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Analysis of Factors Influencing Gyroplane Longitudinal Stick Position and Gradient

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Departmental Report No. 0005

December 2000

Introduction

Stick position and stick gradient as functions of airspeed, can be important indicators of aircraft handling qualities. Gradient is a measure of the stability derivative M_u, which has an important role to play in determining the period of phugoid-type oscillations. Since BCAR Section T dynamic stability criteria are predicated on oscillation characteristics, stick position and gradient may be a significant indicator or check of compliance. Stick position assumes increased importance for the gyroplane because it is one of the few parameters that can be readily measured without sophisticated or dedicated instrumentation.

Background

Simulation and flight test of the VPM M16 have shown the importance of vertical c.g. position in determining the stability of the phugoid-type oscillation of gyroplanes. Raising the c.g. tends to confer positive angle-of-attack stability ($M_w < 0$) which tends to stabilise the phugoid oscillation, which is likely to mean compliance with Section T. However, during technical audit of the work, it was pointed out by Colin Massey, GKN-Westland's Chief Aircraft Performance Engineer, that raising the c.g. could have an adverse impact on stick gradient, and that this could set a limit on the extent to which the c.g. could be raised. Colin Massey used a graphical approach to demonstrate the case, see Appendix. This Report however outlines an alternative approach.

Analysis

The analysis is based on an alternative mathematical method. This provides a dissimilar verification of the graphical approach contained in the Appendix.

The longitudinal aircraft equations of motion for equilibrium flight, incorporating the same schematic as the graphical analysis, and referring to the Figure 1 below, are given by

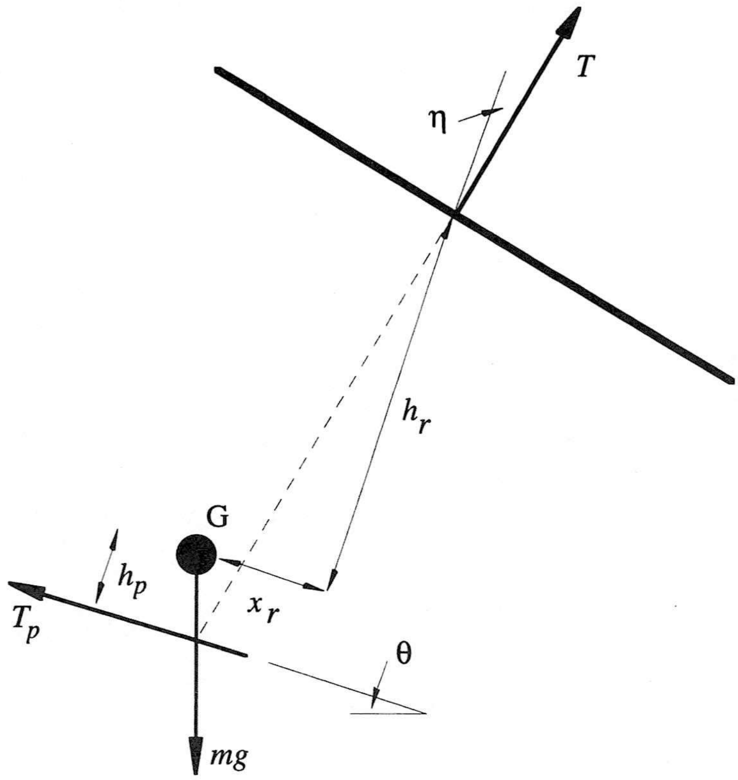


Figure 1 – Schematic of longitudinal forces and moments

$$\sum X = T_P - T\sin\eta - mg\sin\theta = 0$$

$$\sum Z = -T\cos\eta + mg\cos\theta = 0$$

$$\sum M = T_p h_p + T\sin\eta h_r - T\cos\eta x_r = 0$$

These equations are now used to examine stick position with airspeed. The independent variable is not pitch attitude, but rotor angle of attack. (Glauert's original work remember showed rotor thrust to be a function of axial velocity - a constant axial velocity at constant rotorspeed can only be achieved with increasing airspeed if the angle of attack is reduced). We have therefore sought to express our governing equation in terms of this parameter. It can be shown easily from the above equations of motion, assuming small angles and neglecting rotor flapping, that

$$\eta = \frac{x_r - h_p \alpha_r}{h_r} \quad (1)$$

where η is the tilt of the rotor thrust vector (positive aft), x_r is the position of the c.g. ahead of the rotor hub in body axes, h_p is the height of the rotor hub above the c.g. in body axes, h_r is the height of the c.g. above the propeller thrust line in body axes and α_r is the rotor disc angle of attack (we further assume that rotor thrust is normal to the disc). From simple geometric considerations

$$\alpha_r = \eta + \theta \quad (2)$$

We can now engage in some analysis.

From equation (1), it can be seen that if the propeller thrust line passes through the c.g., tilt of the rotor thrust vector (i.e. stick position) is independent of rotor angle of attack and therefore airspeed.

From equation (1), for a given α_r i.e. a given airspeed, a configuration with the propeller thrust line below the c.g. ($h_p > 0$) will have a smaller value of η than for a configuration with the propeller thrust line above the c.g. ($h_p < 0$), i.e. the stick will be further forward. This is consistent with RASCAL model simulation results, as can be seen in Figures 12 & 18 of the Air Command Report.

From equation (1), for α_r reducing (i.e. increasing airspeed), then η increases i.e. the stick moves aft if the c.g. is above the propeller thrust line ($h_p > 0$). Conversely η decreases i.e. the stick moves forward if the c.g. is below the propeller thrust line ($h_p > 0$).

It can therefore be concluded that our mathematical analysis is consistent with the graphical analysis in the Appendix.

The veracity of this qualitative assessment can now be challenged quantitatively, without recourse to more diagrams which is the only alternative if no equation is available.

(a) From the flight test data available for the VPM M16, at 24 knots (lowest airspeed achieved), η=62.9%=11.2deg, and θ=5.3deg. From equation (2), this gives α_r =16.5deg. Using equation (1) then gives h_p =-0.23m.

(b) From the flight test data available for the VPM M16, at 40 knots η=55%=9.8deg, and θ=3.4deg. From equation (2), this gives α_r =13.2deg. Using equation (1) then gives h_p =-0.13m.

We have limited ourselves to 40 knots as above this speed, the assumptions in the model are probably no longer valid (this is true in the graphical approach as well). Both of these values of h_p indicate a c.g. well below the propeller hub axis, substantially more than has been measured (0.03m below at light weight, 0.06 below at high weight). Accordingly, this mismatch indicates the limiting nature of the underlying assumptions (even at low speed where they are most valid) made in the development of the simple model in equation (1), assumptions common with the Appendix.

(c) A further interesting insight can be obtained if we use the flight test data above, to calculate stick position for two nominal values of h_p, of ±2 inches.

A/s (knots)	c.g. 2in above prop. thrust	c.g. 2in below prop. thrust
24	η=8.04deg	η=9.18deg
40	η=8.16deg	η=9.07deg

So it is clear that indeed, the stick gradients are as the graphical method predicts, further verifying that assessment. However, in quantitative terms, a ±2 inch variation in vertical c.g. position has a very small impact on stick *gradient*, about 0.1deg over 16 knots, which is about 0.6% of stick travel, or about 0.005 in/knot, i.e. one or two orders of magnitude smaller than any of the configurations shown on Figure 2, although it has a more significant impact on stick *position* (at either airspeed above, of the order of 1 deg or about 6% of stick travel). These figures double if one assumes ±4 inch variation in vertical c.g. position, which is really quite extreme. So, although the assessment regarding stick gradient is correct, it would appear that the *gradient* is relatively insensitive to vertical c.g. position, although stick *position* is not.

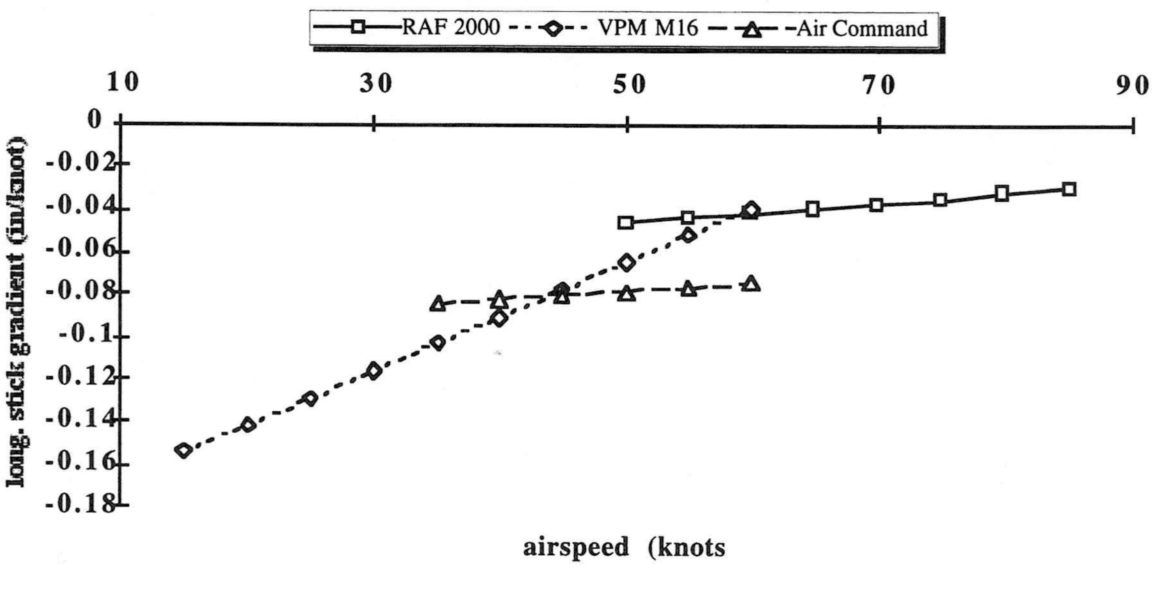


Figure 2 – Longitudinal stick gradient comparisons

The flight test data reproduced in Figure 2 is inconclusive since there appears to be no correlation between stick gradient and vertical c.g. (as the quantitative analysis above would tend to suggest). The RAF 2000 has a very low c.g. when dual as tested (about 9 in below the propeller thrust line; the VPM has a thrust line close to or slightly below the c.g.; the MODAC 503 has thrust line and c.g. almost coincident (it does tend to agree with the simple

analysis in this regard, as it has almost no stick gradient with speed relative to the others); and by consent Roger Savage's Air Command measurements are at variance with Chris Chadwick's.

Discussion

Given a desire to have something simple and easily understood by the wider community, we would argue that our analysis results in ease of interpretation and clarity of understanding that might be absent with the graphical interpretation (both in terms of the number of figures, and their detail).

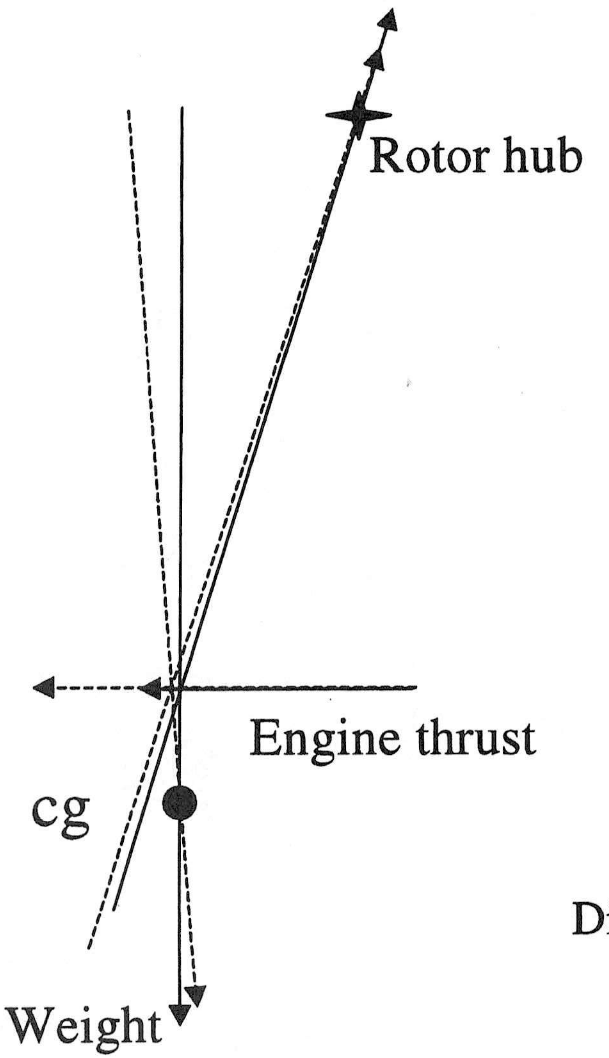
However, given that both approaches lead to the same conclusion, what does this mean for any advisory Section T material? Moving the c.g. up relative to the propeller thrust line, will tend to make $M_w < 0$, tending to stabilise the unstable phugoid oscillation. Leaving aside the quantitative analysis above, the consequence on stick gradient is to flatten and then reverse stick gradient, and tend to render $M_u < 0$ with possible attendant consequences for the phugoid. A compromise therefore seems desirable, but the quantitiative analysis above tends to indicate that stick gradient and hence M_u is much less sensitive to vertical c.g. than is M_w. However, it would be prudent to check as part of any design modification package.

Conclusion

Graphical and analytical approaches concur completely, specifically that, subject to approximation and assumption, the stick position gradient with speed is negative (i.e. stick forward with increasing speed) for configurations with the c.g. below the propeller thrust line; and positive (i.e. stick aft with increasing speed) for configurations with the c.g. above the propeller thrust line. However, it would appear that the *gradient* is relatively insensitive to vertical c.g. position, although stick *position* is not.

Appendix

Figure 1



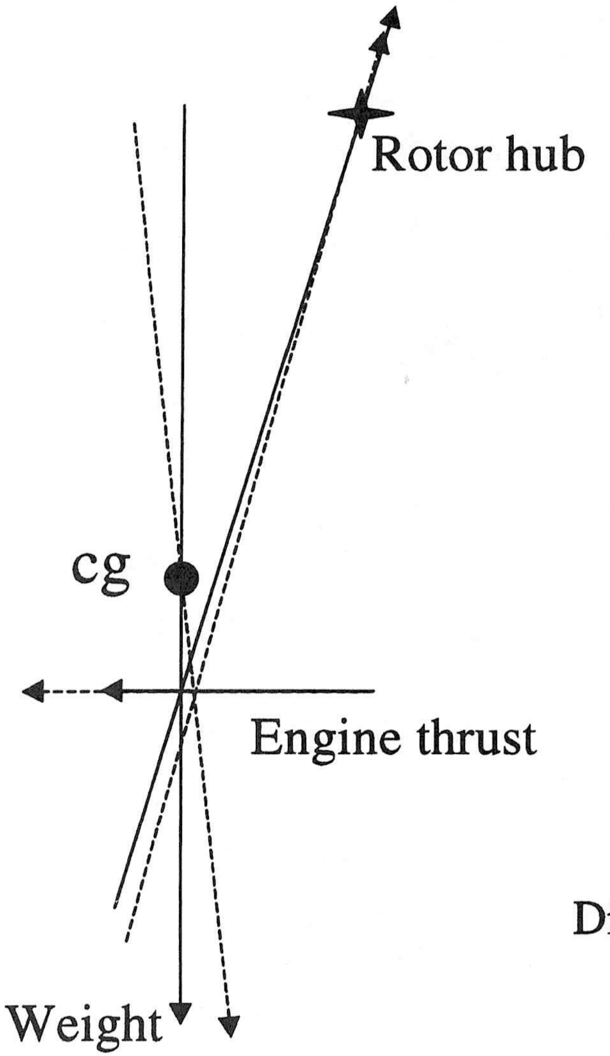
------------ Lower speed, nose up attitude

——— Higher speed, level attitude,
- weight vector moves forward,
- rotor thrust must rotate in negative (top forward) sense to maintain moment balance,
- natural rotor tendency is for increased aft flapping,
- forward stick required to counter flapping and generate additional thrust vector rotation
- Magnitude of engine thrust will vary to maintain force balance, but has no effect on moment balance.

Diagram referenced to aircraft body axes

C P Massey, September 1999

Figure 2

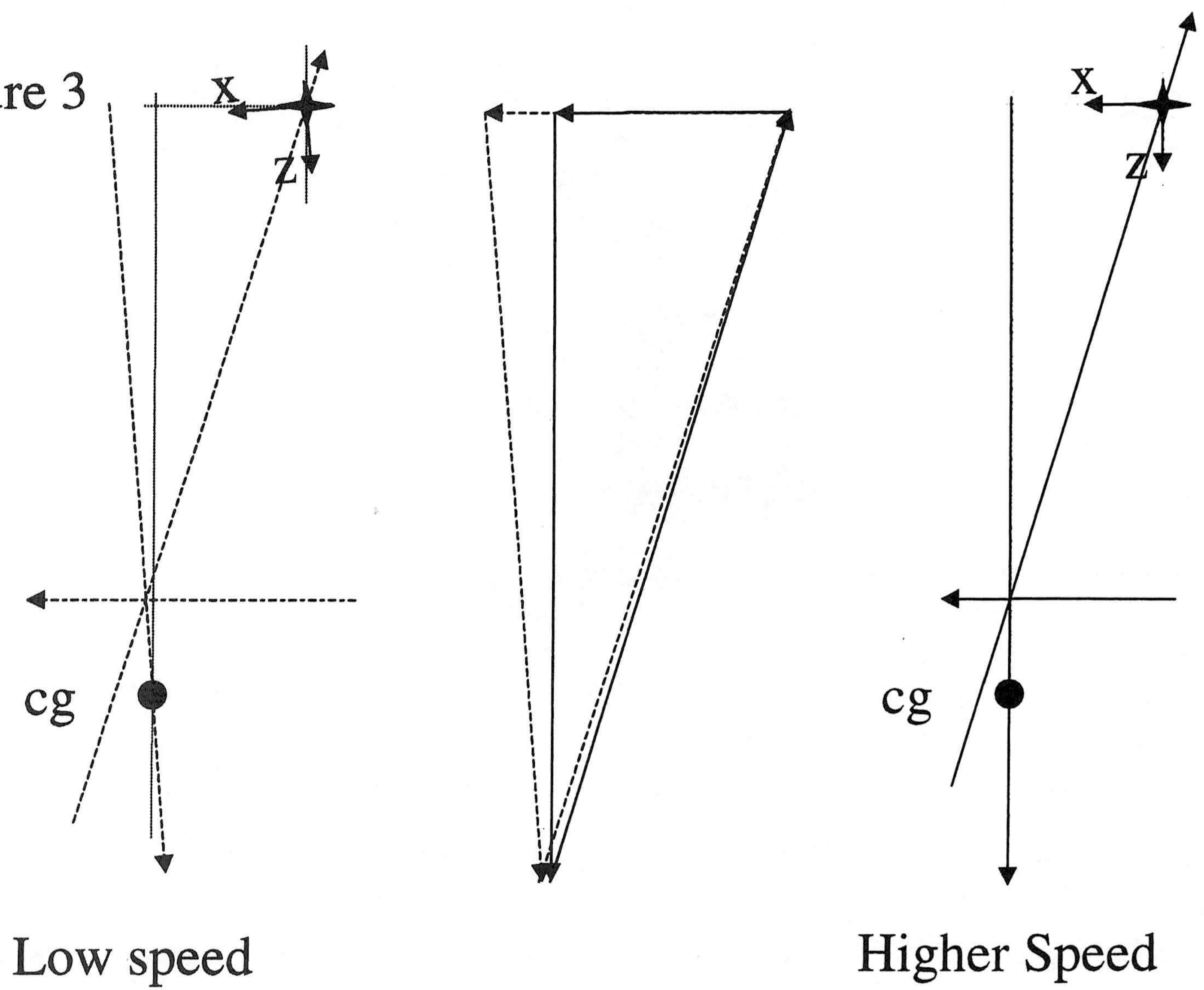


[dashed line] Lower speed, nose up attitude

[solid line] Higher speed, level attitude,
- weight vector moves forward,
- rotor thrust must rotate in positive (top aft) sense to maintain moment balance,
- natural rotor tendency is for increased aft flapping,
- If above is insufficient, aft stick is required, ie negative stick stability
- Magnitude of engine thrust will vary to maintain force balance, but has no effect on moment balance.

Diagram referenced to aircraft body axes

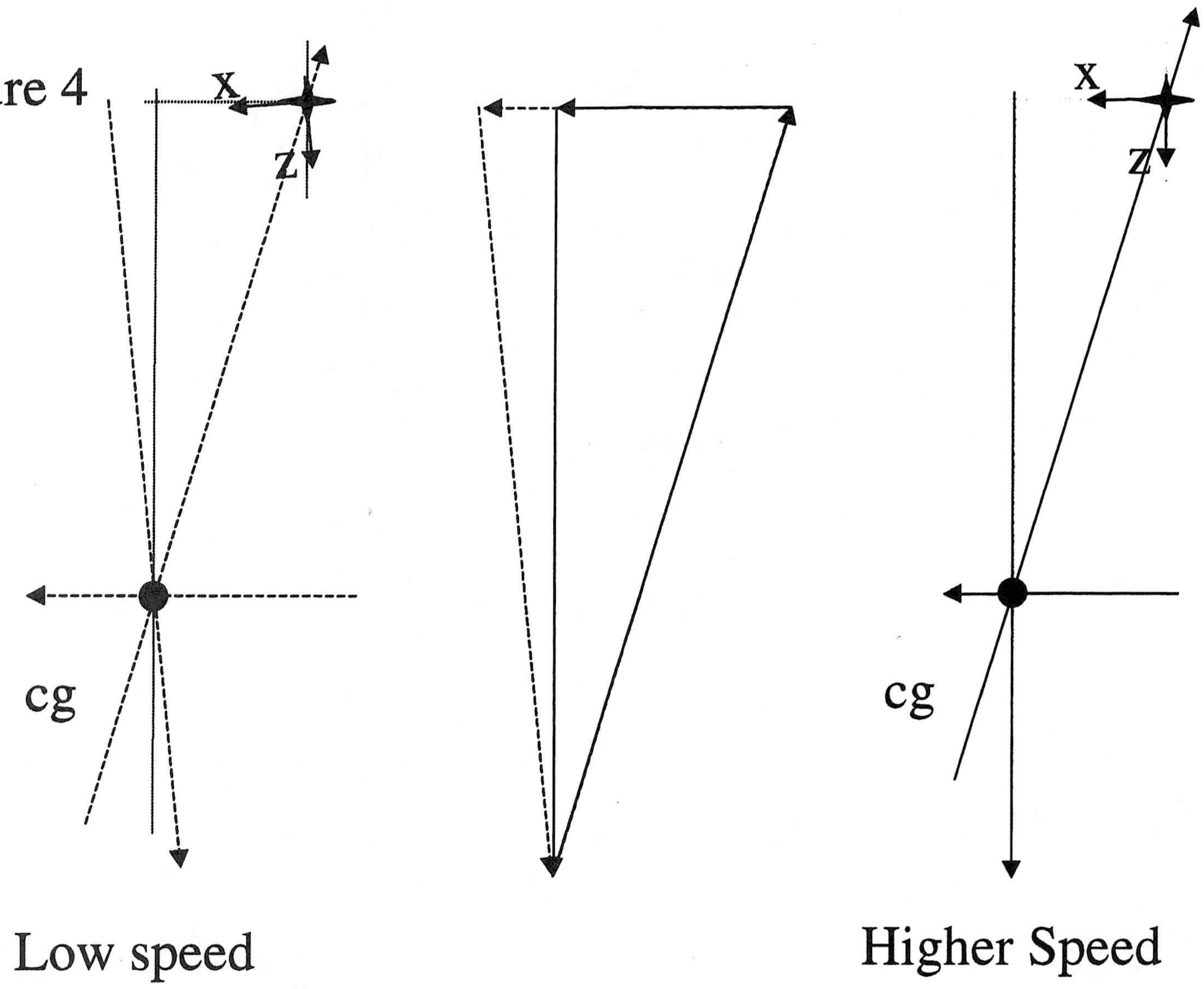
Figure 3



Diagrams referenced to aircraft body axes, x ← ↓ z gives earth axis reference

C P Massey, September 1999

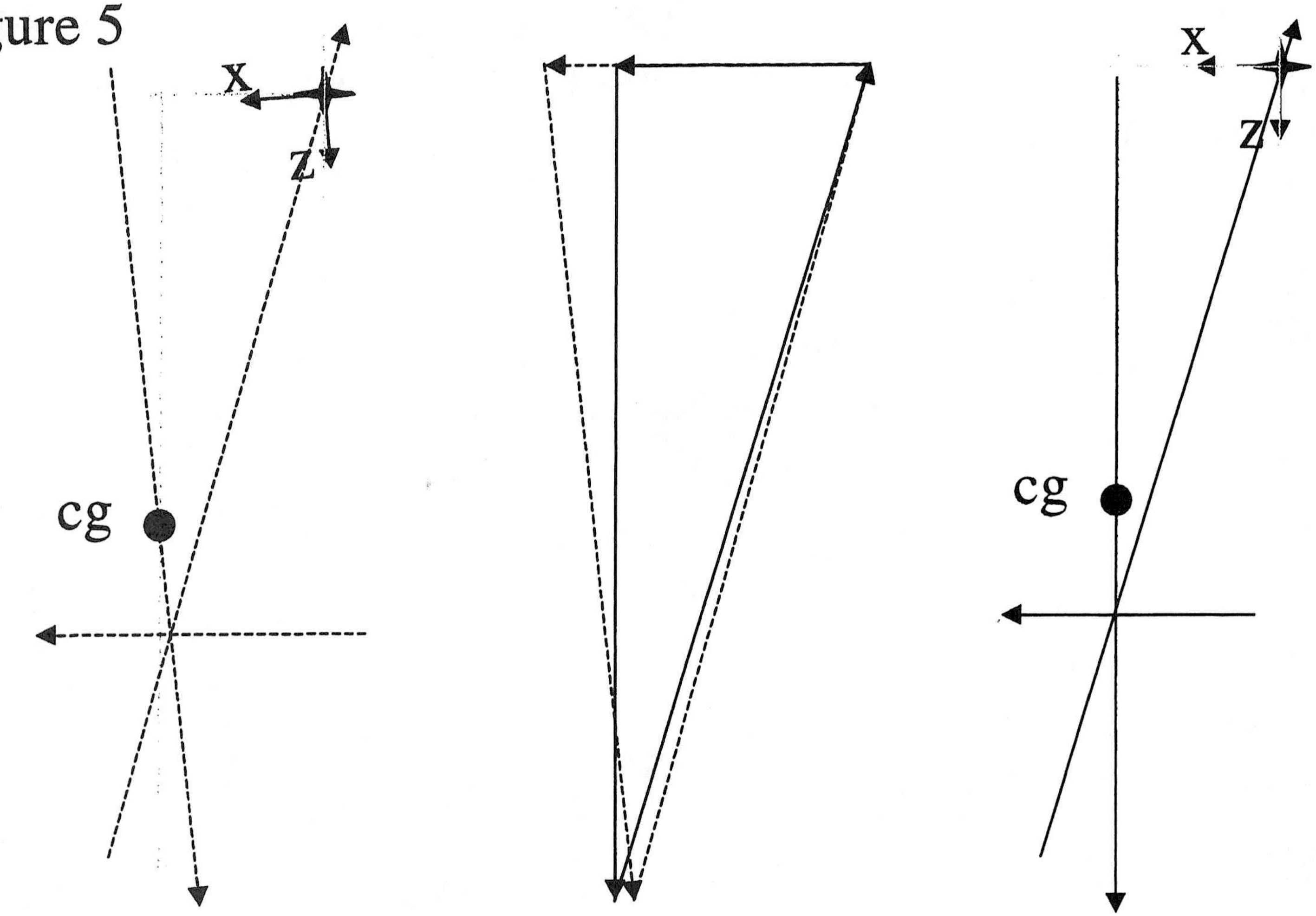
Figure 4



Diagrams referenced to aircraft body axes, x z gives earth axis reference

C P Massey, September 1999

Figure 5



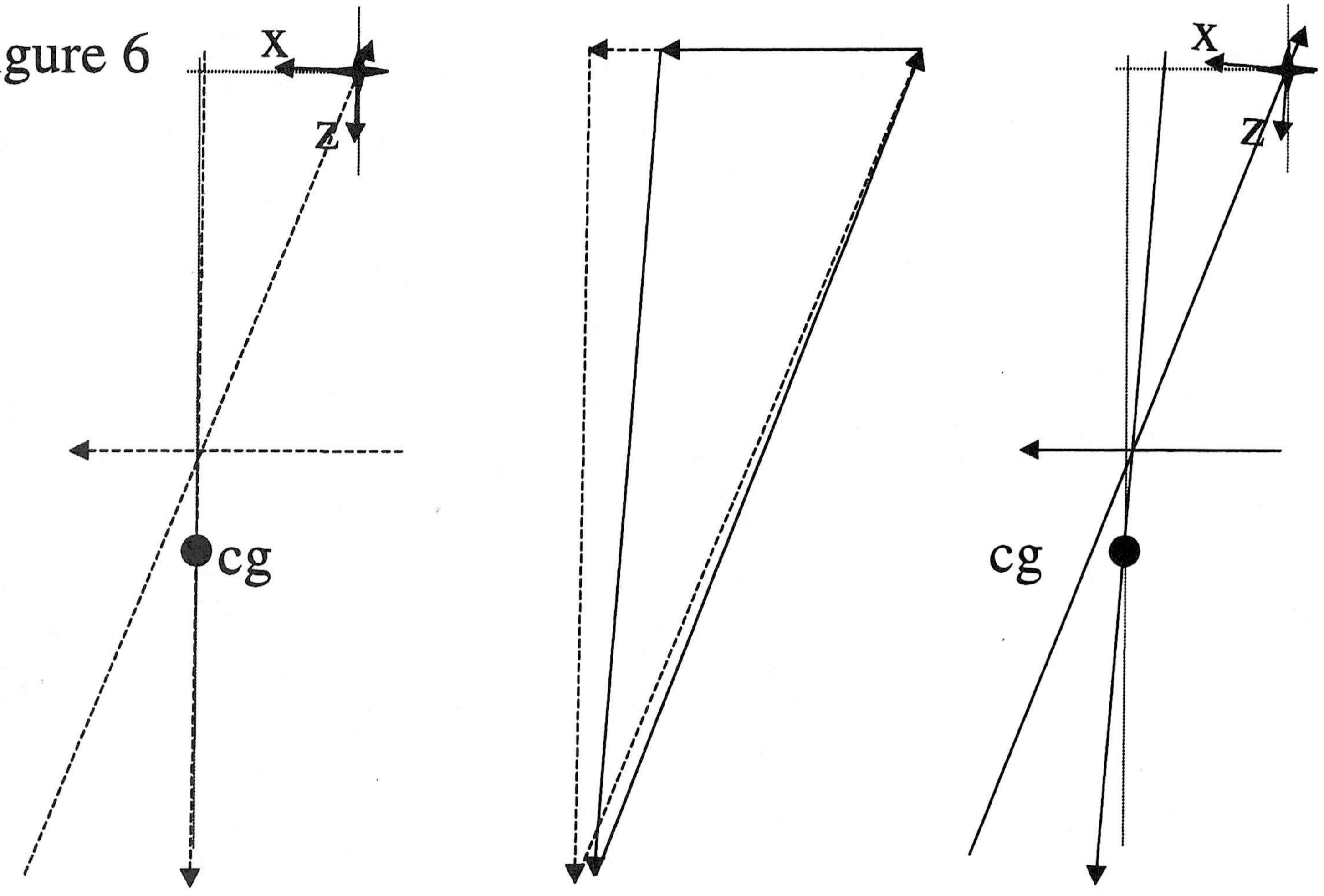
Low speed

Higher Speed

Diagrams referenced to aircraft body axes, x ↞ z gives earth axis reference

C P Massey, September 1999

Figure 6



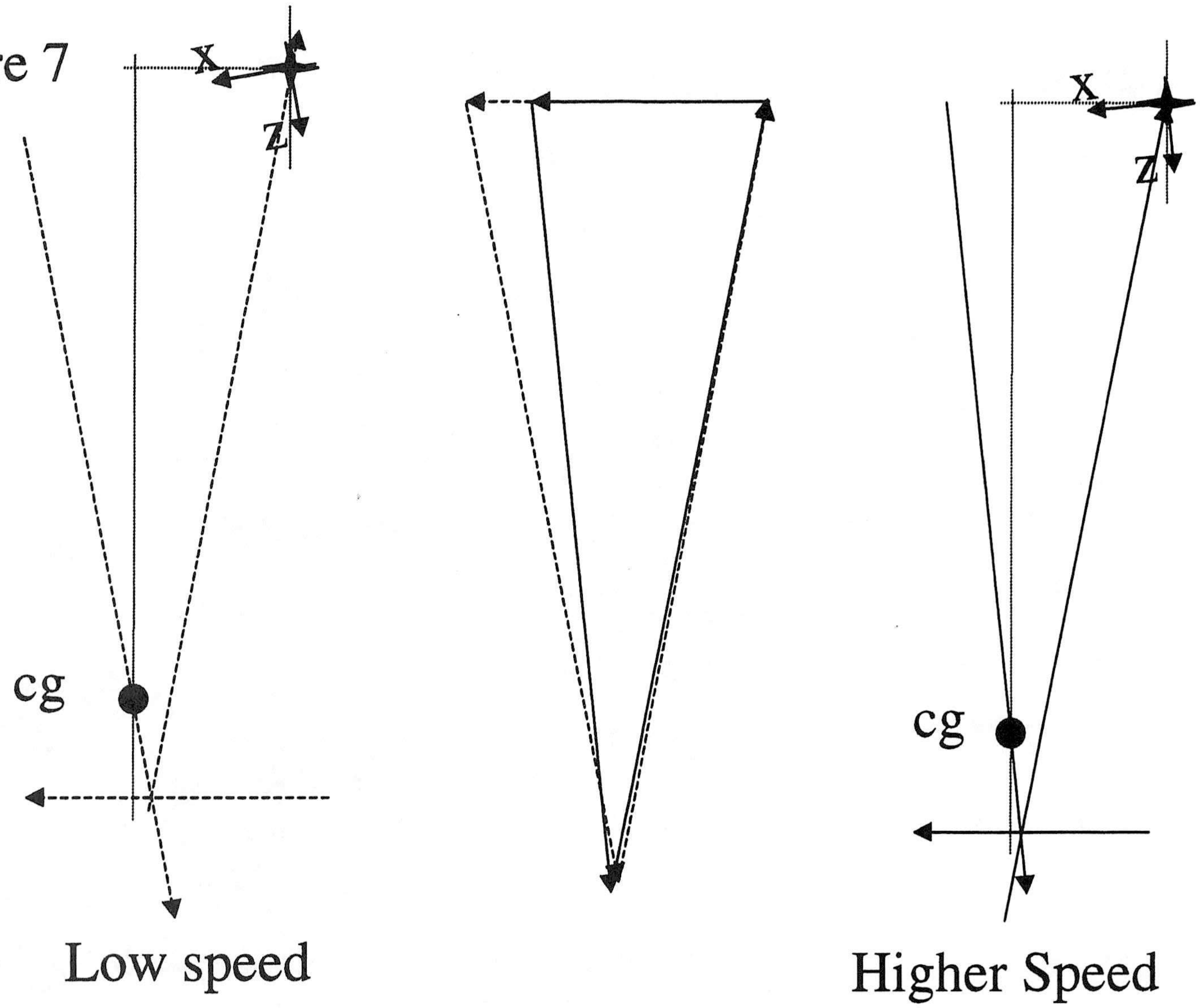
Low speed

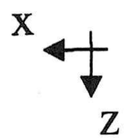
Higher Speed

Diagrams referenced to aircraft body axes, x ← z ↓ gives earth axis reference

C P Massey, September 1999

Figure 7



Diagrams referenced to aircraft body axes, 

gives earth axis reference

C P Massey, September 1999