Offset Thrust Axes and Pitch Stability

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Introduction

A SIGNIFICANT number of aircraft are configured with vertically offset thrust lines, such as flying boats and transports with external engine pylons below the wing or in the vertical tail. The remaining majority of aircraft may be designed for centerline thrust, i.e., the thrust force line of action to pass through the c.g., but actually operate with some thrust line offset due to changes in the vertical c.g. position caused by variations in payload, fuel, stores, etc.

Offset thrust lines cause trim changes with power, which have to be considered for tail sizing, handling characteristics, etc. Besides this concern for adequate control of the aircraft, it is also of interest how offset thrust lines affect longitudinal stability of the trimmed aircraft. Some textbooks treat the effect of a high or low thrust line on the pitch stability of an aircraft like the forward or rearward shift of its neutral point. This implies that offset thrust lines affect the static longitudinal stability in a similar manner as forward and aft locations of the c.g. This study showed that not to be true.

Classic Error in Literature

Perkins and Hage[1] give derivations for props (p. 233) and jets (p. 243) that result in the general conclusion that high thrust lines are stabilizing, and low thrust lines are destabilizing. This conclusion is based on the slope of the C_m vs C_L (or C_m vs α) curve, derived for steady flight conditions at different speeds. However, while the nondimensional derivatives $C_{mCL} = dC_m/dC_L$ and $C_{m\alpha} = dC_m/d\alpha$ are meaningful pitch stability parameters for an airplane that is pitch-rotated in a wind tunnel or in flight at constant speed, they lose their meaning if equilibrium flight at different speeds is considered. In that case, the pitching moment coefficient $C_m = M/(qSc)$ changes because the dynamic pressure q changes, even if the moment M remains constant. For example, the thrust moment $M_T = Tz_T$ of a constant thrust aircraft (turbojet) remains constant during pitch disturbances, since neither thrust T, nor its arm z_T change significantly with angle of attack or speed. Therefore, this thrust does not affect stability.

The conclusion that a high thrust line is stabilizing because speed changes cause the slope of the C_m vs C_L curve to be negative, is therefore an error. For the same reason, it is incorrect to conclude from a positive slope, that low thrust lines are destabilizing. Unfortunately, the above misconception has perpetuated and can be found in some later flight test manuals.[2,3]

Speed Effects

Standard stability flight test methods rely on data taken at different speeds in trimmed flight. The data reduction sequence makes use of the slopes of the elevator deflection δ_e vs C_L (or stick force F_s/q vs C_L) curve. These relate to the stability derivative $C_{m\alpha}$.

Etkin[4] points out (p. 25) that the "trim slope criterion" can be misleading with respect to pitch stability. He uses the definition of $C_{m\alpha} = \partial C_m/\partial\alpha$ as partial derivative, which implies that speed and other parameters remain constant during α changes. Nelson[5] uses the dimensional pitch stability derivative $M_\alpha = d(M/I_y)/d\alpha$, which avoids the problems associated with q.

If pitch stability is considered strictly for pitch disturbances at constant speed, then the contribution of the direct thrust moment to stability remains zero, $(M_\alpha)_T = 0$. This is true for constant thrust aircraft (turbojets), as well as constant power aircraft (propellers), and "in-betweens" (turbofans).

If speed changes are included in the stability analysis, then thrust variations have to be considered, e.g., propellers change thrust if speed u is changed, even if the power setting is left constant. This leads to a speed stability derivative M_u, which can sometimes compensate for a lack of pitch stability.

Raymer[6] (p. 429) describes the physics of this correctly, however, he still maintains that a high propeller thrust line increases the static margin, equivalent to moving the neutral point rearward, "roughly 1/4% for each 1% that the thrust axis is above the c.g." This is misleading, because it implies that the aircraft is longitudinally stable for all c.g. locations ahead of this "speed stability neutral point." That, however, is not true, as can be seen by the following examples.

Examples

A propeller aircraft with a high thrust line has a pitch stability neutral point at 50.1% of its mean aerodynamic chord c, i.e., $h_{np} = 0.501$, as determined from rotating a wind-tunnel model through an α range at constant tunnel speed, or from unconventional flight tests that eliminate the errors associated with speed variation. For all c.g. positions ahead of this neutral point, i.e., $h_{cg} < 0.501$, the pitch stability parameter is $M_\alpha < 0$, meaning the aircraft has positive longitudinal static stability. Conversely, $M_\alpha > 0$ for $h_{cg} > 0.501$, meaning instability.

For a thrust line of 4 ft (0.814c) above the c.g., Raymer's rule of thumb results in a 20.4% c rearward shift of the neutral point, or $h'_{np} = 0.705$. Solies[7] has shown that conventional flight tests result in an apparent neutral point shift of 22.9% c for this example, resulting in a speed stability neutral point $h'_{np} = 0.73$. The high thrust line causes the speed stability parameter to be $M_u > 0$, meaning that the aircraft pitches up as speed increases, because the thrust decreases, and vice versa.

Let the aircraft be cruising in steady flight with a c.g. position at 52.1% c, which results in a small negative static margin (-2%) with respect to its pitch stability neutral point. This makes $M_\alpha > 0$. Furthermore, at the trim condition the resulting moment about the c.g. is zero.

The question is now, if the aircraft experiences a pitch disturbance ($+\Delta\alpha$, $\Delta\theta$), will it display static longitudinal stability, i.e., will it generate a restoring pitching moment ($M < 0$)? Writing the pitching moment as

$$M(\alpha, u) = (M_\alpha\Delta\alpha + M_u\Delta u)I_y \tag{1}$$

the following conclusions can be drawn:

If static longitudinal stability is defined strictly as the initial tendency of the aircraft to return to trim after a pitch disturbance, then the answer to the question above is "no." For a positive α disturbance ($+\Delta\alpha$) at constant speed ($\Delta u = 0$), the airplane generates a positive moment ($M > 0$), which is destabilizing.

If the term "initial" is stretched and enough time is allowed for the speed to decrease, then the answer to the question is "it depends." A sufficiently large speed decrease ($\Delta u < 0$) can make the second term on the right side of the equation large enough in magnitude to overpower the destabilizing first term. The result is then ($M < 0$), a restoring moment. This, however, is only possible if the speed decrease can keep up with the α increase.

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If a high thrust line aircraft has a high mass and low drag, then the speed changes following a pitch disturbance may not be large enough to allow the thrust variation to stabilize the aircraft at this aft c.g. position, and the aircraft's pitch divergence may be difficult or impossible to control without some stability augmentation system. On the other hand, an aircraft with low mass and high drag may benefit from the speed related pitch stability enough to be controllable by a human pilot.

Equation (1) illustrates speed effects on static stability, but cannot predict dynamic stability, which can be defined as the ultimate tendency of the aircraft to return to trim. Investigation of time histories of aircraft motion, convergence of oscillatory modes, and general handling characteristics require a dynamic analysis and go beyond the static margins and neutral points discussed here. It can be shown, that handling characteristics in pitch are driven primarily by the short period natural mode, for most aircraft. Typically, this mode is dynamically stable, showing a damped pitch oscillation even for moderate amounts of static instability. Any static instability in pitch, however, has a positive root in the root locus plot, causing a nonoscillatory divergence (degenerated phugoid). Therefore, static instability also causes dynamic instability.

To illustrate the above effects, the longitudinal dynamics of two different airplanes were modeled in a computer program. The vehicles represent a typical general aviation aircraft and a microlight aircraft with gross weights of 3600 and 525 lb, respectively. Both aircraft are considered to operate with centerline thrust and with a 4-ft-high thrust line. In order to maximize power effects, the program assumes the vehicles to be in a "full throttle" steady climb condition. After 1 s, a pitch disturbance ($\Delta\theta$, $\Delta\alpha$ = +1 deg) is introduced, and subsequent values of dynamic parameters are computed, using a linearized, three-degrees-of-freedom math model.

Curves "a" in Fig. 1 show the pitch and speed response of the general aviation aircraft flying at 100 kt in still air with centerline thrust and positive static stability (+2% static margin). Immediately after the disturbance, the aircraft generates a negative pitching moment. This initiates a nose-down pitch rate, which in turn evokes pitch damping, reducing the pitch rate. The pitch angle disturbance decays rapidly at first, then more gradually, until it reaches zero in less than 20 s. Airspeed is decreasing at first in response to the disturbance, but then starts returning to trim as soon as the pitch angle is stabilized. If the aircraft had a larger positive static margin, it would return to trim much more rapidly.

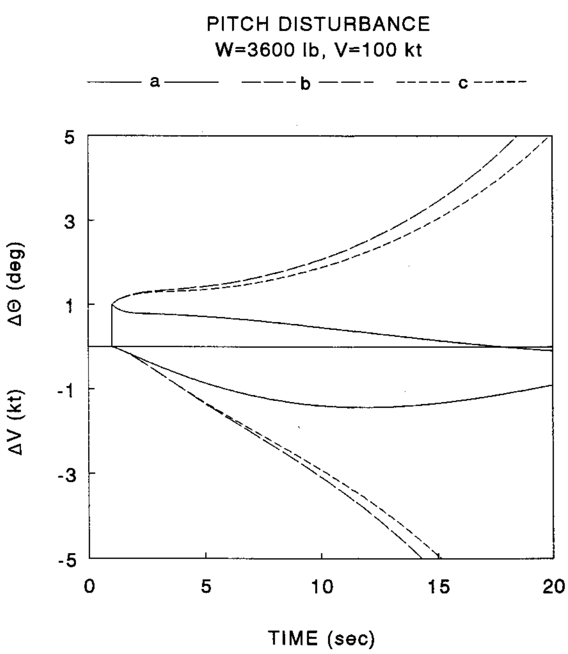

Fig. 1 Pitch angle and speed variation of general aviation aircraft. a—Positive static margin (+2%), centerline thrust (z_T = 0); b—negative static margin (−2%), centerline thrust (z_T = 0); c—negative static margin (−2%), high thrust axis (z_T = −4 ft).

Curves "b" in Fig. 1 show pitch angle and velocity vs time for the same aircraft, having a slightly negative static stability (−2% static margin, z_T = 0). Curves "c" show the aircraft with a high thrust line, 4 ft above the c.g. (z_T = −4). The aircraft is unstable in both configurations: pitch angle and velocity diverge rapidly. The high thrust line has little effect, even though this airplane has a substantial positive margin of 20.9% c with respect to its speed stability neutral point mentioned above.

Figure 2 shows pitch angle and velocity for the microlight aircraft flying at 30 kt in still air with the same static margins as the aircraft in Fig. 1. Again, curves a and b indicate centerline thrust, while curve c shows a high thrust line (z_T = −4). Since the aircraft is lighter and has less pitch inertia, its pitching response is faster than that of the previous aircraft. This time, the high thrust line has a more dramatic effect. The thrust moment variation with speed reduces the pitch divergence significantly, making this vehicle easier to control. Overall, however, pitch and speed still diverge, so the aircraft remains unstable, in spite of its positive margin with respect to the speed stability neutral point.

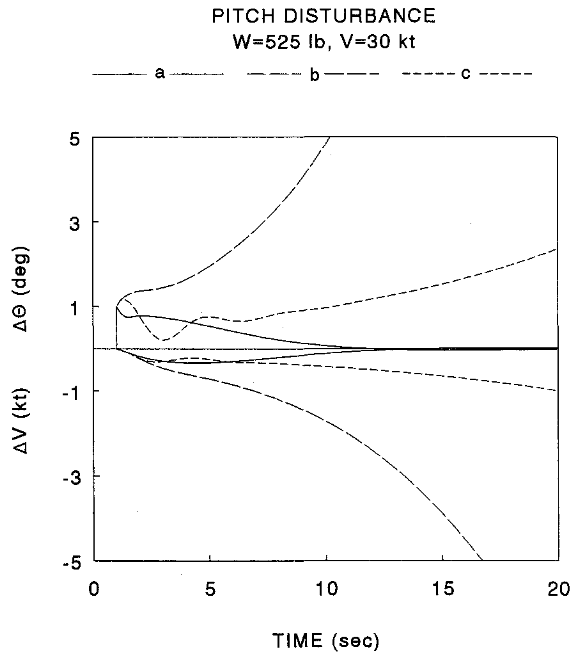

Fig. 2 Pitch angle and speed variation of microlight aircraft. a—Positive static margin (+2%), centerline thrust (z_T = 0); b—negative static margin (−2%), centerline thrust (z_T = 0); c—negative static margin (−2%), high thrust axis (z_T = −4 ft).

Conclusions

High or low thrust lines do not affect static longitudinal stability. Propellers and turbofans do affect longitudinal dynamics through speed changes. Stability predictions require a dynamic analysis. A simple static margin correction based on thrust arm only is unsatisfactory and leads to wrong conclusions.

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Passive Porosity with Free and Fixed Separation on a Tangent-Ogive Forebody

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Nomenclature

C_N = normal force coefficient
C_Y = side force coefficient
α = angle of attack, deg

Introduction

THE passive porosity concept has been extensively studied both experimentally and computationally as a means to control shock/boundary-layer interaction[1–5] and to control flow separation in a weapons bay cavity.[6] The present focus of passive porosity at the National Aeronautics and Space Administration, Langley Research Center is the global application of passive porosity on an aerodynamic vehicle to control the forces and moments of the vehicle.

As a first step in assessing the global application of passive porosity, a review of the literature was conducted that identified high alpha forebody aerodynamics as being of high interest to the aerodynamic community.[7] Experimental data show that slender forebodies at zero sideslip can exhibit large asymmetric loadings about the vertical plane of symmetry at moderate to large angles of attack.[8,9] The character of these asymmetric loads has also been shown to vary with Mach number and boundary-layer state.[7–10] Various experimental studies have been conducted to investigate aerodynamic control effector concepts that control or eliminate the asymmetric loading on slender axisymmetric bodies by controlling the extent of attached flow about the side of the bodies.[11,12] In a recent study by Bauer,[13] passive porosity was successfully employed on a slender axisymmetric forebody to eliminate the loading asymmetry typically observed at moderate to high angles of attack and zero sideslip. The work of Bauer is the first application of passive porosity to control the global pressure loading on a three-dimensional geometry.

Despite the extensive experimental and computational data base within the literature on passive porosity, there is no clear explanation of the governing flow physics. It is theorized that the passive porosity concept modifies the external pressure loading by allowing communication between high- and low-pressure regions on the external surface. One phenomena associated with the communication between high- and low-pressure regions is a minimal transfer of air into the internal chamber at the high-pressure region, and out of the internal chamber at the low-pressure region.[1–4] The second phenomena that may occur is a direct pressure communication between high- and low-pressure regions on the exterior surfaces of the member (i.e., standing pressure wave). Of primary concern within the present research program is determining the dominant flow phenomena that govern the effectiveness of passive porosity (modify forces) with respect to each application.

The present research effort is directed at assessing the contribution of each phenomena as related to a porous slender axisymmetric forebody. To assess the influence of the mass transfer and pressure equalization phenomena to the effectiveness of passive porosity on slender axisymmetric forebodies, strakes were attached to the 5.0-caliber solid and porous forebodies of Ref. 12 to force crossflow separation. The tests were conducted in the NASA Langley Research Center 14- by 22-ft Subsonic Wind Tunnel.[14] Longitudinal force and moment data were obtained at a Mach number of 0.1 over an angle-of-attack range of 0 to 55 deg.

Model Description

The solid and porous wind-tunnel models were 5.0-caliber tangent-ogive with a 2.5-diam (10-in.) cylindrical extension. The models were 30 in. long and had a base diameter of 4 in. The solid and porous models consist of shells of minimum wall thickness that fit over a common centerbody/balance housing. The centerbody, to which the solid and porous shells were attached, is 30 in. long with a maximum diameter of 2.5 in. The region between the o.d. of the centerbody and the i.d. of the forebody shell was used as the plenum for the porous forebody test.

The porous forebody model had a surface porosity of 22% on the 5.0-caliber tangent-ogive section, and had surface porosity that varied linearly from 22 to 0% from the end of the tangent-ogive section to half the length of the cylindrical extension. The rear half of the cylindrical extension was solid. Surface porosity was created by drilling equally spaced (based upon the desired porosity value) 0.020-in.-diam holes over the surface.

As shown in Fig. 1, both large and small strakes attached to the forebody models at the 85- and 265-deg circumferential positions, referenced to the model bottom centerline, and viewed looking forward. The left to right (85 and 265 deg) strake asymmetry was created to induce a unidirectional side force that could be investigated with passive porosity. The

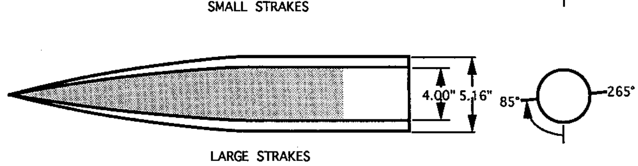

Fig. 1 Sketch showing details of the small and large strakes.

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