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AERODYNAMIC DESIGN OF A MANUAL AILERON CONTROL FOR AN ADVANCED TURBO-PROP TRAINER

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Abstract

The PC-9 is a turbo-prop trainer aircraft designed to offer a cost effective alternative to military jet training aircraft.

As a design objective of the PC-9, the US Military Specifications should be complied with in the area of handling qualities. However, in line with the philosophy of low purchase and maintenance costs, the added complexity of a hydraulic power boost system for the control surfaces could not be accepted.

The control surfaces have been designed for manual control. At flight speeds up to 320 knots, this poses considerable problems to the aerodynamicist.

The paper outlines the design goals derived from the military specifications, some of the configurations tested, their results and the performance of the final aileron design.

Introduction

This paper shows the methodology used in the design of the PC-9 roll control system. The design objective is unique and as such poses some difficult problems to the aerodynamicist. This paper discusses some of these problems, illustrates the method in which solutions were sought and gives the final performance of the resulting design.

Pilatus PC-9

The Pilatus PC-9 is a second generation Turbo-prop trainer aircraft. Details about the aircraft may be obtained in Ref[1]. The PC-9 has been designed as an military trainer aircraft for the Basic/advanced syllibae. Its performance has been selected to achieve an optimum in the training of military pilots after having gained their "wings" on a lower grade "screening" aircraft.

The performance of the PC-9 is be sufficient to conduct this task but performance alone is not the deciding factor; the handling qualities of training aircraft are just as important. In modern-day training philosophies it is undesirable to let a student learn to control a trainer in a certain way and then have to "unlearn" when he moves to the next aircraft.

The specification placed on the aerodynamicists at the beginning of the PC-9 development programme was to achieve the most stringent of the requirements of the Military Specifications for handling qualities. Of particular interest, because it is the most sensitive of the controls, was the roll control system. This is the subject of the paper here.

To allow a breakthrough of the PC-9 into the advanced trainer market,currently controlled by jet-powered aircraft, the PC-9 would have to offer benefits in other areas. The Turbo-prop aircraft by nature of its low fuel burn, can offer a smaller sized aircraft to fulfil the same specification as a jet aircraft. All the components may be smaller and hence cheaper. The turbo-prop can enter this competitive market by nature of its low acquisition cost and low operating costs. But to keep these costs low requires a consequentional policy of simplification wherever possible. This philosophy is very important to the concept of the roll control system. It is this driving concept of simplification, low weight and low maintenance burden which led to the desire to provide a manually controlled aileron, but nevertheless fulfilling the detailed requirements of handling characteristics outlined below.

Requirements

Several requirements for handling requirements were reviewed. These included the British and American civilian and military requirements. The civilian requirements mainly concentrate on providing a defined minimum level of safety. The military specifications on the other hand are based on the results of ergonomic studies and therefore allow the designer to optimise his control charcteristics. The American military specifications of

Ref [2] also provide the baseline for the British specifications (DEF. STAN. 00970) and so were used here as a basis for the optimisation.

There is also a further extremely useful document, the user's guide (Ref [3]) to the Mil. Specs.

The requirements of Ref [2] are divided into several sections, each dealing with a different area of control and divided into the requirements on different types of aircraft. The requirements which are dealt with below and which have been selected as design goals for the PC-9 are for a fighter aircraft (and trainers for this category), for control stick type of control and represent the optimum characteristic (level 1). The most critical flight phase of "Rapid Maneuver" is dealt with in detail here.

Level 1 of the Mil Specs correspond to a Cooper-Harper rating of <3.5 .

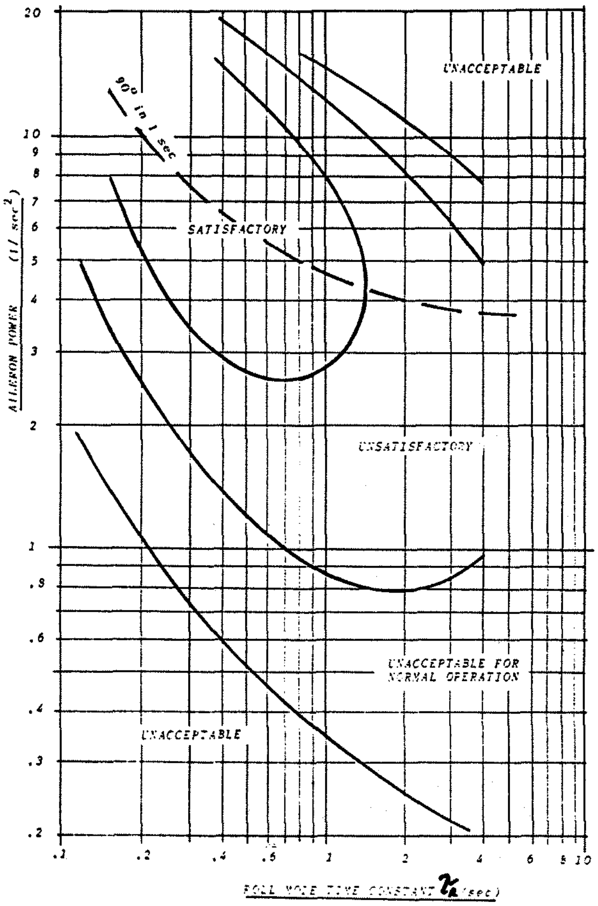

Fig 1 . Pilot opinion of the rolling motion from Ref [3]

<u>Roll Rate:</u> The basic requirement for fighter aircraft is for a roll rate such that a roll angle of 90 degrees is achieved within 1.3 seconds. (This is really an acceleration requirement.)

For the Air-to-Air combat role the requirement is further tightened to 1.0 secs and a complete roll (360° roll angle) must be achieved within 2.8 secs

The above requirement tries to put into simply measureable terms the results of simulator studies. The optimum aircraft response during the rolling manoeuvre, which can be represented in the behaviour shown in Fig 1 has been derived from these studies. This shows the pilot opinion during the roll in terms of roll acceleration and the Roll Mode Time Constant.

<u>Control Forces:</u> The civilian and military requirements are partially in agreement here. The maximum forces which can be allowed for the rolling manoeuvre are 133 N (30 lb). This is for the FAR pt23 and Mil Spec level 2.
The optimum forces (Mil level 1) should not exceed 89 N (30 lb).

<u>Roll response:</u> The roll response is defined in ref[2] as a maximum roll angle to be achieved within the first second for a certain force. Fig 2. shows this relationship. The figure is obtained from two ergonomic studies on simulators. Again, the roll acceleration is plotted against the roll mode time constant. The symbols show the results of the simulator studies. The full and dotted lines show the results of a simple single-degree-of-freedom model to represent the motion, for

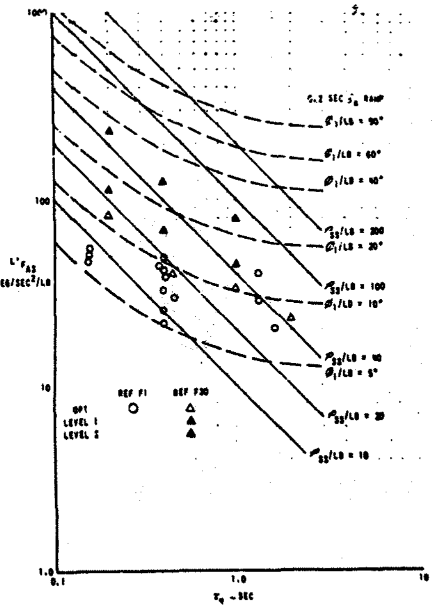

Fig 2. Force sensitivity [from Ref 3]

steady roll rate per lb of stick force and roll angle per lb of stick force in one second, respectively.

If the figure is observed more closely, it will be seen that the representation by a single degree of freedom model is not sufficiently accurate. Nor is it worthwhile to concentrate on the military specifications for this analysis, but it is better to refer to the users guide of Ref[3] directly. A further deficiency is that the simulator studies only give results for the increasing sensitivity above the optimum. In the case of manual controls, the more interesting area is the lower sensitivity: an increasing force or a lower acceleration. Using information from other references, it is possible to complete the diagram to give areas of acceptability, instead of only upper boundaries, similar to the representation of Fig 1.

A similar approach can be made with the sensitivity of the stick movement. From a careful observation of the results of the simulator studies, the author cannot agree with the interpretation of the military specfications of Ref [2]. The mil. specs. do not give significance to the stick deflection sensitivity, whereas the indication of the simulator studies is that this is a very significant parameter, within a certain band of stick forces.

Aileron Sizing

Using the above requirements it is possible to define the optimum sizing of the ailerons. A mathematical model of the rolling motion was derived in order to conduct this task. Initial correlation to a testbed aircraft showed that a three degree-of-freedom model was required, in order to adequately cover the effect of adverse yaw on the motion. The results of this investigation showed that a rolling moment coefficient of 0.06 would be required from the ailerons to achieve the required roll acceleration.

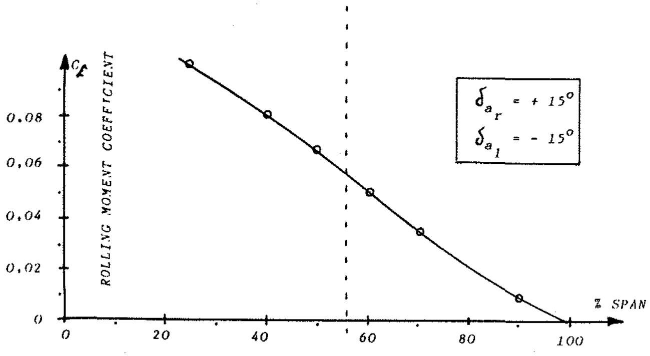

Fig 3. Rolling moment coefficient variation with aileron span

Figure 3 shows the rolling moment coefficient achieved by different aileron spans for the PC-9 wing. An aileron span of about 55% span has been selected. (actually 56.5% for structural reasons).This still allows sufficient flap area to give a satisfactory stall speed.

The next consideration is the selection of aileron chord.Although its effect on the rolling moment is not as significant as that of the span, it has a significant effect on the stick forces, as the force can be directly related to the square of the aileron chord. Fig. 4 shows how the rolling moment coefficient varies with the square of the aileron chord.

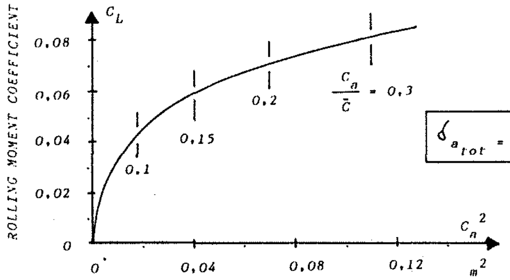

Fig 4. Rolling moment coefficient variation with (aileron chord)²

This figure shows that the minimum chord necessary to achieve the required roll rate must be selected to avoid excessive stick forces. Although 15% should be sufficient, an aileron chord of 18% was considered to still be acceptable from the standpoint of stick forces, whilst giving some margins to achieve the roll performaance goals.

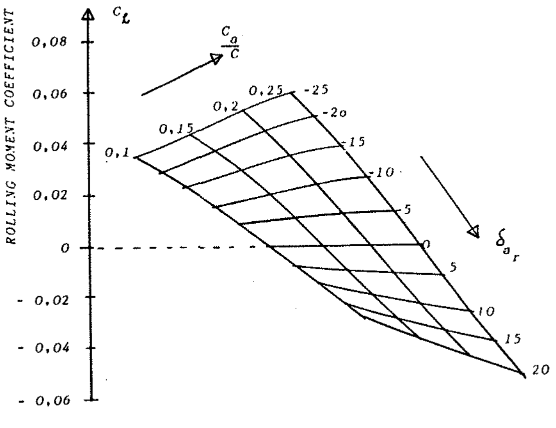

Fig 5 Rolling moment as a function of aileron chord and deflection

A further parameter is the aileron

deflection. A maximum deflection of 30 degrees is usual for an aileron and has been adopted here (later to be increased to 31 degrees as the structure allowed the additional movement). However it is also interesting to examine the rolling moment at deflections lower than the maximum. Figure 5 is a carpet plot of the rolling moment as a function of aileron deflection and chord.

The results of this figure can then be used in the final selection to be conducted in the aileron geometry optimisation: the differentiation to produce the minimum amount of adverse yaw.

The results of figure 5 give the rolling moment associated with a finite aileron deflection. For each of these aileron deflections a local drag difference over the part of the wing affected by the aileron can be computed and hence the corresponding yawing moment.

A carpet plot of the effect of aileron deflections of 0° to 20° for the left aileron and 0° to -25° for the right aileron on the yawing moment are given in Fig 6 below.

To achieve a 30° total aileron deflection the optimum (zero adverse yaw) would seem to be -22.5° and 7.5° for the right and left ailerons respectively. However, a small amount of adverse yaw can be accepted and there was some reluctance to require more than -20° of deflection due to possible separation effects. Added to this, a review of the behaviour at other speeds within the flight envelope, led to a selection of -20°/+11° as the maximum deflection and the differentiation up to that maximum as shown in the full line of Figure 6, with the correspondingly low adverse yaw throughout the flight envelope.

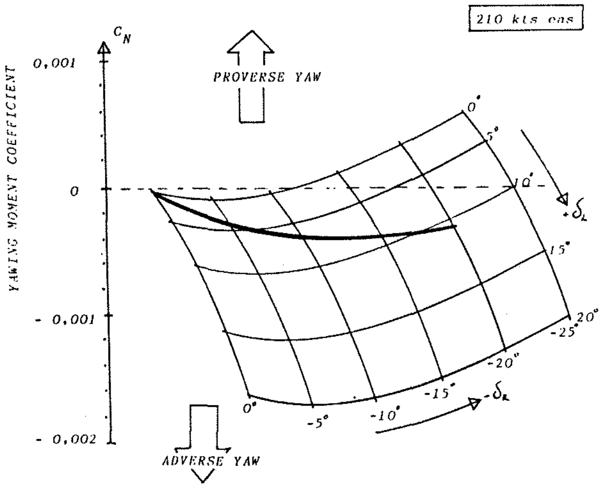

Fig 6. Yawing moments reduced by optimising aileron differentiation

The above description of the methodology of defining the control surface size is, of course, only a simplification of the procedure. In actual fact, the balance selection also influences the roll performance to a small extent and so the optimisation procedure requires several iterations.

<u>Balance Selection</u>

Having decided on the size of the control surface, the next step is to select a form of aerodynamic balance, or a combination several types.

An extensive search of the available literature was conducted without much success. Most of the research into control surface design was conducted up to and during the second World War. References [4 and 5] describe the work which was done in this area and provide numerous detailed references. Ref [6] investigates all NACA reports published during this time and provides an extremely useful series of abstracts on the relevant subjects. Nevertheless, it was found that insufficient information was available to the aerodynamicist to conduct a useful optimisation.

It was decided to, build a technology demonstrator aircraft to investigate in detail some of the possible candidate balances.

<u>Overhang Balances</u> were investigated. The nose shape is defined by a Nose Factor (using complex geometrical relationships) The higher the nose factor, the blunter the control nose is.

Extremes of hinge moment coefficients can be achieved by large, blunt overhang balances, as can be seen in curves 3 to 6 of FIgure 7, including highly unstable gradients. All of these balances are only completely effective over a range of ± 15° aileron deflection, after which the balance effect reduces towards that of an unbalanced control. The sensitivity of the balance can be seen by observing the difference between curves 4 and 6. The difference in nose shape represents only some millimeters on the control contour.

This sensitivity to shape tolerances is a problem area in manufacture, as was experienced in the early days of the Pilatus PC-7 production and is one of the reasons why this type of balance was not selected for the PC-9

Interesting in this investigation was the effect of gaps and hinge cut-outs: If the hinges were not well sealed. the hinge moment coefficient was considerably affected (equivalent to adding 2% balance). The rolling moment coefficient suffered also, but to a lesser extent. Sealing the leading edge gap has a significant effect on the drag at lift coefficients above 0,3.

Frise aileron is really a further form of overhang balance. They are to be seen on many aircraft on the general aviation scene, but do suffer from some problem areas. The Frise aileron is capable of providing a certain amount of proverse yaw by nature of the high drag of its protruding nose. However, this form of control achieves all of its effect from the overbalance of the up-going aileron, the down- going aileron being virtually unbalanced. Some aircraft have experienced problems with this when using cable controls due to the highly uneven forces in the cables. High forces and snatching and shaking of the ailerons have been experienced.
This balance type was not further considered for the PC-9.

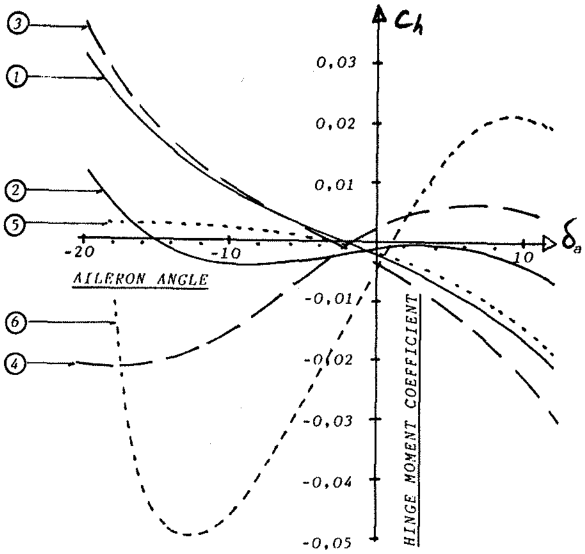

Fig 7. Hinge moments for various shapes and geometries of controls

Key to Fig 7:
1: 42% internal sealed balance
2: 47% " " "

3: 37% O'hang balance: 0,66 NF
4: 45% " " 0,66 NF
5: 45% " " 0,55 NF
6: 45% " " 0,77 NF

Sealed Internal Balance Again, very little literature is available to the aerodynamicist to assist in the design of this type of balance.
Unlike the two previous forms of balance, the effects of this type of balance are not subject to very tight manufacturing tolerances, if the nose gap is sealed by a membrane. Relatively large balance chords are required to provide the same level of balance as an overhang balance (vis Fig 7, curves 1 and 3), but the hinge moments are much less sensitive.

Tests on the test-bed aircraft showed that an air-gap seal at the nose of the control did not provide an acceptable solution. The manufacturing tolerances of ± 1 mm on the combination of wing-to-aileron nose provided sufficiently different aerodynamic forces to increase the pilot's stick forces by 50%.

Also the size of the vent gap between the wing trailing edge and the control surface is an important, but not particularly sensitive, parameter. This can influence both the absolute magnitude of the stick forces and the speed gradient ($Ch\alpha$).

Bevelled Trailing Edge This type of balance achieves its effect from the large lever arm to the hinge axis, and as such is also subject to small tolerances in manufacturing. Although much literature exists on this type of balance, none was really found to provide sufficient data for an optimisation study.

The bevelled control was found, on the test-bed aircraft, to penalise the roll rate by up to 1% of roll rate for each degree increase in bevel angle (between 25° and 40°).

Very flat hinge moment gradients could be achieved by the bevelled control over a large range of aileron deflections. This was partially the characteristic being sought, but it also had negative aspects.

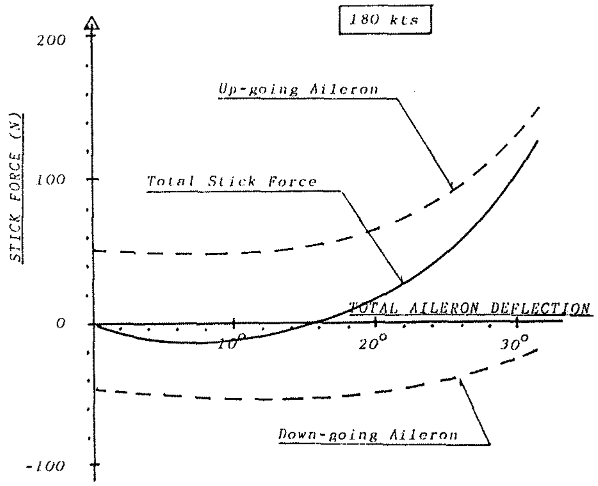

Fig 8 Force build-up for 40° bevelled ailerons

The larger the bevel angle (up to 40°),

the longer the deflection range at which the hinge moment coefficient gradient is almost zero, becomes.

Figure 8 shows the force build up of an aileron with a 40° bevelled trailing edge. It will be seen that the individual aileron's contributions to the total stick force are shown by the dotted lines. The resultant stick force over the first half of the deflection is unstable.

An decrease of the bevel angle will improve this situation, but the stick forces will also increase significantly at the maximum deflection. A 25° bevel gives acceptable stick forces in the central region, but the end forces are greater by a factor of four!

It is also not unusual to experience an aileron oscillation with a very large trailing edge bevel angle. This is purely produced by the lack of self centering forces.

<u>Balance Tabs</u> (or geared tabs)are used by many aircraft. They are very effective at reducing the stick forces. The hinge moments are easy to predict and references such as Ref [8] give simple and accurate methods to do so. However, balance tabs have not been further considered for the PC-9 ailerons because of their relatively large penalty on the aileron effectiveness and hence aircraft roll rate.

A form of tab which could also produce good stick forces is the spring tab. This however does not only have the disadvantage of lower roll rate but is also a very complex and heavy solution, when all the problems associated with flutter are solved. Also the manufacture of the torsion spring is difficult to keep within the tolerances necessary to produce symmetrical stick forces.

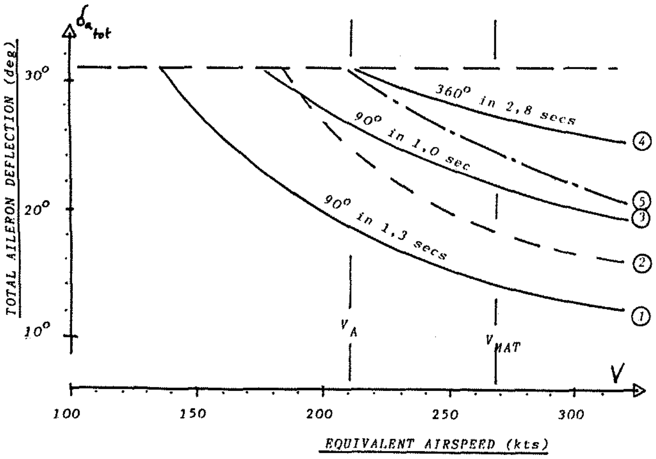

Fig 9. Aileron deflection to achieve roll performance criteria.

Aileron Performance

Figure 9 shows the performance of the PC-9 ailerons, sized according to Figs 3 to 6 above.

The five curves show the required aileron deflection to achieve certain levels of performance. These are as follows:

1: 90° of roll angle in 1.3 secs (basic Mil Spec requirement for "rapid manoeuver")

2: Roll acceleration to satisfy the "Satisfactory" boundary of Fig 1

3: 90° roll angle in 1.0 secs - Mil Spec requirement in Air-Air combat mode

4: 360° of roll angle within 2.8 secs (Mil Spec Air-Air combat)

5: aileron angle required to maintain a constant steady state roll rate from V_A. (not a requirement)

It can be seen that there is a large spectrum in the amount of effectiveness required from the aileron, depending on the selection of the requirement.

Curves Nos 1 and 3 represent only a requirement which has been derived from a simplified model. The actual optimum is better represented in Fig 1 and hence in curve 2.

Nevertheless, the Mil Specs are recognised for their clarity and will be used to demonstrate further performance achievement.

The most difficult requirement to achieve is that defined by curve No 4. This is because the PC-9 has a straight wing with relatively large damping moment. The background for this requirement has not been found by the author and is not dealt with in detail by the Ref [3]. It is not believed that this requirement has much more foundation than that of habit. It will be treated only as a desireable design goal, but not as an essential one.

Using these curves, a selection of the type of aileron balance has to be made in order to fulfil the stick force requirements.

The aileron selected for the PC-9 is a mixture between a sealed internal balance as the primary balance and a low angled bevelled trailing edge to "fine tune" the hinge moments. The resulting aileron performance is shown in the section below.

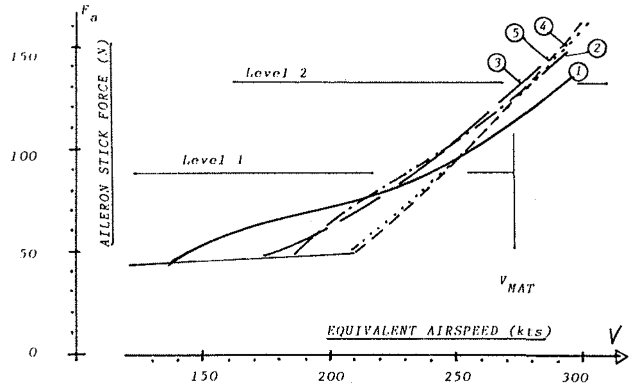

Fig 10. Aileron forces to achieve performance of Fig 9

Figure 10 shows the forces corresponding to the aileron deflections defined in Fig 9. In spite of the large scatter of the curves of Figure 9, by nature of the optimisation of the balance characteristics the force curves lie quite close together.

The maximum values of stick force specified both by the civilian and military specifications is maintained throughout the speed range up to V_{MAT}, the maximum speed for application of the requirements. The optimum stick forces (Mil level 1) are maintained well in excess of the manoeuvre speed for each of the curves.

A further presentation of the performance, is shown in figure 11. This figure shows the forces required to accelerate the aircraft through an angle of roll of 90°, for varying aileron angle and airspeed. All data for all of the above figures was obtained on the PC-9 at altitudes of between 5'000 and 8'000 feet. At an altitude of 25'000 feet the roll rate is increased by as much as 32% due to the reduced roll damping.

Figure 11 shows that the optimisation was sucessful for the area sought: At the manoeuvre speed of 210 kts the toughest criteria of the mil specs can be completely fulfilled - both the Air-Air combat criteria of roll through 90° within 1.0 secs and also maintaining level 1 stick forces. This can also be maintained throughout the required flight envelope up to V_{MAT}, albeit with stick forces increasing to level 2 above 240 kts.

Further goals which have been achieved are in the areas of force sensitivity and deflection sensitivity described in the requirements section above.

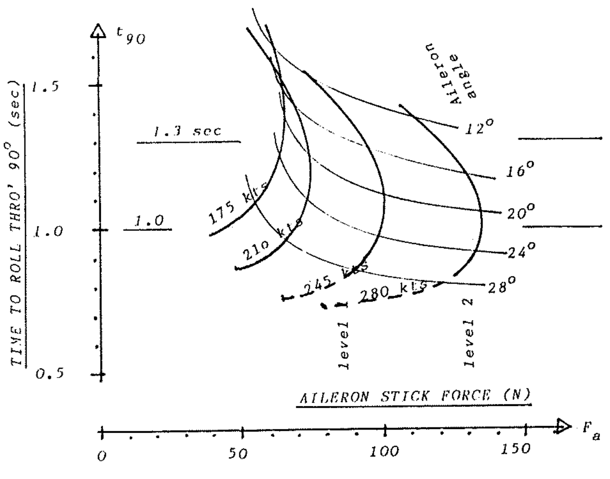

Fig 11. Forces to roll through 90° of bank, for the PC-9

Conclusions

It has been shown in the above text and figures that the main goals of the Military Specifications (and of the studies on which they are based) can be almost fulfilled in their entirity by manually operated ailerons by a careful optimisation of the aileron control system and aerodynamic balance, for a turbo-prop trainer aircraft.

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