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Effects of Aircraft Tail Configurations on Sensitivity to Yaw Disturbances

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Abstract. A wind tunnel test was conducted to compare the characteristics of low speed stability and control for aircraft with conventional tail and V-tail configurations. Comparison was made in terms of static directional stability at selected test speed of 40 m/s, which corresponds to Reynolds number of 0.1622 x 10^6 based on the chord. Three types of simplified tail-only model were tested in Universiti Teknologi Malaysia's Low Speed Wind Tunnel (UTM-LST). Results show that the V-tail configuration greatly affects the aerodynamic characteristics in directional stability as the side force and yaw moment tends to vary linearly with yaw angles up to 25 degrees, compared to conventional tail that has linear characteristics up to only 10 degrees yaw.

Introduction

This paper discusses the details related to aerodynamics forces due to the effects of tail dihedral angle, particularly the effects on the side force coefficient that in turn affect the directional stability and control of the aircraft. The vertical plane design depends on the type of aircraft and the flow regime around it [1, 2]. A lot of results on directional stability on isolated vertical tailplanes, even combined to horizontal tails with and without dihedral angles, were obtained through wind tunnel tests by National Advisory Committee for Aeronautics (NACA). NACA then attempted to separate the effects of fuselage, wing and horizontal tail by testing isolated vertical tail since it involves asymmetrical flow behind the wing-fuselage combination and lateral cross-control by dealing with specific aircraft configurations [3]. In designing an aircraft, the rates of change of yawing moment with yaw angle and of pitching moment with angle of attack are among important characteristics as they provide a safety factor for the aircraft before reaching the neutral stable condition [7].

Directional stability can be improved by introducing tail dihedral [4]. For example, the V-tail configuration promotes good directional stability, if there is sufficient dihedral angle. Analysis of the V-tail found that reduction in drag due to lower tail wetted area [5, 6] leads to lesser tendency towards rudder lock and reduces tail buffeting from wing wakes during high speed flights [4]. But there is a lack of quantitative information on V-tail performance [7, 8]. These reports also stated that the rate of change in yawing moment with side slip angle is important in designing aircraft [6] as the lateral stability characteristics were dependent on sideslip angles [9].

This paper compares conventional tail to V-tail through tests using simplified tail-only model in order to eliminate the effects of sidewash generated by the wing-fuselage interactions. Previous research mostly used complete aircraft configurations with variations in fuselage shapes [10]. Even though there are some NACA reports that study the effects of lateral stability characteristic due to wing alone, fuselage alone and fuselage with tail, these studies concluded that the presence of sidewash affects the tail performance when the model is yawed [11, 12].

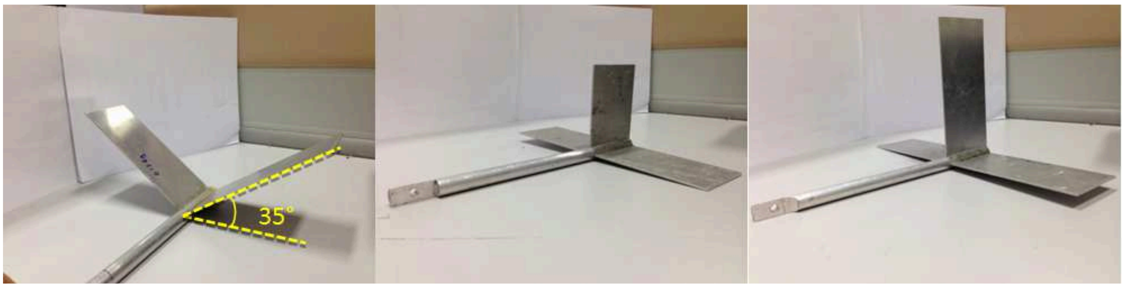
Test Configuration

Three simplified tail models were used in this experiment, with tails made up from flat plates. The reference model is the V-tail with 35° dihedral, second model is the conventional tail with span, $b = 0.141\ m$ and the chord $c = 0.062\ m$ corresponding to a tail with equal dimensions with the V-tail but without dihedral, and the third is also a conventional tail but with span, $b = 0.116\ m$ and $c = 0.062\ m$ corresponding to equal plan area of the V-tail model. The summary of the models dimensions are presented in Table 1 and their photos are in Fig. 1.

The model was mounted on single strut support, which connects to the wind tunnel balance. The strut was covered by a small wind shield that is not connected to the balance. The wind shield would always face the wind as the model is rotated in yaw axis. Fig. 2 shows how the model was installed inside the wind tunnel test section with tunnel axis were in the same direction with wind axis, thus causes the yaw angles coincide with sideslip angle. In further analysis, sideslip angle will be used for discussion. The test configurations were divided into three sections, which is for wind-off, the model's sideslip angle were varied from -25°until 25°at 5°increments, to cater for each positive and negative side of yaw moment. Tests were carried for wind speed of $40m/s$ based on Reynolds sweep test with dynamic pressure equivalent to 936 Pa for the stated range of sideslip angles. Correction data were obtained with tests for strut alone at zero yaw angles and a wind speed of$40\ m/s$, and also at wind-off condition.

Table 1: Summary of the model geometry

Model	**Dihedral angle**	**Flat Plate Span, b $[m]$**	**Chord, c $[m]$**	**Total Surfaces area$[m^2]$**	**Characteristics length$[m]$**	**Reference Area, S$[m^2]$**
V-tail	35°	0.141	0.062	0.01829	0.244	0.01513
Tail-1	0°	0.116	0.062	0.01829	0.244	0.01513
Tail-2	0°	0.141	0.062	0.02703	0.295	0.01829



(a) (b) (c)

Figure 1: (a) V-tail Configuration; (b) Tail-1: Conventional tail with tail equal to projected dimensions of (a), (c) Tail-2: Conventional tail with equal surface dimensions but without dihedral

Figure 2: V-tail model in the wind tunnel test section

The aerodynamic loads (side force and yawing moment) were measured using JR3 160M50 multi-axis load cell, which is a six-component balance having a load range for side force and yaw moment equal to 3500 N and 450 Nm, respectively, with an accuracy about 0.25% from range axis.

The data were acquired at a sampling rate of 30 Hz for 10 seconds on every tail configuration and sideslip angle. All raw data were referenced to the balance moment centre (BMC), which is located at the centre of the sensor. However, the pivot point of the model was at 0.485 meter higher than BMC, which required the transformation of the forces and moments from BMC to the pivot point. The aerodynamic data were averaged and normalised to non-dimensional coefficients by dividing the forces and moments with the dynamic pressure and the tail plan area as well as the characteristic length for the moments, which is the span of the tail. In real aircraft, references area, S is taken as the wing platform area while characteristic length, ℓ is taken as the wing span for yawing moment [13]. However, since there is no wing attached to the models, the horizontal tail platform area is used as reference area and the tail span is used as the characteristic length. For the V-tail case, the reference area is the projected area onto the horizontal plane. All data were corrected for tares caused by the model strut support.

Result and Discussion

The design of the simplified conventional tail model (Tail-1) relative to the V-tail configuration is based on the horizontal and vertical projections of the total tail planform area, while for Tail-2 the dimension of the flat plate in chord and span were kept the same as flat plate on the V-Tail resulting in different total reference area. The total reference area for V-tail was equal to Tail-1, which is 17% less than Tail-2. The comparison of results for the V-tail and the conventional tail is made based on two aerodynamics quantity that are related to lateral stability: yawing moment coefficient, C_n and side force coefficient, C_y as shown in Figs. 3 and 4, respectively.

Fig. 4 shows that the yaw moments were almost linear at all tested yaw angles (max$\pm 25°$) for the V-tail but the conventional tails showed that linearity ended at about $\pm 10°$ yaw angles. Fig. 3, meanwhile, shows that the side force shown by the V-tail is linear at all tested angles. For the conventional tail, the linearity ended at about $\pm 10°$ yaw angles, indicating that the vertical tail started to create a constant value at these angles. These show that the V-tail promotes linear side force and yaw moments at high sideslip angles, even after the conventional tail had a constant.

The linear region for conventional tail is between $\pm 10°$sideslip angles, beyond which the vertical tail is in constant, the condition where C_y and C_n seems to flatten out. Constant C_n indicates that the model is entering the neutral stability state. In an aircraft, it would remain in the same new position after being disturbed by any disturbances like gust or crosswind [13]. This differs to the V-Tail in which after $\pm 10°$ the trend is still linear at all tested angles, indicating the V-tail is not constant at the same yaw angle as the conventional tail thus would still be stable in yawing disturbances.

These results had led to further test for the V-tail configuration in which the yaw angle limit was expanded to $\pm 60°$ and the results are shown in Figs. 5 and 6. Both C_y and C_n start to deviate from linear at yaw angles of $\pm 30°$ but continue to rise until the maximum sideslip test angles. This means that the V-tail cannot be considered to be in constant condition, since both coefficients were still rising. It seems that there is a second linear region past at $\pm 30°$ but with lower gradients than the previous ones.

Table 2 shows the derivatives of the linear part of C_y and C_n with respect to sideslip angle. The values of C_{y_β} and C_{n_β} for Tail-1 are almost identical to those for the V-tail configuration where the differences are only 3.4% for C_{y_β} and 7.0% for C_{n_β}. Value of C_{n_β} for Tail-2 is doubled compared to V-tail configuration while the value of C_{y_β} is 53 % much higher than the V-tail. The results provide the evidence that a fair comparison between V-Tail and conventional tail can only be made with the conventional tail equal projected V-tail area. It could be further deduced that a tail with the same dimensions but with different dihedral angle would result in different derivative values since the projected area is different. This means that the derivative values of Tail-2 configuration will be almost identical to V-tail with dihedral angle of 45 degrees.

In term of stability (refer from derivative) due to the sideslip angle, an aircraft possessing the static directional stability or weathercock stability will always point into relative gust disturbances

[13]. Result of the present work, the V-tail has less stability at lower sideslip angles (0º to ±10º) compared to the conventional tails (Tail-1 and Tail-2) but have higher stability at sideslip angles above ±10º. This also means that at lower sideslip angles (0º to ±10º), the V-tail is less sensitive to crosswind disturbances. However, at higher sideslip angles (above ±10º), V-tail is more sensitive to crosswind disturbances compared to conventional tail. Thus in gusty crosswind conditions, V-tail would easily deviate from the straight flight condition [15].

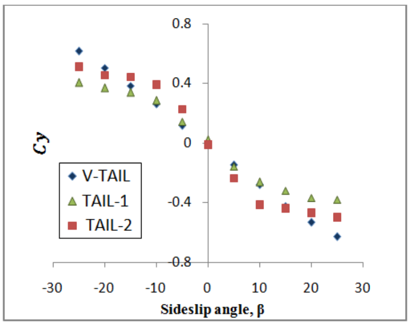


Figure 3: Side force due to sideslip angle

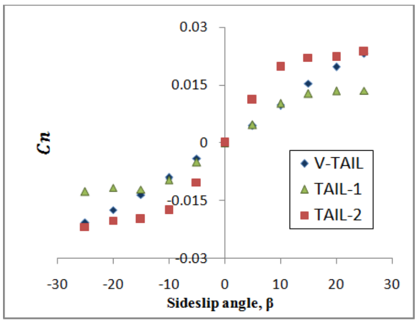


Figure 4: Yawing moment due to sideslip angle

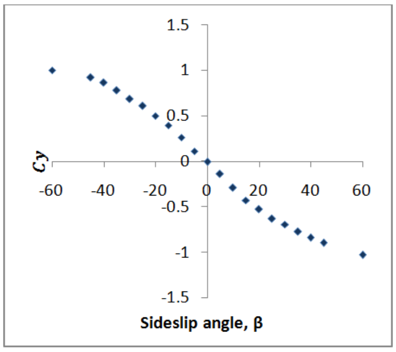


Figure 5: Side force coefficients changes with sideslip angles after further V-tail experiment.

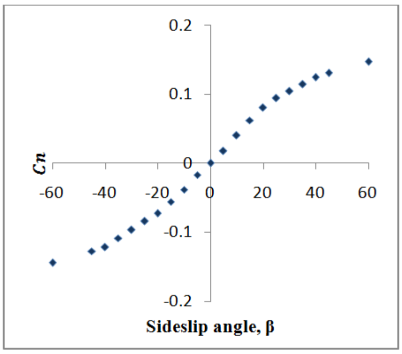


Figure 6: Yawing moment coefficients with sideslip angles after further V-tail experiment

Table 2: Aerodynamics stability and control derivatives for directional stability

Type of Model	C_{n_β}	C_{y_β}
V-tail	0.000920	-0.027036
Tail-1	0.000988	-0.027971
Tail-2	0.001915	-0.041386

The results from the experiment show a good agreement with the NACA report in terms of gradient trend [6, 7] but the C_n value in our case is smaller because the model used in the experiment was smaller in size and the focus was on the tail-only configuration compared to the complete aircraft tested by NACA. In addition, the interferences effects of the sidewash caused by wing-fuselage combination would be present in the NACA case [4, 10, 14]. This indicates that the approach of using simplified model with only tail is sufficient and valid to compare the stability of V-tail to conventional and simulating crosswind effect in wind tunnel.

The role of C_{y_β} to C_{n_β} is in creating the moment; hence the increment of C_{y_β} will result in the increment of C_{n_β}. However, high C_{y_β} value means the response of the aircraft in sideslip will be much higher. On the V-Tail, two surface areas contribute to the side force and yawing moment compared to just one in the conventional tail. However, the total reference area and the total forces and yawing moments remain the same [8].

Conclusion

These series of experiments is to compare the crosswind effects on lateral stability on three types of simplified tail configurations with different sideslip angles to represent yawing disturbances. The results show that V-tail has an advantage in having positive lateral stability at all tested sideslip angles (up to ±60º) whereas conventional tail is only stable up to ±10º, after which C_n becomes constant (C_{n_β} = 0). However, in terms of side gust sensitivity, the conventional tail is more sensitive up to ±10º side slip angle, and thereafter the V-tail will be more sensitive. It had also been found that a simplified tail model is sufficient for the purpose of experimental lateral stability comparison as the results obtained in this work is validated by NACA [10]. Another conclusion that could be drawn from this work is that the projected tail area onto the vertical plane would determine the lateral performance of the tail, rather than the physical plane dimensions of the tail (span).

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