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Dynamic Testing of Aircraft Models in a Water Tunnel

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Abstract

An existing water tunnel, used for testing stationary aircraft models, is being upgraded so that it will be possible to carry out tests with the model in motion. Precise yaw, pitch and roll motions of a model can now be obtained independently. A special roll mechanism has been designed so that dye can be discharged from ports on an aircraft and water can be sucked through the intake(s) on the aircraft, while it undergoes continuous roll, i.e. there is no twisting of dye or suction tubes. A sensitive five-component strain-gauge balance is currently being manufactured. It will be possible to measure forces and moments and capture corresponding images of the flow while the model undergoes a specified dynamic manoeuvre. The dynamic rig will be used to study unsteady aerodynamic effects associated with aircraft motion and to obtain data for use in aircraft flight-dynamic models. Some preliminary flow-visualization images are presented.

Introduction

Forces and moments on an aircraft model in a tunnel are generally measured with the model stationary and set at a known orientation, and similarly for the visualization of flow patterns over the model. This static testing is the most common form of testing carried out in tunnels and there is an abundance of useful static measurements reported in the literature.

On the other hand, dynamic testing of an aircraft simply means that measurements are taken while the aircraft is in motion. Reported dynamic measurements are somewhat limited compared with static measurements. There is a need to carry out dynamic testing on combat aircraft in tunnels to study unsteady aero-dynamic effects associated with aircraft motion, which may have a major impact on the manoeuvrability and controllability of aircraft, especially at high angles of attack. The ongoing interest in flying at high angles of attack to improve aircraft control necessitates developing testing techniques to investigate dynamic flow situations in this flow regime. In a single manoeuvre, an advanced fighter aircraft can experience attached flows, vortex and vortex bursting flows, and totally separated flows. In particular, these vortical and highly separated flows can be very sensitive to unsteady or time variant effects –see Suárez *et al.* [5]. A clear understanding of the behaviour of the flow is an essential requirement for solving flight mechanics problems in the advanced manoeuvring regime. Dynamic force/moment data are also needed to determine approximate stability control derivatives, used in aircraft equations of motion in flight-dynamic models of aircraft. Dynamic data taken in tunnels can be used in the models to supplement data from flight trials on full-sized aircraft.

Most of the experimental dynamic studies reported in the literature have been limited to motion in one plane, either yaw, ψ, pitch, θ, or roll, ϕ. Huang & Hanff [3] indicate that since the behaviour of a vortex and its breakdown are non-linear, it is not valid to superimpose the effects due to the motion in different planes. There is a need for dynamic testing in which motions in all three planes can be obtained simultaneously.

In this paper, details are given of how an existing water tunnel at the Defence Science and Technology Organisation (DSTO), used for testing stationary models, is being upgraded to measure flow-induced loads on a model and simultaneously capture images of the flow over the model, while it undergoes a specified dynamic manoeuvre, with independent yaw, pitch and roll motions. The DSTO dynamic testing system has similarities to that developed by Suárez *et al.* [5] for their water tunnel, but contains significant new features compared with their system. For the DSTO system, water can be sucked through the intake(s) of an aircraft to simulate flow through the engine(s) while the aircraft undergoes continuous roll.

Some preliminary images of the flow over an aircraft, obtained in the DSTO tunnel, are also given in this paper.

Effects of Motion on Measured Data

The instantaneous flow pattern over an aircraft as it passes through a given orientation is different from that on the aircraft when it is stationary at that orientation, and likewise for the loading on the aircraft. This is due to the fact that the flow over the aircraft and the associated loading take some time to stabilize when the aircraft is moved to a new orientation, i.e. the flow lags the motion. According to Brandon & Shah [1], there can be a lag time of up to 30 convective time units (one convective time unit is the time required for a fluid particle to travel across the wing) before the flow re-establishes itself to the stationary condition.

Figure 1 shows a plot of normal force coefficient *vs* angle of attack, C_N *vs* α, for a 70° delta wing in a wind tunnel, as obtained by Brandon & Shah. Both static and dynamic data are shown. The dynamic data corresponds to the wing oscillating in pitch by ±18° about 4 different mean values of α. The measured dynamic C_N *vs* α data for increasing α is different from that for decreasing α, creating a hysteresis loop in the plotted data. The instantaneous loading on the model at say α = 40° varies over a wide range, depending on the motion of the model.

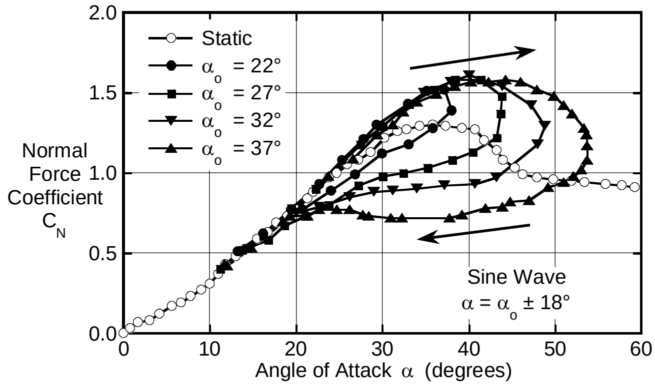


Figure 1. Dynamic wind-tunnel tests for a 70° delta wing, as obtained by Brandon & Shah [1].

For real combat aircraft, α is continuously changing during manoeuvres so that static data taken in tunnels has limited applicability to aircraft in flight. The work program at DSTO is concerned with many aspects of aircraft in flight and there was a need to develop a dynamic testing system to obtain dynamic data for use in investigations undertaken by researchers. The question that had to be answered was "do we develop our dynamic testing system for a wind tunnel or for a water tunnel".

Wind Tunnel vs Water Tunnel

A fundamental principle of dynamic testing is that the non-dimensional rotation rate, $Q = qC/2U_0$, of an aircraft model in a tunnel must be the same as that for a full-sized aircraft, where q is the rate of rotation of the aircraft, C is a characteristic length of the aircraft and U_0 is the free-stream velocity –see Brandon & Shah [1]. Table 1 summarizes parameters for a typical full-sized aircraft, a model in a wind tunnel and a model in a water tunnel. For typical values of pitch rate, characteristic length and free-stream velocity for a full-sized aircraft (see table 1), the value of Q is 0.0188. Applying this to tests carried out in a wind tunnel and a water tunnel, for a 1/9 scale model in a wind tunnel operating at 60 m/s, the pitch rate of the model is 330 deg/s, but for a 1/48 scale model in a water tunnel operating at 0.1 m/s, the pitch rate of the model is only 3 deg/s.

	Full-sized aircraft	Wind-tunnel model	Water-tunnel model
Non-dimensional pitch rate of aircraft Q	0.0188	0.0188	0.0188
Free-stream velocity U_0 (m/s)	65	60	0.1
Mean aerodynamic chord of aircraft C (m)	3.51	0.39	0.07
Pitch rate of aircraft q (rad/s) q (deg/s)	0.698 40	5.760 330	0.052 3

Table 1. Modelling parameters for a high-performance aircraft.

The required rotation rate in a wind tunnel to simulate a scaled dynamic manoeuvre is over 100 times that for a water tunnel. This suggests that problems may occur carrying out dynamic tests in wind tunnels, and that there would be significant advantages in undertaking such tests in water tunnels. The fast model rotation rates required for wind tunnel tests are mechanically difficult to implement ($q = 330$ deg/s) and the effects of model inertia on the measured forces and moments are significant, necessitating the need for inertial tare measurements when calibrating a strain-gauge balance –see Suárez & Malcolm [4]. The fast model rotation also places demanding requirements on the data acquisition system to acquire data at high sample rates. In contrast, the model rotation rates required in a water tunnel are low ($q = 3$ deg/s), so that the effects of model inertia on the measured loads are negligible, and there is no need for inertial tare measurements when calibrating a strain-gauge balance [4]. The response rates for the data acquisition system are also less demanding than for a wind tunnel and are more easily managed.

Although most of the limited number of reported investigations on dynamic testing have been carried out in wind tunnels, rather than water tunnels, there are clearly definite advantages in using a water tunnel.

Features of Dynamic Testing System

Water Tunnel

The Eidetics Model 1520 flow-visualization water tunnel, shown diagrammatically in figure 2, has a horizontal-flow test section 1520 mm long, 510 mm deep and 380 mm wide, and the free-stream velocity can be varied between 0 and 0.6 m/s. It is a closed-circuit tunnel, in which the same water is recirculated, and there is a free water surface in the test section. Further details of the tunnel are given by Erm [2].

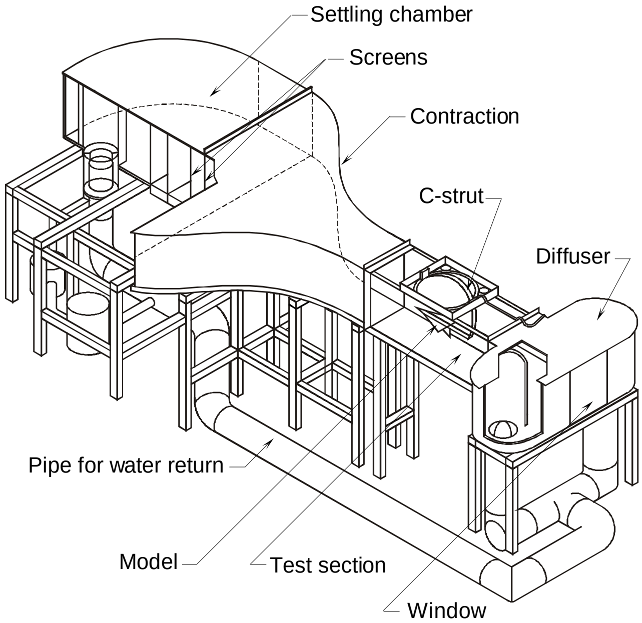


Figure 2. Diagrammatic representation of Eidetics Model 1520 flow-visualization water tunnel.

Control of Model Motion

Models are mounted on a sting attached to a C-strut and are positioned so that all model angular motion is about the centre of rotation of the model. In the original tunnel, it was only possible to alter the yaw and pitch angles of a model and this was done manually using motors controlled by a joystick, so that model motion could not be accurately controlled. A roll mechanism (see below) has now been fitted and three PC-controlled stepper motors have been installed so that precise specified yaw, pitch and roll motions can now be obtained independently. The setup of the upgraded model motion system is shown diagrammatically in figure 3. Yaw, pitch and roll angles can be varied between -20° and +20°, 0° and 45°, and 0° and 360° respectively. The input commands to the stepper motors consist of the required yaw, pitch and roll angles at chosen instants of time, say each 1/15th of a second, as shown in figure 4 for a test dynamic manoeuvre. Input commands can correspond to linear ramped or sinusoidal functions. It is possible to oscillate the model in yaw, pitch and roll, with maximum rotational speeds of 8, 6 and 12 °/s respectively throughout the cycle. With the current system, it is not possible to impart plunging or coning motion to the model.

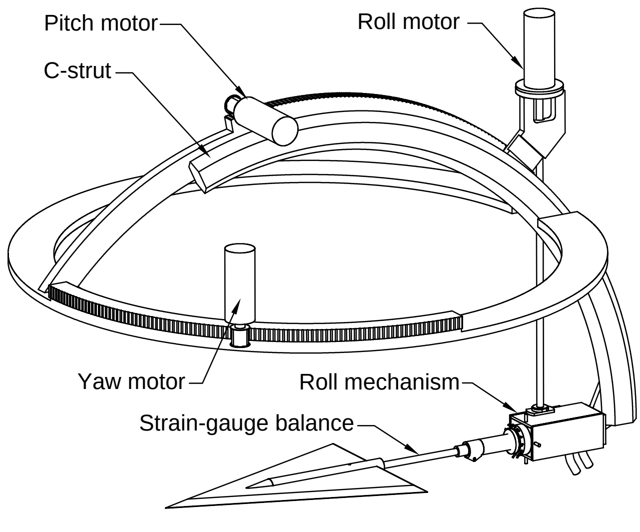


Figure 3. Diagrammatic representation of upgraded model motion system.

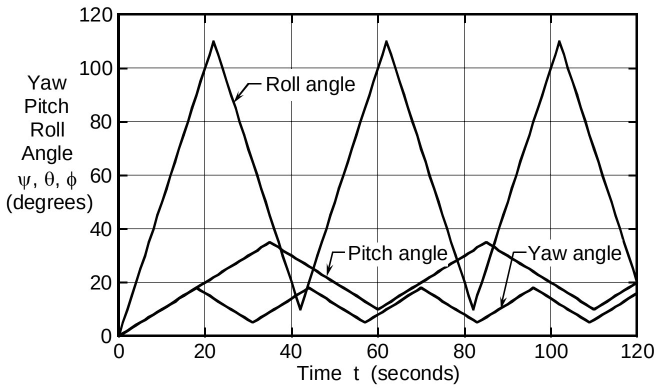


Figure 4. Required yaw, pitch and roll angles for a test manoeuvre.

Roll Mechanism

A special roll mechanism has been designed so that dye can be discharged from circular ports on an aircraft and water can be sucked through the intake(s) on the aircraft, to simulate flow through the engine(s), while the aircraft undergoes continuous roll, i.e. there is no twisting of dye or suction tubes. The roll mechanism is shown in figure 5. The chassis of the mechanism is attached to the C-strut and does not rotate. An input shaft from a stepper motor rotates the central shaft, the strain-gauge balance (see below) and the model via a worm wheel and pinion. A dye reservoir is located between adjoining fixed and rotating parts, with the interface sealed with O rings, enabling dye to be transmitted to dye tubes, which rotate with the model. The central shaft on the mechanism is hollow and is connected to the exhaust(s) on an aircraft using a suction adaptor, which can also rotate. The adaptor shown is for an aircraft with twin exhausts, but adaptors can be made to suit the aircraft under test. The adaptor fits inside the exhaust(s) of an aircraft, but does not actually touch with the aircraft, since this would bridge the strain-gauge balance and invalidate measured loads on the aircraft. The central shaft has been partitioned into two halves, enabling suction through each of the two water circuits to be controlled independently by suction pumps, if required. The features of the system that enable a model to undergo continuous roll without twisting of dye or suction tubes are believed to be unique.

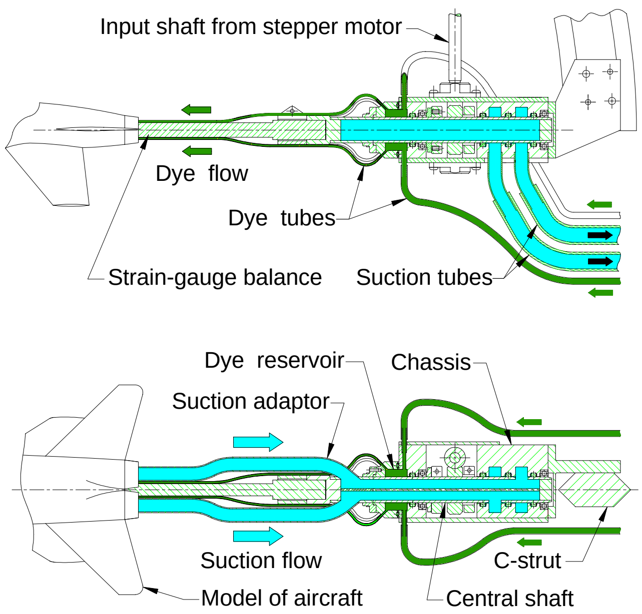


Figure 5. Cross-sectional side- and plan-views of the roll mechanism.

Strain-Gauge Balance

A sensitive five-component strain-gauge balance is currently being manufactured and will measure downwards and sidewards forces, and yawing, pitching and rolling moments. The balance, shown in figure 6, will be an integral unit. Semi-conductor strain gauges are to be used, having a resistance of 1000 Ω, a gauge factor of 145, and dimensions of 2.03 mm by 0.15 mm (length by width). The positioning of the gauges on the balance for each of the five components will be as shown (note that some gauges are obscured). Gauges of this type have been successfully trialed at DSTO on a simplified two-component balance. The gauges will be waterproofed using microcrystalline wax covered with silicon rubber. The balance will be mounted in a sleeve, using the tapered attachment, and the sleeve will be inserted into a model, such as the delta wing shown. The flow-induced loads on a representative 1/48 scale model of a combat aircraft are very small by conventional standards and the balance has been designed to measure downwards and sidewards forces of 1.0 N, yawing and pitching moments of 0.017 Nm and a rolling moment of 0.007 Nm (greater loads can be measured by the balance, due to inbuilt safety factors).

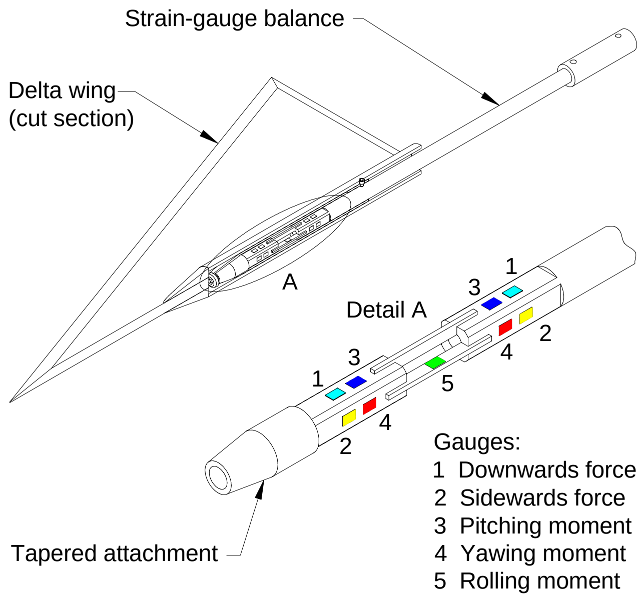


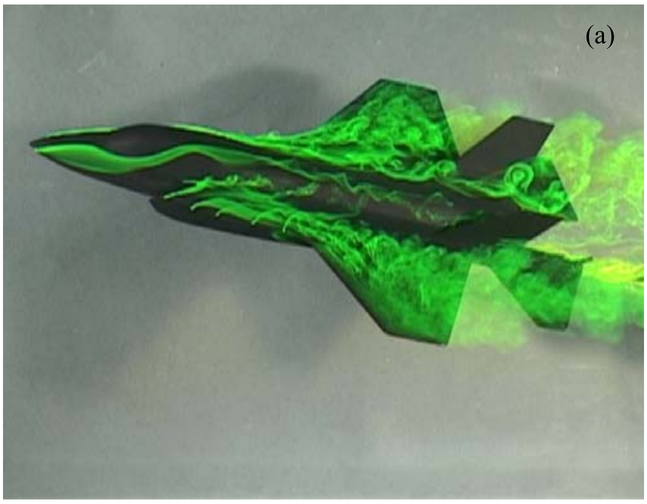
Figure 6. Five-component strain-gauge balance

Output Data From System

For each chosen instant of time during a dynamic manouevre, an output file is created which contains yaw, pitch and roll angles, together with corresponding downwards and sideways forces, and yawing, pitching and rolling moments. For each of the instants of time, side- and plan-view images of the flow are also captured with digital cameras using synchronization software. Thus it is possible to correlate precisely the instantaneous flow patterns over a model and the flow-induced loads on the model.

Preliminary Experimental Results

The dynamic testing system has been completed to the stage where it is possible to capture images of the flow over an aircraft, with or without suction through the intake(s), while the aircraft undergoes preset motions in yaw, pitch and roll. It is not yet possible to measure forces and moments with the five-component strain-gauge balance. Samples of typical instantaneous flow patterns over a 1/48 scale modern high-performance aircraft during a test dynamic manoeuvre are given in figure 7. The flow was visualized using sodium fluorescein dye and there was no suction through the intakes of the aircraft.



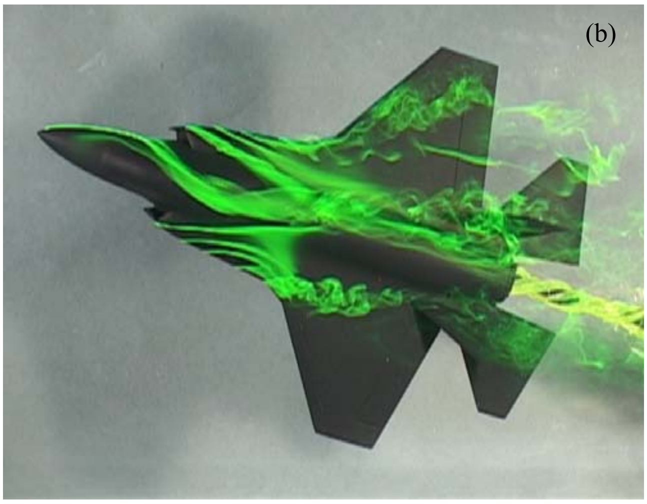


Figure 7. Instantaneous images for the test manoeuvre shown in figure 4.
(a) $t = 7.6$ s; $\psi = 7.6°$, 1°/s; $\theta = 7.6°$, 1°/s; $\phi = 38.2°$, 5°/s.
(b) $t = 64.3$ s; $\psi = 12.3°$, 1°/s; $\theta = 14.3°$, 1°/s; $\phi = 98.6°$, −5°/s.

As can be seen, the flow over the aircraft is complex and is dominated by vortices formed by the rolling up of the flow as it separates along the leading edges of the aircraft. The vortical flow field and associated loading on the aircraft change continuously throughout a dynamic manoeuvre. Due to the low pressure in the cores of vortices, high-performance aircraft generate high lift at high angles of attack and this improves aircraft manoeuvrability and controllability when operating at extreme attitudes. However, in this flight regime, the cores of vortices can become unstable and break down or "burst". The breakdown is characterised by a sudden expansion in the size of the vortex core, a rapid deceleration of the axial velocity in the core, a steep increase in the pressure and an increase in the turbulence downstream of the breakdown region. The increase in the core pressure after the breakdown reduces the lift contributed by these vortices, which can cause the wing to stall, and the increased turbulence can result in significant wing buffeting. The location of vortex breakdown is known to fluctuate in the stream-wise direction and the breakdown can be asymmetric. This behaviour results in significant loss of stability in roll and yaw.

Many uncertainties exist when studying vortical flow behaviour over manoeuvring aircraft. Questions remain about how aircraft instability in the extreme manoeuvring regime is influenced by the prevailing flow patterns over the aircraft. Instabilities need to be explained in terms of the physics of the flow processes involved. Hopefully, using the dynamic rig, the ability to correlate precisely the instantaneous flow patterns over an aircraft with the flow-induced loads experienced by the aircraft will help us resolve some of these issues.

Concluding Remarks

This paper describes how an existing water tunnel, used for testing a stationary model, is being upgraded so that it will now be possible to carry out tests with the model in motion. There is a need to carry out dynamic testing on aircraft in tunnels to study unsteady aerodynamic effects associated with aircraft motion, which will lead to a better understanding of the behaviour of aircraft, especially in the advanced manoeuvring regime. Dynamic force/moment data are also needed for use in the data bases of flight-dynamic models of aircraft to predict their performance.

Precise yaw, pitch and roll motions of a model can now be obtained independently. A special roll mechanism has been designed so that dye can be discharged from circular ports on an aircraft and water can be sucked through the intake(s), while the aircraft undergoes continuous roll, i.e. there is no twisting of dye or suction tubes. A sensitive five-component strain-gauge balance that uses semi-conductor strain gauges is currently being manufactured. Some flow-visualization images corresponding to a test dynamic manoeuvre are given, but no force/moment measurements are yet available.

Using the dynamic rig, it will be possible to directly correlate measured forces and moments with observed flow patterns when a model is undergoing a specified dynamic manoeuvre, and this may be beneficial when trying to understand and solve flight-mechanics problems of manoeuvring aircraft.

Acknowledgments

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