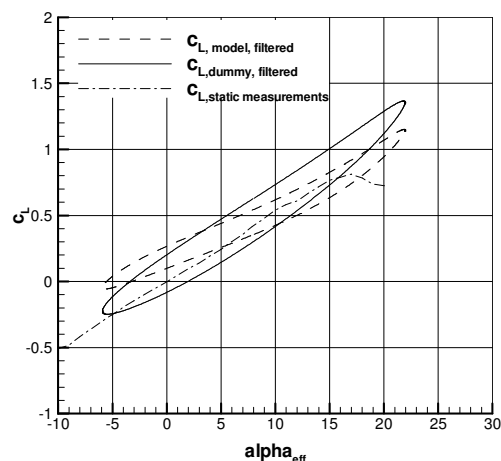


Fig. 7. c_L versus α_{eff} (5 Hz low pass filter) motion A

motion	motion type	plunging amplitude h [mm]	pitching amplitude $\hat{\alpha}$ [°]	mean angle of attack $\bar{\alpha}$ [°]	amplitude of effective angle of attack $\hat{\alpha}_{eff}$ [°]
A	plunging	60	0	8	14.691
B	pitching and plunging	60	8.815	8	8.256

Tab. 2 Characteristic parameters of the presented motion types

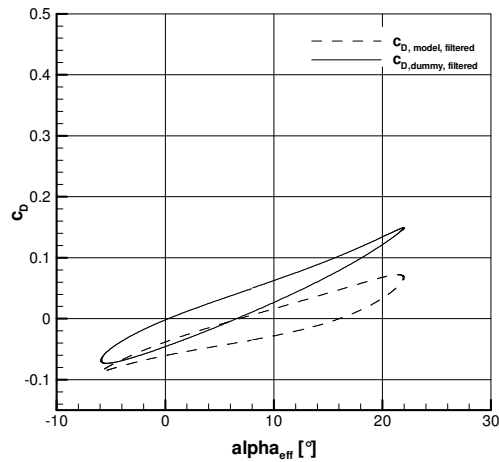


Fig. 8. c_D versus α_{eff} (5 Hz low pass filter) motion A

The effect of the tare method on the dynamic derivatives with respect to $\dot{\alpha}$, which is represented by the width of hysteresis loop, can be seen in fig 7-9, respectively. It is found that these derivatives vary by about 30-50%.

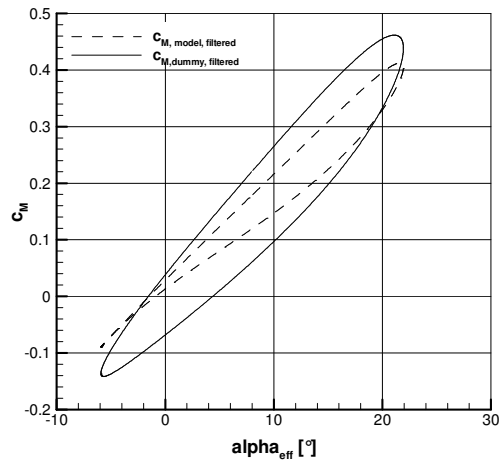


Fig. 9. c_M versus α_{eff} (5 Hz low pass filter) motion A

2.1.2 Results of combined pitch and plunge motion

The combined pitch and plunge motion about the mean value α_0 with plunge amplitude of h and pitch amplitude of α_1 generates a hysteresis loop in the aerodynamic response. This is shown in Fig. 10 for c_L .

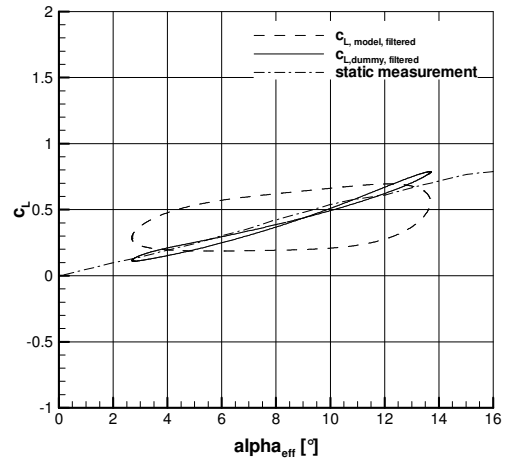


Fig. 10. c_L versus α_{eff} (5 Hz low pass filter) motion B

The behaviour of c_D is shown in Fig. 11. It can be seen the data obtained by the tare measurements using the MAV model suggest little thrust is generated with the combined pitch and plunging motion. The tare data obtained by the dummy model shows that no thrust is generated. These results demonstrate that the tare measurements using the MAV wing model lead to a relevant difference in the aerodynamic coefficients

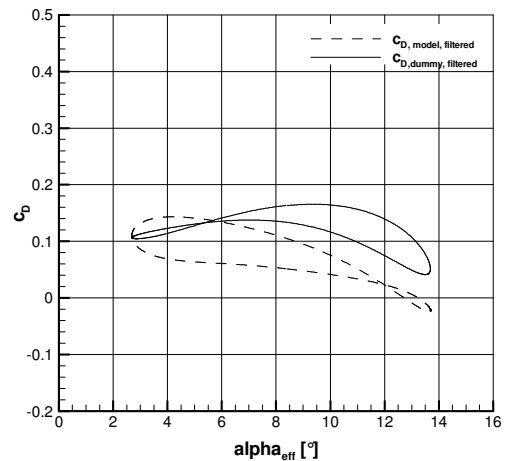


Fig. 11. c_D versus α_{eff} (5 Hz low pass filter) motion B

Fig. 12 shows the pitching moment as a function of α_{eff} . The slope of the hysteresis loop of the pitching moment versus α_{eff} is affected by the different tare measurements. Using the dummy method increases the slope whereas the width of the hysteresis curve of the pitch moment only little affected. The increase of the slope could be caused by increased damping of the system when using the flat plate model for wind off measurements.

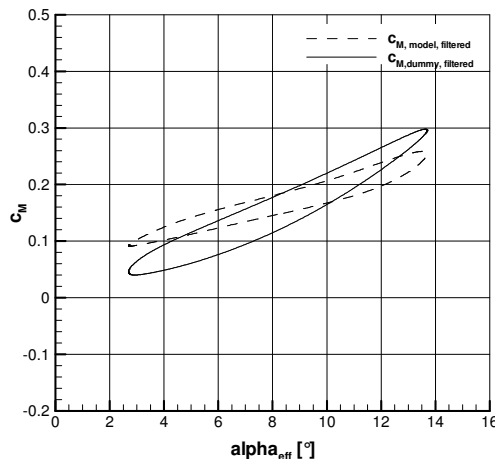


Fig. 12. C_M versus α_{eff} (5 Hz low pass filter) motion B

CONCLUSION

A test facility to investigate low Reynolds number unsteady aerodynamics, relevant for Micro Air Vehicles is presented. The test rig allows to determine dynamic distributions of aerodynamic coefficients.

The dynamic aerodynamic forces and moments of a flat plate wing for two different motions are presented. Two different methods to separate aerodynamic and inertial forces are investigated.

The influence of the different tare measurement is seen in the discrepancy between the hysteresis loops. These differences will lead to different aerodynamic derivatives. The comparison with static data demonstrates the tare measurement using the dummy body for wind off measurements is much more reliable than using the flat plate model. Furthermore a phase lag between the time signals of both methods is found. This could be caused by a stronger bending of the model support when using the flat plate model or by the flow induced by the flat plate model.

Outlook

In a next step also Particle Image Velocimetry measurements will be performed to investigate the flow field around different types of MAV wings to understand the structure of the unsteady wake of MAV wings with small aspect ratio as well as the behaviour of the wing tip vortices.

Acknowledgement

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