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IMPORTANCE OF TRANSIENT AERODYNAMIC DERIVATIVES FOR V-TAIL AIRCRAFT FLIGHT DYNAMIC DESIGN

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Abstract

A new design of aircraft configuration would initially suffer the lack of information about its aerodynamic derivatives. Henceforth, lots of analytical, computational and experimental efforts are needed to gather the information required. Due to that reason, a research is being conducted to study the effects of aerodynamic stability derivatives estimations via steady-state measurement (combination of semi-empirical and static wind tunnel test) and transient measurement (using dynamic wind tunnel test) in aircraft simulation for unconventional aircraft configuration as it affects the design of control system. Results show that the steady-state measurement is inaccurate to describe unconventional aircraft responses but is acceptable to estimate the aerodynamic stability derivatives within higher reduced frequency.

1 Introduction

As the air transport sector continues to grow, there are attempts to innovate the aircraft design configurations to looks attractive yet low in cost and have a limited risk of damage in the event of failure [1][2]. Therefore, it is crucial to have accurate aerodynamic stability derivatives as an input database for modelling and simulation. In fact, too many assumptions in estimation of aerodynamic stability derivatives may increase the imprecise design of control system of a newly designed aircraft [3]. Most of the aircraft modelling were rely on steady-state measurements either through semi-empirical method or traditional static wind tunnel tests for lower angles of yaw or pitch as to describe the aircraft responses [4][5][6][7]. However, those approaches are no longer acceptable to represent sophisticated unconventional aircraft configurations especially during transient conditions.

Due to that reason, a modelling technique of analysing the transient aerodynamic stability derivative have been studied by many researchers as early as 1903 [6][4]. However, until today there are no concrete conclusion in methodology have been made in determining the transient aerodynamic derivatives. To date, the models used are different and most of the models used are fighter aircrafts rather than transport aircraft types [4][5][10][11][12].

An accurate estimation of aerodynamic stability derivatives is significant in the process of designing the control system of an aircraft. Thus, lots of methods have been introduced by researchers either classical or modern approach. Normally, in the preliminary design phase, the dynamicist will use semi-empirical method as their approach due to easy access to the method.

However the degree of confidence is still questionable, then the static wind tunnel test was conducted. Even a higher order CFD is also being used, but the estimation is still based on steady-state measurement to represent the transient condition during flight. As the transient conditions affect the aircraft stability, they are more reliable to illustrate the real conditions. Thus the derivatives derived from transient measurement are more accurate to represent the transient aircraft flight conditions as the motions depended on the reduced frequency and amplitude of oscillations [10]. Nevertheless, the difficulty in estimating the transient data based on the ability to simulate them in the wind tunnel required a special design of dynamic test rig which having a low noise and providing an accurate data based on aerodynamic problem and must possess a lower mechanical effect [8].

The motivation of the past research works was primarily become an interest in the estimation of aerodynamic stability derivatives but now has reached a stage that the transient effects is believed may in some instances to be significant as the magnitude of the perturbation is increased when subject to unsteady aerodynamic loads. This is due to as an aircraft is in flight, it would encounter an aircraft loses its control due to weather or system failures or even flying at higher angle of attack, cause the aircraft flying in transient or unsteady flight regimes which is not well understood. At this point, the aerodynamic stability derivatives are no longer exhibit a constant value as describe by steady-state measurements.

This research work compares and evaluates the estimation of aerodynamic stability derivatives between steady-state measurement and transient measurement. The transient measurement via dynamic free oscillatory tests resulted in C_{n_β} and C_{n_r} through time to half amplitude and oscillating frequency respectively then by moving the location of pivot point, yield C_{y_β} and C_{y_r}. Meanwhile the steady-state measurement measured static derivatives of C_{y_β} and C_{n_β} thru static wind tunnel test by taking the gradient between yaw moment and side force versus yaw angle graph while dynamic derivatives of C_{y_r} and C_{n_r} are derived through formulation as in US-Datcom. Table 1 show the aerodynamic stability derivatives for both measurements.

Henceforth, the differences of the effects would be highlighted through aircraft Dutch roll simulations. This research focused on lateral-directional stability using UTM-UAV CAMAR aircraft model as in Reference [9] with V-tail dihedral angle of 35°.

2 Research Related with V-tail Aircraft Configuration

NACA has been pioneers in conducting a research on V-tail, but the data from NACA technical report generally refer to certain configurations which not representing the typical shape of transport aircraft [13]. At the same time, most of the derivatives were measured using static wind tunnel tests. Their interest at that time was to provide some basic understanding about their aircraft responses.

Nowadays, researchers found that V-tail aircrafts have their own advantages and thus lots of UAVs have implemented V-tail into their designs. These adoptions by UAVs had encouraged more researches to study its behaviour. Most of them, study the effects of tail dihedral angles on the static stability of the aircrafts [14] [15].

Table 1. Aerodynamic Stability Derivatives using Different Estimation Technique

Method	Static Derivatives		Dynamic Derivatives	
	C_{n_β} (rad^{-1})	**C_{y_β}(rad^{-1})**	**C_{n_r}(rad^{-1})**	**C_{y_r}(rad^{-1})**
Steady-State Measurement	0.0917	-0.5501	-1.4482	0.1071
Transient Measurement	0.1108	-0.2603	-0.1640	0.5948

Lately, more researches were conducted to estimate the accurate aerodynamic stability derivatives for V-tail aircraft [16][17][18]. But, the methodologies to provide accurate aerodynamic stability derivatives especially during transient conditions were not taken into consideration [4]. Most of them used steady data to design the controller for V-tail aircrafts. This approach led to inaccurate aircraft response when the aircrafts experience unsteady loads for instances during atmospheric disturbance (i.e; gust, crosswind etc.). As the aircraft fly, it may experience unsteady conditions where the stability derivatives are no longer of a constant value. This is due to the presence of significant motion frequency effects on the static and acceleration derivatives. As noted before, no exact conclusion has been drawn on estimation of accurate stability derivatives for V-tail in transient conditions within small angles of yaw or within the linear region.

3 Model and Test Set up

Static and dynamic oscillatory tests on wind tunnel model were constrained to rotate in yawing motion only. The tests were conducted in the 1.5 m × 2 m × 6 m closed circuit Universiti Teknologi Malaysia Low Speed Tunnel (UTM-LST). This facility is capable to provide maximum wind speed of 80 m/s with turbulence intensity approximately <0.06 % across the test section. The model was mounted on a single strut support while the model angle of attack was fixed to zero degree for both static and dynamic oscillatory tests. The only difference between static and dynamic set up is the attachment of strut. For static wind tunnel test, the strut was covered by windshield to minimise the effects of drag as in Fig. 1. The forces and moments were measured using JR3 160M50 Six Component Balance (see Fig. 3) placed under the test section floor and yawed within linear region only (±10°). For dynamic oscillatory test, the model was attached to a special rig designed to allow rotation only in yawing axis as shown in Fig. 2 and Fig. 4. Initial yaw input was introduced to excite the wind tunnel model. The wind tunnel model was then free to oscillate within the linear region (±10°) until the oscillations damped out with time. The aircraft time response was then recorded using a low friction potentiometer and then converted the data acquired into digital signals using NI-PCI-6235. Data was sampled at 1000 Hz an in line with low pass filter. Both tests were measured at 40 m/s giving a Reynolds number of 0.23×10^6 with respect to the aircraft wing chord.

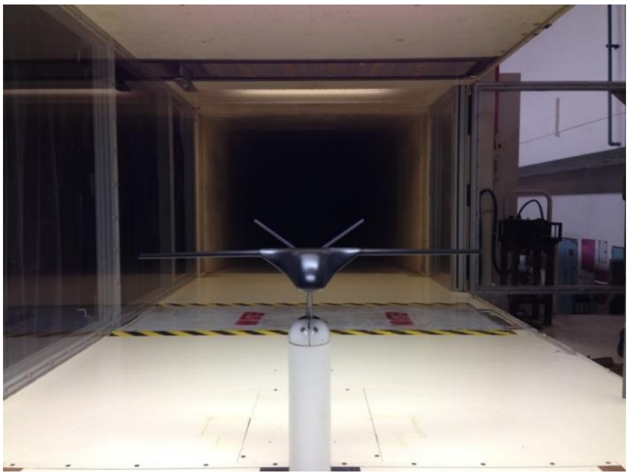


Fig. 1. Wind Tunnel Model in Static Wind Test

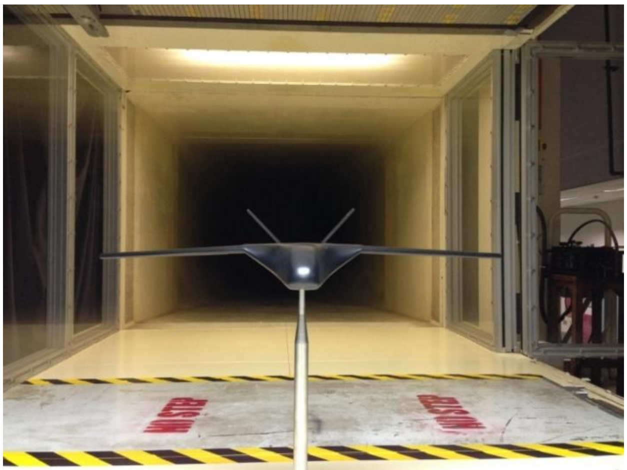


Fig. 2. Wind Tunnel Model in Dynamic Oscillatory Tunnel Test.

Fig. 3. JR3 160M50 Six Component Balance

Fig. 4. Dynamic Oscillatory Rig

4 Results and Discussion

Semi-empirical method widely used in the aircraft industry to obtain aerodynamic stability derivatives in the preliminary design phase. It was developed with aims to provide preliminary aerodynamics stability derivatives on each new aircrafts designed during World War II. It was also to provide the understanding on the aircraft behaviour based on the aircraft configurations during that time [6][19]. Typically, semi-empirical method was developed based on conventional aircraft configuration through a lot of wind tunnel testing and real test flights within small perturbation. However, the uses of semi-empirical method become less reliable in estimating the aerodynamic stability derivatives of aircrafts especially related with unconventional aircraft configurations. This is further proven through this research work.

In this research work, the semi-empirical method was used to calculate dynamic derivatives (C_{n_r} and C_{y_r}). This is due to inability of static wind tunnel test to produce dynamic derivatives. Hence, combinations of dynamic derivative by semi-empirical and static derivatives by static wind tunnel test were used to form the Dutch roll state-space matrix and this would reduce to a transfer function as in equation (1). This was then compared to the transfer function obtained from transient measurement as in equation (2). This highlights the effects of the two methods of estimations of aerodynamic stability derivatives on the Dutch roll response of the aircraft.

In order to highlight the importance of the accurate estimation of aerodynamic stability derivative as an input parameter in the aircraft dynamic simulation, a Matlab programme was written to simulate the Dutch roll motion. In this simulation, the transfer function of sideslip angle and yaw rate due to crosswind disturbance was taken from Dutch roll state-space matrix. This is to study the effects of disturbances on aircraft response with the assumption of zero deflection on the control surfaces.

$$\begin{bmatrix} \frac{\beta}{\beta_g} \\ \frac{r}{\beta_g} \end{bmatrix} = \frac{\begin{bmatrix} 0.0198\ \mathrm{s} + 0.0023 \\ 0.0015 \end{bmatrix}}{S^2 + 0.1259\, s + 0.0746} \qquad (1)$$

$$\begin{bmatrix} \frac{\beta}{\beta_g} \\ \frac{r}{\beta_g} \end{bmatrix} = \frac{\begin{bmatrix} 0.0094\ \mathrm{s} + 0.0001 \\ 0.0008 \end{bmatrix}}{S^2 + 0.0178\, s + 0.0888} \qquad (2)$$

The open loop time response was then plotted and is shown in Fig. 5. From Table 2, it was found that the steady-state measurement is overestimating the damping by over 87% when compared to transient measurement. On the other hand, steady-state measurement has underestimated the natural frequency by 11% as compared with transient measurement. This highlighted weakness in the use of steady-state measurement to estimate aerodynamic stability derivatives during transient condition. It also led to overestimation of the aircraft responses in aircraft simulations. This result validate that the estimation using steady-state measurement is not enough to represent the dynamics of the aircraft in real flight conditions [10][4].

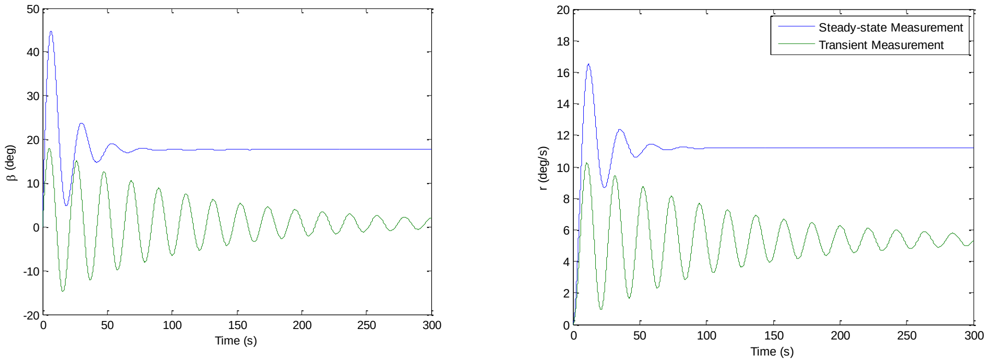
The transient measurement through dynamic oscillatory test resulted in better responses values of the aerodynamic stability derivatives for the transient conditions. Since, the evaluation of the aircraft response through aerodynamic damping and natural frequency result in a function of time [20].

The improper estimation of the aerodynamic stability derivatives would lead to poorly or wrongly designed of control system and even worst during the existence of atmospheric disturbance, as the aircraft response would be exaggerated and may lead to in flight failures.

Due to that reason, further experiments were conducted by varying the wind tunnel speeds from 10m/s to 40m/s with a Reynolds number range of 0.6×10^6 to 0.23×10^6 relative to wing chord respectively. Then the results were presented in term of amplification factor, AF. The amplification factor is a ratio of C_{n_β} measured by transient measurement and steady-state measurement and was used to describe the existence of transient effects in estimation of aerodynamic stability derivatives.

Table 2. Transfer Function Analysis for Different Estimation Technique

Methods	Damping ratio, ξ	Natural Frequency, ω_n (rad/s)	Steady-state Error Value
Steady-state Measurement	0.23	0.27	0.0308
Transient Measurement	0.03	0.30	0.0011



(a)

(b)

Fig. 5. Aircraft Response to Crosswind Input at 20 m/s cruising speed and exposed to the crosswind disturbance at moderate intensity of 10 m/s normal to aircraft speed for two seconds

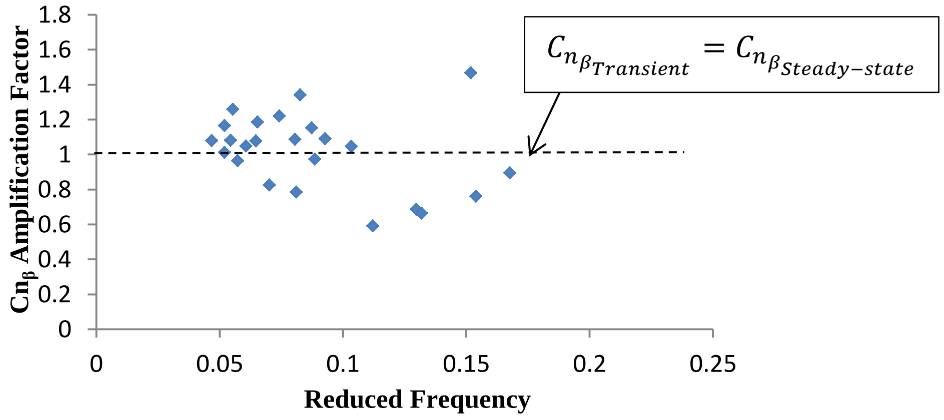


Fig. 6. Yaw Moment Amplification Factor

For instance, the yaw moment amplification factor is:

$$AF_{C_{n_\beta}} = \frac{C_{n_{\beta_{Transient}}}}{C_{n_{\beta_{Steady-state}}}} \tag{3}$$

Referring to Fig. 6, *AF* < 1 which happened at higher reduced frequency indicates that the steady-state measurement is adequate to describe the aircraft response. But as the reduced frequency decrease where *AF* > 1 indicated that the steady-state measurement is no longer adequate to describe the aircraft motion and may lead to incorrect aircraft simulation of aircraft response.

5 Conclusion

In conclusion, the steady-state measurement can be used for certain flight conditions and in this case within higher reduced frequencies region (>0.1). The Amplification Factor, *AF* technique has indicated that, if the control system of an aircraft is design from steady-state measurement, it only can be used at higher reduced frequency but as the reduced frequency decrease, the control system may fail to handle the aircraft responses. The transient measurement is more accurate to deal with real flight condition where the motions are prone to varying the frequency and amplitude of oscillations [10]. In term of estimation of dynamic derivatives, the experimental method has a greater fidelity than semi-empirical methods for the unconventional configuration, as the measurements are recorded from a more real aerodynamic flow conditions.

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