HANG GLIDER STABILITY AND CONTROL

By Ed Geller

PREFACE

The attached Appendix was developed to

1. size the tail,
2. choose the tail airfoil,
3. design the Gurney flap trim control on the tail, and
4. position the control bar and the hang point of a rigid wing hang glider designed by the author.

The three-view of the glider is shown below. Pitch is controlled by pilot weight shift. To minimize the pilot "throw", a Gurney flap (not shown in the three-view) is used as a two-position trim control. The wings are completed except for the control system which is somewhat complex (flaps plus droppable ailerons). The wings are lightweight and made of foam, fiberglass and wood but not state of the art carbon construction. The tail needs to be very light in order to minimize tail heaviness during the takeoff run and thus would benefit from a more "exotic" construction. Any help or advice is welcome.

Please feel free to contact me about this project at these addresses:

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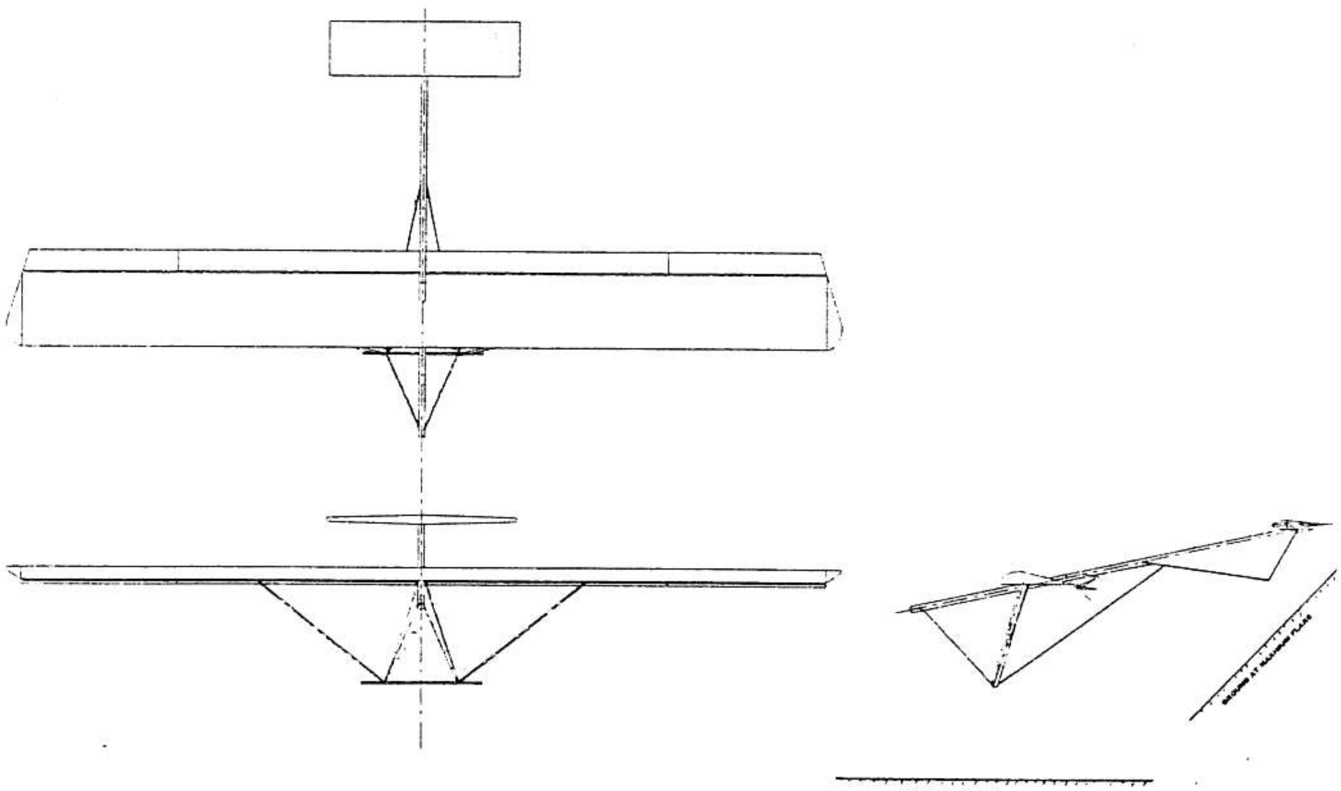


A1 INTRODUCTION

A theoretical analysis of traditional hang glider stability and control is very difficult since the shape is not fixed but changes with aerodynamic loading at varying angles of attack. With the advent of rigid wing hang gliders, a theoretical analysis becomes feasible and the development in this Appendix is intended for that category. Even so, the conclusions in Section A5, some rather surprising, apply to flex wings to some extent.

One special flight condition for a hang glider is hands-off or hang-1Tee flight where the pilot is not holding the control bar and is hanging free. This control-tree condition is similar to the so-called stick-free condition for conventional aircraft, and as for that case, stability is desirable.

Control-tree stability analysis is fundamentally different for a hang glider than for a conventional aircraft. For hang-tree flight, the glider plus pilot cannot be considered as a single rigid body. Instead, the system is two rigid bodies connected at what is called a "pin joint" in engineering mechanics or the "hang point" in hang glider parlance (see Figure A1,1). One body is the glider and the other is the pilot plus the suspension system and any apparatus attached to the pilot.

Intuitively, it seems that if the pilot is hanging tree, the glider should behave as if the pilot were actually attached to the glider at the hang point in which case pendulum stability associated with a low CG should accrue with a low hang point. We show that this intuition is misleading except for the special case where the hang point is level with the glider CG (center of gravity). In Figure A1,1 the hang point is shown in an exaggerated low position to emphasize that this study allows investigation of a low (or high) hang point.

The stability and control analysis is extended to the general flight condition where the pilot controls the equilibrium speed by holding the control bar and moving fore and aft. The control analysis is analogous to classical analysis for aircraft with a control stick for which stick position and stick force are obtained. For hang gliders the control analysis gives pilot fore and aft position and control bar force. The stability analysis, however, is not analogous to classical stick-fixed analysis since in response to a perturbation, the hang glider pilot is not "locked in" but moves with respect to the glider. A conservative pilot response model is identified and stability is evaluated on that basis. An unexpected finding is that for this model, the stability is only weakly dependent on pilot position and very dependent on the hang point position just the opposite of what happens if the pilot is "locked in."

This study includes "powered" hang gliders that have a propulsion unit attached to the pilot. The most common arrangement is the so-called "trike" shown in Figure A1,2a. Another arrangement is the powered harness shown in Figure A1,2b.

Though the analysis is applicable to any pilot system with or without thrust, and applies to either prone or supine pilot suspension, the pilot system will be depicted as in Figure A1,1 with a pusher propeller unit attached to a prone harness or pod. The depiction in Figure A1,1, and elsewhere, can be interpreted as a flying wing (the conventional configuration for a hang glider) or as a wing-horizontal-tail combination (the conventional configuration for aircraft in general). Both types are accommodated in this Appendix.

The analysis through Section A3.6 is mainly concerned with hang-tree flight. However, its applicability to the general case of hands-on flight is revealed in Section A3.7. The presentation in this Appendix is long and detailed. The reader may want to skip directly to Section A4 to see example calculations illustrating important ramifications of this analysis.

A comment regarding approximations is in order. It is often appropriate to make approximations in order to discern first order effects. The equations in this Appendix were developed for use in software. Please excuse the author for not throwing out some of the insignificant terms, for not utilizing standard approximations in some cases and for being inconsistent in this regard.

A3.7 STABILITY AND CONTROL FOR OFF-TRIM FLIGHT, NOT HANG-FREE

Generally, flight is not hands-off. The pilot controls the equilibrium speed by holding on to the control bar and moving fore and aft. To maintain a particular position she must exert a control force on the bar. The flight condition for which the control force is zero is a special condition called trim. At trim, the pilot can release the bar and nothing changes. Hence the trim condition is the same as the hands-off condition, the condition we have also called hang-tree and the condition to which we have restricted our stability analysis up to this point. In this Section the stability analysis for hands-off flight is extended to off-trim flight. As explained below, this extension assumes that the pilot response to a perturbation is to maintain a constant control force.

How do we treat stability for off-trim conditions for which the pilot is holding onto the control bar and exerting a control force B on the bar? We have to know how the pilot reacts to a perturbation. One possibility is that the pilot exerts whatever force is required to maintain the same position relative to the control bar, that is, the pilot is "locked in." She does not move relative to the glider during the perturbation. We maintain that the pilot cannot maintain this "lock-in" except possibly when the pilot's arms are completely extended so that the elbows are "locked." Another possibility is that the pilot does not change the

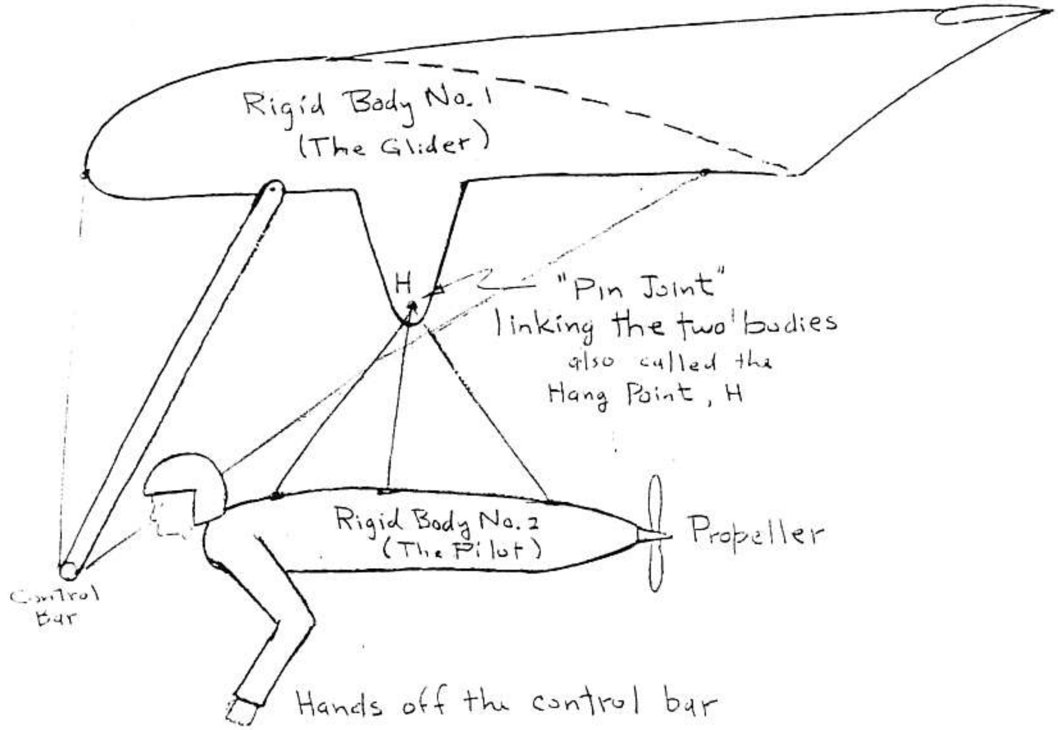
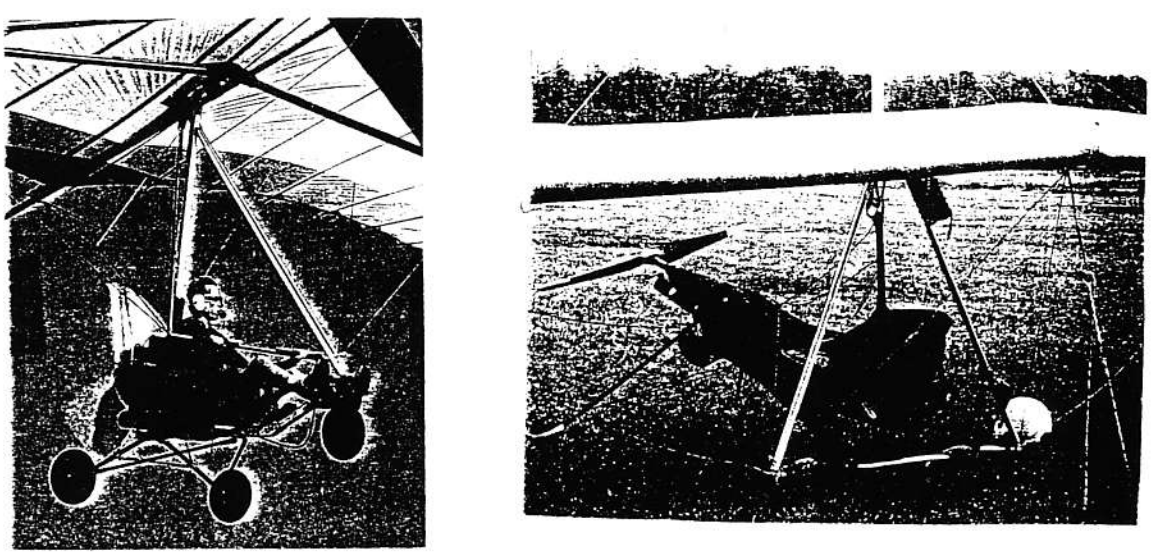


Figure A1,1 Hands-off hang glider flight (a two-body problem).



a. The "trike" configuration.

b. The powered harness

Figure A1,1 Hands-off hang glider flight (a two-body problem).

control force during a perturbation; whatever the control force initially, the pilot maintains the same force on the control bar[1]. The pilot reaction lies somewhere between these two alternatives and likely closer to the latter. Since the latter choice gives the lesser stability, as demonstrated in Section A4.4, it is a conservative choice and is the pilot response for the stability analysis adopted here.

As stated above we assume that the perturbation in the control force is zero; whatever the control force initially, the pilot maintains the same force on the control bar. Now the Newtonian equations of the preceding analysis were derived using the tree-body diagrams in Figures A2,4 and A2,5 where perturbations in the forces are used. The perturbation in the control force B is zero for the hands-off and the same applies to hands-on flight for the constant-control-force response we adopt here. Thus the tree body diagrams and the resulting Newtonian equations developed for the hang-tree case also apply to the general hands-on flight case. The only differences between the hands-on or off stability calculations involve calculation of the direction of the hang line and hence the orientation of the xz axes. Specifically:

1. For the hang-free condition, B and Xx are calculated according to Section A3.4

2. For the general hands-on condition, B and Xx are calculated as shown below.

Although not needed for obtaining the stability for the hands-on condition, the control force, B, is one of the control parameters of interest and equations for its calculation are also developed in the following.

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[1] A helpful model is to think of the pilot being attached to the control bar with a spring. For the first possibility, the spring is infinitely stiff; the length of the spring does not change. For the second possibility, the other end of the spectrum, the spring is infinitely soft; the spring force is the same for all spring extensions.

Before proceeding with this development, we consider the alternative one-body analysis that was shown in Section A3.2 to be valid for hang-tree stability when the hang point is at the same level as the glider CG. Is this alternative also available for the hands-on stability addressed in this Section? The answer is yes! The same arguments used in Section A3.2 prevail here. Thus the following statement applies here:

For the special case where the hang point is level with the glider CG, that is for

$zh=0$

an equivalent simplified analysis obtains. Make the pilot a point mass attached to the hang point and assume the aerodynamic and thrust forces on the pilot act thru that point. This model gives a one-body system that has the same angular acceleration response to a perturbation in angle of attack as that for the two-body system with a hanging pilot who responds to the perturbation by keeping the control force constant.

For this special case (i.e. = 0), the stability is the same regardless of pilot position since the glider behaves as if the pilot were attached to the hang point. A subtle error in this argument exists; zh changes with pilot position except when the hang point coincides with the glider CG. It changes since the xz axes rotate with the hang line (see Sections A2.3 and A2.4). Therefore zh cannot vanish for all pilot positions. See Section A 3.9 for more elaboration. Even so, the above indented statement suggests that stability does not change to a great extent when the pilot moves fore and aft, if the hang point is vertically proximate to the glider CG. Example calculations are needed to establish parameter limits for the accuracy of this assertion (see Section A4.1).

We now proceed with the calculation of B and Xx for the hands on hands-on case. For a particular equilibrium flight condition, the thrust coefficient, Ct, and the lift coefficient, Cl, are given, and the X axis angle of attack, Xx, that provides this lift coefficient is known. Also for this general hands-on case, the tail incidence, It, and the tail flap contribution to the tail lift, $SCltf$, are prescribed except for a flying wing. For a flying wing, the twist distribution is given and $Cmac$ can be obtained using procedures from the literature (e.g. Ref.l or 8).

Calculate C_{L_t} from Eq.A3.6,7 and 8:

$$\alpha_t = \alpha_x - \epsilon + i_t$$

$$C_{L_t} = a_t \alpha_t + \delta C_{L_{tf}}$$

Calculate z_c, d_c, and p from Eq.A3.6,12, 15, and 16:

$$z_c = z_p \tilde{m}_p + z_G \tilde{m}_G$$

$$d_c = (z_{Ac} - z_c)/c$$

$$p = (z_{Ac} - z_p)/c$$

A4 CONTINUED INVESTIGATION USING EXAMPLE CALCULATIONS

The investigation of stability and control is continued using example calculations based on the preceding theoretical analyses. In the following, the stability analysis for off-trim flight, when the pilot is not hanging !Tee, is based on the constant-control-force pilot response model described in Section A3.7. The presentation in Section A4,4 suggests that this model is conservative.

A4.1 VALIDATING THE ALTERNATIVE SINGLE-BODY METHOD

As asserted in the Introduction, intuition suggests that if the pilot is hanging free, the glider should behave as if the pilot were actually attached to the glider at the hang point. If true, an alternative and simpler method for calculating stability is available:

1. Attach the pilot to the hang point
2. Calculate the stability of this single rigid body.

This alternative calculation is simpler mathematically since the system is a single rigid body rather than a linked two-body system. This advantage disappears once soft ware for the two-body system is developed.

The preceding shows that this alternative is valid provided the hang point is "level" with the glider CG. It also showed that it extends to off-trim flight (see Section A3.2 and A3.7). To demonstrate this equivalence and to find out how proximate the hang point must be to the glider CG to provide a sufficiently accurate alternative method, comparison of stability calculation for the two-body method and for the alternative one-body method were made.

We calculated the stability for several vertical hang point locations for a rigid flying wing for the landing configuration (a small inboard flap, fully deflected, and an upright pilot) using the two-body procedure in Section A3.9 and the results are plotted in Figure A4,1 for two lift coefficients, one near stall, $CL = 1.6$, and one near maximum speed with flaps, $CL = 0.4$, (see curves labeled "Hanging pilot"). The stability was also calculated using the analysis for a "locked-in" pilot developed in Section A3.11 with the pilot located at the hang point and the results are also plotted in the figure (see curve labeled "Pilot attached to hang point"). The two stability calculations converge at a hang point level given by $zh=0$ thus validating the analysis of Section A3.2 and its extension, Section A3.1O. Similar results were obtained with no flap deflection.

A similar study was made for a rigid wing glider with a tail for the low speed cruise configuration (CL =1.4, no flaps, and reclined pilot) and for the diving landing approach configuration (CL = 1.2, full flap and drooped ailerons) and the results are shown in Figure A4,2. Again,

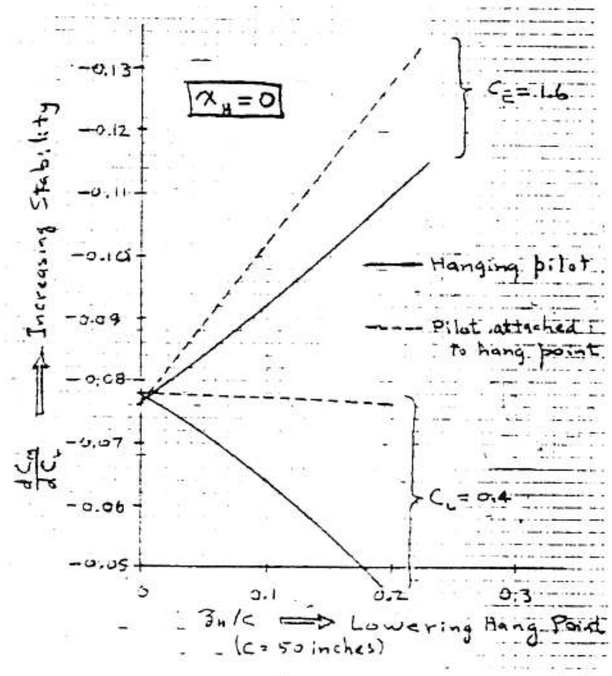

Figure A4,1 Stability versus hang point vertical location for a flying wing.

the equivalence of the two stability calculation methods at $zh=0$ is demonstrated[1].

We now assess the error in using the alternative method for hang points below the glider CG. For the example calculations shown in Figures A4,1 and A4,2, a hang point O.1 chord (approximately five inches) below the glider CG gives an error in dcm/dcl of the order of 0.01 (an error in stability margin of 1% chord), not insignificant but an acceptable error for "rough" design work. For a traditional hang glider using a hang strap around the keel, the hang point is probably within five vertical inches of the glider CG. Thus the alternative method is marginally acceptable for traditional hang glider design.

If the designer wishes to investigate the use of a low hang point to increase the stability (see Section A4.2), the alternative method should not be used. Practical considerations limit the extent of such lowering. A special structure is required for lowering the hang point below a certain point. Also the attendant lowering of the pilot or alternatively the shortening of the hang straps presents problems.

[1] The unequal stability at $zh=0$ for the two configurations is the result of two factors. The aerodynamic center of the wing changes with flap deflection and aileron droop and

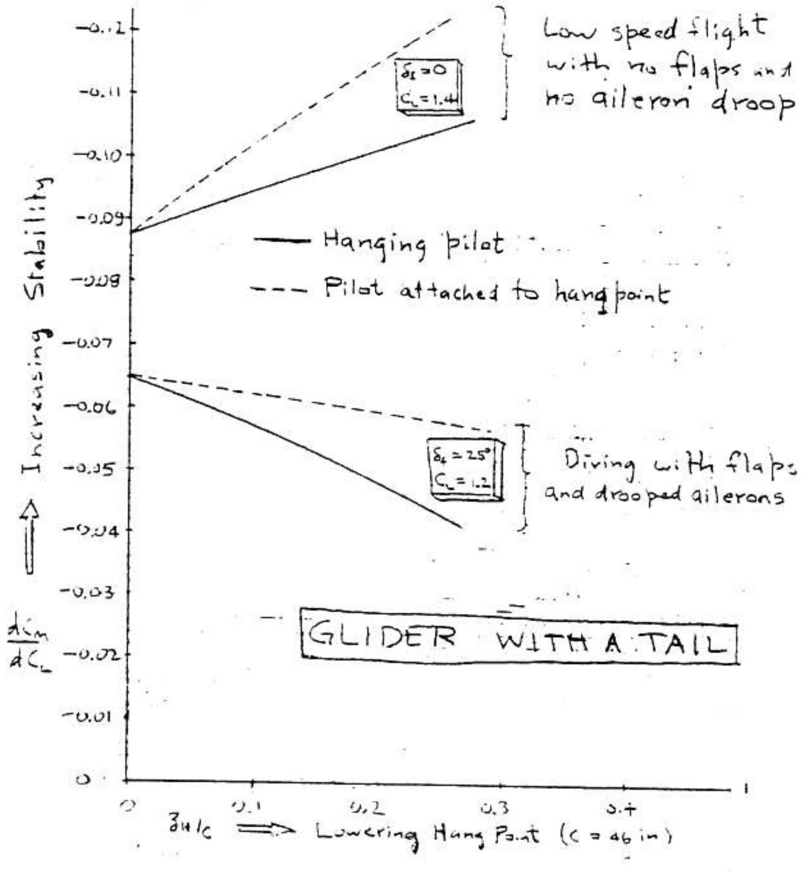

Figure A4,2 Stability versus hang point vertical location for a glider with a tail.

the down wash gradient at the tail depends upon flap deflection and aileron droop, and on wing lift coefficient.

A4.2 THE EFFECT OF LOWERING THE HANG POINT ON STABILITY

In this section the idea of lowering the hang point in order to increase the stability is investigated. As mentioned in the Introduction, intuition suggests that if the pilot is hanging / Tee, the glider should behave as if the pilot were actually attached to the glider at the hang point. If this equivalence is true then lowering the hang point should increase stability (the pendulum stability effect). We have proved that this equivalence is only valid if the hang point is "level" with the glider CG (see Section A3.2). Never the less it seems likely that lowering the hang point should increase stability. The example calculations from the last Section show that this is not always the case. Calculations for both a flying wing and a glider with a tail, show that the small disturbance stability decreases with lowering of the hang point for mildly diving flight with flaps deployed (see Figure A4,1 for the two-body analysis at $CL = 0.4$ and Figure A4,2 for the two-body analysis at $CL = 1.2$ and $\delta f = 25°$). The results for the flying wing are plotted in another form in Figure A4,3. The stability is plotted versus lift coefficient for two vertical hang point locations at high

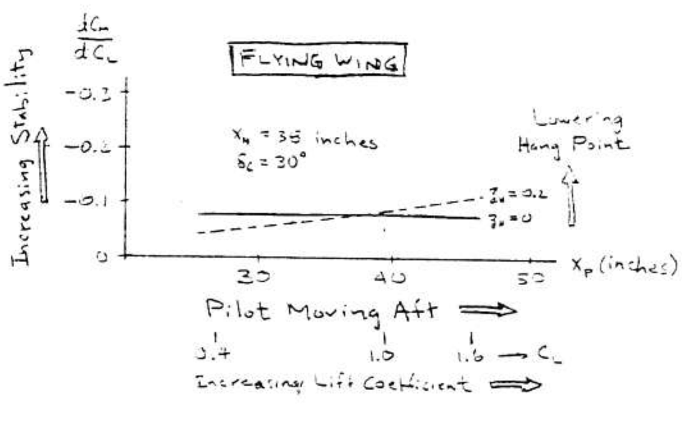

Figure A4,3 The effect of hang point vertical location on small disturbance stability.

speed (low lift coefficient and forward pilot position), the stability decreases with a lower hang point. At low speed (high lift coefficient and aft pilot position), the stability increases.

The preceding addresses the effect of hang point vertical location on small disturbance stability. We now investigate its effect on large disturbance stability using the analysis of

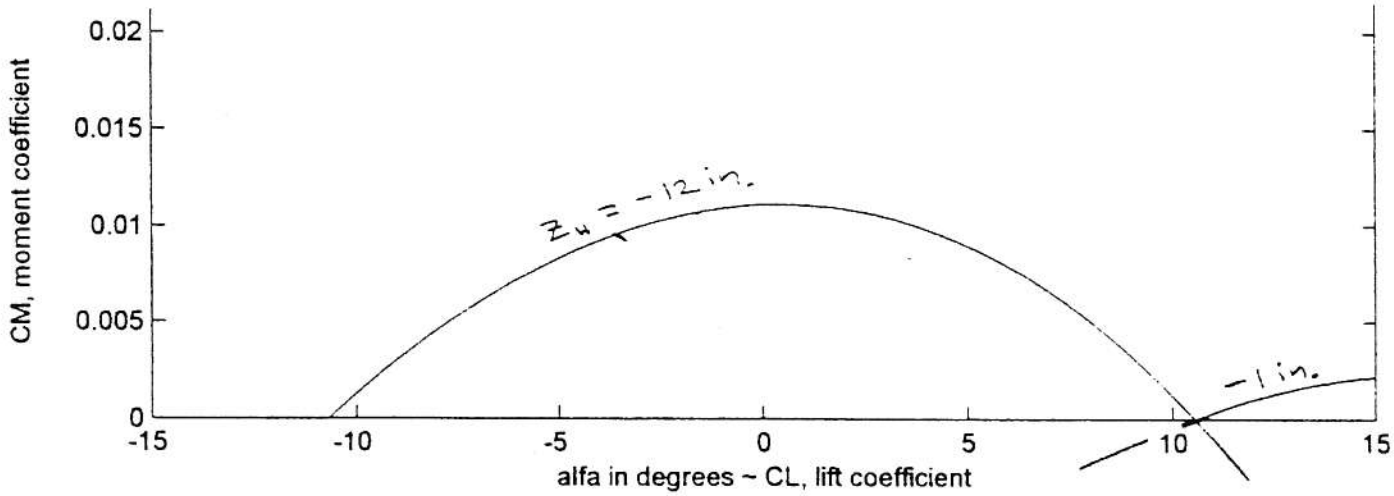

Figure A4,4 The effect of hang point vertical location on large disturbance stability.

Section A3.8. The results of calculations for a glider with a tail are shown for two hang points in Figure A4,4. Equilibrium is at an angle of attack of 10.6 degrees and at a lift coefficient of 3.0 (attainable with full flaps and drooped ailerons). Note that the slope of the curve at equilibrium for a hang point one inch below the X body axis is positive (an unstable situation). Although lowering the hang point to 12 inches below the X body axis provides the negative slope at equilibrium (*dcm/dcl*=-0.027) required for small disturbance stability, it does not quite provide sufficient large disturbance stability since any gust induced angle of attack perturbation more severe than -22 degrees (not impossible for the very low speed flight of this illustration) gives a destabilizing nose down moment. The highly nonlinear curve is not typical. Large lift coefficients and a low hang point and/or a low glider CG can produce such a condition. The author found it difficult to obtain an illustration such as Figure A4,4. Usually, if small disturbance stability is sufficient, large disturbance stability is adequate.

A4.3 THE EFFECT OF PILOT AND HANG POINT FORE AND AFT POSITION

As stated at the end of Section A3.9, when the hang point is at the CG of the glider, and when the aerodynamic moment varies linearly with angle of attack, the typical case, then the small disturbance stability is the same for all lift coefficients. As the pilot moves fore and aft to change the flight speed, the stability does not change. The calculations for a flying wing are plotted in Figure A4,5 and illustrate this independence (see curve labeled $X_{G'} = X_H = 38.6$ inches). For hang points at the same "level" as the glider CG but not aligned fore and aft, the stability changes with pilot position (i.e. with lift coefficient) as shown in Figure A4,5. However, as predicted in Section A3.9, this dependence is weak. The deviation from strict independence increases as the hang point moves further away from the glider CG. Even for a ten inch nonalignment (see curve labeled X_H=48 inches) the stability is nearly constant. On the other hand the hang point location has a large effect on the stability. Moving the hang point 10 inches to the rear of the glider CG decreases the stability significantly (again see Figure A4,5). This behavior is predicted by the equivalent single-body system defined in Section A3.2 for which the pilot is attached to the hang point.

A4.4 STABILITY CALCULATION USING CONSTANT-CONTROL-FORCE RESPONSE - IS IT CONSERVATIVE?

Regarding response to a perturbation, in Section A3.7 we adopted constant-control-force pilot feed back. For the

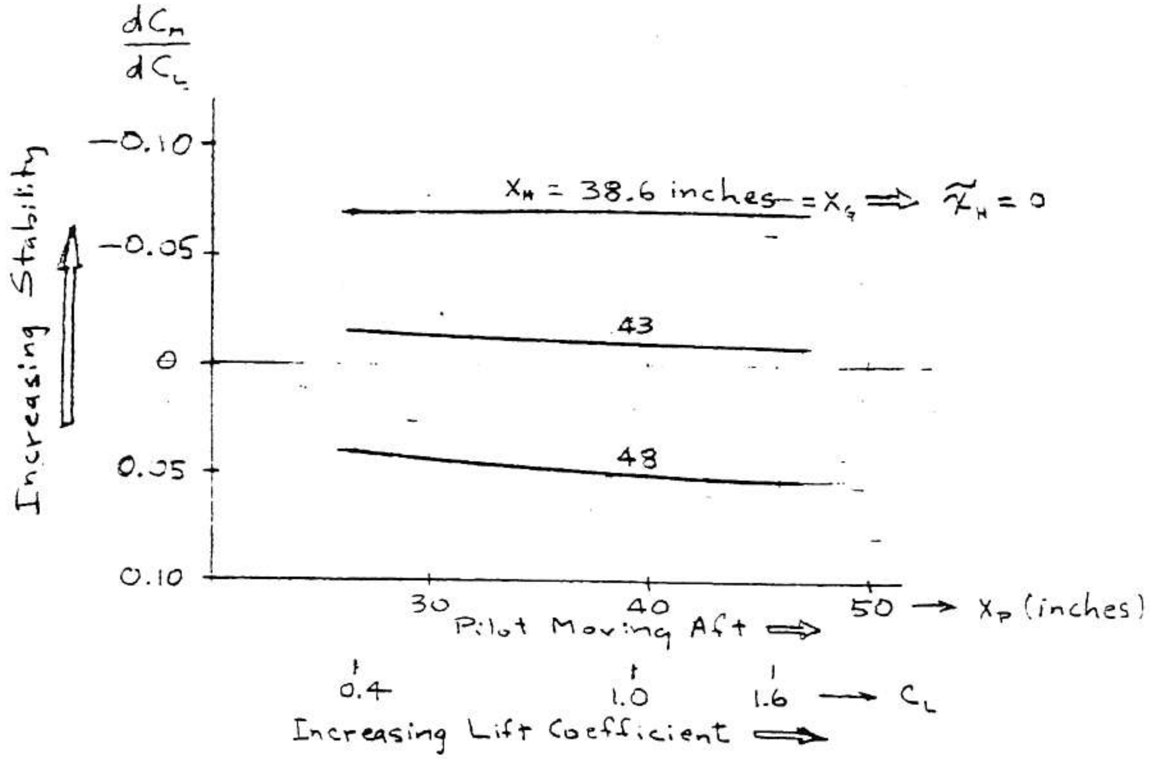

Figure A4,5 The effect of fore and aft position of the pilot and of the hang point.

hang-free case this is obviously correct. For off-trim flight the pilot response is problematic. However, the following example calculations show that the adopted response model is conservative according to this rationale:

The response control force is bracketed by the minimum associated with the constant force response and the maximum associated with pilot "lock-in." If we show that the "lock-in" case provides more stability than the constant force case, then adopting the constant force model is conservative.

The stability of a rigid flying wing with a deflected inboard flap was calculated first, according to Section A3.9, which uses the constant-force model for pilot response and second, according to Section A3.11, which assumes pilot "lock-in." The hang point is at the level of the glider CG. The results are plotted in Figure A4,6.For all pilot positions the stability for constant-force response is less than for "lock-in." Similar results were obtained with no flap deflection.

A4.5 EXAMPLE VARIATION OF CONTROL FORCE AND PILOT POSITION WITH LIFT COEFFICIENT

The Control force and pilot position versus lift coefficient for a flying wing is shown in Figure A4,7. This plot was obtained using the calculation procedure in Section A3.7. Such a calculation is useful during design to check for acceptable pilot movement, acceptable control forces and acceptable control force gradient. Trim or hang-free flight (i.e. flight at vanishing control force) occurs at a lift coefficient of 0.9 for this example.

A5 CONCLUSIONS

Equations developed in this appendix are useful for the design of rigid wing hang gliders. Design factors are pilot throw (limited ergonomically), the magnitude and the gradient of the control force, stability for small and large disturbances in angle of attack, stability during the takeoff run and during tow. Configurations with a tail are accommodated.

The stability of the glider-pilot combination cannot be predicted using traditional aircraft stability analysis since the combination is not a rigid body. In fact assuming that the pilot is "locked in", significantly overestimates the stability. The system should be treated as two rigid bodies, the glider and the pilot, with interacting forces at the two places where they are in contact with each other. These are the hang point and the "point" where the pilot holds the

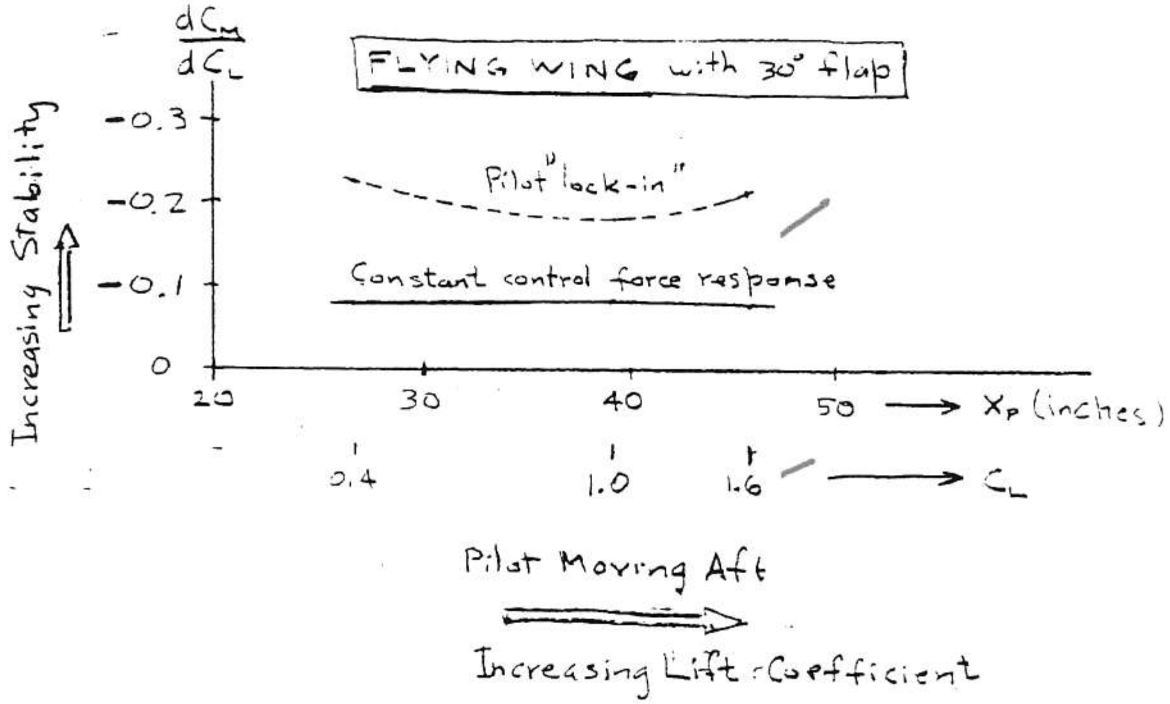

Figure A4,6 Comparison of stability for pilot "lock-in" and for constant-control-force pilot response.

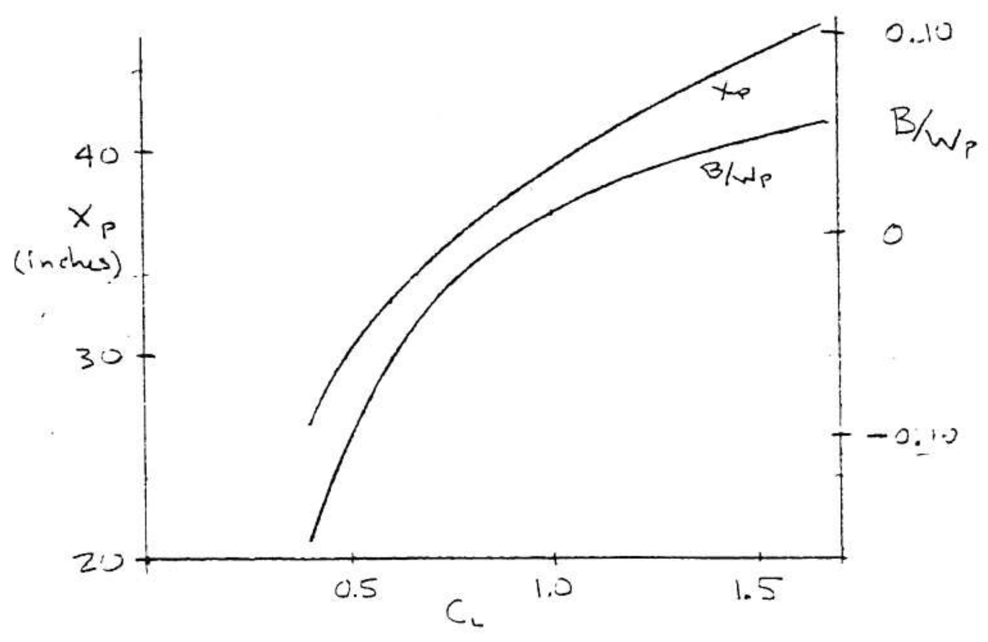

Figure A4,7 Pilot position and control force versus lift coefficient.

control bar. The hang point interaction is treated using the pin joint concept of engineering mechanics. The control bar interaction is more problematic except for the special case of hang-free flight where the pilot lets go of the control bar and the control bar interaction disappears. For the general flight case where the pilot is holding the control bar, the pilot's response to a perturbation is probably close to that of maintaining a constant control force and skewed slightly toward the extreme of the pilot holding a fixed position (the hang glider pilot can not "lock in" but moves with respect to the glider). Example calculations show that the constant-control-force response model gives less stability than for pilot "lock in" and therefore it can be argued that stability calculations based on this response model are conservative.

Theoretical analysis and example calculations support these interesting assertions for constant-control-force response:

1. If the hang point coincides with the glider CG, the stability is independent of the pilot fore and aft position; as the pilot moves aft to fly at a lower speed, the stability does not decrease as would be the case if the pilot were "locked in."

2. If the hang point is vertically aligned with the pilot CG[1], the stability decreases the hang point moves aft but does not change significantly as the pilot moves fore and aft to control the flight speed. This effect of pilot CG and hang point location on the stability is just the opposite of what happens if the pilot is "locked in." For that case, the hang point position is irrelevant and the pilot position has a primary influence.

3. If the hang point is vertically aligned with the glider CG[1], the glider responds to a disturbance as if the pilot were attached to the hang point. Thus for such vertical alignment of the hang point, traditional stability analysis which assumes the pilot-glider combination is a rigid body, can be used by fixing the pilot at the hang point. A sensitivity study showed that for a hang point less than one half vertical feet from the glider CG[2] , this approach is sufficiently accurate. Such an alternative calculation is simpler since the governing equations are simpler but this advantage disappears once software has been developed for the general case.

4. The so-called pendulum stability that is often invoked for hang gliders is a fallacy. It only occurs if the pilot is "locked in", a difficult teat for the pilot and by definition not occurring for hang-free flight.

5.The stability usually increases as the hang point is lowered. One exception is for diving flight (e.g. high-speed flight with flaps deployed). For that reason, lowering the hang point in an attempt to increase stability may not be effective for all flight regimes.

[1]This condition is nearly satisfied for hang gliders using a hang strap around a keel.

[2] This condition is easily satisfied for hang gliders using a hang strap around a keel.