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OBSERVATIONS OF PILOT CONTROL STRATEGY IN LOW LEVEL HELICOPTER FLYING TASKS

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ABSTRACT

A series of exploratory flight trials have been carried out in a collaborative programme between the RAE Bedford and the DFVLR Braunschweig to develop assessment methods for identifying pilot control strategy through the correlation of task performance and pilot workload. Special tasks were defined to highlight low level manoeuvring characteristics, including the circle manoeuvre, designed to induce a continuous and uniform closed loop flight path control strategy. Tests were conducted at both flight test centres and utilised the RAE Research Puma and DFVLR Research BO-105; pilots from both agencies flew both aircraft and were required to concentrate on precise flight path control while maintaining speed and balance. Detailed de-brief sessions required questionnaire completion focussing on task cues, pilot workload, task performance and vehicle dynamics and the interaction between these aspects. Both aircraft were fully instrumented and a range of analysis techniques have been applied to the recorded data to support and check the subjective pilot comments. This included data from ground based tracking facilities providing earth referenced position coordinates and hence height and track errors.

This Paper describes the background to these experiments and presents results comparing different control strategies adopted by the pilots in the different aircraft. A task model is proposed based on pilot comments, comprising the pilot's sensory cue patterns defined as inner and outer feedback loops. Results are presented that both support and challenge the hypothesis, based on describing the pilot as an interactive linear element in the vehicle/pilot system; however, the multi-cue nature of the task with those of an outside visual nature being sometimes poorly defined for the pilot, makes traditional linear analysis difficult. As defined, the circle manoeuvre induces pilot activity across a low frequency task bandwidth and higher frequency compensation bandwidth. Developments are proposed to extend the frequency range of the task.

1 INTRODUCTION

A major issue currently facing the helicopter community both in Europe and the US concerns the specification of the levels of agility and flying qualities required of future military helicopters. Requirements must be realistic, both in terms of service needs and the ability of the Industry to develop the appropriate technology. As specification formats begin to emerge, research is still required to validate and complete the quantifiable criteria and to establish the full range of clinical and role-related flight test evaluation procedures. In the current revision of Mil Spec 8501[1] (US requirements for helicopter handling qualities) for example, the minimum requirements on pitch and roll control are proposed in terms of the bandwidth criteria[2] and quantified on the bandwidth - time delay diagram, the form of which is illustrated in Fig 1. Associated criteria for damping and cross coupling are also specified. An aircraft's ability to meet these criteria can be established on the basis of clinical open loop testing, comprising the measurement of aircraft response to pilot control inputs, from simple steps to more complex frequency sweeps. It can happen however that, while meeting the quantified criteria, an aircraft exhibits handling deficiencies during role-related testing. Although this is recognised as a recurring problem with aircraft certification, two aspects make it difficult to guard completely against. Firstly, all new designs of aircraft are generally built to more stringent mission performance and safety targets and utilise an amalgamation of new technologies for the first time. Criteria based on extrapolation from existing aircraft may not therefore be either appropriate or complete. Secondly, the flight test development phase may not necessarily have covered all of the most critical conditions. Questions that may, for example, be raised regarding Fig 1 include the validity of the criteria for the potentially high gain tracking requirements of air-to-air combat, the need for an upper bandwidth boundary to exclude configurations prone to pilot induced oscillations, or whether compliance demonstrated in, say, level flight conditions implies satisfactory handling in manoeuvring flight. From these potential problem areas has arisen the need for a range of task-orientated, clinical flight tests and the Mil Spec 8501 revision has given special attention to this need by proposing a new section on test requirements. This Paper is also concerned with this topic.

From a research perspective the RAE and DFVLR are continually updating their testing techniques and evaluation methods. Both agencies operate piloted simulation facilities and are committed to research into improvements in helicopter control. The DFVLR BO-105 ATTHES[3] and the RAE ground-based flight simulation complex[4] have already produced a wealth of flying qualities information. Proposed future active control programmes based on DFVLR BK117 and RAE Lynx helicopters will extend this considerably. To further the reaching of the two countries' complementary aspirations, an informal collaboration was set up in 1984 enabling engineers and pilots to work together in joint flight programmes including the exchange of test data. Both agencies have recognised the special need for the development of clinical, task-oriented manoeuvres involving precise flight path control, close to the ground. Future combat helicopters, operating in this environment, will have improved mission effectiveness through carefully tailored flying qualities and the attendant workload reduction, and one of the aims of the joint research is to understand more fully the nature of pilot control strategy and workload for this type of flying. This general aim can be expanded into a number of specific objectives.

(1) To establish a set of discrete pursuit manoeuvres and continuous compensatory tracking tasks that are realistic in terms of outside visual cue patterns, are multi-axis and well enough defined that pilots are able to apply a closed loop control strategy across a reasonably high bandwidth.

(2) To develop a questionnaire series and associated de-brief procedure to aid the evaluation pilot's description of the interaction between task cues and vehicle dynamics and the resultant effects on task performance and workload.

(3) To derive robust and reliable methods for scoring task performance and quantifying workload.

Results from discrete manoeuvre tests, eg side-step and bob-up, have already been published[5,6,7,8] and are currently being used in support of the revision of Mil Spec 8501. The need for closed loop tracking tests has long been recognised[9] in the fixed wing community for the higher gain pilot control activity required for target tracking, directed approaches, air-to-air refuelling etc. Traditionally, helicopter pilots are more accustomed to operating over lower bandwidths, but as military roles develop and higher performance is conferred on new designs, so pilots will need to be trained to use higher bandwidth control to achieve the increased agility and precision required in the missions. As with fixed-wing aircraft, higher frequency pilot inputs can lead to pilot induced oscillations and other handling deficiencies associated with cross couplings, that may not have been covered in the database from which criteria were derived.

This Paper is concerned with closed loop pilot control strategy for continuous low level flight path tracking tasks. In section 2 the importance of control strategy as a crucial element in handling qualities investigations is stressed. Section 3 describes the flight test techniques adopted in a joint RAE/DFVLR programme and introduces the circle and figure of eight manoeuvre; de-brief procedures and questionnaire development are also addressed. Results from the task analysis are presented in section 4 and, in section 5, the status of the programme is reviewed in the light of the findings from this first phase of the collaboration.

2 PILOT CONTROL STRATEGY

Fig 2 illustrates the significance of control strategy in the overall dynamics of a flying task. The task requirements in a given environment will determine the accuracy and spare workload capacity required. The combination of vehicle dynamics and task cues will determine the control strategy adopted by the pilot which, in turn, will be reflected in realised task performance and workload. Pilots generally try to adopt a control strategy that maximises performance while minimising workload. This must involve a compromise and, depending on the consequences for the mission, one or other will usually suffer. The key to understanding how different pilots cope with this compromise, how task performance and workload correlate and therefore how sensible criteria for task operated flying qualities can be constructed, lies in the identification of the pilot control strategy.

Consider, as an example, the task of flying low level over a defined ground track; additional task constraints could require the pilot to maintain height and ground speed and, perhaps, to remain in balanced flight. Although helicopter pilots flying NOE are not normally quite so tightly constrained, the task is not unrealistic as a test case for 'worst' situations and, in any case, error margins could be defined in practice that would allow for tolerable excursions in task variables. The most natural control strategy adopted in this task would be lateral cyclic for track errors, collective for height errors, longitudinal cyclic for speed errors and pedals for balance. Piloted simulation experiments[11] with highly augmented helicopter configurations have demonstrated that a marked reduction in workload is achieved when this simple control strategy can be adopted and the need for compensatory cross control inputs eliminated. In practice however, cross couplings and a range of aircraft limitations inhibit the use of such a simple flying technique and pilots generally need to use a combination of carefully coordinated inputs to cancel a single task error. Additional control strategy problems arise when flying in steeply banked turns close to the ground as required during tightly curved portions of the ground track. The reduced collective pitch available for compensation will force the pilot to use both cyclic controls to assist in maintaining height and hence compromise track and speed control. The relationship between the outside visual cues and the aircraft-oriented control loops becomes more complex and considerably higher skill levels are required to maintain precise flight path control in such situations. Flight safety margins are minimal in the nap-of-the-earth environment and, clearly, control strategy must be natural and instinctive, particularly when gross and unexpected task errors result in an emergency situation.

Future helicopters with active control systems will enable refined and even radical changes to pilot control strategy and it is vital that due account be taken of the current natural pilot response in critical situations. In addition to the objectives outlined in section 1 of the Paper, the joint RAE/DFVLR research is seeking to establish a better understanding of the way control strategy develops in manoeuvring flight. The circle manoeuvre, described in more detail in the next section, has been designed to assist in the quantification of control strategy in this flight régime.

3 TEST TECHNIQUES, AIRCRAFT AND PILOTS

A range of flight tasks that demands continuous flight path tracking from the pilot while flying close to the ground and obstacles has been explored in previous experimental studies at a number of research agencies. Examples include the DFVLR slalom and dolphin[5,8,10] and the RAE serpent and hurdles[11,12]. These tasks all involve a number of different elements (transient turns, reversals, pop-ups) across which the pilot control strategy varies significantly as a result of varying task demands and vehicle dynamics. Experience gained in these tests has highlighted the need for additional tasks that require a more uniform control strategy and produce results that are amenable to stationary time series analysis. From this need the idea of a simple circular task developed. At the RAE a family of circular and spiral tracks have been marked out as lines on the airfield[7], with aircraft position tracked by kinetheodolites. For the DFVLR tests, the track was marked with poles joined with chequered tape; aircraft position was measured with a laser tracking system. Fig 3 illustrates the two schemes arranged as figures of eight.

The two aircraft flown in the trials were the RAE Research Puma (Fig 4) and DFVLR Research BO-105 (S123) (Fig 5). Neither aircraft has a variable stability capability and both were normally flown unaugmented. Both were fully instrumented for flight mechanics research, the Puma with an on-board digital PCM data acquisition system. Normal recording technique with the BO-105 utilised a telemetry link to a mobile ground station. Both DFVLR and RAE evaluation pilots were qualified test pilots with considerable operational experience.

Since neither of the test aircraft were variable stability, configuration changes were introduced in terms of task variables and pilot's controls used, as summarised in Table 1. The principal configuration variables were circle diameter, nominal airspeed and height, and required control technique S1-S4. S1 required the pilot to fly on cyclic alone; S2, cyclic with collective; S3, cyclic with pedals; S4, full controls. The principal task variables were track, height, speed and balance. S1 required the pilot to maintain track and height; S2 - track, height and speed; S3 - track, height and balance; S4 - track, height, speed and balance. The reasons for this somewhat artificial choice of control techniques are twofold. Firstly, it is well known that for multi-axis tasks, pilots are not always able to describe a complex control strategy and associated cue patterns, and can find it difficult to maintain a uniform strategy, when cross coupling effects are strong. The build-up sequence from S1 to S4 makes the task progressively more complex and therefore should allow pilots to understand better how they coordinate controls to cancel task errors. Secondly, it enables the pilot to appreciate how attention is divided between task cues and associated controls. This increased appreciation was intended to lead to a more fruitful interchange of ideas during de-brief sessions.

The principal questionnaire, developed especially for the circle task, is reproduced in Table 2. As shown, the four main areas dealt with are piloting cues, task performance, pilot workload and handling qualities (relating to vehicle dynamics). The pilots were required to return ratings for the last two aspects (HQR, WLR - see Tables 3 and 4). The workload rating (Ref 13) gives a measure of the amount of spare capacity the pilot believed he had for extra tasks. In addition, during the BO-105 trials at the Manching test centre, task performance ratings (TPR)[14] were returned by the pilots.

Wind strength played a significant part in the tests, to the extent that it determined the operating limits pilots were prepared to fly to in terms of maximum speed and minimum height in a given sortie. For example, an increase of wind speed from 5-10 kn for a nominal test speed of 80 kn resulted in a pilot downgrading by at least one HQR and two WLR. Above 15 kn of wind, aircraft limits in terms of power, bank angle and sideslip angle were easily encroached on at the higher test speeds. The once per circle variation in test conditions induced by the steady wind gave rise to strong and well defined low frequency pilot control activity. Compensation for unsatisfactory control response and turbulence increased the bandwidth of the pilot input to much higher values, beyond 1 Hz in some cases, and these distinct régimes will be addressed further in the next section.

A final point needs to be made on task cues and the associated error margins. Initially there was uncertainty regarding how well the pilots would be able to maintain the task variables. It became clear that two modes of flying could be adopted by the pilots, a relaxed and aggressive mode. In relaxed mode, the pilot would fly at a comfortable workload and accept larger task errors. Flying more aggressively, the pilot could minimise the task errors at the expense of a significant increase in workload. Both strategies were adopted on various occasions. There was also some uncertainty concerning the task cues the pilots would find most useful; primary height and track information was expected to come from outside visual cues while speed and balance were presented to the pilot as airspeed and sideslip. The questionnaire specifically addressed this aspect and required the pilot to quantify his complete, primary and secondary, cue pattern.

4 TASK ANALYSIS

Within the framework of the objectives discussed in the Introduction to this Paper, task analysis comprises the interpretation and correlation of both qualitative and quantitative results. If the approach is to be at all useful in the evaluation and comparison of different configurations, it is clearly desirable that simple, unambiguous measures of performance and workload can be derived.

Some progress along these lines is made in this Paper and the following discussion will address the four different areas - cues, performance, workload and handling qualities separately. Results from data analysis and pilot comments are combined in an attempt to convey a consistent story. Several anomalies remain to be explained however, and these will be mentioned as they arise. Most, in fact, come from inconsistencies between pilot comment and the flight data analysis. Task training appeared to play a vital part regarding performance and workload consistency; this was offset by the physical demands made on the pilot who became more tired as a sortie developed. Sortie duration was generally restricted to about 30 min with pilots taking turns as evaluators.

The presence of a steady wind gave rise to the fundamental low frequency task. In fact, in low turbulence conditions as was normally the case, the variation in direction of the steady wind relative to the aircraft was strictly the only task input. Furthermore, the test pilot was able to anticipate the wind effects in his control inputs. A basic pattern emerged, more or less common across aircraft type, pilots and test conditions. This can be summarised in the form of a so-called 'target' diagram as shown in Fig 6. The case corresponds to pilot P2 flying the Puma with S1 control strategy at 80 kn. These results are strictly qualitative (data being scaled to zero mean and three standard deviations), but give an impression of how task variables are affected by wind aspect. One curious feature is the orientation of bank angle variations relative to the wind; one might expect the maximum bank angle to occur on the lower cross wind leg. Typically this actually occurred on the downwind leg where the ground speed was increasing and higher turn rates were therefore required. Figs 7 and 8 illustrate a sample of time histories including cyclic control activity and flight path errors; the cases include pilots P1 and P2 flying both aircraft in right and left turns with strategy S1 (cyclic only). Aspects of these and other results will be addressed in the following discussions.

4.1 Task Cues and Performance

The task cue pattern is best summarised by Fig 9. Track errors assume the highest priority and were determined entirely by outside visual cues. Pilots tended to fix attention on the ground track some 50 m ahead of the aircraft, correcting anticipated errors with roll control. Pilots considered that they could achieve the track with an error of ±10 ft, although as shown in Figs 7 and 8, in practice excursions considerably greater than these were measured. As indicated in Fig 9, height and speed received second priority. In practice they were closely related in terms of pilot impression of task errors. Increased 'ground rush' cues on the downwind leg gave the impression of a descent condition with the opposite occurring on the into-wind leg. At the height flown in the trials, usually above 50 ft, the height cues were deemed inadequate for the task. The flat surface of both airfields lacked texture and pilots were reluctant to fly at very low altitude for safety reasons. There were no primary height cues since from outside visual cues alone it was difficult for the pilots to detect height changes of less than 10-15 ft. It became clear that at the lower mean heights the task errors reduced; Fig 10 illustrates the point clearly with the standard deviation of height error plotted against mean height flown (strategy S1). A striking feature of the Puma results, shown in the height traces in Fig 7, is that when the evaluation pilot was sitting on the outside of the turn (P1, right; P2, left) the mean height flown was some 20 ft lower than when sitting on the inside of the turn. The pilots did not comment on this during the trials and the reasons for the height change have yet to be satisfactorily explained. No such height change was experienced in the BO-105 tests.

Speed cues were derived from the pilots airspeed indicator, which, along with the balance reading (sideslip) was scanned between 4 and 8 times per circle. This diverted attention from the important outside visual cues causing some degradation in flight path tracking. It is now recognised that forcing this divided attention on the pilots is probably unrealistic and that a better pair of task variables would be visual ground speed and lateral 'g' as a balance cue. These were used as secondary cues for the tests described in this Paper (see Fig 9).

Flight path control, in relation to track and height accuracy, is a relatively low frequency task for the pilot. Nevertheless, considerable higher frequency control inputs are visible in the data of Figs 7 and 8 and this will also be reflected in flight path accuracy. Any measure of task performance should attempt to distinguish between errors incurred across the frequency band of the principal task and those at the higher frequency, usually associated with compensatory control inputs. The power spectrum of task errors should accommodate this and Fig 11 presents recommended Level 1 and Level 2 task performance boundaries for track error. The boundaries shown in Fig 11 have been derived from the task performance ratings of pilot P2 flying the BO-105 across the control strategies S1-S4. Results from both pilots are shown in Fig 12. Clearly, P2 achieved the best task performance with S4 (all controls) and returned his only Level 1 rating for this configuration. Why S1 should have been awarded such a poor Level 2 rating is not clear, although it should be remembered that the TPR related to the whole task and, generally speaking, height accuracy was never quite as good with collective fixed. Curiously, pilot P1 did better with the mixed configurations S2 and S3 and his results do not conform to the recommended boundaries based on pilot P2; in particular P1 appears to have tolerated a higher bandwidth of the track error. However, although impressions of task performance (and hence their TPR) may vary from pilot to pilot, unlike workload and handling qualities the actual task performance can be determined precisely. Further analysis of both BO-105 and Puma results should serve to check the validity of the task performance boundaries postulated. Similar boundaries can be drawn for the other task errors to form a complete picture of the overall task performance across the primary and compensatory bandwidths.

4.2 Pilot Workload and Handling Qualities

Piloting workload for the circle task was, generally speaking, tolerable but unsatisfactory (insufficient spare capacity for attention to other tasks), as might have been expected from unstabilised aircraft flying tight manoeuvres. Level 1 ratings (satisfactory) for both workload and handling qualities were recorded only in very low wind conditions (< 5 kn) and then only by pilots familiar with the test aircraft (P1, Puma; P2, BO-105). Both wind speed and task airspeed played a significant part in pilot opinion, to an extent that it would be erroneous to compare pilot ratings without reference to these conditions. Fig 13 illustrates the point showing ratings from both pilots flying the Puma with S1 strategy. It must be emphasised that this result is not a peculiarity of circle flying; in operational situations, workload would be significantly effected by the same task parameters. The increased workload with speed arose from the need for the pilot to increase the bandwidth and amplitude of his control inputs to maintain the same task performance. This in turn could, and on occasions certainly did, lead to vehicle dynamics being excited that further impeded the pilot from achieving the task. This characteristic tended to have a stronger influence on the pilots when flying the unfamiliar aircraft (P1, BO-105; P2, Puma), a feature that favoured a more relaxed flying technique, particularly early in the trials programme.

Pilot ratings for workload and handling qualities across the four control strategies are summarised in Fig 14. To some extent the spread of ratings highlights the problems that can arise with only a limited sample of pilots. For example, pilot P1 considered the handling qualities of both aircraft to be fairly uniform across the strategies while, at least for the BO-105, P2 returned ratings across the three levels. Cross coupling was considered to be the most serious degrading factor, noticeably roll/pitch, pitch/roll and roll/yaw in the BO-015 and yaw/roll and collective/ yaw in the Puma. In both unaugmented aircraft the primary response characteristics were also considered less than ideal (too sluggish in the Puma, too sensitive for the BO-105), the only Level 1 rating being awarded by P2 for the BO-105 with S4. There is also some evidence that the handling qualities of the aircraft varied with turn direction, this being reflected in the task performance and control activity but not in the pilot ratings. Theoretical analysis has shown that, particularly for the Puma, coupling between longitudinal and lateral motion changes with turn direction, but again, this was not reflected in the pilots' comments. It must be emphasised that these results are particular to the current tests and do not necessarily apply to the stabilised aircraft in operational service use. Aircraft handling deficiencies, together with the less than adequate task cues, accounted for the somewhat greater variability in workload ratings. There is no evidence in Fig 14 that workload (ratings) increased with number of controls used, a surprising result perhaps, and contrary to what was expected. The correlation of control activity with pilot ratings is the subject of current analysis and measures similar to those proposed for task performance in Fig 12 will be proposed. This is proving a perplexing task and no firm and consistent results have yet been derived.

As in so many other studies, the quantification of piloting workload for the circle task is proving difficult. The questionnaire in Table 2 was designed to ease this task. However, one wondered on occasions whether the pilots found this form of 'interrogation' more arduous than the flying itself. There is no question that the pilots took the approach seriously but the de-brief sessions were often hard work, particularly with regard to the description of control strategy. This experience has highlighted the need for further development of the questionnaire concept and the engineering approach to de-briefing, and this aspect is of great concern in the continuing collaboration between the two agencies. In support of the qualitative analysis of pilot comments, work is underway on the identification of control strategy through task modelling. Some tentative ideas relating to this analysis are introduced in the Discussion to this Paper.

5 DISCUSSION

In seeking to meet the objectives set out in the Introduction to this Paper, a number of important aspects have been encountered and need to be highlighted. The need for carefully and precisely defined flying tasks that provide the pilot with continuous cues, guiding his appreciation of performance, has been emphasised. Where cues proved inadequate, as in the case of height errors, task performance inevitably suffered and pilots understandably flew with a safe margin and relegated this element of the task to a lower priority. Thus, in the circle task, the two components of flight path control, track and height did not receive equal attention and an unbalanced control strategy resulted. This was a disappointing result and efforts to improve the height cues, so that pilots are prepared to fly at lower mean heights, must be sought.

The need for pilots to monitor cockpit instruments for speed and balance errors interfered with the principal flight path tracking task. Future tests will explore the use of ground speed and motion balance cues as more realistic alternatives, resulting in a totally outside visual cue task.

The use of a small sample of pilots (namely two) inevitably introduced some uncertainty as to the generality of results derived from these tests. This is not particularly important in itself, as the aircraft themselves were not under test. Where confusion can arise is when inconsistencies appear between, for example, pilots impression of, and actual, task performance. Results from a larger number of evaluation pilots can often help to shed light on problems of this kind and are certainly required to provide a firm validation of proposed performance or workload criteria. Increasing the number of test subjects increases the test engineer's workload of course, and in this context the collaborative exercise has pointed to the need for more efficient and sharply focussed de-brief procedures. Perhaps the single most important issue here is the need for analysed test results available at the de-brief. Simple task performance and workload scores similar to those proposed in Fig 12 would be likely to initiate more productive dialogue, and plans are in hand to enable the required inter-sortie data processing.

Another aspect of some concern is the use of multiple pilot rating scales. To some extent this is a consequence of International collaboration, where different agencies are familiar with different standards eg HQR and WLR at RAE, TPR and stress factor at DFVLR. The latter has not been considered in this Paper but is akin to the WLR, although inevitably, it is not quite the same. The very real danger here is that the pilots will get confused as to what they are rating and which scale they are supposed to be using. A rationalisation is required in the interests of clarity and future joint tests will be conducted in this light.

The final topic to be covered in this Paper concerns the identification of control strategy through task modelling. No definitive results have yet been derived in this area and the arguments put forward here are somewhat tentative. The general approach adopted in this kind of analysis is to model the pilot's behaviour as an element in the pilot/vehicle closed loop system[15]. With the input (task cues) and output (pilot's controls) to the pilot element well defined, in certain conditions it is possible to synthesise a parametric pilot model from the flight measurements. Individual parameters in the model can then be closely associated with meaningful workload parameters, eg overall gain with concentration factor and lead time constant with anticipation factor. Variation in these estimated parameters with task parameters can then be correlated with pilot ratings and task performance. The theory of this human pilot modelling can be expanded to include multi-axis tasks and hence estimate how the pilot is sharing his workload between the various control loops involved. The potential benefits of this form of analysis are attractive and have encouraged many applications but, in practice, the successes have largely been derived from single axis tasks under fairly clinical test conditions. Pilots, engaged in applied flying tasks, tend to operate in an adaptive and nonlinear fashion making their description as a constant linear element a rather naive concept.

The circle task was designed to induce stationary properties in the pilot control strategy. In the event, of the task variables, track error was the only one which the pilot was able to close the loop around strongly, with lateral cyclic. Fig 15 gives a picture of the task model. Based on pilot comments, the basic inner roll loop and outer flight path loop are proposed, although it is expected that the component of lateral cyclic generated in this model will not account for the total pilot control activity. The commanded bank angle ϕ_c will vary with position around the circle, not only through the wind effect, but to a lesser extent through speed, sideslip and climb rate changes. This will need to be estimated before the inner loop model can be derived. Fig 16 illustrates typical power spectra, plotted on a log scale, for the variables circulating in the control loop. The case corresponds to pilot P1 flying the Puma (S1) at 80 kn in a left circle. Control activity and track error are distributed over two frequency ranges; the task range extending up to 0.1 Hz and the compensation range between 0.1 and 1.5 Hz. Clearly, flight path excursions at the higher end of this range are negligible. If $f_{ec}(\omega)$ is the cross spectrum and $f_{ee}(\omega)$, $f_{cc}(\omega)$ the auto-spectra of the task error and pilot control, then the gain and phase of the associated transfer, or describing, function can be written[16],

$$G(\omega) = \frac{|f_{ec}(\omega)|}{f_{ee}(\omega)} \tag{1}$$

$$\Phi(\omega) = \tan^{-1}\left(\frac{I_m(f_{ec})}{Re(f_{ec})}\right) \tag{2}$$

These relationships are strictly only valid within the frequency range of the input task input or disturbance. The coherency function, reflecting the degree of linear correlation between e and c can be written,

$$W(\omega) = \frac{|f_{ec}(\omega)|^2}{f_{ee}(\omega)f_{cc}(\omega)} \tag{3}$$

The transfer function given in equations 1 and 2 represents the 'best' linear functional relationship between task error input and pilot control output, in the sense that it minimises the mean square difference between its output and c . Sample results for the case in Fig 16 are given in Fig 17, where rate of roll is the input. Coherency is high across the lower 'task' bandwidth and rises again above 0.2 Hz, up to about 1 Hz when the relationship becomes 'fuzzy'. Strictly speaking, with such a multi axes task, the coherency function can hide the effects of task error correlation with other task variables. Partial coherency analysis is required to separate out the individual contributions to task errors[9] and tools are currently being assembled to extend the analysis for this purpose. This is likely to be essential for modelling S4 control strategy for example. The gain function in Fig 17 is characterised by a fairly flat portion over the task bandwidth, rising to a high peak at around the dutch roll natural frequency (0.2 Hz). Again, two distinct regions are revealed. It can be shown[17] that the transfer function model given by equations 1 and 2 is strongly influenced by the aircraft transfer function over the higher bandwidth. Fig 18 shows a generalised single loop system with task error $e(t)$ and pilot control $c(t)$. In recognition of the fact that the pilot control is not entirely derived from the output of the element P, a noise source or remnant $n(t)$ is included, assumed to be uncorrelated with the task input $i(t)$. The pilot remnant is made up of any strongly nonlinear compensation and inputs caused by random errors of judgement. Normally the remnant has a considerably higher bandwidth than the task input, Fig 19 highlighting the effect in power spectrum terms with exaggerated, sharply cut-off signals. The error spectrum following from Figs 18 and 19 will therefore have two distinct peaks, one at the input bandwidth, the other at the closed loop natural frequency. The significance of this reasoning is that a pilot model P^* generated by equations 1 and 2 will actually be related to the pilot element P and aircraft transfer function S through the relationship[17].

$$P^* = \frac{\{f_{ee}\}_i}{f_{ee}} P - \frac{\{f_{ee}\}_n}{f_{ee}} \frac{1}{S} \tag{4}$$

where the subscripts i and n refer to the components of the error spectrum due to the task input and pilot remnant respectively. At the higher frequencies then, this analogue model is likely to be dominated by the inverse of the aircraft transfer function.

For the circle task, the considerable pilot remnant and associated aircraft motion above the basic task bandwidth for both aircraft in almost certainly a product of flying unstabilised aircraft combined with the less than perfect task cues. For the low frequency task model the pilot will dominate P^* and analysis is underway to derive model structures and parameters for both inner and outer loop dynamics over this range. In order that pilot closed loop control be extended over higher frequencies, some development of the circle-task is required. A circular slalom course is being discussed, with irregular deviations marked around the course (Fig 20). This additional flight path tracking requirement should force the pilot to increase his bandwidth to the extent that the validity of handling criteria such as proposed in Fig 1 can be tested in steady manoeuvring flight.

6 CONCLUSIONS

For flying qualities research with highly augmented helicopters and to support compliance demonstration of future agile rotorcraft, a range of new task-oriented flight test techniques need to be developed that are sufficiently demanding to expose all handling deficiencies. This Paper has presented results from the first phase of a joint RAE/DFVLR collaboration in which knowledge and facility resources have been shared to further this development. The test techniques comprise task definition, flight test, de-briefing and task analysis, the latter including both subjective pilot comments and flight data analyses. The circle manoeuvre has been introduced as a task for exploring pilot control strategy and hence flying qualities associated with precise flight path control at high bank angles. Tests have been conducted with instrumented Puma and BO-105 aircraft involving low level tracking of ground marked courses. Task definition included task height and speed and basic control strategy, ranging from cyclic only for flight path control, to full controls adding speed and balance to the task variables. During de-brief sessions pilots were required to complete a questionnaire that covered task cues, task performance, pilot workload and handling qualities. Results presented, including pilot ratings, are derived from the correlation of pilot opinion with results from the analysis of both performance and pilot control activity.

Task performance levels are proposed that cover both the low frequency task bandwidth and higher frequency compensatory bandwidth. Results for track errors analysed in this manner are encouraging although some inconsistencies between pilot opinion relating largely to their understanding of the task, remain unresolved. To an extent this problem will always arise when only two evaluation pilots participate in the tests. While track error cues were satisfactory, at the heights flown (generally above 50 ft), height error cues were inadequate which resulted in a somewhat unbalanced flight path control strategy.

Wind strength and airspeed had a significant effect on pilot workload ratings, Level 1 ratings being returned in low wind and Level 3 in high wind for the same aircraft. Both aircraft were flown unstabilised which increased workload through the need for higher frequency, compensatory pilot control. Surprisingly, pilots did not feel that their workload increased significantly with the use of more controls and task performance did not always improve in these situations.

An approach to task modelling has been proposed and some preliminary results discussed. Over the low frequency task bandwith the pilot dominates the traditional analogue pilot model while, at the higher end of the spectrum (up to 1.5 Hz) the natural, coupled aircraft dynamics prevail. More detailed analysis now underway in this area, including the use of partial coherence functions, will be reported on in due course.

This collaboration has provided a unique opportunity for the two institutions to share resources in their research towards a common goal. The exploratory tests described have been successful but further refinements are required before simple and robust measures of workload and task performance can be derived. Other areas requiring attention include the use of common rating scales, the need for improved task cues (particularly height), the availability of analysed results during de-brief sessions and the development of pilot questionnaires. To increase the task bandwidth a modified circle manoeuvre has been proposed akin to a circular slalom; flight tests are planned with this new task in the near future.

ACKNOWLEDGEMENT

The authors wish to extend their thanks to the two principal test pilots for the circle manoeuvre Lt Cdr Rory Cowan and Mr Manfred Rössing.

Task Variable	Condition		
Circle Radius	C1 = 330 feet	C2 = 515 feet	C3 = 800 feet
Airspeed	V1 = 60 knots	V2 = 80 knots	V3 = 100 knots
Height	H1 = 75 feet	H2 = 50 feet	Minimum H3 = attainable
Control Strategy	S1 = Cyclic only S2 = Cyclic + Collective		S3 = Cyclic + Pedals S4 = Full Controls

Control Strategy	Task Definition
S1	Maintain track and height: collective and pedals to be trimmed in the turn
S2	Maintain track, height and speed: pedals to be trimmed in the turn
S3	Maintain track, height and balance: collective to be trimmed in the turn
S4	Maintain track, height, speed and balance

Table 1 Circle Task Variables and Control Configurations

1 PILOTING CUES

- 1a What were the principal cues determining control activity?
- 1b Were the cues adequate for performing the task?
- 1c Were any additional/secondary cues used?

2 TASK PERFORMANCE

- 2a What task error thresholds was the pilot flying to?
- 2b Was the pilot able to perform the task within the error threshold?

3 PILOT WORKLOAD

- 3a Was the pilot flying in a relaxed or aggressive manner?
- 3b Can the pilot distinguish short term from long term workload?
- 3c Return a pilot workload rating?
- 3d Physical or mental workload?
- 3e How much spare capacity?

4 HANDLING QUALITIES

- 4a Any natural tendencies of aircraft that pilot had to overcome?
- 4b What were the good handling qualities?
- 4c Return an HQR? - emphasise principal deficiencies

5 GENERAL

- 5a Distinguish between compensation required for vehicle performance, handling qualities or task cue deficiencies.
- 5b Does the pilot feel that assessing his own performance and workload in the task is interfering with his ability to perform task?
- 5c Any learning effects?

Table 2 Task Questionnaire

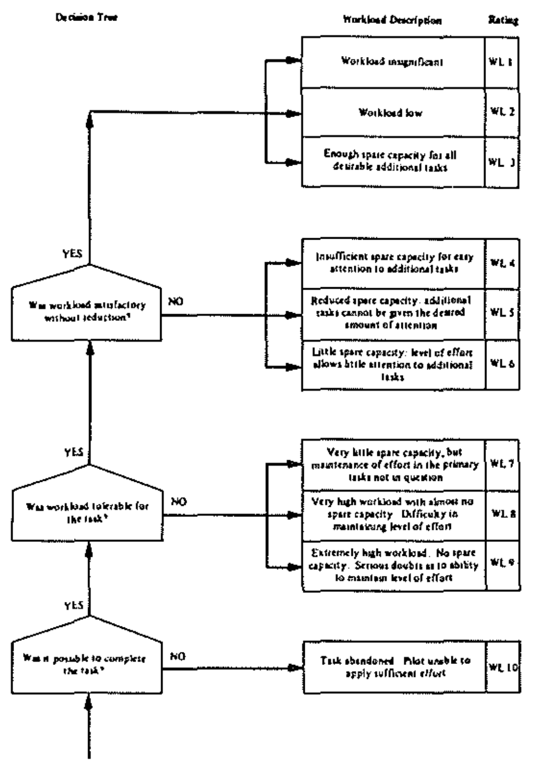

Table 3 Pilot Workload Rating Scale

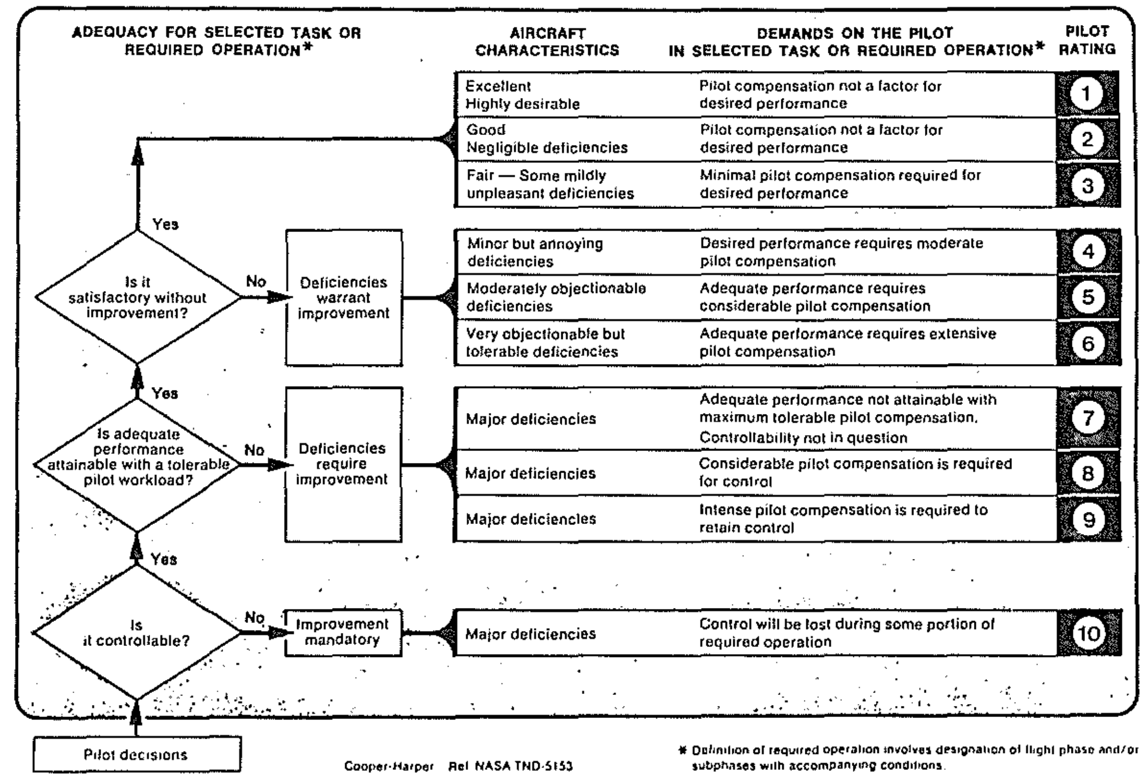

Table 4 Cooper-Harper Handling Qualities Rating Scale

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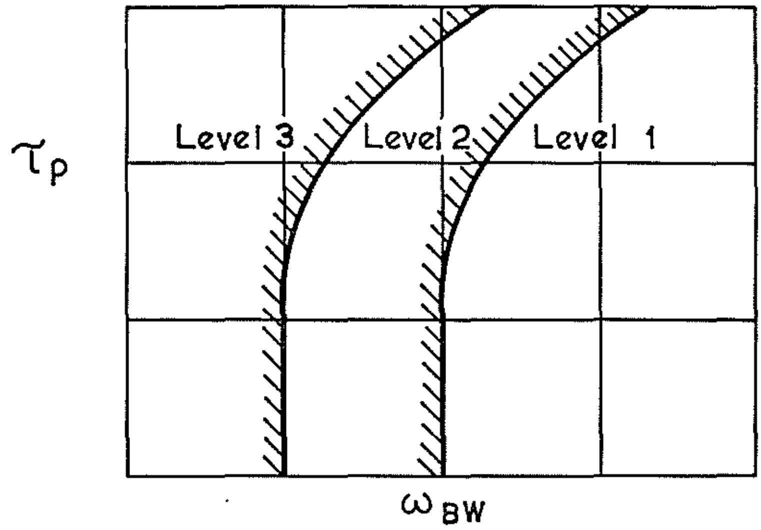


Fig 1 Bandwidth/Time Delay Handling Criteria

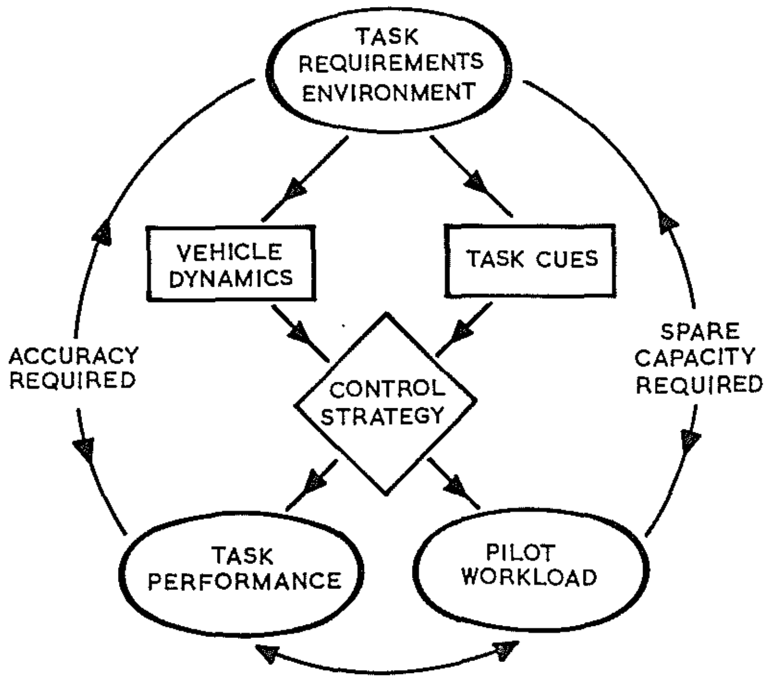
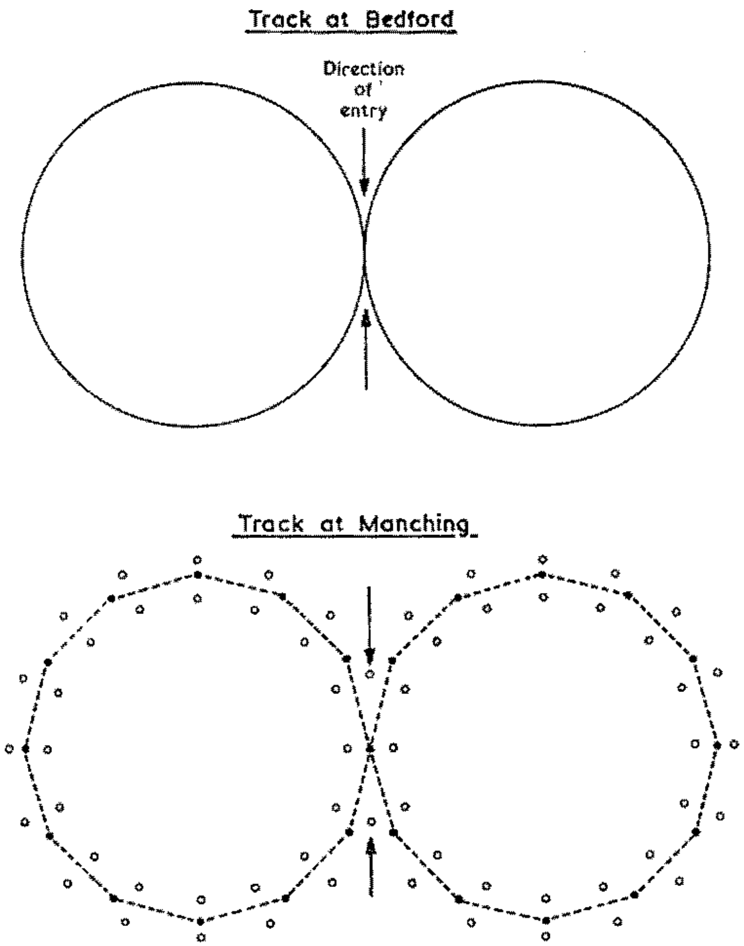


Fig 2 Elements of Task Dynamics



———	Single dark painted line approx. 10 ins wide
- - - - -	Black & white chequered tape
•	Posts approx. 18 ins high
o	White paint marks approx. ± 15 ft. from the track at 100 ft. intervals

Fig 3 The Circle Task

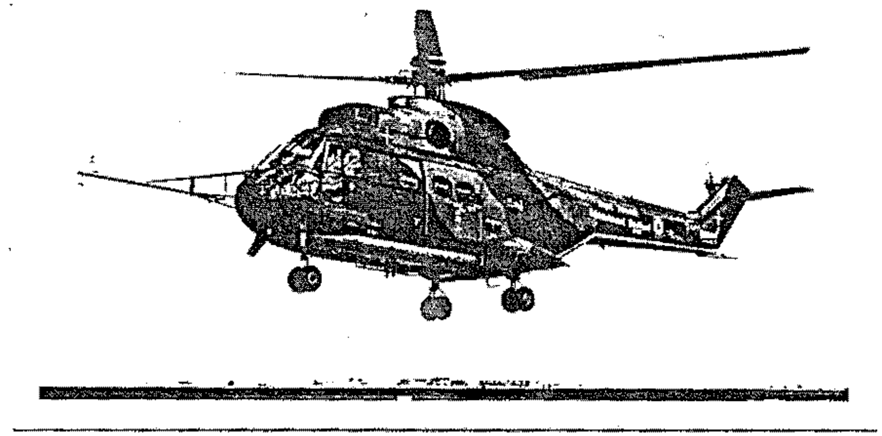


Fig 4 RAE Research Puma

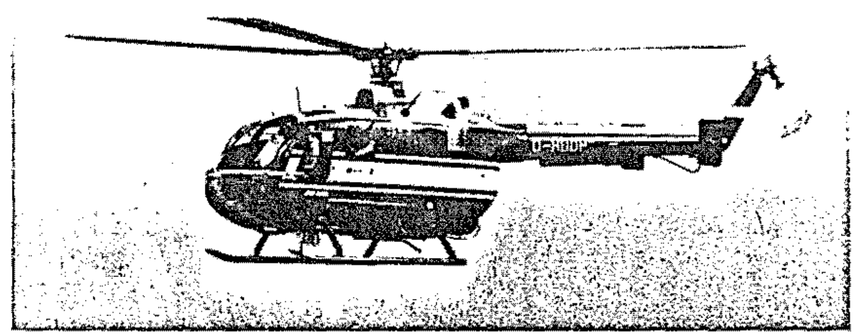
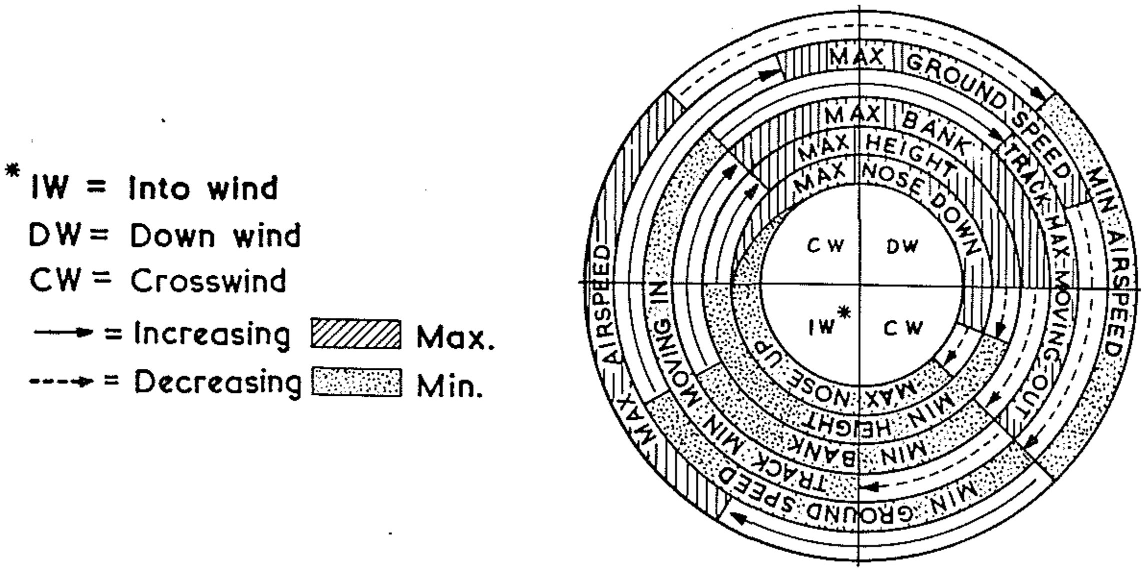
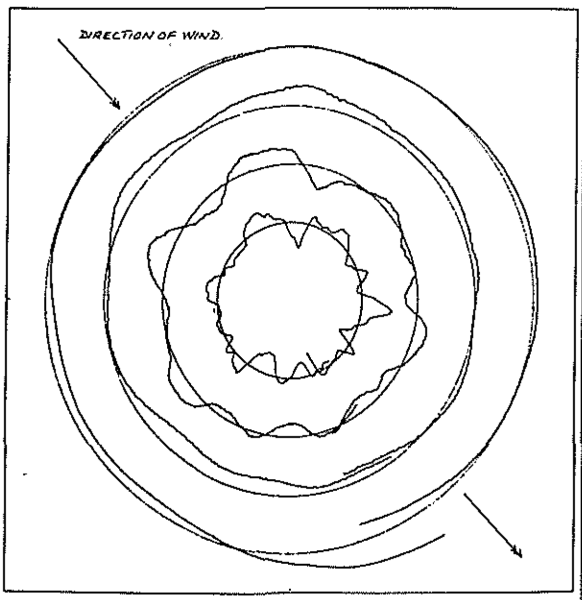


Fig 5 DFVLR Research BO-105

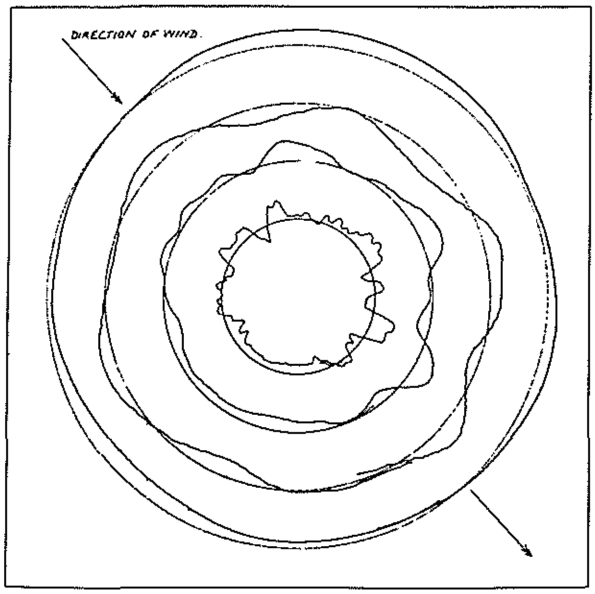




515 FT RADIUS CIRCLE TRACKING TASK: RIGHTHAND TURN

AIRCRAFT: PUMA
PILOT: ROSSING
FLIGHT NO: 558
AIRSPEED: 80 KNOTS
WIND CONDITION: 318/13 KNOTS
CONTROL STRATEGY: S1

CHANNEL 1: LATERAL CYCLIC
2: ROLL RATE
3: ROLL ATTITUDE
4: TRACK ERROR



515 FT RADIUS CIRCLE TRACKING TASK: RIGHTHAND TURN

AIRCRAFT: PUMA
PILOT: ROSSING
FLIGHT NO: 558
AIRSPEED: 80 KNOTS
WIND CONDITION: 318/13 KNOTS
CONTROL STRATEGY: S1

CHANNEL 1: F/A CYCLIC
2: PITCH RATE
3: PITCH ATTITUDE
4: HEIGHT

Fig 6 Target Diagram (P2, Puma, Right Circle, S1)

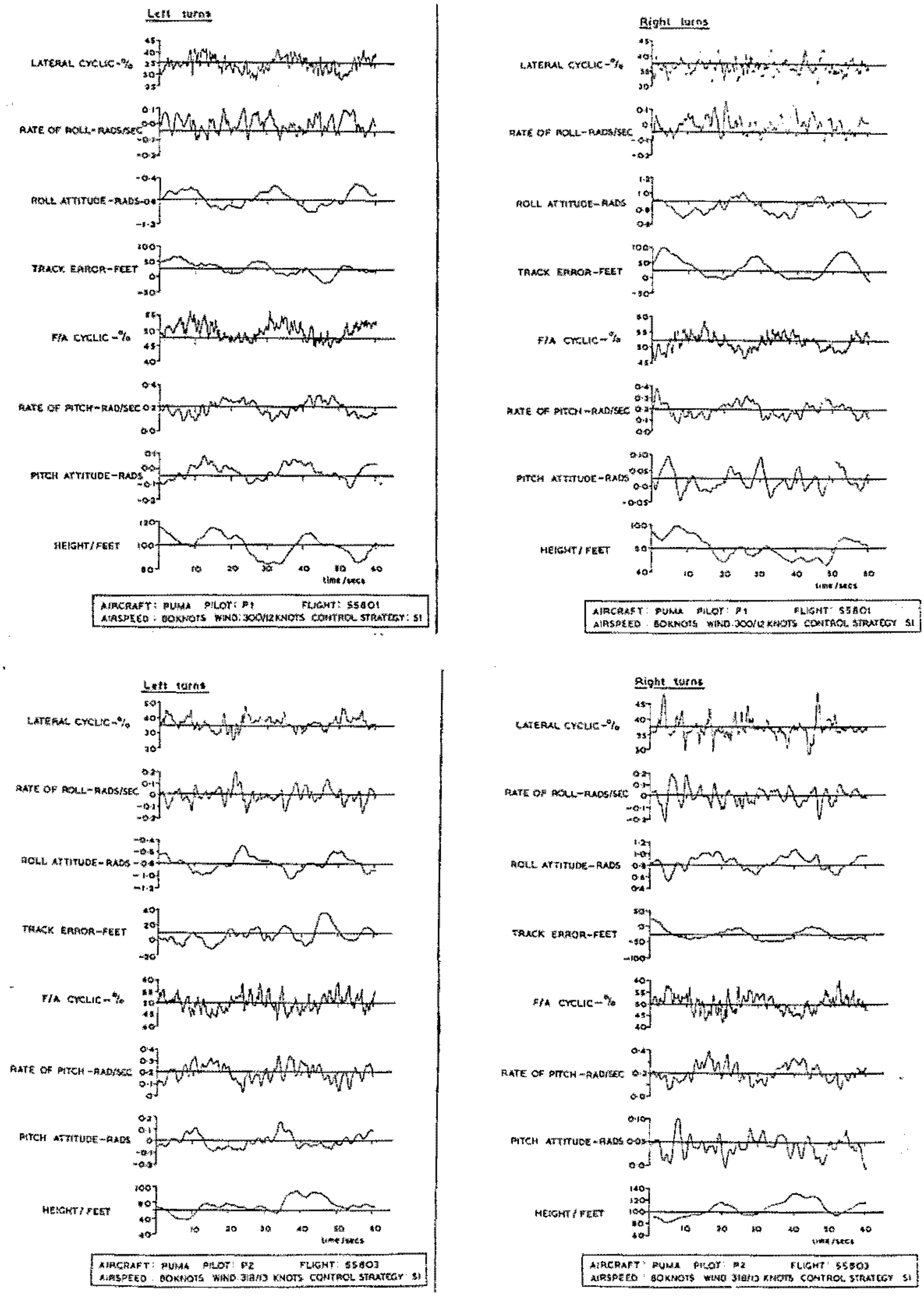


Fig 7 Task Variables - Puma (P1, P2, Right/Left Circles, S1)

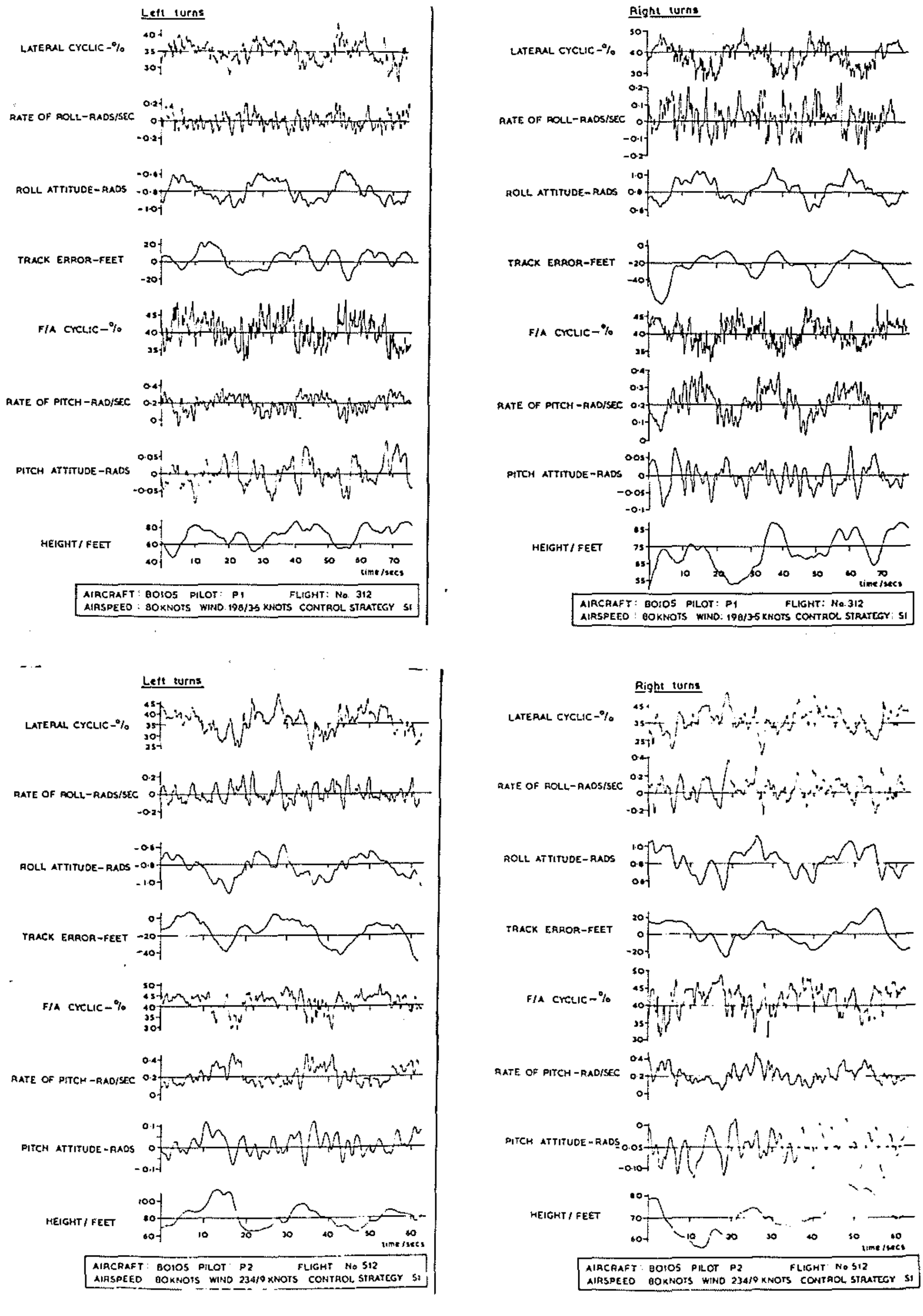


Fig 8 Task Variables - BO-105 (P1, P2, Right/Left Circles, S1)

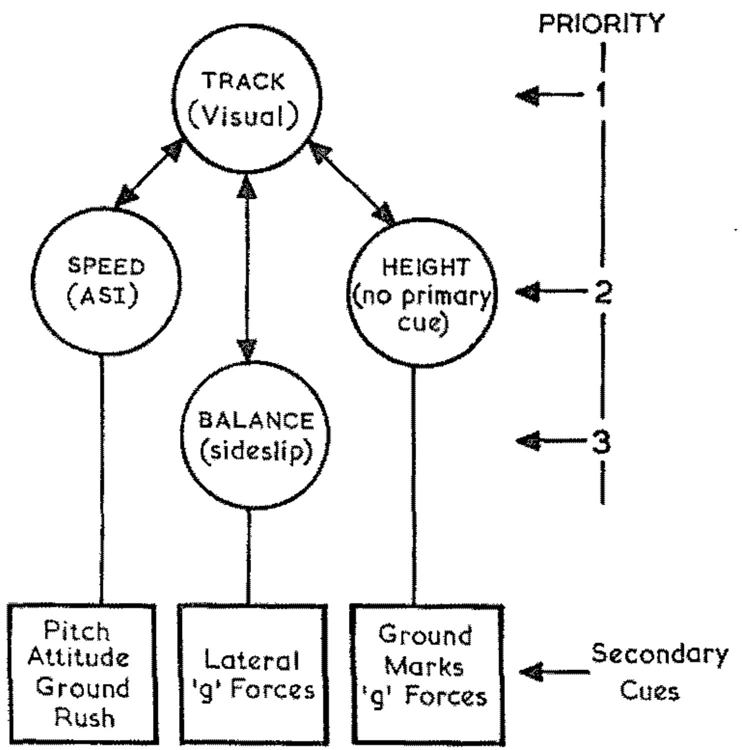


Fig 9 Task Cue Pattern

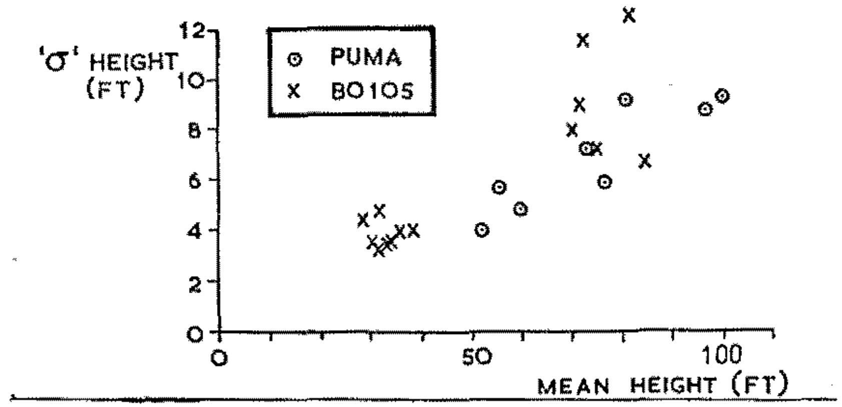


Fig 10 Height Errors vs Mean Height (Configuration S1)

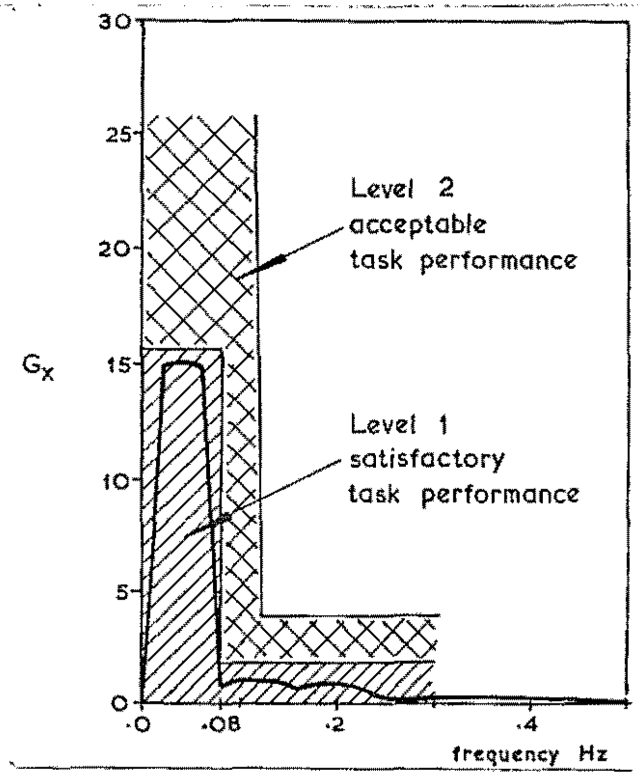


Fig 11 Task Performance Levels -
Power Spectrum of Track Error

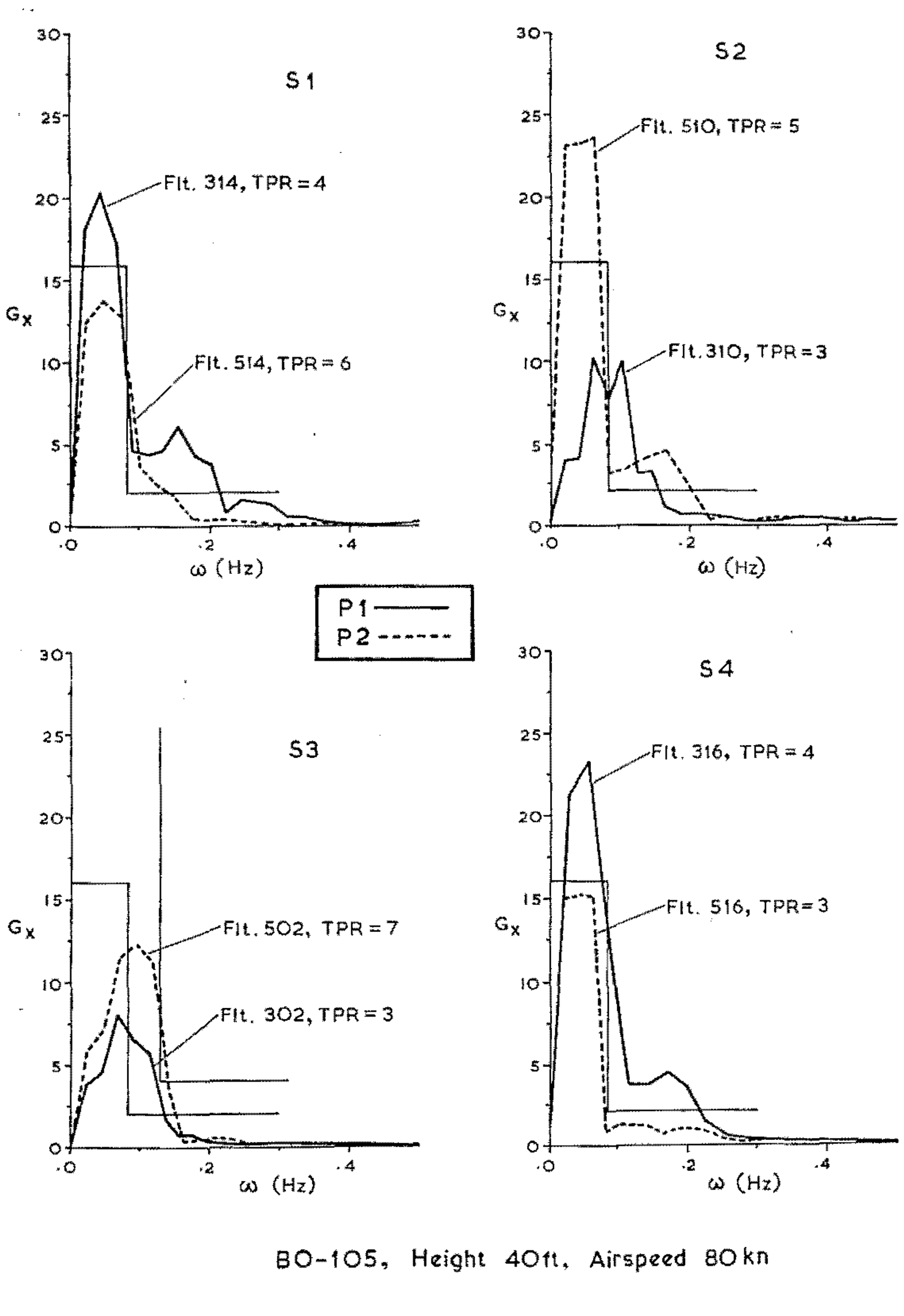


Fig 12 Variation of Task Performance with Control Strategy - Power Spectra of Track Error

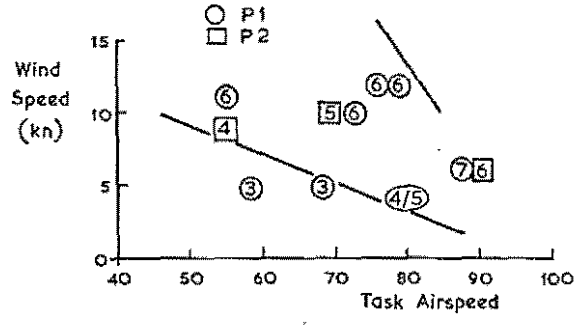


Fig 13 Variation of Pilot Ratings with Wind and Task Airspeed

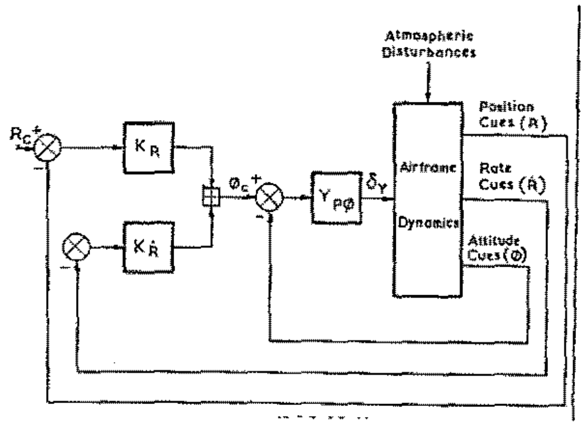


Fig 15 Task Model for Flight Path (Track Error) Control with Lateral Cyclic

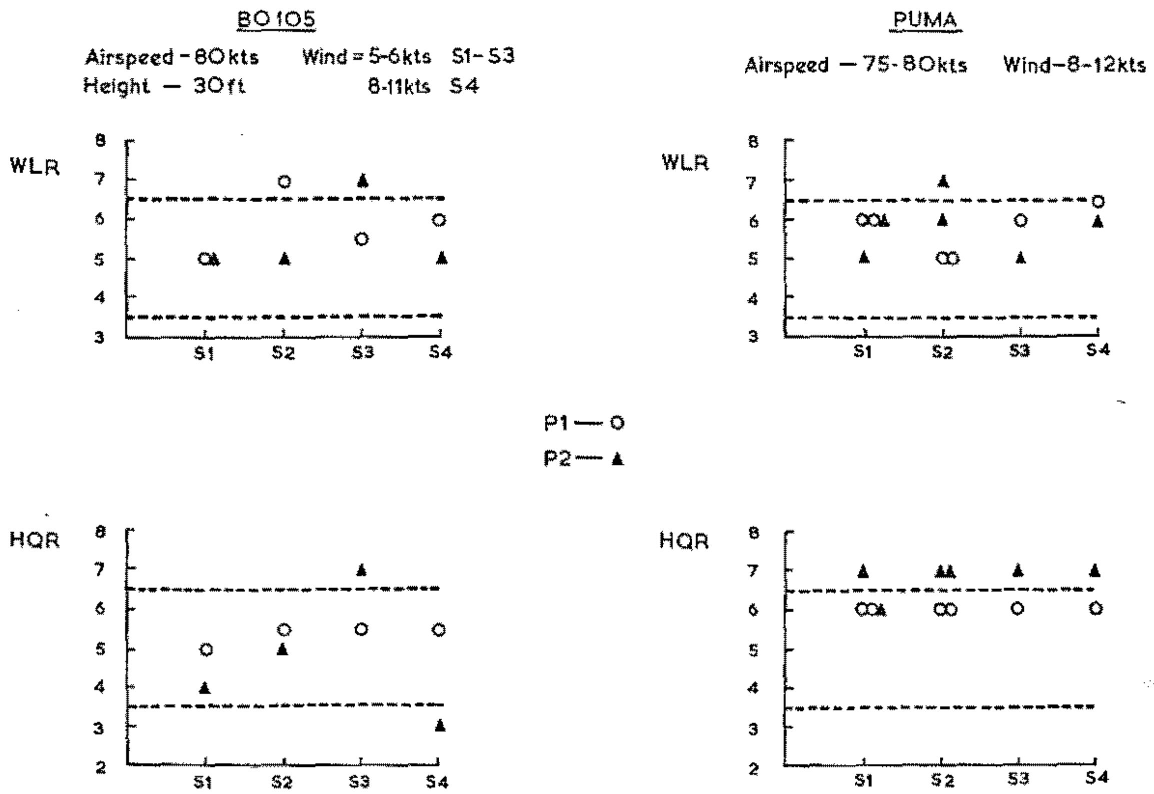


Fig 14 Variation of Pilot Ratings with Control Strategy

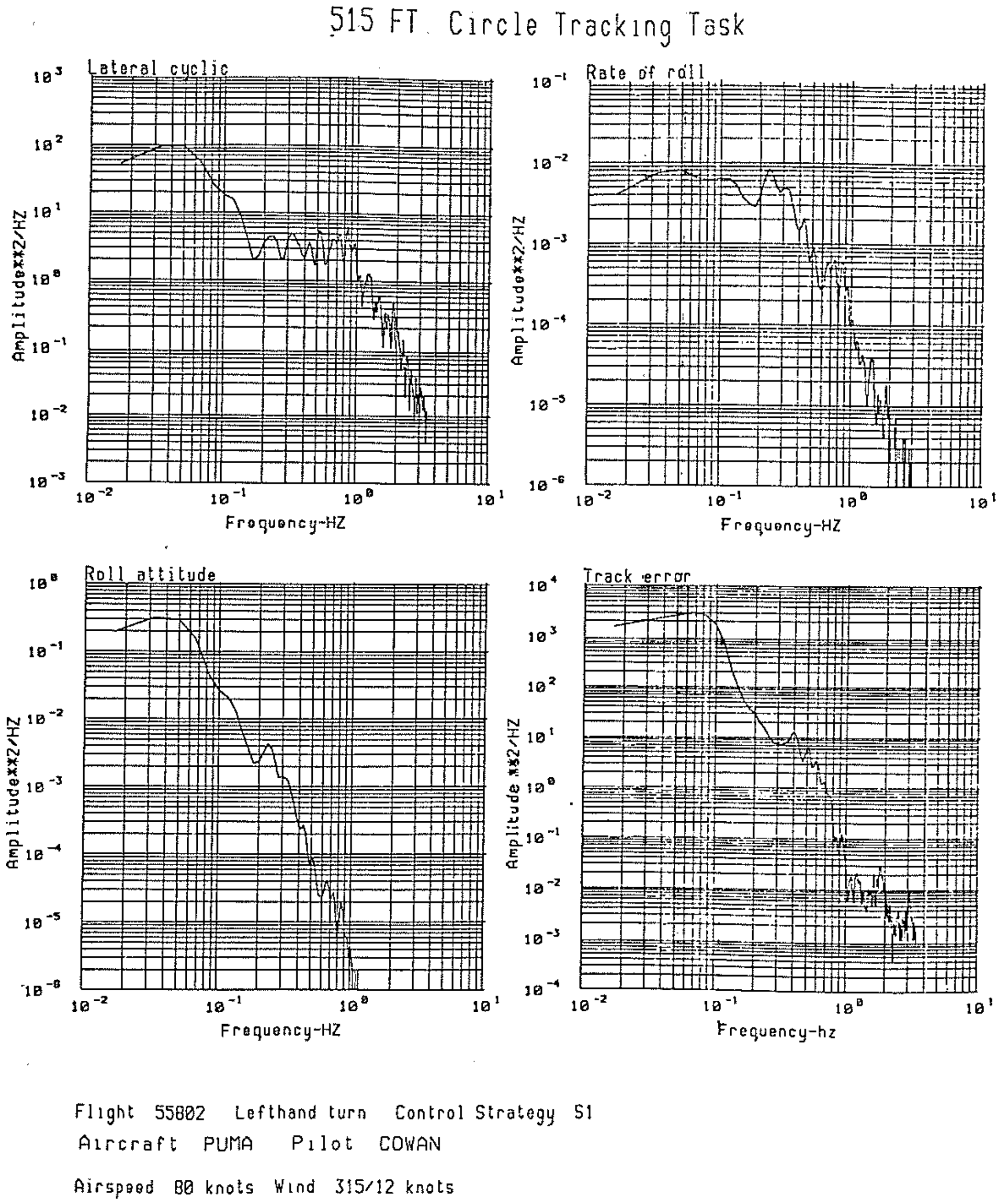
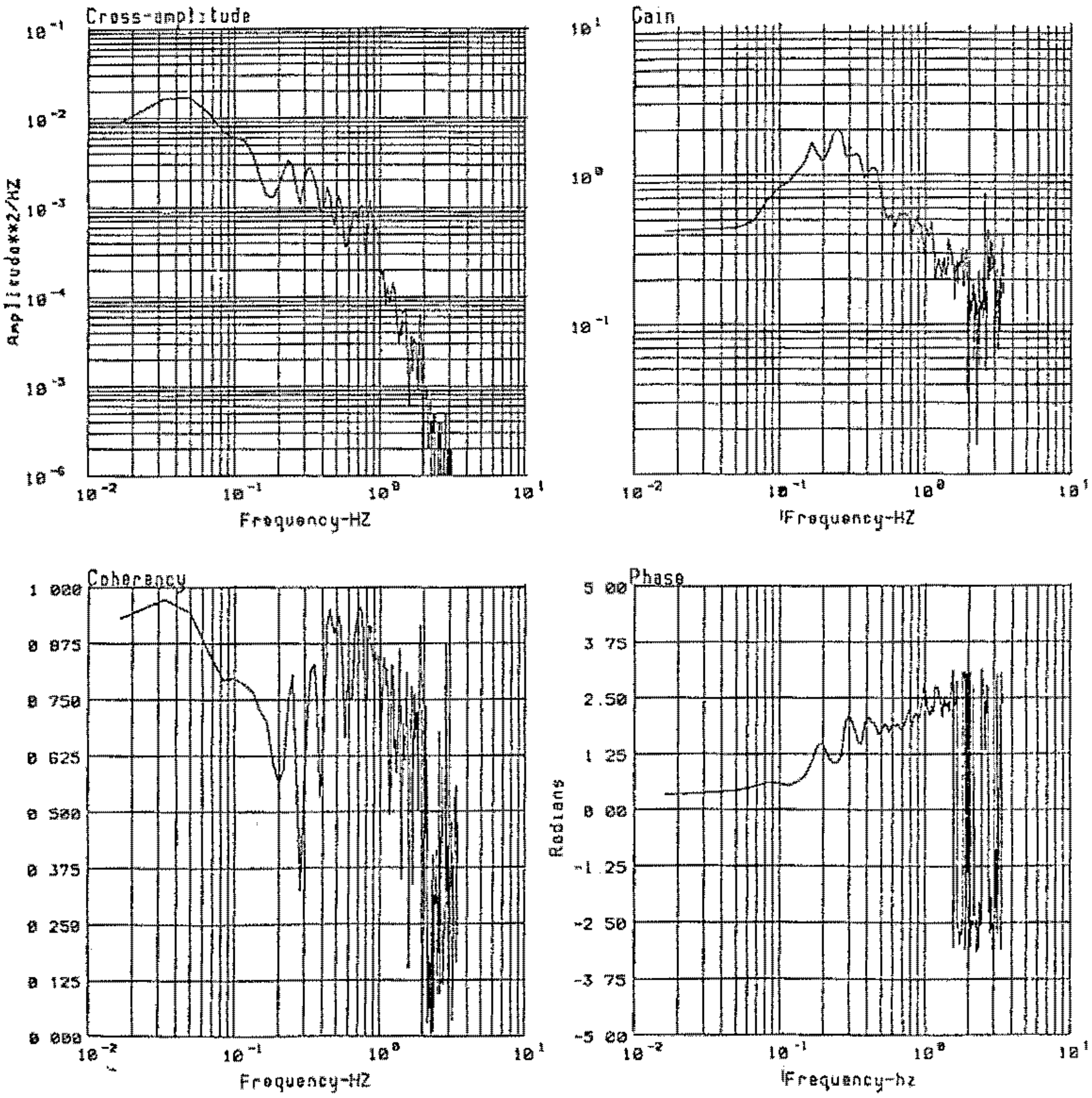


Fig 16 Power Spectra for Task Variables - Puma (P1, S1)

515 FT Circle Tracking Task



Lateral cyclic V Rate of roll

Flight 55802 Lefthand turn Control Strategy S1

Aircraft PUMA Pilot COWAN

Airspeed 80 knots Wind 315/12 knots

Fig 17 Transfer Function Relationships between Lateral Cyclic and Roll Rate - Puma (P1, S1)

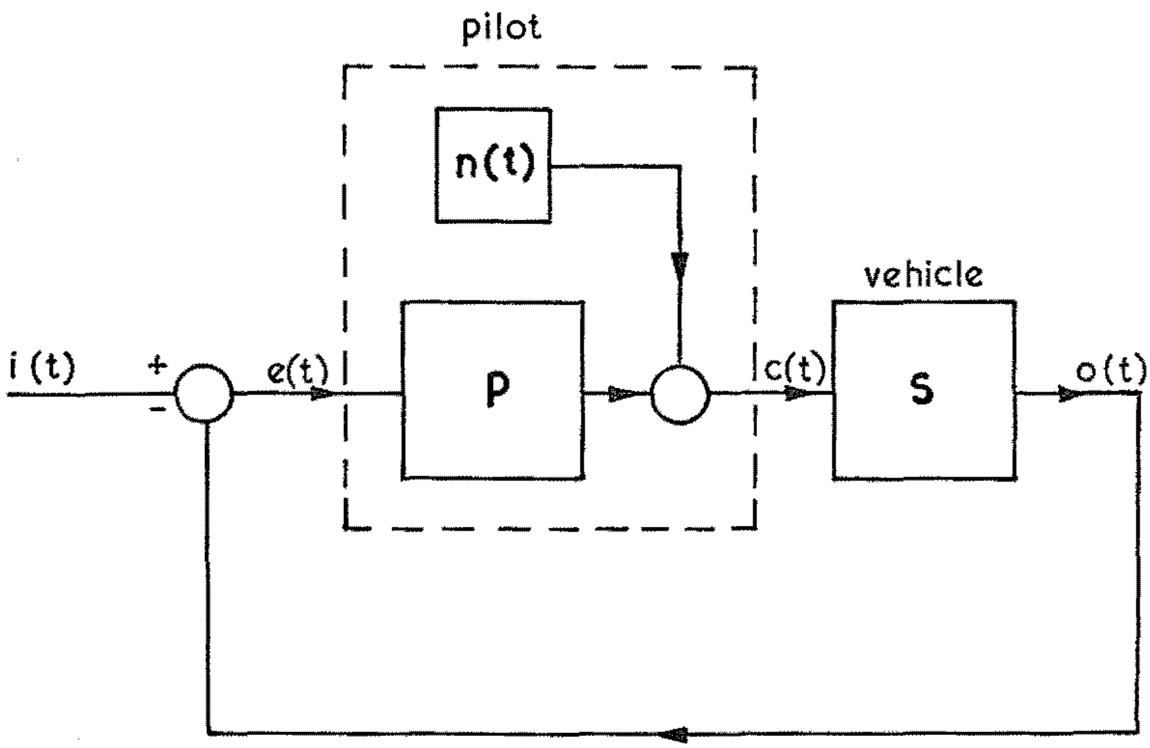


Fig 18 Generalised Closed Loop System Showing Pilot Remnant

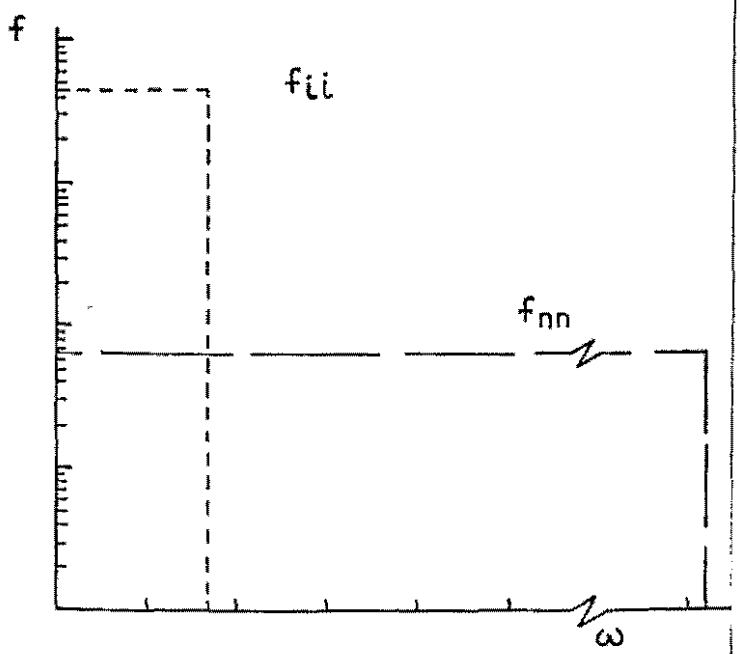


Fig 19 Task Error and Remnant Spectra

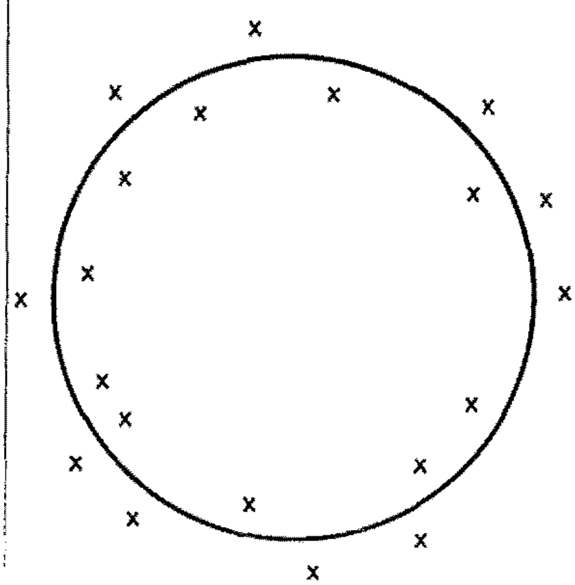


Fig 20 Higher Bandwidth Circle Task