DEVELOPMENT OF A DYNAMIC WIND TUNNEL RIG FOR AIRCRAFT PURE PITCHING MOTION

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ABSTRACT

This paper presents the design, fabrication and testing of a dynamic wind tunnel test rig that is used in conjunction with aircraft dynamics theory in estimating aerodynamics stability derivatives. The value of Cm_α *and* $Cm_q + Cm_{\dot{\alpha}}$ *can be obtained from free oscillation theory of pure pitching motion. The rig comprises a scale down 1:30 full model of two-seater light aircraft, accelerometer, charge amplifier, A/D converter and IBM-PC. The result of the study has shown that the test rig is capable of predicting the derivatives. The effect of Reynold's number to the dynamics testing can be considered small as in dynamic testing, where the rate of change was measured rather than the absolute value. Finally, the rig can be used as part of the experimental testing in flight dynamics for aircraft design.*

1.0 INTRODUCTION

In an aircraft design process, it is essential to have the ability to predict the aerodynamic stability and control derivatives through wind tunnel testing. The main objective of the present study was to design a digital computer interface system, to develop a small-scale model, a model support system and procedures to perform the test for estimating the pure pitching stability derivatives.

Free oscillation technique was used to determine the aerodynamic stability derivatives. From the model oscillation due to disturbance, the oscillation period and time to half amplitude were recorded and used in the determination of derivative calculation.

The model was tested for two conditions, wind-off condition and wind-on condition. The wind-off testing was mainly done to test the weight distribution and also the stiffness and damping generated from the model support system. The wind-on testing was performed to estimate the effect of aerodynamic force on the model. The model must be set in equilibrium position before any testing can be performed. For the lateral position, the wing must be level with zero sideslip angle. For the longitudinal trim, the model can be positioned by changing the angle of incidence of the stabilizer (horizontal tail) to let the model on a straight and level flight or in climb position. The free oscillation was implemented by giving an initial displacement (as disturbance), then releasing the model and letting the model return to its equilibrium conditions. The model and the full-scale aircraft must posses the same Reynolds number if possible in order to simulate the same flow pattern and thus the same aerodynamic characteristics. On the other hand, the Froude number should be the same for model and full-scale if elasticity is to be emphasised.

2.0 THEORY

The equation of motion for the airplane was derived by considering the aircraft flying on a straight path without sideslip and banking. It was based on the basic longitudinal for pure pitching motion assuming the angle of attack and the pitch angles were identical. The stability derivatives related to pure pitching motion were Mq (pitching moment with respect to the pitching velocity), $M\alpha$ (pitching moment due to variations in angle of attack) and $M\dot{\alpha}$ (pitching moment with respect to the rate of change of angle of attack).

The model aircraft was free to pitch up and down about its center of gravity during the test. Figure 1 shows the simple set of the system used.

The equation of motion can be developed from the rigid body equation [1]. The governing equation is from Newton's second law,

$$\sum \text{Pitching moments} = \sum M_{cg} = I_{yy}\ddot{\theta}$$

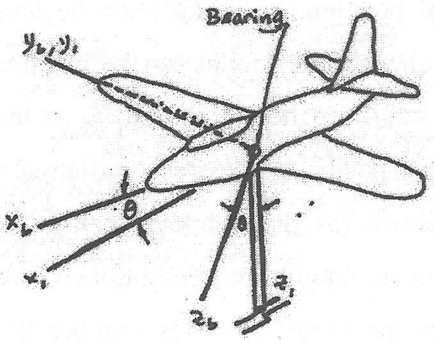

Figure 1 Simple model setup.

The characteristic equation for the system is given by

$$\left[s^2 + (Mq + M\dot{\alpha})s + M\alpha \right] \theta = 0 \qquad (1)$$

When compared with the standard second order system, the natural frequency ω_n and damping ratio, ζ can be represented by

$$\omega_n = \sqrt{M_\alpha} \quad \text{and} \quad \zeta = \frac{(Mq + M\dot{\alpha})}{2\sqrt{M_\alpha}} \tag{2}$$

The aerodynamic and dynamic normalized derivatives can be written as

$$Cm_\alpha = \frac{M_\alpha I_{yy}}{\frac{1}{2}\rho U^2 S\bar{c}} \quad \text{and} \quad \left[Cm_{\dot{\alpha}} + Cm_q\right] = \frac{\left(M_{\dot{\alpha}} + M_q\right)2 \cdot U \cdot I_{yy}}{\frac{1}{2}\rho U^2 S\bar{c}^2} \tag{3}$$

where U is the airspeed, S is wing area, $\bar{c}$ is the wing mean chord and I_{yy} is the moment of inertia of the model.

3.0 FREE OSCILLATION MODEL TESTING

The equation of motion for a single degree of freedom pitching motion with the model returning to its initial equilibrium position is given by

$$I_{yy}\ddot{\theta} + C_1\dot{\theta} + K_1\theta = 0 \tag{4}$$

If the model pitch angle was displaced from its equilibrium position and released in still air (wind off), the values of P and $T_{0.5}$ can be obtained directly from the displacement time history.

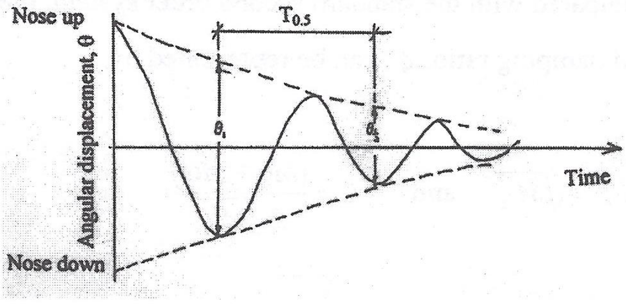

Figure 2 Typical oscillation graph

P = Period of one cycle of oscillation

$T_{0.5}$ = The time required for the amplitude of model oscillation to decay from a reference value to a value equal to half the reference value.

$$C_1 = \frac{1.3863 I_{yy}}{(T_{0.5})_f} \quad \text{and} \quad K_1 = I_{yy}\left[\frac{4\pi^2}{P_f^2} + \left(\frac{0.69315}{(T_{0.5})_f}\right)^2\right] \tag{5}$$

With the values of P and $T_{0.5}$, C_1 and K_1 can be obtained using equation (5) The subscript f shows condition with wind off. When the model was displaced with initial pitch angle from its equilibrium position in moving air (wind on), the equation of motion of the oscillation is given by

$$I_{yy}\ddot{\theta} + (C_1 + C_2)\dot{\theta} + (K_1 + K_2)\theta = 0 \tag{6}$$

where

C_2 / I_{yy} = aerodynamic damping per unit value of θ which is equivalent to $M_q + M_{\dot{\alpha}}$

K_2 / I_{yy} = aerodynamic stiffness per unit value of θ which is equivalent to M_α

From the time response plot, the equation for the aerodynamic damping and stiffness can be expressed respectively as given below

$$C_2 / I_{yy} = -(M_q + M_{\dot{\alpha}}) = 1.3863\left[\frac{1}{(T_{0.5})} - \frac{1}{(T_{0.5})_f}\right] \qquad (7)$$

$$K_2 / I_{yy} = -M_\alpha = \left\{4\pi^2\left(\frac{1}{P^2} - \frac{1}{P_f^2}\right) + (0.69315)^2\left[\frac{1}{(T_{0.5})^2} - \frac{1}{(T_{0.5})_f^2}\right]\right\} \qquad (8)$$

4.0 MODEL AND SUPPORT SYSTEM

The model was entirely made from wood. The load requirements of the model and the support system were based on maximum forces and moments acted on the model and model support system. The maximum allowable load used to design the support strut was 6.4 N and was calculated from the maximum drag of the model multiplied by a safety factor of 1.5 [6].

The 1:30 scale model Reynold's number was 0.0766 x 10^6 and was far smaller than 3.445 x 10^6 for the real full scale aircraft. Due to the limitation of wind tunnel maximum speed and pressure adjustment, it is almost impossible to achieve the actual Reynold's number. As a result, a transition strip made from sandpaper was attached at 25% Mean Aerodynamics Chord (MAC) to trip the flow and trigger the turbulent flow.

The model was mounted and pivoted about its center of gravity. The study assumes that the centre of gravity location coincides with the centre of rotation. Simple testing was conducted separately to determine the aircraft centre of gravity and moment of inertia about its axis of rotation. The moment of inertia I_{yy} of the 1:30 scale model of 3D aircraft was 4.55 x 10^{-4} kgm^2 and the centre of gravity was 25% MAC.

The support system was made from mild steel and shaped into airfoil section to reduce drag and support interference effect. Rubber was used to hold the model to the support to give a small damping and stiffness effect.

Calculations were done to estimate the load from various factors that might occur during the testing to ensure that the support was able to withstand the force due to the drag on the model during testing [4].

5.0 DIGITAL SYSTEM INTERFACES (DSI)

The schematic layout of the test rig is shown in Figure 3. During the test, the model was placed inside the wind tunnel with the accelerometer attached to the model as a transducer to sense the motion of the model. A charge amplifier was used to control the signal data of time response before it goes to the analog to digital interfacing card. A switch was used to trigger a pneumatic directional control valve, which created a wind gust through an air nozzle.

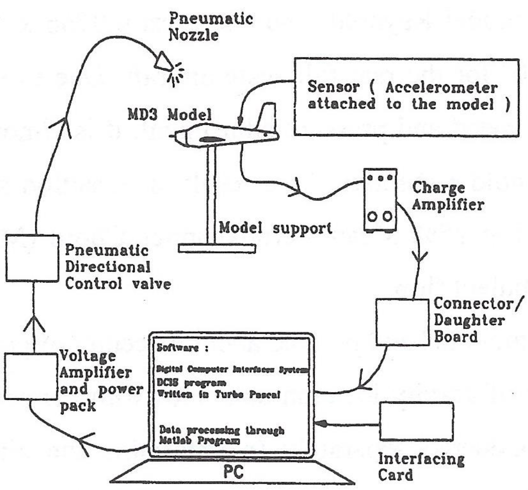

Figure 3 DSI layout

A computer program was written in Turbo Pascal Version 7 specifically to suit the study. The software was used to initialize the data acquisition system, record the data, switch the wind gust and display the time response on the monitor screen in real time mode. The test, evaluation, and validation of time response data from the data acquisition system were compared with the time response display from electrical oscilloscope and used as calibration method.

6.0 WIND TUNNEL TESTING AND RESULTS

The actual test rig was set up together with a digital data acquisition system shown in Figure 4. The 1:30 full model of a light aircraft was placed inside the wind tunnel as shown in Figure 5.

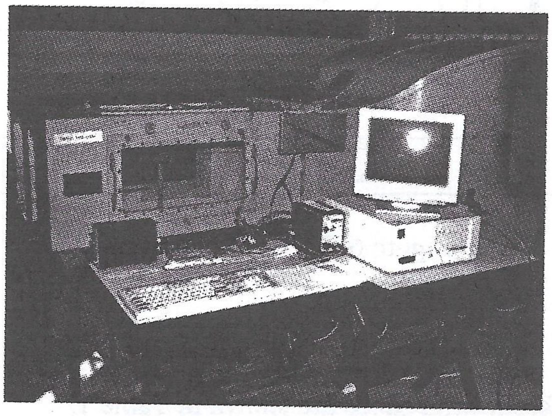

Figure 4 Test rig Layout

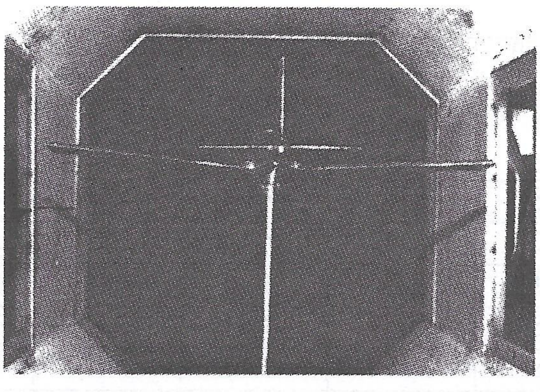

Figure 5 Model in Wind Tunnel

Wind-off Test

An example of data for wind-off condition is shown in Figure 6. The results obtained from the graphs show that the average value for period of oscillation is 0.376 second and the time to half amplitude is 0.560 second. The average values for ω_n and ζ are 11.29 rad/s and 0.11, respectively.

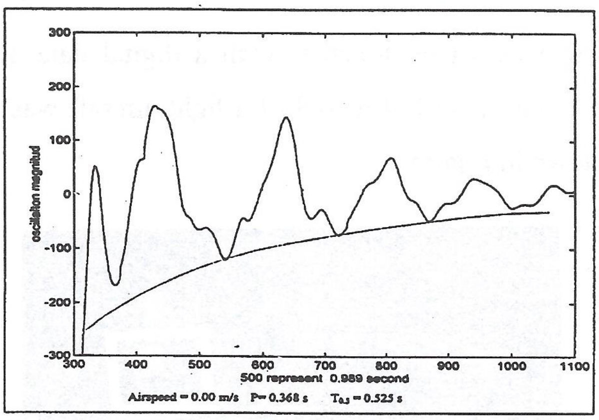

Figure 6 Wind-off condition

Wind-on Test

The results for different wind speed are shown in Table 1.

Table 1 Summary of Results

Airspeed (m/s)	Period (s)	Time to half amplitude (s)	$M_q + M_{\dot{\alpha}}$ (Nm)x10^{-3}	$C_{M_q} + C_{M_{\dot{\alpha}}}$ (rad^{-1})	M_α (Nm) x 10^{-1}	C_{M_α} (rad^{-1})
9.8	0.287	0.367	-0.592	-4.704	0.913	-1.860
13.6	0.228	0.342	-0.718	-3.808	2.19	-2.327
15.5	0.211	0.276	-1.16	-5.580	2.77	-2.258
17.9	0.189	0.159	-2.84	-12.172	3.77	-2.305
18.6	0.188	0.134	-3.58	-14.88	3.83	-2.176

The results show that the static stability derivative M_α was almost constant as the airspeed increased while the dynamic stability derivative $M_q + M_{\dot{\alpha}}$ increased as the air speed increased. The sample time response plot for airspeed of 9.8 m/s and 18.6 m/s are shown in Figures 7 and 8.

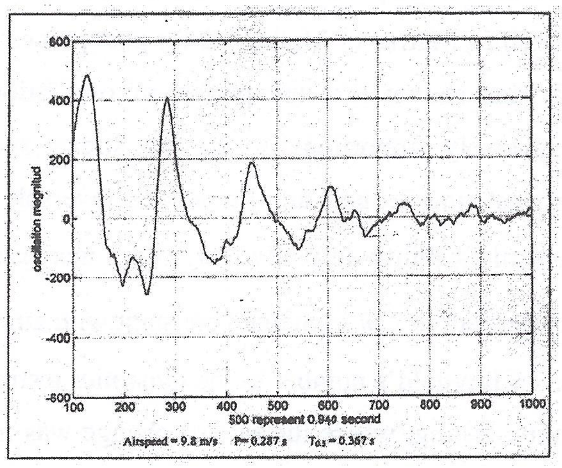

Figure 7 Wind-on 9.8 m/s

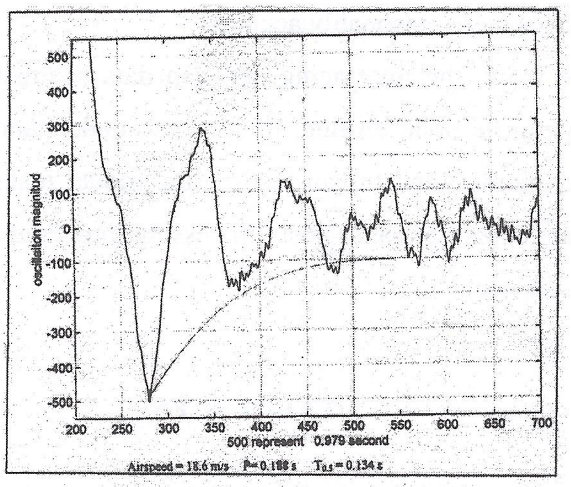

Figure 8 Wind-on 18.6 m/s

7.0 CONCLUSION

The design of wind tunnel test rig for pure pitching motion was implemented. The values of Cm_α and $Cm_q + Cm_{\dot{\alpha}}$ can be obtained from free oscillation theory of pure pitching motion. The settling time of the digital computer interface enables one to acquire the time history data. This can be stored as text file and can be accessed using EXCEL, Matlab or MathCAD for post processing.

The study has shown that the period of oscillation and time to half amplitude were inversely proportional to the free stream speed. It is found that the trend implies that time to half amplitude was inversely proportional to the airspeed. The dynamic stability derivative $Cm_q + Cm_{\dot{\alpha}}$ increased with airspeed and the static stability derivative Cm_α remained constant with airspeed.

The effect of Reynold's number to the dynamics testing can be considered small as in dynamic testing, where the rate of change was measured rather than absolute value. For aircraft short period pitching motion, the derivatives of interest were not influenced by the drag term. As the effect of Reynold's number significantly influenced the drag rather than lift, the final results for the pure pitching derivatives were reasonably accurate.

In future work, the interfacing between data acquisition system and the post processing can be done on-line. Finally, the understanding of fundamental aspects of the dynamic wind tunnel testing, the model making and installation, the digital data acquisition and post processing procedures was successfully gained from this project.

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