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Engineering Notes

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Stalling Speeds and Determination of Maneuver Speed for Rogallo-Winged Microlight Airplanes

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Nomenclature

C_{Ae} = aeroelastic coefficient for a wing (used in determining stalling speed under load).
C_L = lift coefficient of the aircraft
$C_{L.\max}$ = maximum (stall point) lift coefficient of the aircraft
L = lift
N_1 = aircraft structural positive normal acceleration design limit at V_A
N_2 = aircraft structural positive normal acceleration design limit at V_D
R = coefficient of determination defining the quality of a line fit, with a value of 1 for a perfect line fit and a value of 0 for totally random distribution, $(n\Sigma xy - \Sigma x \Sigma y)/\sqrt{n(\Sigma x^2) - (\Sigma x^2)}\sqrt{n(\Sigma y^2) - (\Sigma y^2)}$
V = airspeed in knots calibrated air speed
V_A = maneuver speed (maximum speed at which aircraft will stall before exceeding structural limits in the normal axis)
V_D = structural design speed limit (normally, $V_D \geq 1.11 V_{\mathrm{NE}}$)
V_{NE} = velocity to never exceed (aircraft operating limitation)
V_{RA} = maximum airspeed for flight in severe turbulence
V_S = stalling speed
W = aircraft weight

I. Introduction

IT HAS been observed for many years that the stall speed of weight-shift-controlled microlight airplanes [1] does not necessarily follow the pattern considered normal for a fixed-wing airplane as loading is increased, which is

$$V_S = V_{SO_{\mathrm{MTOW.1}\,g}} \left(\frac{W}{W_{\mathrm{MAX}}} N_Z \right)^{1/2} \tag{1}$$

Rogallo-winged aircraft are instead known to display higher stalling speeds at high loadings (for example, in a steep turn) than are necessarily predicted by Eq. (1) and would be considered normal for a conventional rigid-winged airplane. It is believed that this phenomenon was first observed by Venton-Walters [2], who designed the Sprint and Raven wings in the early 1980s. Venton-Walters stated that the behavior could be shown to follow the following relationship:

$$V_S = V_{SO_{\mathrm{MTOW.1}\,g}} \left(\frac{W}{\mathrm{MTOW}} N_Z \right)^{C_{\mathrm{Ae}}} \tag{2}$$

C_{Ae} will be referred to here as the aeroelastic coefficient for the wing (which is the author's terminology, not that of Venton-Walters [2], who uses α). It was Venton-Walters's assertion that C_{Ae} will have a fixed value that is dependent upon the characteristics of the wing ,and a perfectly rigid wing would show $C_{\mathrm{Ae}} = 0.5$, but real Rogallo wings, tending to show a reducing $C_{L.\max}$ with increasing load, show $0.5 < C_{\mathrm{Ae}} < 1$.

This has generally been observed to be true, although using the form of definition of the stall that is contained in airworthiness standards rather than any supposed or investigated airflow behavior. That is, the stall is defined by "a downward pitching motion or downward pitching and rolling motion not immediately controllable or until the longitudinal control reaches the stop" [3] (paragraph S201.a), the latter part of this definition being most usually applicable.

II. Potential Significance of C_{Ae}

One significance of this is that greater caution needs to be observed by pilots during steep turns. For example, in an aircraft with $W_{\mathrm{MAX}} = 367$ kgf and $V_{S.W\max} = 29$ kt, loaded to 350 kgf, making a 2-g (60-deg banked) turn with $C_{\mathrm{Ae}} = 0.8$ (the stated values for the Raven wing), conventional theory would give a stall speed of about 40 kt, whereas the Venton-Walters [2] approach would give a stall speed of about 50 kt. Given that a 60-deg banked turn is a permitted maneuver and a typical cruising speed would be about 45 kt, the risk of an inadvertent stall during a turn becomes more significant. Although the reasons for this have not historically been quantified, pilots in this class of the aircraft are indeed taught to pull the bar in (accelerate) before initiating a steep turn [2].

Further significance is seen when considering the operating limits for the aircraft. V_{NE} for the Raven wing is 87 kt and the positive normal acceleration limit is $+4\ g$. Using the more conventional model for stalling speed, this combination necessitates a maneuver speed V_A to be defined, in this case, at 58 kt. However, if the Venton-Walters [2] model is accepted, then at 4 g and maximum takeoff weight (MTOW) the total loading is 1460 kgf and the stalling speed at this loading would be 88 kt, or slightly greater than V_{NE}. The consequence of this is a degree of natural protection that may be used to allow "carefree" handling of the aircraft with respect to structural limits up to V_{NE}, particularly in regard to gust limits (the normal practice in microlights and simpler light aircraft being to limit flight in turbulent conditions to below V_A, rather than introduce a separate V_{RA} term). Conversely, however, it presents a greater risk of an inadvertent stall, which piloting advice and associated training must guard against.

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Fig. 1 Photograph of the Air Creation KISS-400 aircraft.

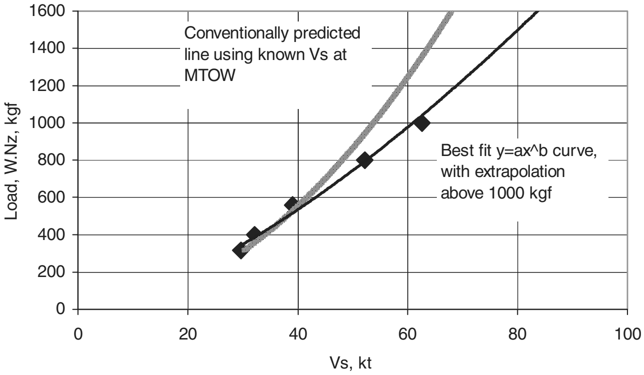

Fig. 2 Actual and classically predicted stalling speeds for Air Creation KISS-400.

III. Non-Square-Law Stalling Speeds in the KISS-400, KISS-450, and iXess

During certification testing of the Air Creation KISS-400 (see Fig. 1), KISS-450, and later iXess aircraft,[†] each aircraft was stalled over as large a range of wing loading as could safely be achieved, from a single crew with minimum fuel at 1 g to MTOW in steep turns, with an installed gravity meter providing a value for N_Z immediately before the stall. No other instrumentation was fitted to these aircraft, although airspeed indicator systems were calibrated using procedures contained in [4]; the relationship explored was therefore between apparent stalling speed and total loading only.

Figure 2 shows the results for the KISS-400, which were typical of these and other aircraft types. Two curves are shown: that which corresponds to the known test value for V_S at V_{MAX} following the pattern of Eq. (1) and that which fits the test data and follows the pattern of Eq. (2). Clearly, Eq. (2) shows the best fit; in this instance, $C_{\mathrm{Ae}} = 0.66$. The $R^2 > 0.98$ line fit is extremely good and gives high confidence in the result, although it should be emphasized that no theoretical basis exists for this relationship. In this case, a value of V_A for the wing of 83-kt calibrated air speed (KCAS) is shown, which is greater than V_{NE} of 76 KCAS.[‡] Carefree handling in pitch may therefore be assumed for this aircraft insofar as any pitch mishandling or flight in turbulence up to V_{NE} may be considered unlikely to cause any overstress of the aircraft through exceedence of the normal acceleration limit.

Based upon the preceding work, which was carried out during the United Kingdom's certification program for the aircraft, two decisions were made with regard to the operating limitations:

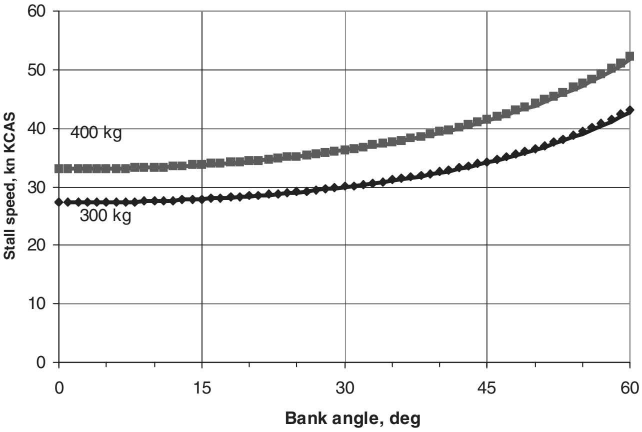

Fig. 3 Diagram of stall speed vs bank angle from the KISS-400 operators manual (reproduced courtesy of Flylight Airsports Ltd).

1) Because V_A had been calculated at 83 KCAS, which was greater than the V_{NE} of 76 KCAS, it was not included in the normal operating documentation (although it still lies slightly below the flight test limit of $V_{\mathrm{DF}} = 85$ KCAS and therefore remained listed in the series test schedule and type data sheet).

2) Specific data based upon this relationship was included in the operators manual, showing stalling speeds at various bank angles to warn pilots of the risk of inadvertent stall in steep turns.

Figure 3 reproduces the diagram that was included in the operators manual [5]. The bank-angle limit for the aircraft, as is common practice for most microlight airplanes, is 60 deg, which is why the bank-angle scale does not extend beyond this value.

IV. Justified Modification of N_1 and N_2

N_1 and N_2 define the positive N_Z limits for an aircraft at V_A and V_D, respectively. Light aircraft certification standards will define minimum values of N_1 and N_2 (in general, $N_1 = N_2 = +4\ g$ for this aircraft class [3]) and V_A. However, V_A is typically defined within certification codes (e.g., [6]) by

$$V_A = V_S \sqrt{N_1} \tag{3}$$

where N_1 in this context is the minimum value. When V_A is permitted to vary from this value, it is normal that it is only required not to have a value less than that defined by Eq. (3) and is not necessarily required to have any greater value (e.g., [6]). Thus, it is possible to define V_A as given in Eq. (3) but to use the form of O–A curve given in Eq. (2). It is possible to combine Eqs. (2) and (3), while treating N_1 as a variable. To do this, first assume that the aircraft is at MTOW and modify Eq. (2), giving the following result:

$$V_A = V_{S_0} N_1^{C_{Ae}} \tag{4}$$

These are apparently incompatible, but can be made to work together if it is accepted that the value of N_1 in Eq. (3) is a variable, and that value in Eq. (3) is based upon the requirements given in the certification standard, which will now be retermed $N_{1.\mathrm{cert}}$ Thus,

$$V_A = V_{S_0} \sqrt{N_{1.\mathrm{cert}}} = V_{S_0} N_1^{C_{\mathrm{Ae}}} \tag{5}$$

which becomes

$$N_{1.\mathrm{cert}}^{0.5} = N_1^{C_{\mathrm{Ae}}} \tag{6}$$

and thus

$$N_1 = N_{1.\mathrm{cert}}^{1/(2.C_{\mathrm{Ae}})} \tag{7}$$

So it is justifiable to reduce the value of N_1 and thus reduce primary structural mass without reducing the magnitude of V_A. It may be noted that as C_{Ae} tends toward 0.5 (a perfectly rigid wing), the relationship tends toward $N_{1.\mathrm{cert}} = N_1$.

[†] Data available from Homebuilt Aircraft data sheets (HADS) HM7, HM11, and HM13, respectively.

[‡] Data available from Homebuilt Aircraft data sheet HM7.

With an alternative method of modification of N_1 and N_2 pioneered by Pegasus Aviation (now P&M Aviation) in development of the Quantum and later aircraft, it was the demonstrated that after a step nose-up pitch input from a dive to V_{NE}, it is impossible to exceed a given value of V_Z. In the Pegasus Quantum, only 2.4 g was achievable, allowing (with a substantial safety margin) N_1 to be reduced from the usual minimum of 4 to 3.8 g and thus permitting a useful reduction in structural weight.

V. Conclusions

It has been shown that Rogallo-winged airplanes can display a non-square law of stall speed versus loading. This Note has shown, from experimental data, the form of this relationship and how this has been used during the certification of such airplanes, through operating data and modification of either maneuver speed or the normal acceleration limits

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