A METHOD FOR ESTIMATING CRITICAL FLIGHT LOADS ON A SMALL AIRCRAFT FUSELAGE USING NUMERICAL METHODS, CONVENTIONAL DESIGN TOOLS, AND RISK ASSESSMENT TECHNIQUES

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Abstract - The STOLMA One bush plane is a heavily modified version of an existing light aircraft designed for medical evacuations from jungle and short-field runways. The primary structural modifications are a fuselage extension, increased wingspan, increased horizontal tail span, and a loading door in the aft fuselage. For the design, analysis, and testing of the new structure, no aerodynamic data existed, no full-scale wind tunnel was available, and CFD models for the entire aircraft were deemed unreliable. A conservative method for estimating flight loads on the fuselage is presented. Aerodynamic characteristics of the horizontal tail and vertical tail are modelled with a panel method numerical solver. Design calculations are performed for individual components of the flight loads. Flight maneuvers are selected from appropriate flight manuals for the class of aircraft and mission profile under consideration. Load components are combined according to the maneuvers selected within each part of the flight envelope. The discrete portions of the flight envelope are assembled in a risk assessment matrix, and the test loads are selected accordingly. In a selected example, in order to simulate the steep climb portion of a chandelle maneuver, the STOLMA One fuselage extension assembly is tested with a downward load of 2,000 kg located 3.8 m aft of its respective CG. This test is considered a conservative evaluation of the structure's performance at ultimate loads.

Keywords - Critical Flight Loads, Light Aircraft Testing, Medical Evacuation Aircraft, Panel Method.

I. INTRODUCTION

A.Background

Lightweight experimental aircraft are often produced by small design teams or individuals. Without the support of large wind tunnel labs or complex CFD codes, these small teams and individuals have limited design resources. The experimental aviation community very frequently produces aircraft that rely on non-traditional airfoil shapes and alternative airframe designs. These non-traditional structures often lack the established aerodynamic data that is published for NACA airfoils. This research is driven by the need for low-cost design tools for lightweight aircraft. A method is presented here with specific examples for determining flight loads in lightweight aircraft.

B.Literature Review

Important concepts from the flight envelope, vertical gust factors, and total inertial load factors are covered by David Peery [1]. A technique for evaluating the effects of side slip to produce asymmetric horizontal tail loads are presented by Braun [2]. The Vortex Panel Method Solver produced by Auld and Srinivas is used for numerically determining airfoil characteristics[3]. John Anderson's work is used for explanations of vortex panel methods, lift, and drag calculations[4]. The frequency and importance of mountainflying maneuvers are covered by Fletcher Anderson[5]. The Pilot's Handbook of Aeronautical Knowledge is used for estimating the inertial effects of certain maneuvers [6]. Chris Heintz's work [7]and the US Federal Government 14 CFR 25.333 [8]are used for guidance on the flight envelope.

II. METHODS

A.Overview of Methods

The load development method is summarized as follows. First, load centers are located on the airframe. For example, the aerodynamic center of the horizontal tail is a very important location for forces in the aft fuselage. Once load centers are located, the load components must be determined. A brief search of the literature will show the variety of methods available for estimating load components. With the load components identified, they can then be combined according to the aircraft maneuvers being considered. Turns, dives, spin recovery, stalls, navigating gusts of wind, and aerobatic maneuvers should be considered. These maneuvers will vary in frequency and intensity, and so they must be ranked accordingly. High risk maneuvers are those which have the most potential for destroying the aircraft. The method outlined above will be applied specifically to the STOLMA One fuselage extension assembly.

B.Locating Load Centers

The first step in developing a load program is the determination of load centers. Forces in the airframe

are generated by payloads, aerodynamic loads, and thermo-mechanical loads. Therefore, load centers are located at payload centers of gravity, aerodynamic centers, and points of high restraint in extreme temperature conditions. Additionally, loads on components are passed through the airframe assembly; making attachment points an important consideration in some analyses.

C. Identifying Load Components

Load components are identified according to the airframe components under consideration. Load components are all of the possible loads associated with the airframe members being considered.

D. Associating Loads with Maneuvers

Maneuvers determine the magnitude of load components. Maneuvers are grouped according to condition. The conditions establish the boundaries of the flight envelope. In general aviation, and for the purposes of this exploration, seven conditions are considered. However, it is important to note that aircraft designers have included additional conditions for special aircraft.

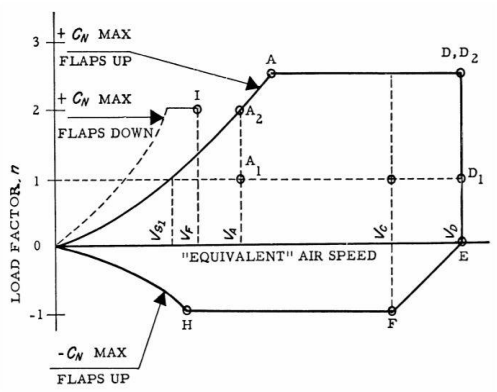


Figure 1: Flight Envelope [8]

E. Risk Assessment

A basic risk assessment matrix illustrates the magnifying relationship of probability and consequence. Each event considered in the risk assessment matrix has a certain probability and a certain consequence. In design, the magnitudes of these need not be calculated precisely. For example, an event may be high probability but low consequence. This would be a moderate-risk event. An event with high probability and high consequence is a very high-risk event. Designers must consider the qualitative risk level offlight maneuvers expected for the aircraft they are designing, modifying, or testing. In flight, certain maneuvers will be very frequent (high probability). However, high frequency maneuvers like turning or landing are not usually dangerous (high consequence). However, a maneuver such as spin recovery may have a low probability, but carries a very high load consequence. The risk level is therefore very high. The example risk assessment matrix shown in Fig 2 illustrates the relationship of probability and consequence to risk-level. It is important to remember that the risk assessment matrix in this study is used qualitatively. While this tool can be used more quantitatively in flight performance and aircraft life management, it is only useful as a qualitative tool for design of new aircraft. Therefore, probabilities and consequences are not assigned precise values. Their magnitudes are estimated.

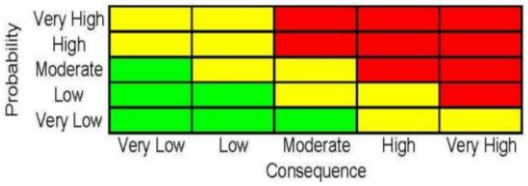


Figure 2: Risk Assessment Matrix [9]

III. RESULTS

A. Load Diagram

For the STOLMA One fuselage extension assembly, it was determined that there were two types of loads passed through the empennage into the fuselage extension—payload carried in the fuselage and aerodynamic loads generated by the control surfaces and generated by drag on the empennage. The load center locations are shown in Fig 3. Aerodynamic force generated by the vertical tail in maneuvers (F_{VT}) is centered on the rudder control surface. It produces a moment about the cross-sectional center of the empennage (T_{VT}). An additional moment about this axis is produced by asymmetric horizontal tail loading (T_{HT}). The horizontal tail produces an aerodynamic load centered at the center of pressure of the horizontal tail airfoil (F_{HT}). The weight of the tail (W_T) and the aerodynamic force generated by the horizontal tail control surfaces are supported by the empennage at the tail mounting brackets.

The aerodynamic force applied to the fuselage by side gusts of wind (F_{SG}) is centered on the fuselage center of gravity. The payload and fuselage weight are summed and centered together (W_{SG}). The payload and fuselage weight are multiplied by inertial factors (η_{TOTAL}).

B. Load Condition Chart

Flight load components are calculated for each loading location and flight maneuver being considered. These are assembled into a load condition chart which groups the component loads with the appropriate flight condition. The component loads for the STOLMA One aft fuselage are calculated as follows.

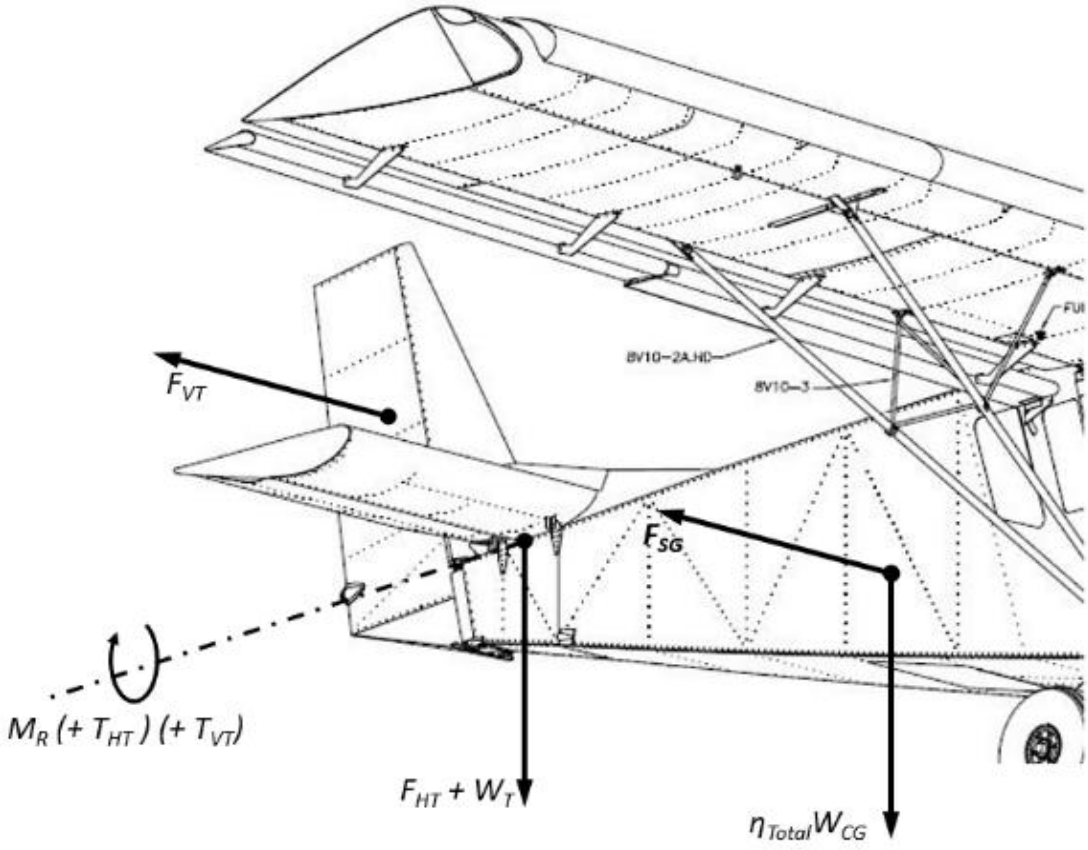


Figure 3: Load Diagram

Horizontal and vertical tail forces are estimated by a composite method that uses a vortex panel method solver to calculate a lift coefficient value (C_L) and then uses the standard lift equation to calculate aerodynamic loads. The airfoil profile is taken at maximum control surface deflection. To load the airfoil profile into the numerical panel method solver, the airfoil shape must be discretized with cartesian coordinates as shown in Fig 4. The point density of the airfoil shape coordinates is increased in regions with complex geometry. The cartesian coordinates are captured in an ASCII format file, and then loaded into the solver.

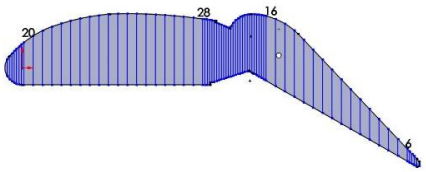


Figure 4: Discretization of Horizontal Tail Airfoil

The discretized airfoil profile is loaded into the vortex panel numerical method solver with angle of attack and flow velocity information for each flight maneuver being considered. For high speed emergency maneuvers, the airfoil is considered travelling at V_{NE} with maximum elevator deflection. This is an extreme case, but it allows the designer to consider the worst possible event.

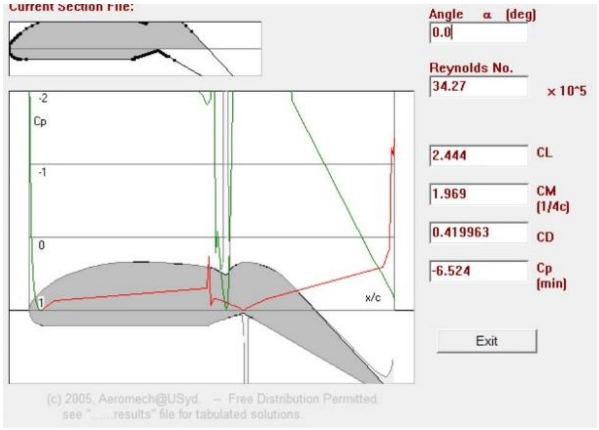


Figure 5: Vortex Panel Method Solver

With the airfoil shape and air velocity characteristics established, the solver can then approximate C_L data. The C_L data can then be used in the equation 1:

$$F_{HT} = F_{L,VNE} = \frac{\rho V^2 S C_L}{2} \quad (1)$$

Here, ρ is air density, V is air velocity, and S is control surface area. The same form is used for calculating vertical tail forces.

Asymmetric horizontal tail loading can be estimated by Braun's technique with equation 2.

$$M_R = \frac{1}{2}\rho V^2 S_H b_H K\beta \quad (2)$$

Here, ρ is air density, V is air velocity, S_H is the horizontal tail surface area, b_H is the horizontal tail chord length, K is the rolling moment coefficient per radian of sideslip, and β is the angle of sideslip.

Vertical gust load factor is calculated by Equation 3

$$\Delta\eta = \frac{.1\beta KUVS}{W} (3)$$

where β is the slope of the $C_{z,a}$ vs α curve, KU is the effective gust velocity, V is the air velocity, S is the wing surface area, and W is the weight of the aircraft.

Force from a side gust is calculated by Equation 4

$$F_W = \frac{1}{2}\rho V^2 A (4)$$

Maximum load factors for maneuvers are taken from Peery and the FAA Pilot's Handbook of Aeronautical Knowledge.

The resulting load estimates are summarized in Table 1.

Maximum Load Values Acheivable Within Each Flight Envelope Condition						
	Condition I	*Condition II*	*Condition III*	*Condition IV*	*Condition V*	*Condition VI*
F_{HT} (N)	13785	13785	11846	11846	Outside of Placarded Operations	--
F_{VT} (N)	3252	3252	3252	3252		---
T_{VT} (Nm)	1064	1064	1064	1064		---
F_{SG} (N)	352	352	352	352		352
ηgust	1.75	1.75	1.75	1.75		1.75
M_R (Nm)	388	388	388	388		No sideslip in glide
η	4	2	2	2		1
W_{CG1} (N)	3721	3721	3721	3721		3721
W_T (N)	325	325	325	325		325
Condition Descriptions	Positive High Angle of Attack. This include steep climbs, the top of some chandelles, and hammerhead turns	Negative High Angle of Attack. This represents a steep dive.	Positive Low Angle of Attack. This occurs during climb out and as a part of lazy eights and chandelles	Negative Low Angle of Attack. Beginning of most high speed maneuvers. This is the shallow dive to gain speed.	Inverted Flight	Gliding. Here, loads are assumed as sudden loads applied during gliding that terminate the "glide"

Table 1: Load Condition Chart

C. Risk Assessment Matrix

The risk level for flight conditions is established as follows. Condition I flight is defined by David Peery as the positive high angle of attack [1]. Condition I includes maximum climb out from short field takeoff, vertical climbs for emergency maneuvers, dive recovery, pull-out from stall recovery, pull-out from spin recovery, and chandelles. At low speeds during climb out from takeoff, Condition I flight is not dangerous.

However, it becomes very high-consequence flight at high speeds. During emergency maneuvers and pull-out from spin recovery, this is the most high-consequence flight condition anticipated for the STOLMA One. Because of the moderate probability of these high consequence maneuvers, Condition I is rated as the highest risk flight condition for STOLMA One.

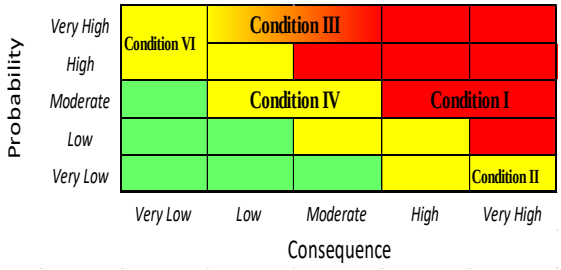


Table 2: Risk Assessment Matrix for STOLMA One Flight Operations

Condition II is defined as the negative high angle of attack [1]. This isa steep dive.Because STOLMA One is not intended for serious aerobatic flight, steep dives are considered a very low probability maneuver. However, the loading imposed by a steep dive is very high consequence. Therefore, Condition II is moderate risk.

Condition III is defined as positive low angle of attack flight [1]. This occurs during normal climb out, and as a part of many common maneuvers. It will occur during every flight. Condition III is a very high probability maneuver, but only a low to moderate consequence maneuver. Condition III is therefore a moderate to high risk flight condition.

Condition IV is defined as negative low angle of attack flight [1]. This is the shallow dive to gain speed for any high speed maneuver. High speed maneuvers are not a part of most flights in the STOLMA One mission profile. Condition IV is a moderate risk flight condition.

Condition V is defined as inverted flight [1]. This is mentioned here because it is a part of classic aircraft design considerations. However, inverted flight is outside of the maneuvering limits of the STOLMA One. Condition V is therefore not considered in this study.

Condition VI is defined as gliding [1]. While this may seem like an unnecessary consideration, it is important for establishing a baseline for normal flight. The loads during gliding are low, and gliding will occur during almost every flight. It is very high probability and very low consequence. Condition VI is therefore considered a moderate risk flight condition.

IV. DISCUSSION

A.Load Selection for Quasi-Static Structural Test

The major outcome from a load development program is the determination of key loads for design and structural testing. Static structural testing should establish that the aircraft is safe for the highest risk maneuver; establishing that the aircraft is airworthy for flight testing.From the risk assessment matrix in Table 2, it clear that Condition I is the highest risk flight condition and should therefore be simulated in static structural testing of the airframe.

B.Informing Other Tests

Additionally, the load development program defines the relative magnitude of other flight conditions. This informs further testing, maintenance schedules, and other design considerations.

C.Limits

The load development method outlined above is helpful for design, but it is severely limited by the imagination and experience of the designer. A load development technique dependent on estimation techniques is at greater risk of oversight than wind-tunnel testing. There is still significant risk of oversight in testing, but testing carries lower risk of oversight than estimation, analysis, or numerical modelling. It is critical that the designer is aware of the weaknesses inherent to the load development method.

V. CONCLUSION

This study explores some of the estimation techniques available for establishing structural loading during standard flight conditions. Condition I flight—high speed, high angle of attack flight—was determined to be the highest risk flight condition for the fuselage section being considered. For independent designers and small companies, the techniques employed here are readily available at low cost.

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