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HELICOPTER MANOEUVRE STABILITY

A NEW TWIST

by

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HELICOPTER MANOEUVRE STABILITY - A NEW TWIST

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ABSTRACT

Modern helicopters, with their wide manoeuvre and speed envelopes, need to have their manoeuvre stability carefully assessed using up to date techniques which set realistic limits, easily respected by operational pilots.

The phenomenon of manoeuvre stability is explained in theory and practice with a brief discussion on the classical flight test methods used in the past to establish acceptability criteria for a helicopter's manoeuvre stability. This approach is then extended to encompass modern helicopters capable of high sustained turn rates, negative g, having sophisticated automatic flight control systems, hingeless rotors and the tandem rotor configuration. Modern manoeuvre stability flight test techniques which are taught to student helicopter test pilots at Boscombe Down are described with recommendations from typical flight test results including manoeuvre limitations and methods of communicating them to the helicopter pilot.

INTRODUCTION

1. In the dawn of rotary wing flight, designers were preoccupied with the fundamental problems of the safe control of the 3 axes of motion. The early helicopter was exploited for its unique ability to hover and rectilinear flight was considered merely as a means of conveying the machine from one hover station to another. Furthermore, the low power to weight ratio of early helicopters gave little potential for agility in forward flight, and the problems of manoeuvring at high or negative load factors were unworthy of serious study.

2. Early articulated and teetering rotor systems generally exhibited satisfactory manoeuvre characteristics within the helicopters restricted 'g' envelopes, however, the divergent pitch response of tandem configurations gave manoeuvre stability a new significance. In early tests on the Piasecki XHJP-1 General Utility Naval Helicopter, aimed at demonstrating structural integrity at high g, an aft cyclic input in a dive caused the helicopter to "dig-in". A rapidly divergent pitch response put the helicopter in a vertical position from which the pilot recovered by continuing through a loop. Calibrated readings showed a positive load factor at the top and careful examination of the craft showed no structural damage during this, the first known loop to have been successfully performed by a helicopter.

3. With the introduction of gas turbine engines and lighter methods of airframe construction, helicopters were at last blessed with some reasonable measure of excess power to manoeuvre over that required simply to maintain level flight. However, it is only since the introduction of hingeless rotors and modern articulated designs that it has been possible to exploit their manoeuvring potential. At last, many modern helicopters have the structural strength, performance and aerodynamic capability to manoeuvre at high load factors and in negative g.

4. The value of the helicopter in support of ground forces has now been realised, and the flying qualities during manoeuvring flight have assumed a new importance. The flying tactics used to ensure survival at high speed and extreme low level include rapid pull-ups and push-overs and high g turns for terrain following and evasion. In this high workload environment, the pilot must be able to manoeuvre aggressively yet safely without fear of overstressing his aircraft, having little time to refer to his cockpit instrumentation.

5. With the use of sophisticated automatic flight control systems and stability augmentation it is possible to give the helicopter a manoeuvrability potential more akin to that of modern fixed wing aircraft than to the rotorcraft of yesteryear. The Force Augmentation System of the CH-53E in providing longitudinal cyclic force feel cues proportional to load factor during manoeuvring flight is one example of this concept. Devices to warn the pilot if he is rapidly approaching maximum or minimum load factors may be necessary. A step change in cyclic force gradient, audio/visual warnings or even a collective shaker have been considered as possible g limiters.

6. Good manoeuvre stability is an essential characteristic of the modern battlefield helicopter, and it is important that the test pilot has a clear understanding of the subject. The flight testing involved in ensuring role suitability is becoming increasingly more challenging as the helicopter advances technically to meet its full military potential. It is with these aims in mind that the manoeuvre stability testing of modern agile helicopters is taught at the Empire Test Pilots' School (ETPS).

MANOEUVRE STABILITY - WHAT DOES IT MEAN?

7. A helicopter is said to exhibit positive manoeuvre stability when an aft cyclic input is required to cause an increase in normal acceleration during manoeuvring flight, ie pull-ups or turning flight. The reverse is also true, that a forward cyclic input is required to reduce normal acceleration during a push-over manoeuvre.

8. The level of manoeuvre stability relates to the size of the control inputs required to produce the normal accelerations. Pilots prefer a level of stability that is slightly stable - too much manoeuvring stability will require excessive control movements to carry out normal flying manoeuvres. Too little manoeuvre stability, or even negative stability will produce an aircraft which is extremely difficult to fly, particularly in gusty air, and which may tend to "dig-in" with possible overstress in high g manoeuvres.

THEORY OF MANOEUVRE STABILITY

9. There are two approaches to the problem of determining the manoeuvre stability of a helicopter:

a. Measurement of the longitudinal cyclic control force and position displacement required in:

(1) Wings level pull-ups and push-overs.

(2) Steady turning flight.

b. Examination of the response to a step cyclic control input. If the response to a specifically defined input satisfies certain conditions, then the level of manoeuvre stability will be greater than a minimum value which has been deemed to be adequate. This test is known as the NACA test.

MANOEUVRE MARGIN

10. The conventional approach to manoeuvre stability is to consider first the forces required to produce the centripetal accelerations needed for the curved flight path and then to consider the resulting moments acting. A final equation is then used to deduce the cyclic control displacement needed to balance these moments and hold the required g values.

11. With a helicopter the centripetal forces result from:

a. An increased thrust from an increased angle of attack.

b. An increased thrust from the aft cyclic stick movement.

c. An increased thrust from an increased collective pitch setting.

12. The moments acting will result from:

a. Rotor Stability with Angle of Attack (M_w). In forward flight, a change in fuselage angle of attack results in a greater change in the angle of attack of the rotor disc. Thus the rotor is usually unstable with respect to changes in fuselage angle of attack, the effect increasing with forward speed.

b. Rotor Stability with Pitch Rate (M_q). When the helicopter is pitching at a constant angular rate of q radians/second, the rotor disc rotates at the same angular rate, but it lags behind the fuselage motion by a constant amount (δ) given by:

$$\delta = \frac{16q}{\gamma\Omega} \text{ radians} \qquad (1)$$

This rotor lag produces a stabilising moment about the centre of gravity of the helicopter.

c. Increase in Collective Pitch. Any change in collective pitch will cause a change in the rotor thrust and hence a change in the moments acting on the helicopter which may be stabilising or destabilising depending on the position of the thrust vector relative to the centre of gravity of the helicopter.

d. Fuselage and Tailplane Contributions. The fuselage and tailplane may produce stabilising or destabilising moments depending on the particular flight conditions.

For a stable helicopter the sum of the above moment contributions will be balanced by an aft cyclic pitch deflection. The cyclic is therefore needed to balance moments (or to control the speed) and the collective is used to control the centripetal force required to execute a steady pull-up.

13. In theory, equations for cyclic control movement per g in a steady pull-up can be derived, and in order to balance both forces and moments at the bottom of the pull-up, it is necessary to consider both collective and cyclic pitch changes from the level flight condition. A manoeuvre margin, H_m, can then be derived in terms of collective per g ($d\theta/dn$) and cyclic per g (dB_1/dn). (This approach has been used by O'Hara in reference 1.)

14. However, in practice, a pilot will normally be interested in the manoeuvring properties of his aircraft at a constant collective pitch setting and studies of manoeuvre stability recognise this fact by producing equations relating the manoeuvre margin, H_m, to the cyclic pitch angle change per g, dB_1/dn.

15. The manoeuvre margin may be defined in terms of the change of the mean value of the pitching moment coefficient with fuselage angle of attack, ie:

$$H_m = -\frac{\overline{dC_M}}{d\alpha} \qquad (2)$$

(Following Bramwell's method outlined in reference 2). The manoeuvre margin may be calculated from measured values of the cyclic pitch to trim in steady pull-ups from trimmed level flight by use of the relationship:

$$H_m = \frac{\mu z_w}{2t_c'} \left[\left\{ \left(\frac{dB_1}{dn}\right)_1 (1 + n_1) + \left(\frac{dB_1}{dn}\right)_0 \right\} t_c' \left(1 + \frac{\partial a_1}{\partial \alpha}\right) \right] \quad (3)$$

Equation (3) therefore gives the manoeuvre margin in terms of measured values of stick position to trim in steady pull-ups. The larger the value of H_m the more rapidly will the helicopter reach a steady normal acceleration following a rapid stick movement.

16. A similar analysis could have been made for the helicopter in a steady descending (because of the constant collective requirement) turn, but if the pitch rate in a pull-up for a given excess acceleration ($n_1 g$) is q, then the corresponding pitch rate (q_T) in the turn is given by:

$$q_T = q \left[1 + \left(\frac{1}{n_1 + 1}\right) \right] \quad (4)$$

Thus the difference in pitch rates will give rise to different pitch angles/g and different margins. A theoretical correction can be applied and O'Hara suggests (for a tail-less helicopter) that a possible correction has the form:

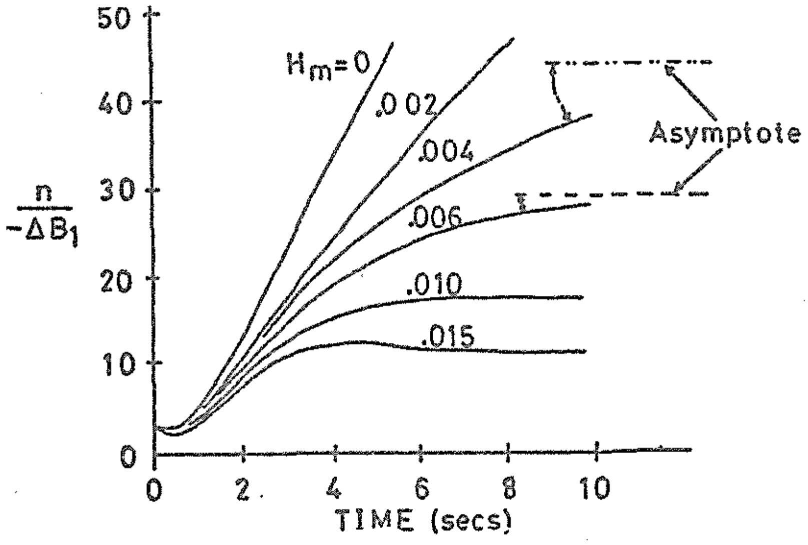
Hence $$\left(\frac{dB_1}{dn}\right)_{\text{Pull-up}} = \left(\frac{dB_1}{dn}\right)_{\text{turn}} + \frac{16q_T}{\gamma \Omega^2 R} \frac{1}{(n_1 + 1)^2} \quad (5)$$

The value of $\left(\frac{dB_1}{dn}\right)$ from equation (5) and then be substituted in equation (3) to give the manoeuvre margin where $\left(\frac{dB_1}{dn}\right)_{\text{turn}}$ is determined from the trim curves for steady turning flight.

NACA PULL-UP TESTS

17. In this approach to determining manoeuvre margins, the way in which the normal acceleration varies with time following a specified step input to the longitudinal cyclic control is investigated. The response depends on the size of the manoeuvre margin (H_m) as is shown in Figure 1.

Figure 1. Growth of Normal Acceleration Per Unit Cyclic Angle Change



18. It can be seen from Figure 1 that:

a. The time taken to achieve a steady value of $(^{n}/-\Delta B_1)$ depends on H_m; the smaller the value of H_m the longer the time required.

b. After the initial response in the first second, except for low values of H_m, the slope of $(n/-\Delta B_1)$ increases and then passes through an inflexion point where $d^2(n/-\Delta B_1)/dt^2 = 0$ and finally decreases to level off at zero when the steady state has been achieved. The time to the point of inflexion depends on H_m and this provides the basis for the NACA criterion. In order to satisfy the criterion the inflexion must occur within 2 seconds of the start of the manoeuvre.

FACTORS AFFECTING MANOEUVRE STABILITY

19. Aerodynamic Derivatives. It can be shown that, for symmetrical pull-ups and push-overs, the manoeuvre margin is proportional to:

$(Z_w M_q - u_o M_w)$ (sometimes known as the manoeuvre margin parameter)

The factor $Z_w M_q$ is always positive because both Z_w (vertical damping) and M_q (pitch rate damping) are both negative and stabilising. Consequently the manoeuvre margin parameter depends upon whether the angle of attack stability derivative $(M_\alpha = u_o M_w)$ is positive (destabilising) and greater than $Z_w M_q$ or negative (stabilising).

20. It is worth noting that for steady turning flight, the control position/normal acceleration curve gradient will not be exactly proportional to the manoeuvre margin parameter introduced above. This quantity is replaced by $(Z_w M_q - \frac{1}{2} u_o M_w)$, where the $\frac{1}{2} u_o M_w$ results from the change in the Z component of gravity in the turn. Additionally, the different pitch rate in the turn, as outlined in paragraph (16) combines to give the result that the angle of attack stability derivative, M_w, has less effect on pilot-perceived manoeuvre stability in turning flight than in a symmetric pull-out.

21. Tailplane. The angle of attack instability of the main rotor can be offset by the use of a horizontal stabilizer which will also increase the pitch rate damping. Since the destabilizing effect of the aft rotor flapping is approximately proportional to the square of the forward speed, the area of the horizontal stabilizer selected should be suitable for all speeds. The stabilizer, however, spends much time operating in heavy downwash from the main rotor, so there may be sudden changes in the tailplane contribution to the stability of the helicopter which need to be carefully investigated.

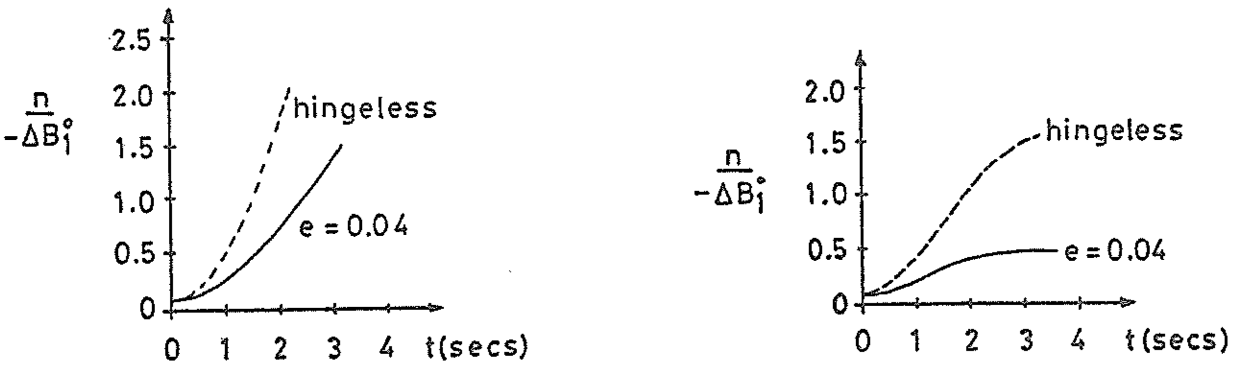
22. Centre of Gravity (CG) Position. The position of the longitudinal CG of the helicopter will have a significant effect on the manoeuvre stability. If it is forward of the main rotor thrust line, an increase in rotor thrust will produce a stabilizing nose-down pitching moment. However, the converse is true, and an aft CG position will mean that an increase in rotor thrust will add to the destabilizing aft flapping effect and cause M_w to increase, so reducing the manoeuvre margin. This is normally the reason for setting the maximum allowable aft CG position as specified in the operator's manual.

23. Load Factor. The manoeuvre stability of a helicopter will vary with the load factor produced by the main rotor. High load factors will accentuate the instability of the aft rotor flapping which may cause the helicopter to lose its manoeuvre margin during high g flight when the horizontal stabilizer is unable to counterbalance the main rotor's large thrust which gives an unstable pitching moment. This causes the helicopter to "dig-in" during the manoeuvre, producing an even higher load factor which produces a vicious circle of events, leading possibly to overstress or structural failure.

24. Unfortunately, the problem is not confined to high load factors For rotors on which control power depends entirely on thrust, such as teetering rotors, the ability to control the helicopter will disappear if the load factor should ever reach zero. Hingeless rotors or those with some effective hinge offset will maintain more control power at low rotor thrust, but it might be noticeable that more cyclic control is required to return to level flight from a 0.5g push-over than from a 1.5g pull-up. Not only is control power reduced at low rotor thrust, but it can set up the potentially dangerous condition leading to mast bumping on teetering rotor helicopters or droop-stop pounding on those with articulated rotors. The tip path plane will respond normally to cyclic inputs, but the low rotor thrust will have little effect on fuselage attitude. The ultimate effect of this critical situation is that the rotor can flap outside design limits, leading to blade/fuselage contact, loss of tail section, or rotor separation due to mast shearing.

25. Hingeless Rotors. Bramwell (reference 3) has compared the longitudinal acceleration time histories in response to a sudden cyclic pitch change for a helicopter with an articulated rotor with a flapping hinge offset at 4% and with a hingeless rotor. The hingeless rotor was assumed to have a hub moment 5 times that of the articulated rotor. The results of the comparison for both helicopters with and without a tailplane are shown in Figure 2.

Figure 2. Comparison of Response of Articulated and Hingeless Rotor Helicopters



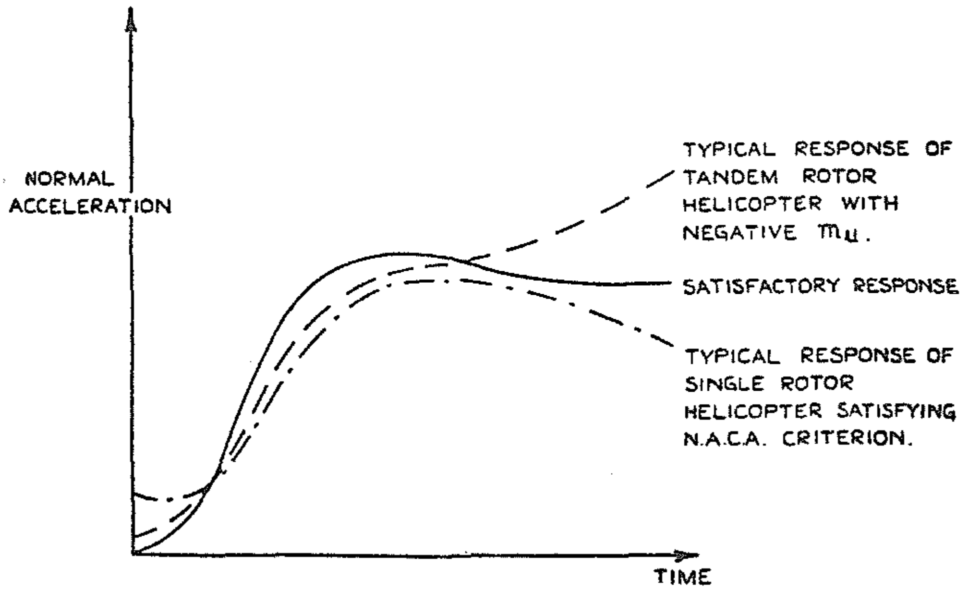
a. Tail-less

b. With Tail

It can be seen that the greater control power and reduced angle of attack stability of the hingeless rotor result in a rapid increase in the normal acceleration. Fitting a tailplane to the hingeless and articulated rotor helicopters ensures that both have inflexion points (which were absent in the tail-less case). However, it is worth noting that the time to inflexion of the hingeless rotor helicopter is greater than that of the articulated rotor helicopter, indicating a reduced manoeuvre stability of the hingeless rotor helicopter. The ability of the hingeless rotor to generate large control moments tends to encourage 'spirited manoeuvring' with the use of high and low load factors. Care needs to be taken in the design of horizontal stabilizers for these helicopters to ensure that the manoeuvre margin is adequate throughout its large manoeuvring flight envelope.

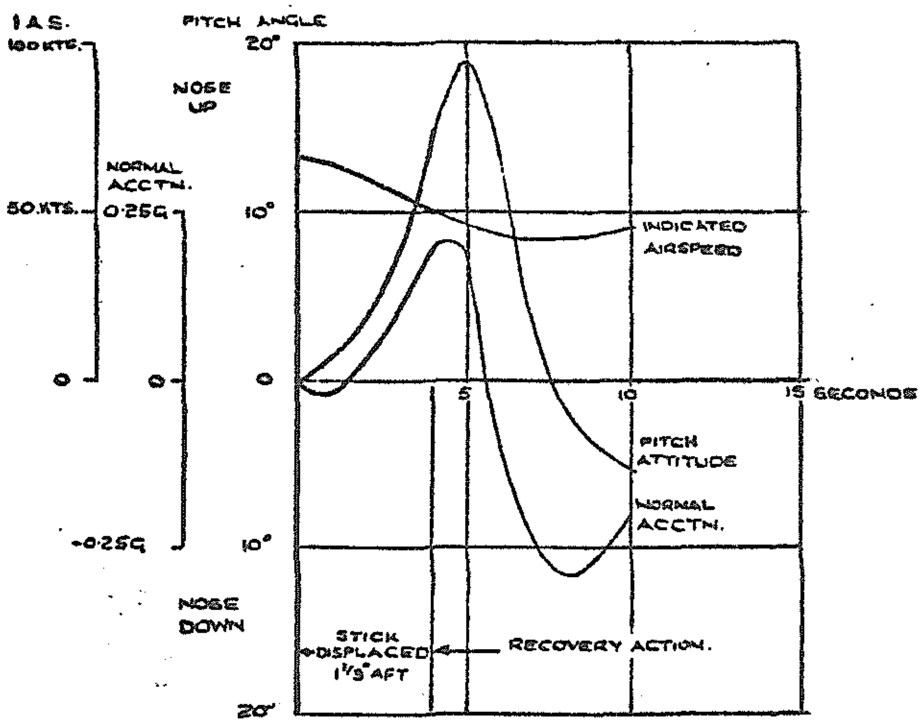
26. Tandem Rotors. The response of a tandem rotor helicopter to a step control displacement is unusual in that it may satisfy the NACA criterion with a "concave downwards normal acceleration within 2 seconds", but may then fail to settle down and continue to increase. Figure 3 below taken from reference 4 shows how the response of a tandem rotor helicopter compares with a satisfactory response and that of a typical single rotor helicopter which satisfies the NACA criterion.

Figure 3. Normal Acceleration Response Curves



It is not surprising, therefore that UK Def Stans 00-970 Part 2 excludes the tandem rotor helicopter configuration when defining the NACA criterion. The results of tests carried out on the Bristol 173 from reference 5 appear below and show how recovery action was required after 2 to 4 seconds as pitch angle, normal acceleration and speed all continued to vary.

Figure 4. Response to Step Longitudinal Input - 65 kts (Bristol 173 Flight Test)



27. The reason for these curve changes is that there is large damping in pitch (large M_q) which damps the motion in its early stages, but as speed decreases the divergent M_u effect predominates and causes the acceleration to 'runaway'. Forward movement of the CG improves the response but is most effective if there is some swashplate dihedral. Stalling of the rear rotor at high load factors may also give a tendency to pitch-up in manoeuvring flight.

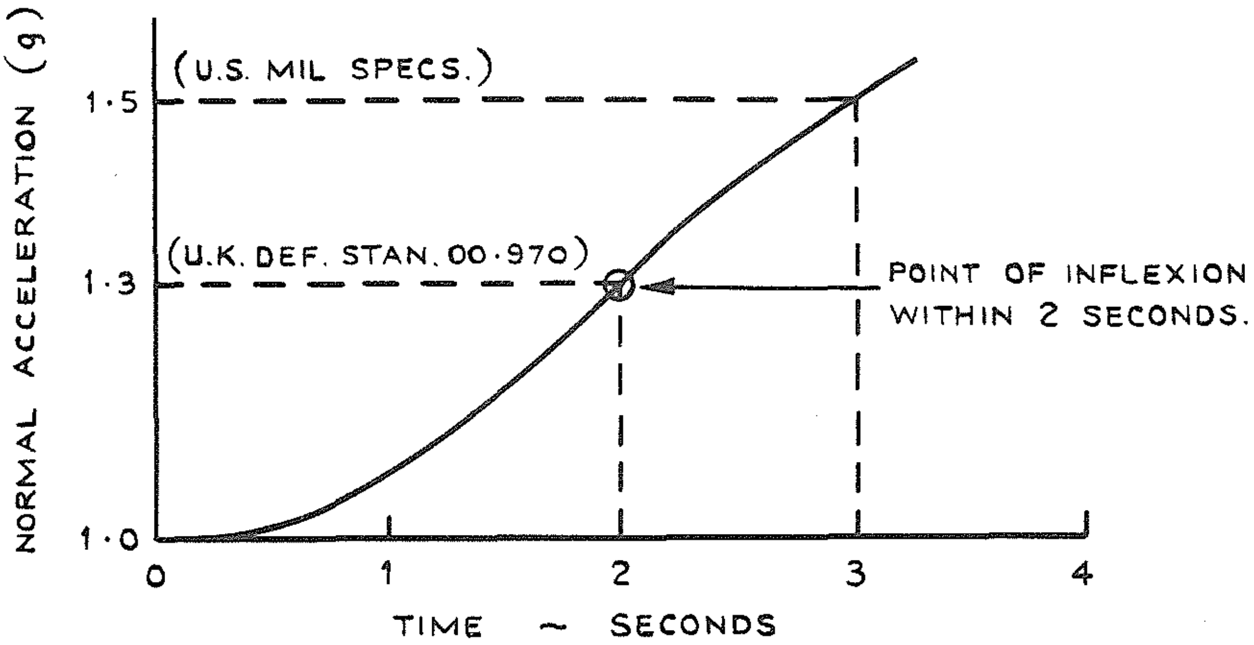
28. Bramwell concluded in reference 4 that satisfaction of the NACA criterion does not necessarily indicate acceptable manoeuvrability of the tandem rotor helicopter, and that it was clear (in 1961!) that the NACA criterion, which was intended to describe an acceptable response curve, was not detailed enough to cater for the case of the tandem rotor helicopter.

REQUIREMENTS FOR MANOEUVRE STABILITY

29. Within the bounds of his helicopter's lift and thrust performance, the military pilot requires carefree manoeuvring throughout a flight envelope wide enough to accomplish the mission. The laid down Design Requirements Specifications are rather more relaxed than this although often easier to define in engineering terms.

30. Military Specifications. UK Military Design Requirements Specifications Defence Standards 00-970 Part 2 (reference 6) for helicopter manoeuvre stability is based upon the old NACA criterion. US Military Specifications MIL-H-8501A (reference 7) requires that a similar NACA pull-up test be successfully demonstrated. This NACA pull-up requires that following an aft cyclic step input sufficient to generate a 0.2 radian/sec pitch rate in 2 seconds (MIL-H-8501A) or to develop a normal acceleration of 1.5g within 3 seconds (MIL-H-8501A) or 1.3g within 2 secs (UK Def Stans 00-970 Part 2) or a one inch input, whichever is less, then the time history of normal acceleration shall become concave down within 2 seconds following the start of the manoeuvre. This is graphically illustrated at Figure 5.

Figure 5. Normal Acceleration Response NACA Pull-Up Criteria



Obviously this test excludes the requirement for manoeuvre stability at higher load factors than 1.5g (US) or 1.3g (UK) or following an aft cyclic displacement of greater than 1 inch. Furthermore, manoeuvre stability during low g flight is not addressed.

31. Civil Specifications. Civil requirements in British Civil Airworthiness Requirements (BCAR's) and Federal Aviation Regulations (FAR's) are predictably even less demanding. BCAR's Chapter G12-10 simply requires that:

> "There shall be no serious tendency for the rotorcraft to tighten up in the turn of its own accord during a turn at normal accelerations up to 1.5g at all engine powers."

However, for civil applications this requirement is probably adequate.

32. Fixed Wing Specifications. Perhaps the current and future generations of battlefield helicopters, with the need for a wide manoeuvre envelope to achieve terrain following and evasive manoeuvring, require a level of manoeuvre stability more akin to their fixed wing counterparts. The new UK Defence Standards 00-970 Part 1 for fixed wing aircraft calls for the following longitudinal manoeuvring characteristics:

> "CONTROL FEEL AND STABILITY IN MANOEUVRING FLIGHT
>
> In steady turning flight and in pull-ups at constant speed, increasing pull forces and aft displacement of the pitch control shall be required to maintain increases in normal acceleration factor. Increases in push forces and forward control displacement shall be required to maintain reductions of normal acceleration factor in push-overs.

> The values of pitch control force per g shall not be so large or so small as to cause piloting difficulties incompatible with the required levels.
>
> At constant speed in steady turning flight, pull-ups, and push-overs, the variations in pitch control force with steady-state normal acceleration factor shall be approximately linear. With the approval of the Aeroplane Project Director, forces may be non-linear where appropriate to limit the normal acceleration factor, or to limit the behaviour of the aeroplane.
>
> The peak pitch control forces developed during abrupt manoeuvres shall not be so light as to cause piloting difficulties incompatible with the required levels and the increase of force during the entry to a manoeuvre shall occur before the resulting increase of normal acceleration factor.
>
> The pitch control motions in manoeuvring flight shall not be so large or so small as to cause piloting difficulties incompatible with the required levels."

MANOEUVRE STABILITY TESTING AT THE EMPIRE TEST PILOTS' SCHOOL (ETPS)

33. It is towards these manoeuvre stability characteristics of the fixed wing aircraft that the testing at the ETPS (Rotary Wing) is directed. Furthermore, to ensure that the limits of normal acceleration defined by the Design Certificate or Release to Service document are not inadvertently exceeded, the helicopter should also exhibit an effective means of warning the pilot by natural or artificial cues of the approach to normal acceleration limits.

34. The School's Fleet. The fleet of ETPS (Rotary Wing) comprises Scout, Sea King, Wessex Mk 5, Army Lynx and Gazelle helicopters. The Army Lynx and Gazelle are comprehensively equipped with a magnetic tape Airborne Data Acquisition Module to record flight parameters and aircraft control position including stabilization equipment actuator activity. This, combined with their relatively wide manoeuvre envelopes and agility make them ideal aircraft for teaching test pilot students manoeuvre stability testing and flying qualities evaluation. The ETPS Gazelle has normal acceleration limits of +3.2g to -0.5g and it is equipped with a visual g indicator. Manoeuvres at very high load factors are naturally limited by the onset of jack stall, when the blades' aerodynamic pitching moments exceed the force applied by the hydraulic jacks on the pitch operating arms. The Lynx on the other hand with its semi-rigid rotor displays exceptional agility, has a g envelope of +3g to +0.25g and is equipped with a g meter and audio g warning with an alarm light set at predetermined thresholds. The Lynx's response to normal acceleration is further complicated by the "Computer Acceleration Control" which, as a means of improving pitch stability, automatically reduces collective pitch when increased load factors are sensed and increases collective at load factors of less than 1.0g.

35. The Test Exercise. The manoeuvre stability testing forms an important part of the longitudinal stability, control and flying qualities exercise. After the academic instruction, the exercise brief, and a dual demonstration of techniques, students evaluate their aircraft during four hours of flight testing. The NACA pull-up technique is no longer flown, since it is felt that a pull-up of only 1.5g (1.3g for UK Def Stans 00-970) is an unrealistic manoeuvre in modern military helicopters. Instead, the helicopter's manoeuvre stability is evaluated by noting the variation of longitudinal control position and force with normal acceleration during steady turns, symmetrical pull-ups and push-overs. Each test consists of incrementally increasing normal acceleration (load factor) while holding collective position constant.

36. Steady Turns. Steady turns, in both directions, are accomplished by stabilizing in level unaccelerated flight at the desired test airspeed. Load factor is increased to the maximum allowable by incrementally increasing bank angle (in both directions). Ball centred, constant airspeed, and fixed collective are maintained during the turn. Rotor speed should not be adjusted during the turn except to maintain the rotor speed within the power-on limit.

37. Pull-Ups. The symmetrical pull-up tests are performed by establishing a level unaccelerated flight condition at the aim trim airspeed. All control forces are reduced to zero and not retrimmed throughout the test. Without changing the trim collective position and rotor speed, the aircraft is decelerated with cyclic to an airspeed slower than trim. The nose is then lowered and the aircraft accelerated to the trim airspeed. The longitudinal control is rapidly displaced (step input) against a control fixture so that the desired normal acceleration is obtained as the aircraft reaches the trim airspeed in a level attitude. The longitudinal cyclic should be held fixed for at least one second following the step input to develop maximum normal acceleration. Small lateral control inputs may be used to maintain a level attitude.

38. Push-overs. The symmetrical push-over tests are performed in a similar but opposite manner to the symmetrical pull-ups. While maintaining the trim collective position and rotor speed, the aircraft is pitched nose down to accelerate to an airspeed greater than trim. Using cyclic only, the aircraft is then decelerated to an airspeed slightly higher than trim, and then the longitudinal cyclic is rapidly displaced forward against the fixture. The desired normal acceleration should be obtained as the airspeed reaches trim in a level attitude. The control is held fixed for at least one second following the step input.

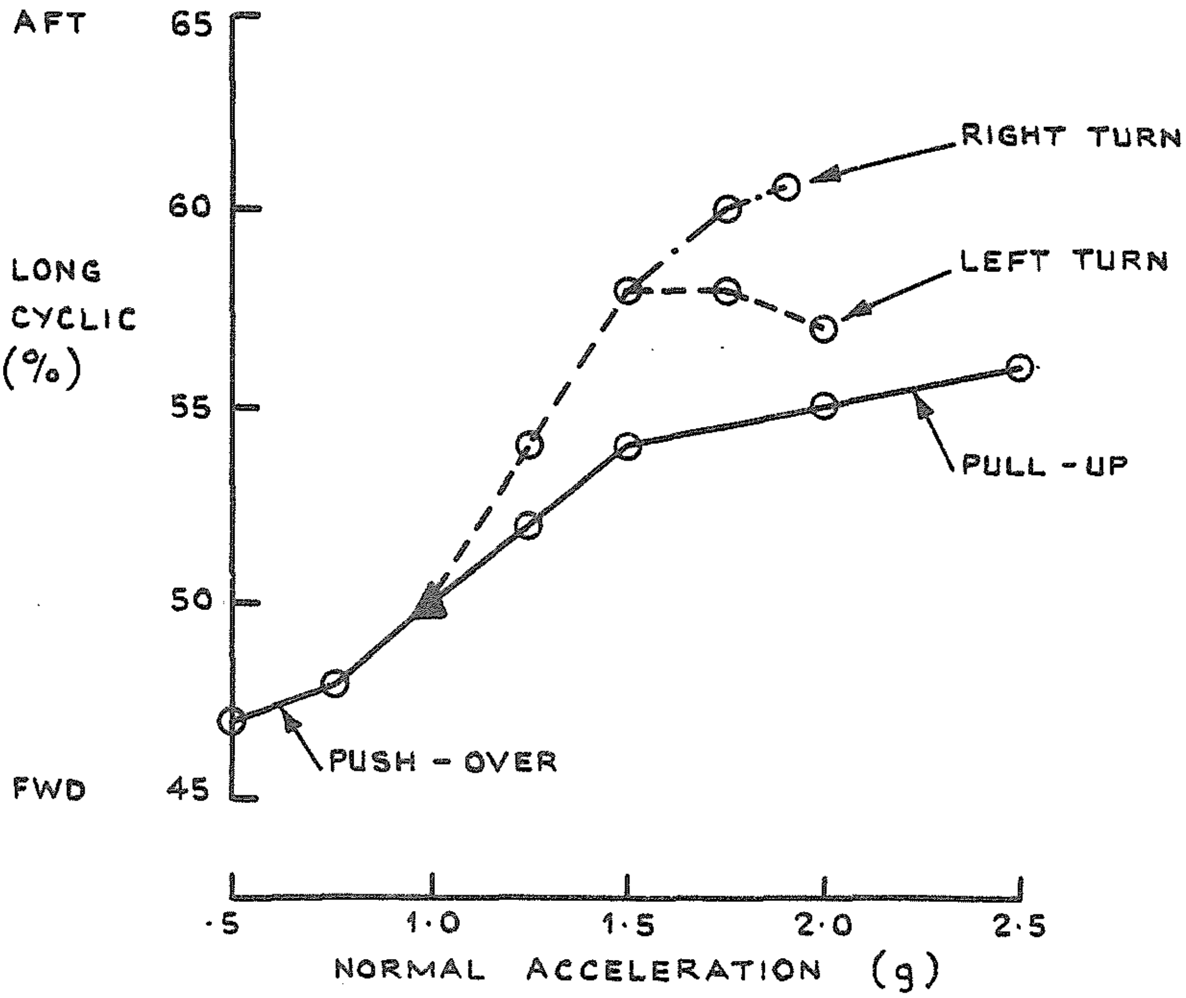
39. Axis Coupling. The pull-up and push-over tests are continued for increasing step inputs until the desired normal acceleration range is completed. Coupling may be evaluated at each airspeed by observing the lateral and directional control inputs required to maintain a wings-level, ball-centred flight condition.

40. Divergent Long Term Response. Should an aircraft exhibit a rapidly divergent long term response, then symmetrical pull-ups and push-overs might be inappropriate, since the cyclic required to control the divergence could be in excess of the input required to develop the normal acceleration. In this case the NACA pull-up might be the only usable technique besides steady turns.

41. Qualitative Assessment. The evaluation is completed by assessing role-orientated manoeuvres (such as fighter evasion, terrain avoidance etc) using the collective as necessary to achieve the desired performance. Time histories are recorded, and subsequent analysis can determine the cause of any handling difficulties. Qualitative assessment should include the control force cues to increasing/decreasing load factor, any tendency to dig-in/pitch-over, ease of observing g limits, g indications/warnings, and general manoeuvrability of the aircraft.

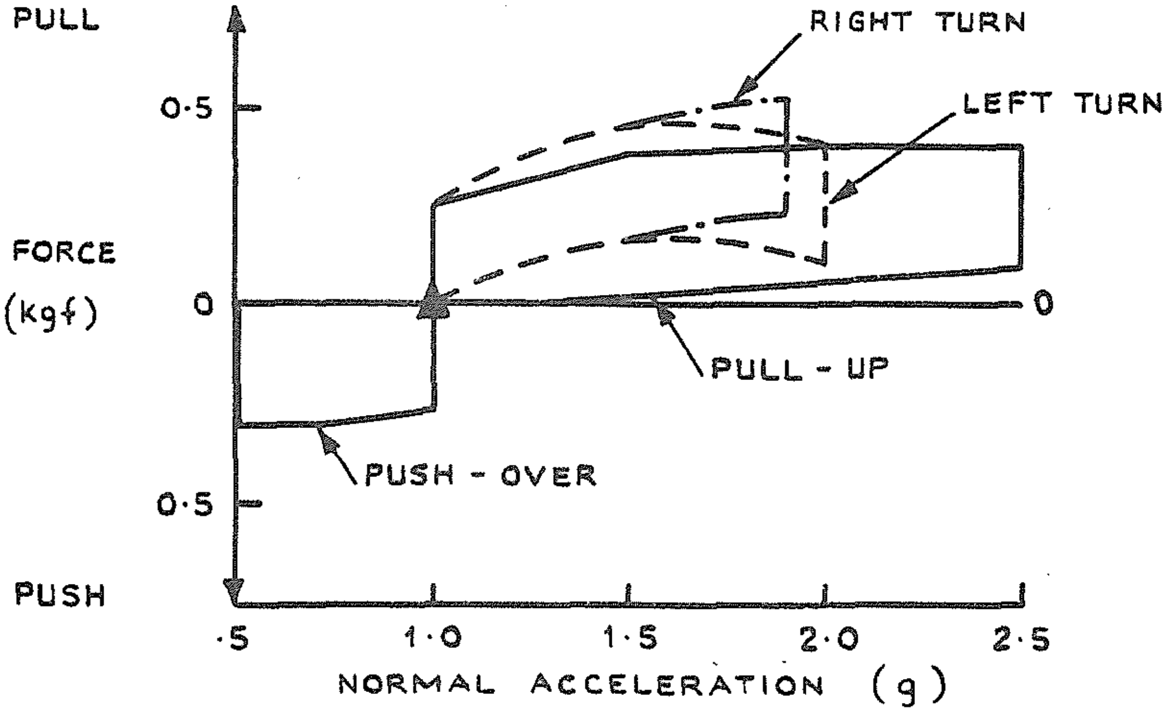
42. Quantitative Data. The quantitative data are recorded to support the qualitative impressions of the aircraft's manoeuvre stability at test airspeeds appropriate to the role. Figure 6 shows a typical plot of longitudinal cyclic position against normal acceleration for steady turns and pull-ups and push-overs. As can be seen, in a left hand turn at above 1.5g increasing forward cyclic is required with increasing load factor (and angle of bank). This would support the qualitative assessment of a tendency to dig-in. The increased collective required to maintain a level turn at above 1.5g would probably aggravate the situation, as more forward cyclic is required to overcome the increased speed stability (M_u) at high collective settings.

Figure 6. Collective Fixed Manoeuvre Stability



43. To support qualitative impressions of stick force cues a plot of stick force against normal acceleration can be constructed. Forces can be measured in flight if the flying controls are unboosted. If the control system is irreversible and control forces are not affected by normal acceleration, then the mechanical characteristics can be measured on the ground and forces cross-plotted from the force/displacement diagram of the longitudinal cyclic. A typical stick force per g plot is shown at Figure 7 using displacement data from Figure 6. The graph would support the assessment of weak force cues with normal acceleration during turns (a push force in left turns above 1.5g) and during push-overs down to +0.5g, and pull-ups to +2.5g.

Figure 7. Collective-Fixed Stick Force per 'g'



44. Reporting Requirements. It is emphasised to the students that they are assessing whether the helicopter's manoeuvre stability is safe and compatible with the designed roles. Specification compliance, although important is secondary to these overriding requirements. The exercise is completed by the students giving a formal presentation of their results to an audience of fellow students and staff of the ETPS. Typical recommendations from the manoeuvre stability tests might include:

a. Expansion of the g envelope to enable successful completion of the mission.

b. Improvement of cyclic control displacement and force cues to normal acceleration.

c. Artificial enhancement of the manoeuvre stability by exploiting the aircraft's AFCS potential.

d. If modification cannot be carried out, appropriate limitation of the aircraft's manoeuvre envelope.

e. Provision of suitable artificial warning cues to the pilot of approaching the maximum and minimum load factor.

CONCLUSIONS

45. This paper has outlined the theory behind manoeuvre stability of helicopters and has shown that, for the modern breed of agile helicopter, the specifications for an acceptable level of manoeuvre stability are inadequate and need to be brought closer to those laid down for fixed wing aircraft. The flight test methods for investigating the manoeuvre stability of helicopters, taught to student test pilots at ETPS, look towards the future where advanced materials and active control technology will place in the hands of the next generation of operational pilots, responsive and highly manoeuvrable rotary-winged machines with the ability to generate high and low load factors to perform their roles safely and effectively in the battlefields of tomorrow.

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8 British Civil Airworthiness Requirements - Civil Aviation Authority, (Section G)

SYMBOLOGY AND ABBREVIATIONS

g – acceleration due to the force of gravity

M_w – change in pitching moment with change in normal velocity w

M_q – change in pitching moment with change in pitch rate q

q – pitch rate

δ – rotor disc lag angle

γ – Lock number

Ω – rotor speed

H_m – manoeuvre margin

θ – collective pitch angle

n – load factor

B_1 – longitudinal cyclic control angle

C_M – pitching moment coefficient

α – fuselage angle of attack

μ – advance ratio

$\dot{z}_w$ – non-dimensional change in normal force with change in normal velocity (vertical damping)

$t_c{}'$ – thrust coefficient in level flight

a_1 – angle between rotor-disc axis and no-feathering axis

q_T – pitch rate in turn

R – rotor radius

Z_w – change in normal force with change in normal velocity (vertical damping)

u_o – trim forward velcity

CG – centre of gravity

M_u – change in pitching moment with change in forward velocity (speed stability)

BCAR – British Civil Airworthiness Requirements

FAR – Federal Aviation Regulations

ETPS – Empire Test Pilots' School