C.P. No. 902

C.P. No. 902

MINISTRY OF AVIATION

AERONAUTICAL RESEARCH COUNCIL

CURRENT PAPERS

A Preliminary Flight Simulation Study of Jet-Borne V.T.O.L. Aircraft Handling Qualities

by

D. H. Perry *and* **H. W. Chinn**

LONDON. HER MAJESTY'S STATIONERY OFFICE

1967

PRICE 14s 0d NET

U.D.C. NO. 5.001.58 : 629.136-118 : 629.13.014.6 : 533.6.013.67

C.P. No.902*
June 1965

A PRELIMINARY FLIGHT SIMULATION STUDY OF JET-BORNE V.T.O.L. AIRCRAFT HANDLING QUALITIES

by

D. H. Perry

H. W. Chinn.

SUMMARY

A piloted flight simulator, having cockpit motion in pitch and roll, together with a simplified visual representation of the outside world, has been used to study attitude control requirements for jet-borne V.T.O.L. aircraft in hovering flight and low speed manoeuvring. Values of control effectiveness and aircraft rate damping which were found to give satisfactory control characteristics in roll and pitch are presented and compared with the results of previous studies and with V.T.O.L. control criteria. Brief studies of some non linear control gearings, and tests of pilots' control following autostabiliser failure, are also reported.

*Replaces R.A.E. Tech. Report 65128 - A.R.C.27367.

CONTENTS

		Page
1	INTRODUCTION	3
2	SETTING UP AND VALIDATION OF THE V.T.O.L. SIMULATION	5
	2.1 Equations of motion and their solution on the computer	5
	2.2 Equipment and methods used for representing the aircraft behaviour to the pilot	6
	2.3 Validation of the simulation by comparison with flight experience	8
3	SIMULATOR INVESTIGATION OF ROLL CONTROL CHARACTERISTICS	12
	3.1 Variation of handling characteristics with roll control sensitivity (or control power) and damping	12
	3.2 Discussion of results of the lateral control investigation and comparison with previous studies	16
	3.3 Investigation of various non-linear control gearings	20
	3.4 Investigation of control following autostabiliser failure	21
4	INVESTIGATION OF PITCH CONTROL CHARACTERISTICS	23
5	CONCLUSIONS	24
Appendix A	Complete equations of motion for a symmetrical, rigid, aircraft, together with approximations used in the present tests	26
Appendix B	An expression for the single-degree-of-freedom rotational motion of a reaction controlled vehicle with damping when subjected to an idealised control input	29
Appendix C	Block diagrams of the computer set up	
Table 1	Table of numerical data used in setting up the simulation	32
Table 2	Experience of pilots taking part in the simulation	34
Symbols		35
References		36
Illustrations		Figures 1-19
Detachable abstract cards		-

1 INTRODUCTION

This paper is concerned with the control characteristics needed in jet-borne V.T.O.L. aircraft to enable a pilot to manoeuvre the aircraft at low speed and to stabilise it at the hover. The investigations were made on a ground-based piloted flight simulator, the purpose of the tests being to examine the usefulness of such a device for studying control requirements for V.T.O.L. aircraft and then, if possible, to extend the range of control characteristics studied beyond those already covered by full scale research projects such as the Rolls-Royce 'Bedstead' [1] and the Short S.C.1 [2] aircraft.

Tho particular feature of the jot-borne vehicles considered here is that the translational motion needed for manoeuvring at low speed is obtained by tilting the whole aircraft, so as to produce a component of lift-engine thrust in the desired direct-ion of movement, rather than by rotating only the engine or its nozzle to generate the force required. This method of manoeuvring is currently used on almost all jet lift aircraft at low speed, even when provision for changing the engine thrust line relative to the body has been made to help in the transition from wing-borne to jet-borne flight. But it means that the ability to control tho aircraft's position over tho ground is effectively determined by the attitude changes which can bo produced, and this depends in turn, of course, on the characteristics of tho aircraft's attitude control system.

A considerable quantity of research work into the control characteristics of V.T.O.L. aircraft has already been published, based on a variety of experimental techniques, ranging from fixed cockpit simulators on the ground to variable stability helicopters in flight. Somo of this work has also boon collated to frame tentative sots of design requirements[3,4]. Despite the volume of this work, however, some uncertainty still exists as to the basic requirements for control power, control sensitivity and damping. For instance, a simple comparison between the boundaries relating satisfactory control sensitivity (or control power) and damping, found by different investigators, reveals, apparently, fairly large discrepancies. There are probably several reasons for this. Faye[5], in a simulator study of single-axis and multi-axis hovering tasks, has shown that controllability about ono axis may bo markedly affected by tho control characteristics about the other axes. Breul[6] has suggested that these differences may be partly explained by differences in the type of manoeuvre performed in the various tests - in some oases a tight attitude control task, in others a translational manoeuvro. Past experience with conventional aircraft suggests that purely mechanical imperfections in the control system, such as excessive friction and backlash, may play a considerable part in the assessment of an aircraft's control characteristics, and these features might well have varied from one investigation to another. Finally we are faced with the sheer difficulty of forming a precise subjective judgement as to when control characteristics fall below an 'acceptable' level if the deterioration is progressive and fairly gradual. Boundaries which appear as hard lines dividing satisfactory and unsatisfactory regions on the plots of aircraft control characteristics are sometimes aimed more at producing some sort of readily assimilated order into the experimental results than in laying down rigid requirements. Judged against this background many of the apparent discrepancies between the work of different. investigators assume less importance.

The present experiments were conducted in two stages. The first consisted of setting up the simulation and then of attempting to assess its validity by comparison with full scale flight work, particularly that made at R.A.E. on the Short S.C.1 aircraft. The results of this stage of the work, which is described in section 2, of the paper, were that the simulation gave a fairly good representation of the V.T.O.L. control task in the lateral plane, but that, because of limitations in the simulation equipment, the representation in the pitching plane was not wholly satisfactory, while it was considered that studies of height control and of yawing control would give results bearing little relationship to the full scale task. As a result of these findings work in the second stage was concentrated on the lateral characteristics, (roll attitude and the associated translational freedom of sideways movement), and, to a lesser extent, on longitudinal control (pitch attitude with its associated freedom in fore and aft translation). In these lateral control studies, described in section 3 of the paper, the limited range of control sensitivity and damping investigated in the first stage of the experiment was extended to cover a much wider range of characteristics than those which could be currently studied in flight. A brief assessment was also made of some suggested non-linear gearings between the pilot's stick and the roll control which were intended to improve the overall roll control characteristics. Finally the investigation of lateral control included some studies of the pilot's ability to control the aircraft following a sudden failure in the autostabiliser.

Because of the limitations in realism of the longitudinal simulation the investigation in this plane was confined to brief study of a wider range of sensitivity and damping than has been covered in the initial stage. This work is described in section 4.

2 SETTING UP AND VALIDATION OF THE V.T.O.L. SIMULATION

There are two fairly distinct facets to the process of setting up a ground based simulation for studying aircraft handling characteristics. The first is the formulation of a sot of mathematical equations which can be solved in the computer section of the simulator to provide a continuous output, representing, at any instant, the behaviour of the aircraft in response to the pilot's control actions. The second concerns the conversion of these computer outputs, occurring initially as voltage signals, into lifelike representations of the pilot's flight environment, causing him to respond to the simulated aircraft's behaviour in a realistic manner. These two facets are, of course, common to the simulation of all types of aircraft, but the special features which are of importance in representing V.T.O.L. aircraft in low speed jet-borne flight will be discussed in the next two sections.

2.1 Equations of motion and their solution on the computer

The particular characteristic of V.T.O.L. aircraft which most clearly affects the form of the equations of motion is the absence of any clearly defined direction in which the resultant velocity vector may be expected to lie. For conventional aircraft in normal flight this velocity vector is confined in direction to a fairly small region about the aircraft's forward body axis. But a V.T.O.L. aircraft must be expected to move with roughly equal ease in any direction. An immediate consequence of this is that axis systems based on the flight path, which have proved to be amongst the most convenient for simulating aircraft in conventional flight, are unsuitable for V.T.O.L. work, because the orientation of the axis systems becomes Indeterminate at the hover, with a consequent discontinuity in the equations as the velocity passes through zero. For the same reason the concepts of incidence and sideslip, as normally applied to conventional aircraft, are difficult to use in V.T.O.L. aircraft'.

For the present tests the equations of motion with respect to an axis system fixed in the aircraft were used. The complete equations for a rigid aircraft are given in Appendix A, together with the approximations which were necessary in the present case because of limitations in the amount of computing equipment available. Several terms in the equations which are frequently omitted, because of their small size, in the well known small perturbation theory for conventional aircraft, must now be retained. This arises from the feature mentioned above, that the velocity components along the lateral axis may be as large as those in the fore and aft direction, so that product terms such as VR and VP in the translational equations cannot now be neglected.

Moments arising from the gyroscopic effect of the rotating parts of the lift engines were not represented in this simulation since calculation had shown that they were negligible compared with other factors affecting the aircraft's handling.

Most of the approximations which had to be made through lack of computer capacity in the present simulation were concerned with resolving the velocity components, computed with respect to aircraft axes, into velocity components over the ground. As a result the aircraft's motion was only represented accurately when the heading changes from the runway direction were small, but this condition was satisfied in all of the tests reported here.

The present tests were concerned only with hovering and manoeuvring at low speeds, below, say, 20 knots, a situation in which the aerodynamic forces acting on a jet-borne aircraft are usually relatively small. It was considered that these aerodynamic effects could be adequately represented in this case by forces and moments about each axis which were simply proportional to the velocity component along that axis. The numerical values for these aerodynamic effects used in the simulation, which corresponded to those measured in flight on the S.C.1 aircraft, are given in Table 1 together with the other aircraft data used.

The actual computing arrangement, which is shown in block diagram form in Appendix C, involved the use of 79 operational amplifiers (21 summers, 45 sign reversers or buffers and 13 integrators) with a further 15 amplifiers for instrument, cockpit and visual background driving signals. Non-linear operations needed five multipliers, some with up to five channels, together with two resolvers.

2.2 Equipment and methods used for representing the aircraft behaviour to the pilot

The general layout of the equipment used in these tests is shown in Fig.1. The pilot's cockpit was mounted on a moving mechanism driven by hydraulic rams to represent changes in the aircraft's pitch and roll attitude. There was no yawing movement. The cockpit attitude was controlled directly according to the computed pitch attitude and bank angle of the aircraft, no attempt being made to represent sustained translational accelerations. In some of the tests where large attitude changes were encountered, particularly the investigations into control following an autostabiliser failure, (section 3.4), it was necessary to reduce the ratio of cockpit movement to computed aircraft movement in order to prevent the cockpit moving mechanism from hitting its stops. Except in those cases, a one-to-one correspondence between cockpit and computed aircraft movement was maintained. Even when the reduced ratio mentioned above was necessary tie visual simulation equipment described in the next peragraph continued to give the pilot a correct impression of the aircraft's orientation.

Besides the information he gained from the cockpit motions, the pilot was given visual indications of the aircraft's bchaviour by means of the cockpit instruments, Fig.2(b), and by an optical projection'system which was used to represent his view when looking outside the aircraft. Fig.1 Shows that the cockpit was almost completely surrounded by a curved screen, with the pilot's head located roughly at its centre. The projector was mounted just above the cockpit and worked on the 'shadowgraph' principle - a point source of light being usod to cast tho shadow of a suitably shaped cut out onto tho viewing screen. In this case tho cut out took the form of a triangular semi-transparent plate, having scribed on it a number of lines radiating from tho apex, Fig.2(c). When projected, this plate formed an image having the principal perspective features of an airfield runway as seen from above, Fig.3. The apex of the triangular plate was pivoted to a ring on the projector, the shadow of this ring representing the earth's horizon on the screen. The base of the triangular plate could be moved relative to the projection lamp by two small servomotors acting on signals from tho computer. Movement of the plate closer to the lamp caused the projected image to expand and gave the impression of the aircraft coming closer to tho ground. Movement of tho plate sideways, out of alignment with the lamp, gave the impression of the aircraft being laterally displaced from tho runway centre line. A single transvorse bar, positioned by another servomotor, produced a line shadow at right angles to the runway which could ho used to represent, for instance, the runway threshold. Finally tho whole assembly was carried on a three axis gimbal system which could be rotated to give the impression of the aircraft pitching, rolling and yawing.

Two photographs showing the view seen from the simulator cockpit with this equipment are reproduced in Fig.3. In tho lower view the aircraft was displaced to the right of tho runway nnd banked to the left. For comparison, Fig.4 shows two photographs taken by a camera attached to the S.C.1 aircraft during hovering and low speed manoeuvring, the aircraft being in very roughly the same sort of situation as that dcpicted in the simulator photograph.

2.3 Validation of the simulation by comparison with flight experience

If any confidence is to be placed in the results of ground based simulation tests it is obviously important that an attempt should be made to validate the experiments by comparison with flight experience. But this must depend largely on the subjective judgement of experienced pilots, and although they are readily able to point out any of the grosser differences between aircraft and simulation, they would be amongst the first to emphasise the difficulties of making detailed quantitative comparisons of aircraft handling characteristics. Six R.A.E. pilots took part in the simulation tests and, of these, three had flight experience in jet-borne V.T.O.L. aircraft and all had experience on helicopters. One visiting pilot with considerable Jet-borne V.T.O.L. experience also flew the simulator. The experience of' the pilots taking part in the tests is summarized in Table 2.

One feature which became apparent very early in tho simulation was the important part played by ground detail in the visual. background. Although control of attitude is the fundamental feature when hovering or manoeuvring at low speed it was evident that the pilot was also continuously monitoring his notion over the ground, and was using this motion as the principal guiding factor in deciding what attitude to demand. With the present visual background the pilot had to judge his position over the runway by watching changes in the shape of the perspective pattern, and to Judge his rate of movement by tho speed with which the pattern seemed to be passing him. Not surprisingly, pilots found it more difficult to judge their position and speed in the simulator, whore the amount of detail in the ground pattern was very limited, compared with the case of doing this in flight when surrounded by the detail and texturo of a real landscape.

Of the three translational motions the pilot's found that sideways movement across the runway was by far the easiest to judge and they felt that, in this respect, the simulation gave a valid representation of real visual flight. This was largely due to tho presence of numerous lines parallel to the runway centre line which gave a good indication of sideways velocity. In contrast, the motion along the runway was indicated only by movement of tho single threshold bar and this gave a relatively poor impression of forward speed. Pilots found that, as far as fore and aft motion was concerned, they could operate best over a limited range of distances fairly close to the threshold, but there was occasionally some confusion between forward motion and pitch attitude changes. Altogether the visual simulation of forward motion was not considered to be wholly satisfactory, but pilots were prepared to accept it, with reservations, for a preliminary study into pitch attitude control.

The portrayal of height changes on the visual projection was superficially quite convincing but it was found that, in practice, pilots could not control their height on the simulator with anything like the same accuracy as in flight. There was an optimum height of about 40 feet, at which the excursions could be kept within five to ten feet of the required value while hovering, but this needed much more concentration than in real hovering. At heights much above the optimum the changes in the perspective pattern with changing height began to become rather small, while at heights below the optimum the picture became blurred because of the finite size of the projection lamp. In either case it was the pilot's perception of vertical velocity which was most affected. Pilots found that because of these deficiencies they were not attempting to use the type of height control movements in the simulator that they normally used in flight and it was therefore felt that no great value would be gained from making a systematic investigation of height control with the present simulation equipment.

In attitude control the visual indications of the shadowgraph projector were supplemented by motion cues from the moving cockpit in pitch and roll. For these two freedoms the simulation was felt to be quite representative, apart from the confusion between pitch attitude and forward movement already mentioned, and some slight jerkiness in the cockpit rolling motion which became apparent at the highest operating frequencies.

Cockpit movement was used in nearly all of the tests reported here and no systematic tests have yet been made on this simulator to assess its value in V.T.O.L. studies. When the movement was switched off at the request of a visiting pilot, (Pilot G), a vigorous pilot-induced oscillation in roll resulted for a condition which he had previously controlled quite satisfactorily with the movement switched on. ($K = 0{\cdot}57$ rad/sec^2/inch $R = 0{\cdot}6$ sec^{-1}.) A brief series of further tests with this pilot at the same level of aircraft roll damping ($R = 0{\cdot}6$ sec^{-1}) indicated a preference for lower control sensitivity when the cockpit was fixed, (optimum between $K = 0{\cdot}26$ and $K = 0{\cdot}52$ rad/sec^2/inch), than when it was moving, (optimum $K = 0{\cdot}57$/rad/sec^2/inch).

A more comprehensive investigation into the role of the motion cue in V.T.O.L. simulation has been reported by Foddersen[8].

There was no cockpit movement to aid the pilot in controlling the yawing motion and pilots found this much more difficult than the other two rotational freedoms. To some extent this was true of the S.C.1 aircraft as well, but most pilots felt that the simulator exaggerated the difficulty. It was found that small rates of yam were hard to detect and the indication of heading, although perspectively correct, was confusing, particularly when the aircraft was displaced from the runway centre line. As with the height control, it was felt that little would be gained from making a systematic study of yaw control with the present simulation equipment.

From the general findings reported in tho previous paragraphs it was evident that limitations in the simulation equipment available for these tests precluded any detailed studies of control about all six degrees of freedom. Pilots found that with practice they could hover and manoeuvre the simulator in six degrees of freedom for long periods without danger of loss of control, but they affirmed that much more concentration was needed than for the corresponding task in flight. The added. effort needed to control, particularly the height and yaw freedom, would undoubtedly have affected their assessment of the remaining freedoms even though these were better represented. For the tests reported in the remainder of this paper the simulation was therefore modified to try to produce a 'work load' on the pilot which was more representative of real flight. Firstly the height was fixed at about 35 foot, thus reducing the degrees of freedom to give five instead of six. Pilots who were familiar with S.C.l aircraft thought that this was a reasonable step, since in the aircraft they found height control so good that it took relatively little of their concentration. Secondly the yaw damping of the simulated aircraft was increased until the pilots felt that yaw control on the simulator was absorbing about the same proportion of' their effort as it did in flight. (The value of damping actually chosen on the simulator corresponded to a damping: inertia ratio, λ, of 1 sec^{-1}, compared with a value believed to be about 0·1 sec^{-1} for the actual aircraft.)

With these modifications the simulator was considered suitable for undertaking the roll control investigation described in section 3 and the more limited pitch investigation in section 4. In a further effort to validate the simulation under these conditions the two pilots who were most familiar with tho S.C.1 aircraft, (Pilots A and B), were asked to comment on the simulation when it was set up to represent the specific values of damping available on tine S.C.1 [2]. In roll these were 0·6 sec^{-1}, for the autostabiliser off, and values of 3·7, 4·8, 5·9 and 7·0 sec^{-1} were available at different autostabiliser settings. The corresponding values in pitch were 0·5 sec^{-1}, and 3·0, 4·0, 4·9 and 5·8 sec^{-1}. Two higher damping settings available in the aircraft were not included in this assessment. The pilots found it difficult to make point-by-point comparisons at the three lowest autostabiliser settings, but this seems to bo consistent with their flight experionco where the changes in handling characteristics for those settings were not, apparently, very marked. Both pilots felt that the simulator seemed to respond to control movements in both pitch and roll slightly more immediately than did the aircraft. A careful examination of the timo records for control stick displacement and nozzle opening on tho aircraft, (e.g. Fig.7 of Ref.3), showed that thorc was a slight delay between these two quantities, and this had not been represented in the simulation where 'perfect' control operation was assumed. Breul[6] has shown that time delays of 0·1 sec and less were quite noticeable in V.T.O.L. control tests and it appears that more attention will have to be paid to this aspect in future simulation exercises.

When tho damping was reduced to the value for autostabiliser off, or increased to the higher autostabiliser settings, tho changes in handling characteristics on the simulator were much more marked, as in the aircraft, and seemed to reproduce tho flight changes fairly faithfully.

The effect of atnospheric turbulence on the simulated aircraft's handling was investigated by introducing white noise, shaped to represent a turbulence power spectrum, into the computer at appropriate points. Bocauso of tho small values of the aerodynamic forces and moments occurring on jet lift aircraft at low speed the effect of these gust disturbances was hardly noticoablo. This agreed with flight experience on the S.C.1 aircraft, where the only noticeable affect of turbulence is that caused by feedback from the aerodynamic control surfaces for the mode in which they are not operated irreversibly.

Another check on tne validity of' the simulation was given by the visiting pilot, (Pilot G), most of whose flight experience was on tho Hawker P1127 aircraft. The pitch and roll dampings of this aircraft were set up on the simulator and the control sensitivities varied, under the direction of the pilot, until he judged the response to be similar to the aircraft's. The sensitivities so obtained were very close to those actually used on the'aircraft.

Before turning to the systematic tests reported in the next two sections of this report, mention may be made of the steps being taken to overcome some of the deficiencies in simulation equipment noted in the previous paragraphs. Many of thorn ware centred on the limitations of the present visual background and it is hoped to tackle these in two ways. An improved shadowgraph projector is under active development, which, by using a semi-transparent scale model in place of the simple cut out of the present equipment, will greatly enhance the mount of ground detail which can be portrayed. Fig.5 shows a typical pilot's view obtained with a development mock-up of this equipment. This method of visual simulation combines the features, essential for V.T.O.L. work, of a wide field of view and considerable ground detail. Its main limitation is tine rather small area over which the aircraft can be manoeuvred, a circle 1000 feat in diameter in the present case. As an alternative, where a larger field for manoeuvre is required, a visual background based on close circuit television principles, (and intended primarily for simulation work on conventional fixed-wing aircraft), is at present being installed. While this equipment allows a virtually unlimited area for manoeuvring, the actual field of view is confined to an angular range of about 40° in pitch by 50° in azimuth in the forward direction, and this may prove to be rather small for V.T.O.L. work at very low speed.

3 SIMULATOR INVESTIGATION OF ROLL CONTROL CHARACTERISTICS

As reported in section 2.3, pilots found the present simulation more convincing in the roll freedom and its associated sideways translational motion than in the other directions, and it was therefore decided to concentrate most of the work on this aspect. The steps described previously for trying to ensure that the overall 'work load' on the pilot was comparable in flight and in the simulator were taken in all of these tests, i.e. the number of degrees of freedom was reduced to five by locking the height, and the yaw damping was increased.

The investigations included, (a) the variation of handling characteristics with damping on the one hand and with control sensitivity and control power on the other, (section 3.1); (b) the effect of various non-linear gearings in the control system, (section 3.2) and (c) a study of the pilots ability to control the aircraft following certain failures in the autostabiliser, (section 3.3).

3.1 Variation of handling characteristics with roll control sensitivity (or control power) and damping

Two terms are used in this report to describe different aspects of the effectiveness of the aircraft's controls. The first, Control power, is taken to mean the ratio of the control moment arising from full control deflection, divided by the aircraft moment of inertia about the appropriate axis. It is therefore a measure of the initial angular acceleration which will result from a step control displacement to full travel, and has the units radians per second^2. The second, Control sensitivity, is defined as the initial angular acceleration per unit step control displacement and has the units radians per second^2 per inch. For linear gearing between the control stick and the moment applied to the aircraft these two terms are, of course, directly related by the total control stick movement. Which of them constitutes the more significant measure of control effectiveness depends on several factors and will be discussed later in this section.

The quantity used as a measure of the aircraft damping is the ratio of the total moment resisting angular velocity, divided by the aircraft moment of inertia about the appropriate axis. This damping: inertia ratio is denoted by R in this report and has the units 1/sec. The ratio determines the time constant of the exponential motion following a step application of the controls, (see Appendix B), and has been generally accepted as having an important influence on V.T.O.L. aircraft flying qualities.

The purpose of the tests reported in this section was to extend the range of control characteristics which had already been investigated in flight on the S.C.1 aircraft, (i.e. seven levels of damping:- R = 0·6, 3.7, 4·8, 5·9, 7·0, 9·1 and 11·9 sec^{-1}, at one level of sensitivity K = 0·37 $rad/sec^2/inch$) so as to cover a broader field of sensitivity and damping. Two piloting tasks were considered; the case of hovering over a given spot on the ground, and the case of translating the aircraft sideways through a distance of roughly 100 feet. Breul[6] has already pointed out that differences between the requirements of these two tasks might account for the apparent discrepancies between the results of previously published work, and it was evident in the present tests that the requirements were, to some extent, conflicting. Hovering, being in the nature of a stabilisation task, led to a requirement for a well damped and fairly insensitive air-raft, while manoeuvring required a more lively aircraft with brisker response to the controls.

During these tests a series of different control characteristics was represented on the simulator and after evaluating each for hovering and manoeuvring the pilot was asked to give his opinion of its handling qualities. He was not generally told what changes to expect from one configuration to another and the changes were not made in a fixed, nor usually in a particularly systematic manner. Figs.6 and 7 illustrate the order in which the configurations were tested by two of the pilots and the tables beneath record the pilot's comments.

It may be noted that no attempt has been made here to use the system of numerical rating for recording pilot opinion, which has been gaining increasingly widespread use over the past few years. In this method the pilot is presented with a number of descriptive statements concerning the ease of controlling the aircraft, ranging in a graded series from good to bad. The pilot is asked to indicate which statement is nearest to his own opinion, his choice being recorded as a number, corresponding to the position of the chosen statement in the series. Although this method is very concise and gives a certain air of precision to the work, it has in the authors' opinion a number of disadvantages, particularly for exploratory tests of the type described here. For one thing it is felt that the numerical rating system places too much emphasis on making a formal judgement as to the overall 'acceptability or otherwise of a configuration, often at the expense of appreciating the underlying reasons for that judgement. And as a method of placing a pilot's opinion on record it frequently suffers from its own conciseness in that any provisos made by the pilot in assigning the numerical rating cannot conveniently be registered. (It is then a small but potentially dangerous step to regarding the numerical rating as akin to any other measured quantity and, therefore, as fit a subject for statistical tests and other methods of numerical analysis.)

In the present tests the pilots were not asked to make any overall judgements of this sort but simply to discuss the charaotcristios of each configuration as they found it. The process of digesting the mass of resulting information was then the task of the investigator, obviously in consultation with the pilots, but without being tied to any strict averaging of pilot opinion.

The type of comments made by the pilots is illustrated in Figs.6 and 7, these being slightly edited versions of what was actually said. It is evident that the pilots assessment of any configuration cannot be entirely divorced from what has gone before, most of the comments containing both comparison with the last few test conditions and an attempt at an absolute assessment.

There were three sources of criticism of the handling characteristics which could bo so readily identified that for brevity they will be described in this report by the adjectives 'sluggish', 'underdamped' and 'oversensitive'. The term 'sluggish' denotes the inability to change the attitude of the aircraft from one steady value to another rapidly enough. The most noticeable feature of an 'underdamped' aircraft was that the aircraft's response to stick deflection tended to have the characteristics of an acceleration rather than a rate control. A result of this was that, instead of the aircraft's rate of rotation ceasing almost as soon as the pilot recentralised his stick, the motion would only die away after an appreciable time interval, depending of course on the amount of damping available. Alternatively, for precise control of attitude the pilot was forced to us e a carefully timed counter control movement to stop the rotation, (see, for example, case 4 of Fig.6). In the 'over-sensitive' case the aircraft's response to small, and perhaps involuntary stick movements by the pilot was too large. This usually led to continuous hunting by the pilot for the correct stick position with a consequent small amplitude roll disturbance of the aircraft.

Fig.8 show how each of the configurations tested was assessed in these terms for the two tasks of hovering and manoeuvring. The tests were made without any external atmospheric disturbance, a previous trial having established that the effect of turbulence on this configuration was extremely small, (section 2.3).

For hovering, (Fig.8(a)), pilots preferred a reasonably well damped aircraft which was free from any tendency to hunting due to control over-sensitivity. But too docile an aircraft led to difficulty in maintaining an accurate hovering position, because the attitude changes needed to control the aircraft's translational speed could not be made rapidly enough. With a very sluggish aircraft pilots found themselves performing long period translational oscillations about the required hovering point because they could never get the attitude exactly right at the right time.

The translational manoeuvre may best be considered in three phases. Starting from a hovering position the first phase consists of establishing the desired translational velocity by a cycle of bank application, and removal, the necessary sideways acceleration thus being introduced by a component of the lift engine thrust. Control requirements in this period of initiating the motion tend to be less critical than later in the manoeuvre, but the translational velocity that the pilot is prepared to use may, nevertheless, be effectively determined by the control characteristics, for he knows that later on he must be able to stop the motion fairly precisely. This second, decelerating, phase occurs as the aircraft is approaching its new hovering point and again involves an attitude change to bring an appropriate component of lift engine thrust into play. Finally, as the aircraft arrives at the hovering point, the attitude must be rapidly changed back to its hovering value so that the translational motion ceases at precisely the correct point. Correct timing of these attitude changes becomes progressively more important in these three successive stages, and so consequently do the control requirements become greater.

Fig.8(b) shows the pilot's assessments for manoeuvring of the configurations tested, again in terms of them being 'too sluggish' 'underdamped' or 'over-sensitive'. Two main changes are apparent when they are compared with the requirements for hovering given in Fig.8(a). The area in which control characteristics were felt to be too sluggish has expanded into the area where they were previously satisfactory for hovering, and the area of high sensitivity and low damping, which had given difficulty with hunting at the hover, was liked for manoeuvring because it gave fast aircraft response. The latter point may however be somewhat academic since this hunting was of course objectionable once the aircraft returned-to the hover.

The two boundaries of Fig.8(a) and 8(b) have been combined in Fig.9 to show those combinations of aircraft roll damping and control sensitivity which were free from major criticism both as regards hovering and manoeuvring. An attempt has also been made to indicate on this figure how rapidly the characteristics deteriorated outside the satisfactory region.

Figs.10 and 11 show two sets of time histories of sideways translation& manoeuvres made by different pilots. Each set contains examples of tests made with aircraft chnractoristics which were assessed as 'too sluggish', 'near optimum' and 'over-sensitive'. Although Pilot B in Fig.11 tends, overall, to make more vigorous manoeuvres than Pilot D in Fig.10, there is a marked general similarity in the behaviour of the two pilots when faced with the different configurations.

The sluggish nature of the first configuration is evident from the large control displacements used by the pilots and the length of time they had to be maintained to bring about the required attitude changes. The translational manoeuvre was consequently relatively slow. Much smaller control movements sufficed with the 'near optimum' configuration and a faster manoeuvre could also be achieved. An even faster manoeuvre resulted from the more rapid control response in the *'over-sensitive' condition, but Fig.10(c), especially, shows how this was accompanied by a continuous rolling oscillation, superimposed on the rolling motion needed for manoeuvring and caused by the pilot constantly hunting for the correct stick position.

In all of these manoeuvres the increase in control activity *needed in* successive phases of the manoeuvre is evident.

3.2 Discussion of results of the lateral control investigation and comparison with previous studies

In describing the results of tho present tests the quantity control sensitivity has been used as the measure of control effectiveness, (Figs.7, 8 and 9). Clearly, however, in some of the configurations described as 'sluggish' it was not merely the low control sensitivity which caused the pilot concern, but also a lack in tha total control power available. He spoke, for instance, of 'using full control travel all the time', (case 3 of Fig.6). It is sometimes difficult to distinguish clearly between the importance of those two quantities, control power and sensitivity. It would almost certainly be an oversimplification to assume that, because the pilot was not constantly moving the control to its stops, he was, therefore, necessarily satisfied with the control power. His desire to ensure that he always had some additional control power in hand might lead him merely to manoeuvre the aircraft more gently.

The issue is further complicate3 in our own, and in much of the published experimental work, by the fact that any change in control power involved a change in control sensitivity as well, since the maximum stick travel was hold constant and linear gearing between stick and control actuator was used for most of the tests. Some further tests, in which a non linear control allowed independent variation of control sensitivity and control power are briefly discussed in section 3.3.

To aid this discussion Fig.12 shows a hypothetical model of how the three quantities: control power, control sensitivity and damping might be expected to affect the aircraft's handling characteristics. For very low control powers it is assumed that no combination of control sensitivity and damping, however favourable, can compensate for the overall lack of power, so that it is not possible to produce a satisfactory control system. As the control power is increased a stage is reached at which the handling characteristics become just satisfactory, provided that the limited power occurs with the optimum values of control sensitivity and aircraft damping. At other values of sensitivity and damping a further increase in control power will be needed to produce a satisfactory system. When the control power becomes fairly large, quite a wide range of control sensitivity and damping can be tolerated, and eventually the stage is reached when the control power is more than adequate for all practical purposes. In this case the pilot is never likely to use control displacements anywhere near the maximum and the relationship for satisfactory control reduces to one involving only sensitivity and damping.

In treating control power and control sensitivity as independent variables the assumption is made that the maximum stick travel is not constant but is altered to accommodate the combination of power and sensitivity being considered. Where a constant stick travel is used, as in most experimental studies, the fixed relationship between control sensitivity and control power which results may be represented by a plane, cutting diagonally across the hypothetical model, as shown by the broken lines in Fig.12. In this case the quantities control power and control sensitivity may both define the control effectiveness equally well for one particular set of tests, but neither is likely to be entirely satisfactory when comparing different tests involving different maximum stick travels, for these correspond to different 'diagonal slices' across the model.

In Figs.13 and 14 the results of the present investigation are compared with those from previous studies, using control sensitivity as the basis for comparison in Fig.13 and control power in Fig.14. The data is again given in the form of boundaries delineating good and poor control characteristics on a plot of control effectiveness and aircraft damping. In Fig.14, where the measure of control effectiveness is taken to be the control power, those boundaries which obviously depend only on the control sensitivity have been omitted. Comparison is made in these figures with both the results of previous simulator studies[5,6], (boundaries shown by heavy hatchuring), and with various control criteria for V.T.O.L. aircraft which have been proposed[4,10].

Of several previously reported simulator studies into the control of V.T.O.L. aircraft at the hover, two in particular were sufficiently similar in the equipment used and in the tasks investigated to allow a more or less direct comparison with the present tests. These were the work of Faye[5] at the N.A.S.A., and that of Breul[6] at the Grumman Aircraft Engineering Corporation. Both used moving cockpit simulators having freedom about two axes, and both were concerned with hovering and manoeuvring tasks of the type discussed in this paper. In the Grumman work the outside visual world was also represented by an optical projection system giving a picture very similar to that used in the present tests. For the N.A.S.A. tests there was no special visual representation and the pilot had to judge for himself how the aircraft would have manoeuvred over the ground as a result of the attitude changes he could produce on the cockpit.

In both the N.A.S.A. and the Grumman investigations the pilot rating method of assessing the aircraft's characteristics was used and the results were present as contours of constant pilot rating on the plot of control effectiveness and damping. With this method the boundary usually taken as being most significant is that lying mid way between the contour for rating point 3, which has the description 'Satisfactory, but with some midly unpleasant characteristics' and that for rating point 4, which has the description 'Unsatisfactory. Acceptable but with unpleasant characteristics'. As discussed earlier this rating method was not used in the present tests and the boundary shown in Pig.9 is that for characteristics which were 'free from criticism'. It might be felt that this is a somewhat more stringent assessment than that corresponding to 'a pilot rating of $3\frac{1}{2}$' used in the previously published work. However Fig.13 shows that the 'free from criticism' boundary of the present tests agrees closely the 'pilot rating $3\frac{1}{2}$' boundary of Faye, at least when compared on the basis of control sensitivity. Bred's results, on the other hand, show greater tolerance in the range of sensitivity and damping considered acceptable, particularly with regard to the more sluggish aircraft characteristics.

The maximum stick travel usod in both Faye and Breul's tests was ±5 inch compared with a stick travel of $\pm 3\frac{1}{2}$ inch in the present case. When plotted on the basis of control power, rather than control sensitivity (Fig.14), the effect of this larger travel is to move tho boundaries to the right, so that the . results of the present tests then lie about mid-way between those of Faye and Breul. But, as discussed earlier, the tcsts with different maximum stick travel may be likened to different cross sections of a three dimensional surface, so that a straightforward comparison either on the basis of control sensitivity or control power may not be strictly valid. As yet there is insufficient data to define those matters clearly and further work on the lines followed by Patiernc and Isca[9] may be needed.

..As well as comparing the present experimental results with those from previous simulator tosts, Figs.13 and 14 also show boundaries for acceptable aircraft characteristics calculated from two of the tentative sets of control criteria which have so far been put forward. Tho A.G.A.R.D. recommendations[4] hnve actually been framed with V.T.O.L. operation under I.F.B. conditions in mind, so that they might be expected to be rather more stringent than the results of the simulator tests, which wore concerned with ordinary visual flight. In as far as the A.G.A.B.D. recommendation for minimum damping is concerned, this appears to be the case, for in all three sets of simulator tests tho pilots were prepared to accept lower levels of damping than those recommended for instrument flight. As regards both minimum sensitivity (Fig.13) and minimum control power (Fig.14) the A.G.A.R.D. recommendations are in good agreement with the present experimental results, but the boundary for maximum control sensitivity (Fig.13) suggests more tolerance of over-sensitive conditions than that found in the simulator tests.

Most of the A.G.A.R.D. recommendations are actually stated in terms of tho attitude change which should bo produced in the first second as tho result of a given control displacement. Lynn[10] has based his recommendation on a slightly different concept - that of defining the control characteristics need to perform manoeuvres which had been found from helicopter experience to be typical of operational tasks. For given aircraft characteristics Lynn's recommendations may be reduced to a boundary relating control effectiveness and damping which is also shown in Figs.13 and 14. For the case of the S.C.1 considered here this manoeuvre criterion is seen to be more tolerant of sluggish aircraft characteristics than the A.G.A.R.D. recommendations.

Mention was made earlier, (section 3.1), of the need for a considerable counter control movement in an aircraft with low damping in order to arrest any rotational motion at precisely the attitude required. Lynn[10], and later Dathe[11], have derived expressions for the timing of this counter control movement which show that considerable anticipation by the pilot would be needed when the damping: inertia ratio has a value of less than about two. The present experimental results seem to be in good agreement with this conclusion.

3.3 Investigation of various non-linear control gearings

In providing satisfactory control characteristics for V.T.O.L. aircraft at the hover the designer is faced with several compromises. He must weigh the balance between providing adequate reaction control power from the nozzles, while avoiding excessive demands for bleed air from the lifting engines. The control gearings and stick travel may be dictated by the requirements of high speed flight, leading to values of control sensitivity in jet-borne flight which are well below the optimum. One method which has been suggested[9] for overcoming this particular difficulty is the use of non-linear gearings between the stick and the control nozzle so that control power and control sensitivity may be treated, to some extent, as independent.

Fig.15 shows three non-linear gearings which were briefly evaluated in the present tests for comparison with the basic S.C.1 linear control gearing. Fig.15(b) and (c) show gearings in which the control sensitivity varies with stick displacement according to a quadratic law, that shown in Fig.15(b) having a sensitivity in the stick neutral position which is double that of the linear control, while that in Fig.15(c) has a control sensitivity for stick neutral which is a half that of the linear control. Fig.15(d) shows a different type of non-linearity in which the control sensitivity has a relatively high value for the first part of the control travel, but with the moment from the control nozzles remaining constant at the larger stick displacements.

It was soon evident in these tests that a considerable programme of work would be involved in investigating each of these configurations fully and in optimising the actual values of sensitivity and stick throw. Since time would not allow this, only a brief study to gain pilot's general impressions of the non-linear gearings was made. None of the gearings tested provoked any great enthusiasm from the pilots when compared with the linear control gearing. Several pilots felt that gearings of the type shown in Fig.15(b) and 15(d) might give a false sense of security because the amount of stick displacement used in the cockpit would suggest that they had plenty of control in hand, whereas in reality most of tho available control power was being used.. Conversely the type of gearing shown in Fig.15(c) was felt to provide a genuine sense of security because the larger stick displacements were particularly effective. In this case however the control was much too sluggish for small stick displacements.

Another type of roll control characteristic investigated was one in which the artificial damping in roll was reduced when the control stick was displaced. The intention here was to produce an aircraft having fairly heavy damping at the hover, where only small stick displacements are used, while at the same time having brisk response to the larger movements which might be used for manoeuvring.

Again only a brief evaluation without previous optimisation of the various parameters was possible, but even 90 this modification was felt to give quite an improvement in aircraft handling characteristics; particularly at the lower control sensitivities. For the case-of the S.C.1, having a roll control sensitivity of 0·375 rad/sec^2/inch and a damping: inertia ratio of 3·7 sec^{-1}, the tests indicated that a reduction in damping by about 40% at full stick travel gave the most improvement.

3.4 Investigation of control following autostabiliser failure

Whenever autostabilisation is used to alter the flying characteristics of aircraft, consideration must be given to the effect of failure of some component on the control of the aircraft. (In the S.C.1 aircraft special precautions have been taken in the design of the autostabiliser to ensure that no single failure can render the autostabiliser suddenly inoperative.)

Although control investigations of the type &scribed earlier in this report may show that pilots could control an aircraft with characteristics corresponding to those for the autostabiliser inoperative, additional problems are created when the autostabiliser fails suddenly, for the pilot must then rapidly adjust his control behaviour to suit the now situation.

In the present tests two oases were considered. In the first, failure of the autostabiliser merely reduced the damping from its normal value to zero. In the second case the failure also introduced an out of balance rolling moment, as well as causing the damping to fall to zero.

An experimental difficulty in investigating this situation is that of creating the element of surprise which would normally be a major feature in the problem being represented. This can be genuinely achieved only for the first few tests in any investigation; thereafter the pilot is naturally suspicious that a failure is about to occur and at best it can only' be made to occur at the most unlikely moment.

Fig.16 shows time histories of the aircraft behaviour during some of these tests. In all oases the flight condition before failure was that of the S.C.1 in damping setting 1 (control sensitivity 0·37 rad/sec^2/inch, damping: inertia ratio 3·7 sec^{-1}). The pilot generally found it fairly easy to maintain control when a failure which simply reduced the damping to zero occurred in steady hovering flight. Fig.16(a) shows that there is a tendency for him to over control and thus produce a continuous small amplitude bank oscillation but this is not too serious for an emergency condition. When a similar failure occurred during manoeuvring the results were very variable, depending on the exact condition of the aircraft at the instant of failure. Fig.16(b) shows a case where the failure occurred just after the start of a sideways translational manoeuvre, and hero the pilot managed to retain quite reasonable control and complete the manoeuvre. But on other occasions when the failure occurred as the pilot was initiating an attitude change it was easy for control to be lost altogether.

Some types of autostabiliser malfunction may not only cause the damping to fall to zero but may also introduce an out of balance rolling moment, which requires the stick to be held in a new, off-centre position for trim. This combination of circumstances was found to be very difficult to control. There was a natural tendency to relax the stick displacement back to the neutral position once the first disturbance had been overcome, and the out of balance moment, combined with tho lack of damping, would then cause the aircraft to roll rapidly out of control. Figs.16(c) and (a) show two examples of this condition. For the comparatively small out of trim moment needing an eighth of the full control travel to trim pilots found the situation reasonably easy to deal with provided the aircraft was well stabilised beforehand. Even a malfunction needing a quarter of the control travel to trim was controlled on the simulator but the pilots felt less certain of equal success in flight.

For one thing they did not have to worry about height control on the simulator, whereas in flight constant adjustments to power would be necessary to counteract the effect of attitudo changes.

4 INVESTIGATION OF PITCH CONTROL CHARACTERISTICS

As already described in section 2.3 tho simulation of the longitudinal flying task was felt to be less realistic than that in the lateral plane because of limitations in the visual simulation equipment, and the pilots had some reservations about the results which would bo achieved with it. For this reason only a cursory investigation into pitch control characteristics was attempted.

Many of the comments made whon discussing the results of the rolling investigation in section 3 are equally applicable to this study of pitch control, including those concerning tho relationship between control power and control sensitivity.

For the pitching tests the roll control characteristics nere held constant with values of damping: inertia ratio (4 sec^{-1}) and control sensitivity (0·5 $rad/sec^2/inch$) which were close to the optimum, (see Fig.13).

Fig.17 shows the pilots' assessments of pitch control on a plot of damping and control sensitivity. The general picture is broadly similar to that found for the roll case - a satisfactory region bounded on one side by an area in which control was too sluggish and on the other by one in which it was too sensitive. It was felt howover that the satisfactory region was less tightly bounded in pitch then in the roll case. There was also a tendency to prefer lower control sensitivity and to tolerate lower damping in the pitch control characteristics compared with those in roll.

This data is compared in Figs.18 and 19 with the results of previous investigations again by Faye[5] and Breul[6] and with various control criteria[10,11,12]. The pattern of the comparison is again very similar to the rolling case. When compared on the basis of control sensitivity, Fig.18, the present test results are consistent with those of Faye, but allow a smeller region of satisfactory control than that indicated by Breul. In Fig.19, when the measure of control effectiveness is taken to be the control power, those boundaries which obviously depend only on the control sensitivity have been omitted.

As regards the comparison with control criteria, the A.G.A.R.D. recommondations[4] for minimum damping are more severo then those indicated by tho results of tho simulation studios, but again this probably reflects the requirements for operation under I.F.R. rather than the purely visual flight tasks considered here. Both the A.G.A.R.D. and Lynn's[10] recommendations for minimum control sensitivity agree reasonably well with the results of the present simulator tests. Tho criteria proposed by Lollar[12] for maximum control sensitivity is slightly more stringent than the results of the present tests but again his work was concerned with operation under I.F.R. rather than V.R.F. conditions.

5 CONCLUSIONS.

Pilots' general assessment of the realism of the present simulation showed that the representation of ground detail in the visual background was of great importance in providing the indications of translational velocity needed for controlling the aircraft at the hover and. in low speed manoeuvring. The present visual simulation equipment was only really adequate in this rcspeot for representing sideways translational motion. Difficulties in controlling the aircraft's yawing motion on the simulator also indicated the need for a better representation of the visual background and also, probably, the need for cockpit motion which was not available about this axis.

Tests of the aircraft's roll control characteristics, for a wide range of control effectiveness and aircraft rate damping, allowed a carpet plot of those parameters to be drawn, with a boundary indicating combinations which gave satisfactory aircraft handling qualities. This boundary has been compared with those derived from previous simulation tests and with boundaries calculated from various V.T.O.L. control criteria. In general reasonable agreement was found between the present results and those from previous work. The reasons pilots gave for not liking tho characteristics which were felt to be unsatisfactory have been recorded and discussed. They were fairly consistent from different pilots and scorned to arise logically from the type of tasks they were asked to perform and the given aircraft characteristics.

Some brief tests with non-linear gearing between the control stick and the control actuator did not show any outstanding advantages over a linear control, but these tests were by no means exhaustive. Another brief set of tests in which the aircraft rate damping was reduced with control stick position did show a noticeable improvement in handling qualities over those with linear control.

Some tests to investigate tho ease of controlling the aircraft in the event of an autostabiliser failure showed that the simulator could be controlled fairly easily when a simple reduction in damping occurred in stabilised hovering flight. Results for the same typo of failure when the aircraft was being manoeuvred wore very variable and depended critically on the exact condition of the aircraft at the instant the failure occurred. When the auto-stabiliser malfunction resulted in an out of balance rolling moment, as well as a reduction in damping, the simulator was very much more difficult to control and the pilots were doubtful whether they would have been able to control such a failure in flight, even from a stabilised hovering condition, if the out of balance needed more than a small fraction of the total control travel to trim.

Because of linitntions in the simulation equipment a less comprehensive study of pitch control was made, but a carpet plot of control effectiveness and aircraft rate damping was again obtained and hns been compared with the results of previous studies. Reasonable agreement between the various results was found.

Appendix A

COMPLETE EQUATIONS OF MOTION FOR A SYMMETRICAL, RIGID AIRCRAFT, TOGETHER WITH THE APPROXIMATIONS USED IN THE PRESENT TESTS

A.1 Translational motion w.r.t. aircraft body axes

(a) Longitudinal

$$m\dot{U} = P_x + X - mg \sin \theta - mWQ + mVR$$

(complete equation used)

(b) Lateral

$$m\dot{V} = P_y + Y + mg \cos \theta \sin \phi - mUR + mWP$$

(complete equation used)

(c) Vertical

$$m\dot{W} = P_z + Z + mg \cos \theta \cos \phi - mVP + mUQ$$

(complete equation used)

A.2 Rotational motion about aircraft body axes

(a) Pitch

$$I_{yy} \dot{Q} = (I_{zz} - I_{xx}) RP + I_{xz}(R^2 - P^2) + T_y + M$$

(complete equation used)

(b) Roll

$$I_{xx} \dot{P} = (I_{yy} - I_{zz}) QR + I_{xz}(\dot{R} + PQ) + T_x + L$$

(complete equation used)

(c) Yaw

$$I_{zz} \dot{R} = (I_{xx} - I_{yy}) PQ + I_{xz}(\dot{P} - QR) + T_z + N$$

(complete equation used)

A.3 Euler axis conversion from rotation about aircraft body axes to changes in aircraft orientation w.r.t. the earth

(a) Attitude angle

$$\dot{\theta} = Q \cos\phi - R \sin\phi$$

(complete equation used)

(b) Bank angle

$$\dot{\phi} = P + Q \sin\phi \tan\theta + R \cos\phi \tan\theta \; (= P + \dot{\psi} \sin\theta)$$

approximation used in simulation:-

$$\dot{\phi} \approx P + Q \sin\phi \sin\theta + R \cos\phi \sin\theta \, , \text{ for } \theta \text{ small} \, .$$

(c) Azimuth angle

$$\dot{\psi} = Q \sin\phi \sec\theta + R \cos\phi \sec\theta$$

approximation used in simulation:-

$$\dot{\psi} \approx Q \sin\phi + R \cos\phi \, , \text{ for } \theta \text{ small} \, .$$

A.4 Translational velocity components w.r.t. earth co-ordinates

(a) Along runway

$$\dot{S}_x = U \cos\theta \cos\psi - V(\cos\phi \sin\psi - \sin\theta \sin\phi \cos\psi) + W(\sin\theta \cos\phi \cos\psi + \sin\phi \sin\psi)$$

approximation used in simulation:-

$$\dot{S}_x \approx U - V \frac{\psi^\circ}{57 \cdot 3} + W \sin\theta \, , \quad \text{all attitude angles small} \, .$$

(b) Across runway

$$\dot{S}_y = U \cos\theta \sin\psi + V(\cos\phi \cos\psi + \sin\theta \sin\phi \sin\psi) - W(\sin\phi \cos\psi - \sin\theta \cos\phi \sin\psi)$$

approximation used in simulation:-

$$\dot{S}_y \approx U \frac{\psi^\circ}{57 \cdot 3} + V - W \sin\phi \, , \quad \text{all attitude angles small} \, .$$

(c) Height

$$\dot{S}_z = -U \sin\theta + v \cos\theta \sin\phi + w \cos\theta \cos\phi$$

approximation used in simulation:-

$$\dot{S}_z \approx -U \sin\theta + V \sin\phi + W, \quad \text{all attitude angles small .}$$

A.5 Resolution of wind components w_x, w, w_z measured w.r.t. earth axes into components U_w, V_w and W_w along the aircraft body axes

(a) Component along the longitudinal axis

$$u_w = w_x \cos\theta \cos\psi + w_y \cos\theta \sin\psi - w_z \sin\theta$$

approximation used in simulation:-

$$U_w \approx w_x + w_y \frac{\psi^\circ}{57\cdot3} .$$

(b) Component along the lateral axis

$$V_w = -w_x(\cos\phi \sin\psi - \sin\theta \sin\phi \cos\psi) + w_y(\cos\phi \cos\psi + \sin\theta \sin\phi \sin\psi) + w_z \cos\theta \sin\phi$$

approximation used in simulation:-

$$V_w \approx -w_x \frac{\psi^\circ}{57\cdot3} + w_y .$$

(c) Component along the vertical axis

$$W_w = w_x(\sin\theta \cos\phi \cos\psi + \sin\phi \sin\psi) - w_y(\sin\phi \cos\psi - \sin\theta \cos\phi \sin\psi) + w_z \cos\theta \cos\phi$$

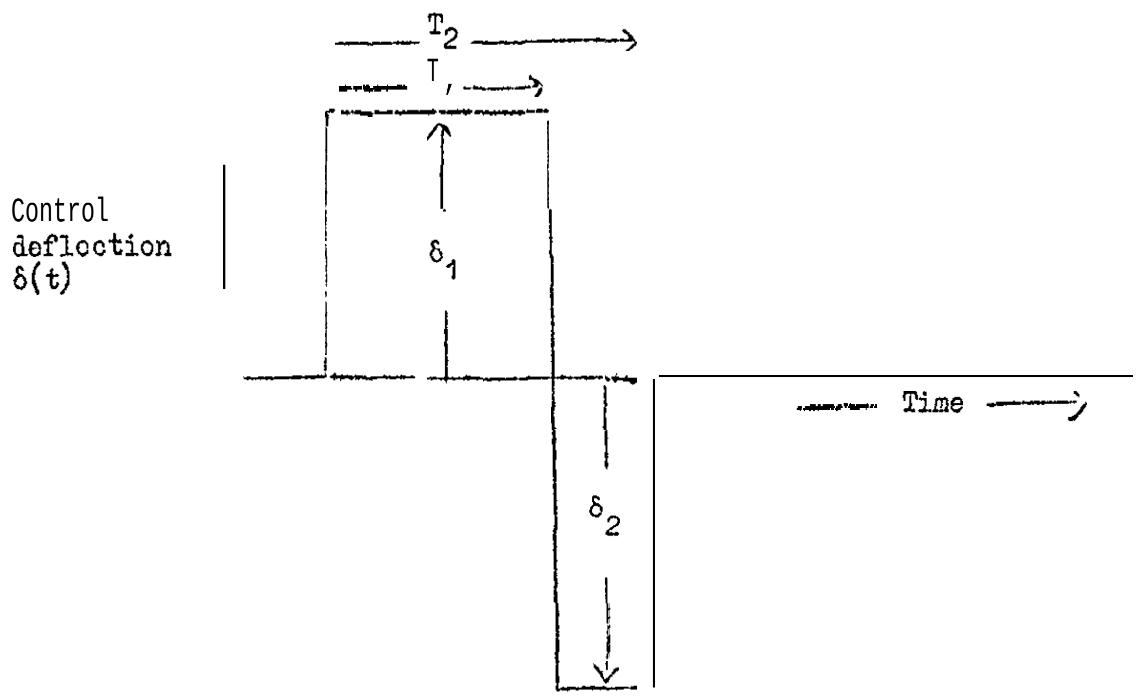
approximation used in simulation:-

$$W_w \approx w_x \sin\theta + w_z .$$

Appendix B

AN EXPRESSION FOR THE SINGLE-DEGREE-OF-FREEDOM ROTATIONAL MOTION OF A REACTION CONTROLLED VEHICLE WITH DAMPING WHEN SUBJECTED TO AN IDEALISED CONTROL INPUT

In order to change the attitude of a reaction controlled aircraft the pilot must make a sequence of movements which may take roughly the form of the idealised, step changes in control position shown in Fig.A.



In this control sequence the control deflection s(t) has the values:-

$$s(t) = 0 \quad \text{for} \quad t < 0$$

$$6(t) = +\delta_1 \quad \text{for} \quad 0 < t < T_1$$

$$s(t) = -\delta_2 \quad \text{fcr} \quad T_1 < t < T_2$$

$$\delta(t) = 0 \quad \text{for} \quad T_2 < t$$

The aircraft motion is governed by an equation of the form:-

$$I\ddot{\phi} + C\dot{\phi} = N\,\delta(t) \qquad (B.1)$$

where ϕ is the aircraft attitude (rads)

I is the moment of inertia (slug-feet^2)

C is the damping moment (lb ft per rad per sec)

M is the control moment (lb ft per inch)

6(t) is the control deflection (inches).

This may be rewritten:-

$$\ddot{\phi} + R\dot{\phi} = K\,S(t) \tag{B.1a}$$

where $R = -\frac{C}{I}$ is the 'damping to inertia ratio' (per sec)

$K = \frac{M}{I}$ is the 'control sensitivity' (rad/sec^2/inch)

The method to be used for solving this equation is that of the Laplace transformation:-

$$?(P) = \int_0^\infty e^{-pt} f(t)\,dt .$$

The transform of the time function of control deflection, $\delta(t)$, shown in Fig.A is therefore:-

$$\bar{\delta}(p) = \int_0^{T_1} \delta_1 e^{-pt}\,dt - \int_{T_1}^{T_2} \delta_2 e^{-pt}\,dt$$

$$= \frac{\delta_1}{p}(1 - e^{-pT_1}) - \frac{\delta_2}{p}(e^{-pT_1} - e^{-pT_2}) \tag{B.2}$$

so that the transform of equation (B.1a) is

$$p(p+R)\,\bar{\phi} = \frac{K\,\delta_1}{p}(1 - e^{-pT_1}) - \frac{K\,\delta_2}{p}(e^{-pT_1} - e^{-pT_2})$$

having the solution

$$\bar{\phi} = \frac{K\,\delta_1}{p^2(p+R)} - \frac{K(\delta_1 + \delta_2)\,e^{-pT_1}}{p^2(p+R)} + \frac{K\,\delta_2\,e^{-pT_2}}{p^2(p+R)} . \tag{B.3}$$

The inverse of this expression may be found from a list of known transforms, together with the application of the Shift Theorem in the case of the last two terms.

$$\phi(t) = \frac{K\delta_1}{R}\left[t + \frac{1}{R}(e^{-Rt} - 1)\right] - \frac{K(\delta_1 + \delta_2)}{R}\left[(t-T_1) + \frac{1}{R}(e^{-R(t-T_1)} - 1)\right] H(t-T_1)$$

$$+ \frac{K\delta_2}{R}\left[(t - T_2) + \frac{1}{R}(e^{-R(t-T_2)} - 1)\right] H(t - T_2)$$

. . . (B.4)

where $H(t - T)$ is an operator having tho property that, if

$$g(t) = f(t-T)\,H(t-T)$$

then

$$g(t) = 0 \quad \text{for} \quad t < T$$

and

$$g(t) = f(t-T) \quad \text{for} \quad t > T \;.$$

An expression for rate of change of attitude is obtained from the inverse of $px\bar{\phi}$, i.e.:-

$$\dot{\phi}(t) = \frac{K\delta_1}{R}\left[1 - e^{-Rt}\right] - \frac{K(\delta_1 + \delta_2)}{R}\left[1 - e^{-R(t-T_1)}\right] H(t-T_1) + \frac{K\delta_2}{R}\left[1 - e^{-R(t-T_2)}\right] H(t-T_2) \;. \qquad \ldots (B.5)$$

Table 1

TABLE OF NUMERICAL DATA USED IN SETTING UP THE SIMULATION. MOST VALUES ARE THOSE FOR THE SHORT S.C.1 AIRCRAFT

Weight 6900 lb

Moments of inertia	Pitch	I_{yy}	5480 slug feet^2
	Roll	I_{xx}	1865 slug feet^2
	Yaw	I_{zz}	7000 slug feet^2
	Product	I_{xz}	taken to be zero

Engine characteristics

Max. combined thrust of four lift engines. 8400 lb.

Engine respcnso characteristics represented by a first order lag with time constant 0·11sec, together with a limitation on max. rate of change of thrust to 3500 lb/sec.

Lift throttle sensitivity (in hovering region) 1000 lb/inch.

Idling thrust of propulsion engine. 400 lb.

Control system characteristics

Pilot's controls

Longitudinal control travel	±3½ inches
Lateral control travel	±3½ inches
Directional control travel	±3 inches

Force gradients (on simulator)

Longitudinal control	Breakout force 2 lb Force at full travel 11 lb
Lateral control	Breakout force 2 lb Force at full travel 4 lb
Direction control	Force at full travel cpprox. 25 lb.

Control power, control sensitivity and damping were varied during the test programme. In representing tho S.C.1 aircraft values taken were:-

Longitudinal control power (full travel)	1·1 rad/sec^2
Lateral control power (full travel)	1·3 rad/sec^2
Directional control power (full travel)	0·35 rad/sec^2

Table 1 (Contd)

The corresponding control sensitivities were 0·31, 0·37 and 0·12 rads/sec^2/inch for the longitudinal, lateral and directional control powers respectively.

Aerodynamic characteristics

Forces produced by relative wind

Longitudinal X_u = -7 lb per ft/sec

Lateral Y_v = -12 lb per ft/sec

Vertical Z_w = -20 lb per ft/sec

Moments produced by relative wind

Pitching $\frac{M_u}{I_{yy}}$ = +0·3°/sec^2 per ft/sec

Rolling $\frac{L_v}{I_{xx}}$ = -0·4°/sec^2 per ft/sec

Yawing $\frac{N_v}{I_{zz}}$ = +0·05°/sec^2 per ft/sec

Table 2

EXPERIENCE OF PILOTS TAKING PART IN THE SIMULATION

Pilot	Types of jet-borne V.T.O.L. aircraft flown	Helicopter experience hours	Hours on present simulation
A	Short S.C.1 Hawker PI 127 Bell X.14	90	11
B	Short S.C.1	90	5½
C	-	40	9
D	-	40	8
E	Short S.C.1*	100	4½
F	-	100	4
G	Hawker P1127 Short S.C.1† Bell X.14†	10	1¼

*denotes only limited experience on these types.
†denotes only one flight on each of these aircraft.

SYMBOLS

g	acceleration due to gravity	ft/sec^2
I_{xx}, I_{yy}, I_{zz}	moment of inertia about the rolling, pitching and yawing body datum axes	slug $feet^2$
I_{xz}	product of inertia	slug $feet^2$
L	rolling moment due to aerodynamic forces	lb feet
L_v	rolling moment due to relative wind along the lateral body axis	lb feet
M	pitching moment due to aerodynamic forces	lb feet
M_u	pitching moment due to relative wind along the forward body axis	lb foot
N	yawing moment due to aerodynamic forces	lb feet
N_v	yawing moment due to relative wind along the lateral body axis	lb feet
P	rate of roll about body datum axis	rad/sec or deg/sec
P_x, P_y, P_z	engine thrust component3 along the forward, lateral and normal body datum axes	lb
Q	rate of pitch about body datum axis	rad/sec or deg/sec
R	rate of yaw about body datum axis	rad/sec or deg/sec
$S_{\dot{x}}, S_{\dot{y}}, S_{\dot{z}}$	velocity component3 along, across and normal to the runway	ft/sec
T_x, T_y, T_z	rolling, pitching and yawing moments due to engine and reaction control forces	lb feet
U	velocity component along the forward body datum axis	ft/sec
V	velocity component along the lateral body datum axis	ft/sec
W	velocity component along the normal body datum axis	ft/sec
X	aerodynamic force component along the forward body datum axis	lb
Y	aerodynamic force component along the lateral body datum axis	lb
Z	aerodynamic force component along the normal body datum axis	lb
ϕ, θ, ψ	Euler attitude angles of roll, pitch and yaw	rad or deg
W_x, W_y, W_z	wind components along, across and normal to the runway	ft/sec

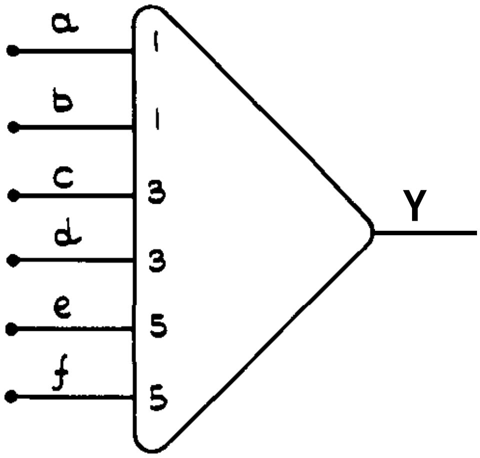
REFERENCES

No.	Author	Title, etc
1	J. K. B. Illingworth	Flight tests of a hovering jet-lift aircraft (Rolls Royce Flying Bedstead) A.R.C. R & M 3336, May 1961
2	J. K. B. Illingworth H. W. Chinn	Variable stability and control tests on the S.C.1 aircraft in Jet-borne flight, with particular reference to desirable V.T.O.L. flying qualities.. A.R.C. 25001,. May 1963 May 196
3	S. B. Anderson	An examination of handling qualities criteria for V/STOL aircraft. N.A.S.A. TN D-331, July 1960
4		Recommendations for V/STOL handling qualities:. A.R.C. 24657, March 1963
5	A. E. Faye	Attitude control requirements for hovering determined through the use of a piloted flight simulator. N.A.S.A. TN D-792, April 1961
6	H. T. Breul	A simulator study of tilt-wing handling qualities. Grumman Research Department Report m-162, March 1963
7	G. Isakson, H. Buning	A study of problems in the flight simulation of VTOL aircraft. W.A.D.C. Technical Note 59305, February 1960
8	W. E. Feddersen	The role of motion information and its contribution to simulation validity. Boll ANIP Report No. D228-492-001. Bell Helicopter Co. April 1962
9	J. Patierno J. 3. Isca	Instrument flight'simulator study of the V.T.O.L. controllability - control power relationship. I.L.S. paper No. 61-118-1812, Juno 1961

REFERENCES (Contd)

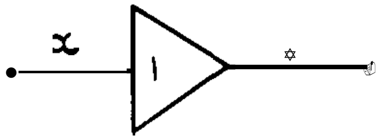
No.	Author	Title, etc
10	R. R. Lynn	New control criteria for VTOL aircraft. Aerospace Engineering Vol.21, No.8, August 1962
11	H. M. Dathe	Review of hovering control requirements for VTOL aircraft by a flight dynamics analysis. AGARD Report 472, July 1963
12	T. E. Loller	A rationale for the determination of certain VTOL handling qualities criteria. AGARD Report 471, July 1963

APPENDIX C BLOCK DIAGRAMS OF THE COMPUTER SET UP

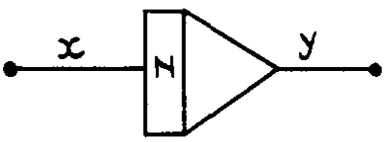


SUMMING AMPLIFIER HAVING AN OUTPUT VOLTAGE y GIVEN BY

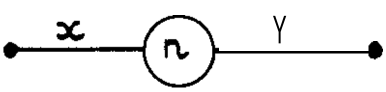
$$y = -(a+b+3c+3d+5e+5f)$$



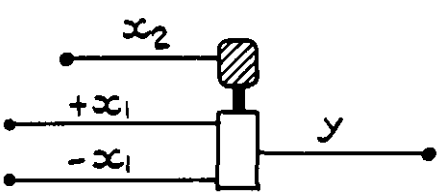
SIGN REVERSING AMPLIFIER HAVING AN OUTPUT $y=-x$. ALSO USED AS A 'BUFFER' TO PREVENT INTER- ACTION BETWEEN COMPUTING ELEMENTS



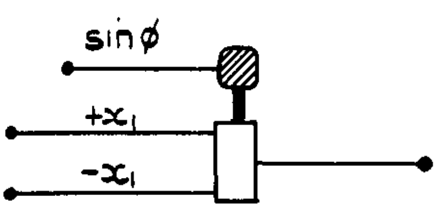
INTEGRATING AMPLIFIER HAVING AN OUTPUT $-N\int x\,dt$



COEFFICIENT SETTING POTENTIOMETER GIVING $y = nx$ WHERE n CONSTANT <1



SERVOMULTIPLIER HAVING AN OUTPUT $y = \frac{1}{100} x_1 \times x_2$



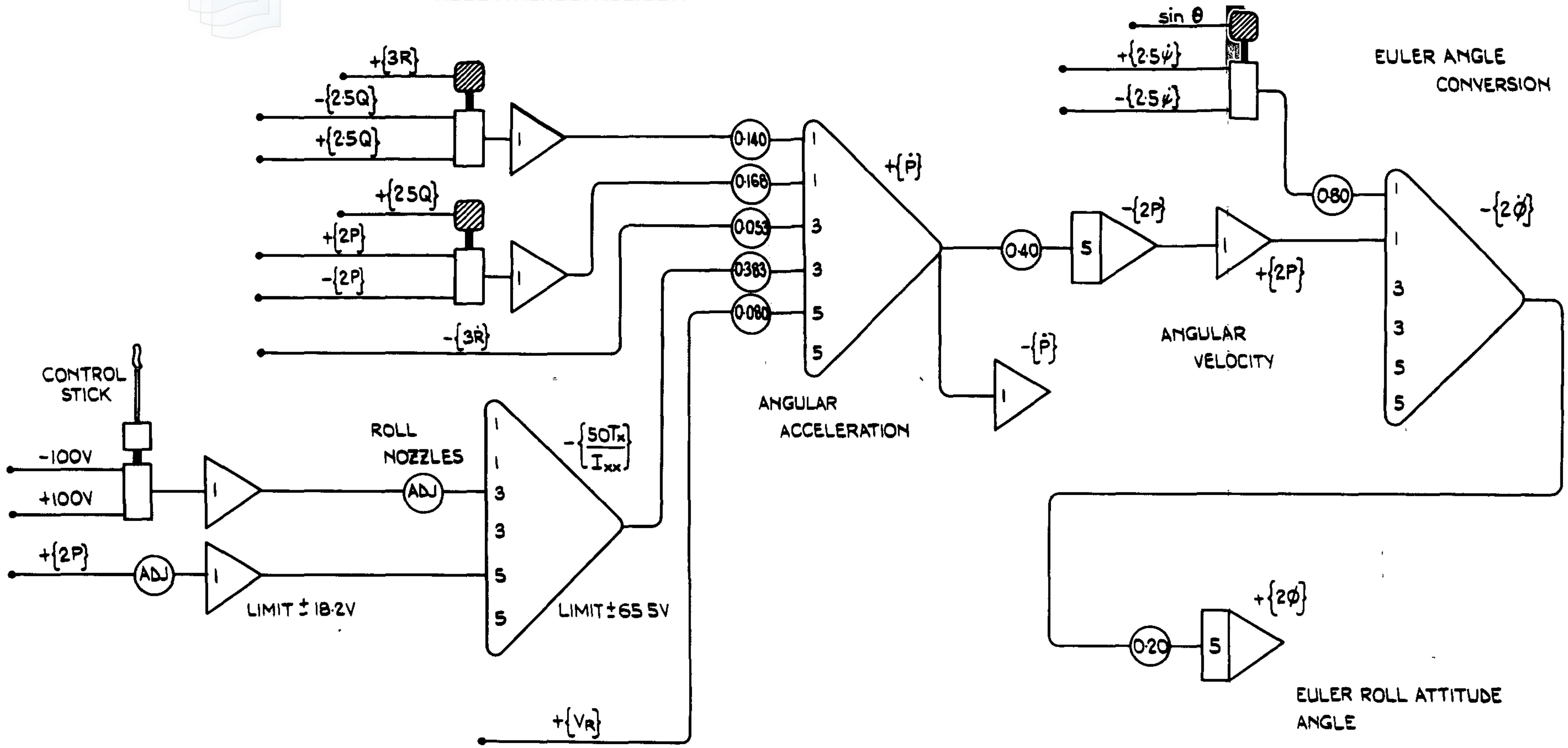
SERVORESOLVER HAVING AN OUTPUT

$y = x_1 \sin\phi$ [OR $\cos\phi$]

{3R}

DENOTES THE VOLTAGE ANALOGUE OF A VARIABLE [FOR INSTANCE {3R} MEANS THAT A GIVEN RATE OF YAW R°/SEC WOULD BE REPRESENTED BY A VOLTAGE 3RV]

FIG. CI KEY TO COMPUTER BLOCK DIAGRAMS



EQUATIONS

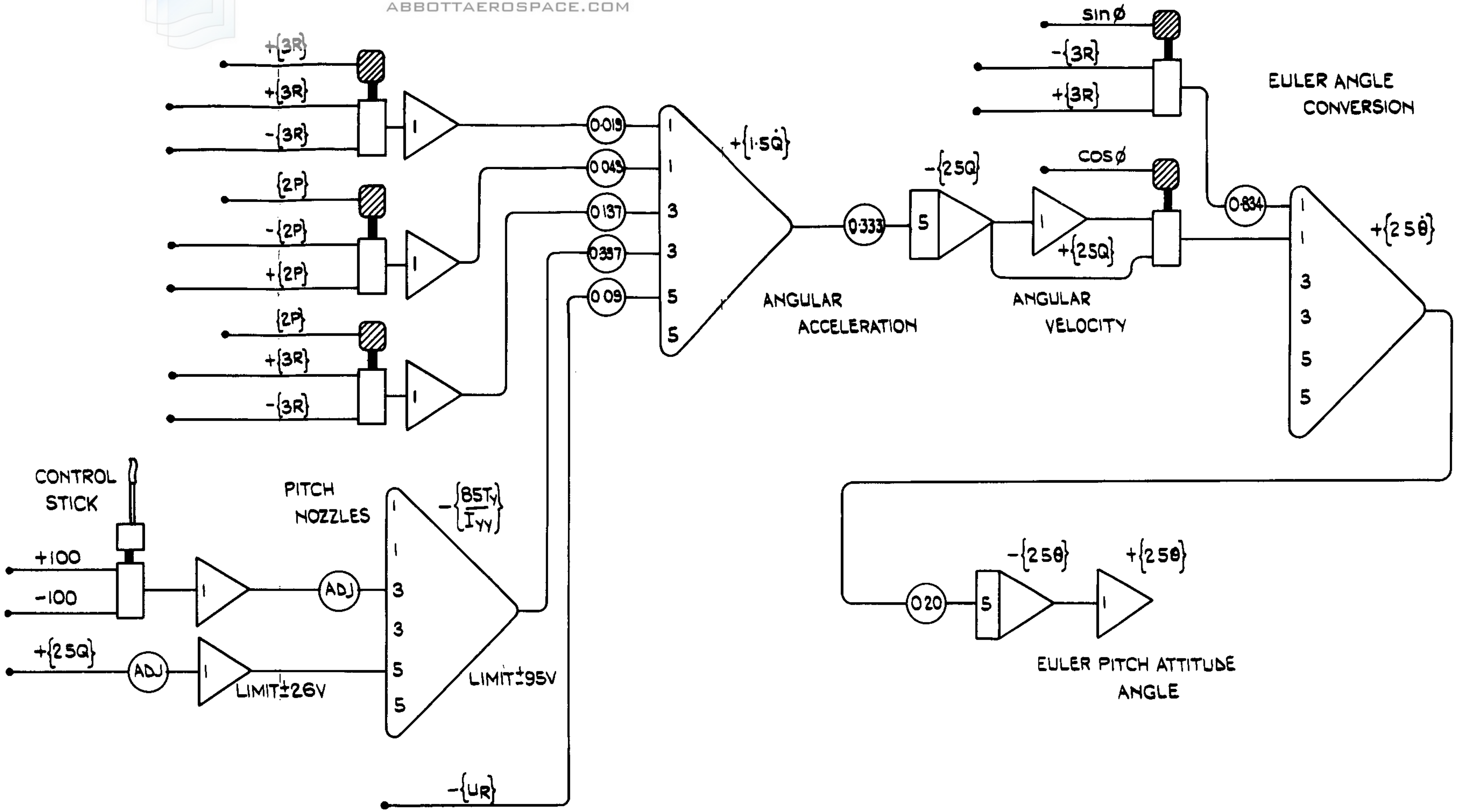
$$\{\dot{P}\} = -(0.140)\frac{1}{100}\{2.5Q\}\{3R\} + (0.168)\frac{1}{100}\{2P\}\{2.5Q\} + (0.160)\{3\dot{R}\} + (1.15)\left\{\frac{50T_x}{II_{xx}}\right\} - (0.40)\{V_R\}$$

$$\{2P\} = 2\int\{\dot{P}\}dt$$

$$\{2\dot{\phi}\} = \{2P\} + (0.80)\{2.5\dot{\psi}\}\sin\theta$$

$$\{2\phi\} = \int\{2\dot{\phi}\}dt$$

FIG. C2 COMPUTER DIAGRAM FOR ROLLING MOTION



EQUATIONS

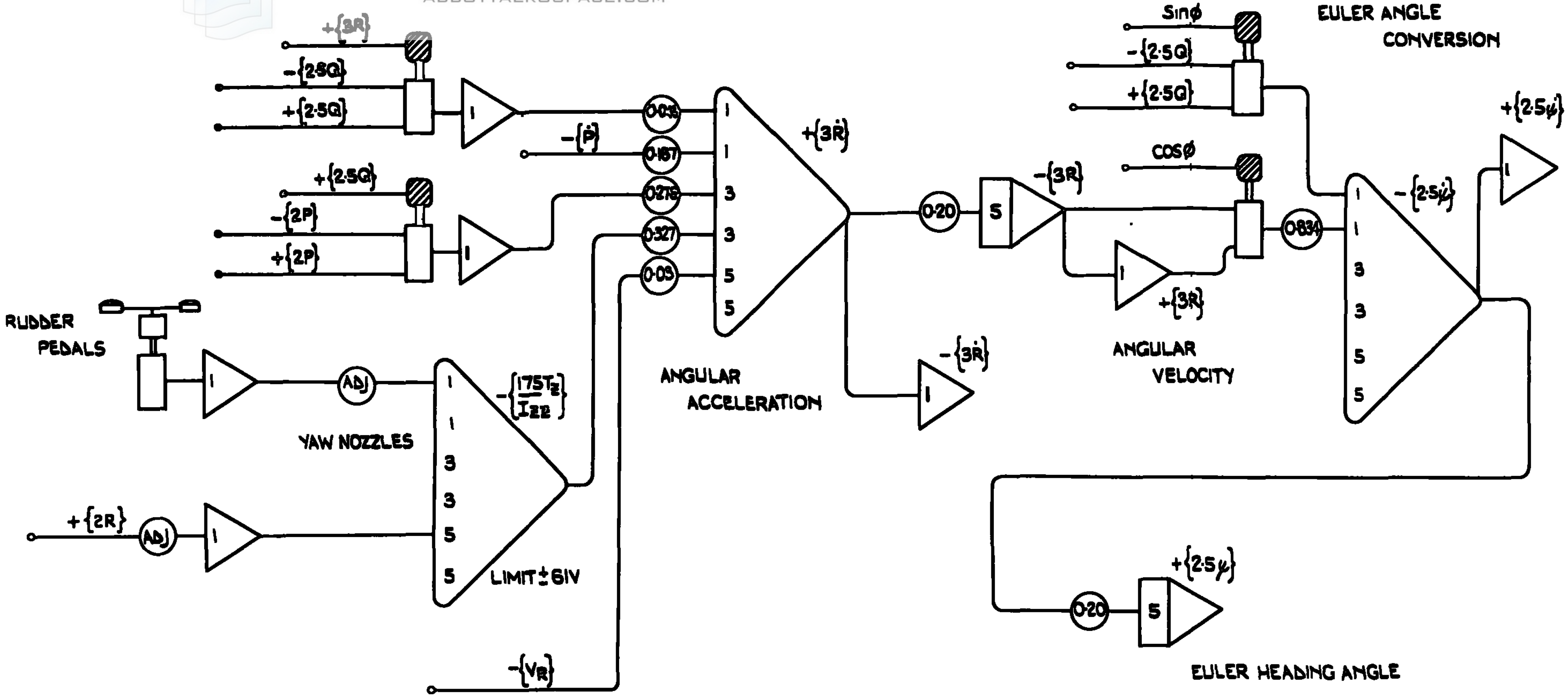
$$\{1\cdot 5\dot{Q}\} = (0\cdot 019)\tfrac{1}{100}\{3R\}\{3R\} - (0\cdot 043)\tfrac{1}{100}\{2P\}\{2P\} + (0\cdot 412)\tfrac{1}{100}\{3R\}\{2P\} + (1\cdot 01)\left\{\frac{85T_Y}{I_{YY}}\right\} + (0\cdot 45)\{UR\}$$

$$\{2\cdot 5Q\} = (1\cdot 67)\int\{1\cdot 5\dot{Q}\}\,dt$$

$$\{2\cdot 5\dot{\theta}\} = \{2\cdot 5Q\}\cos\phi - (0\cdot 834)\{3R\}\sin\phi$$

$$\{2\cdot 5\theta\} = \int\{2\cdot 5\dot{\theta}\}\,dt$$

FIG. C3 COMPUTER DIAGRAM FOR PITCHING MOTION



EQUATIONS

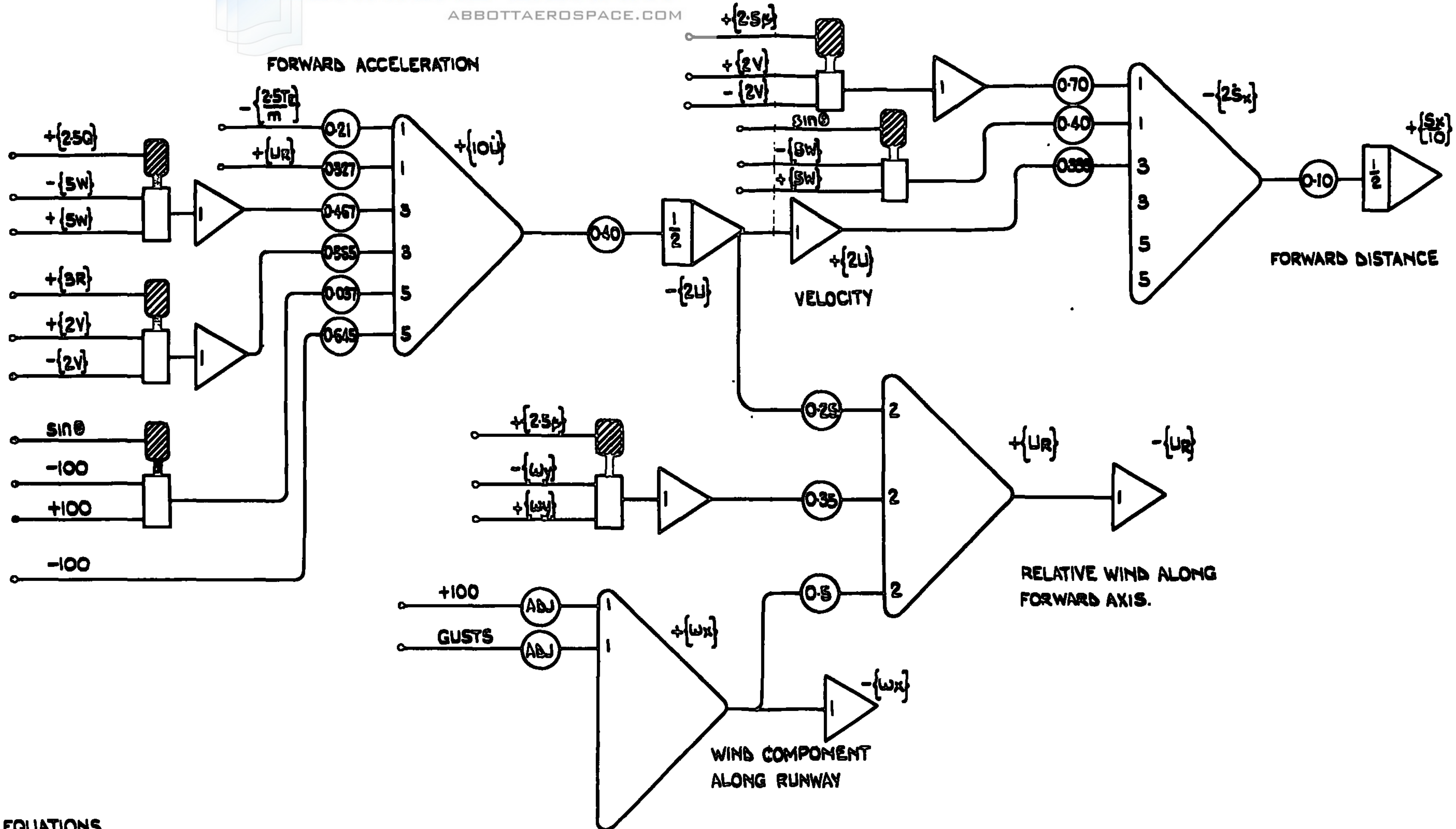
$$\{3\dot{R}\} = -(0{\cdot}043)\frac{1}{100}\{2{\cdot}5Q\}\{3R\} + (0{\cdot}187)\{\dot{P}\} - (0{\cdot}83)\frac{1}{100}\{2P\}\{2{\cdot}5Q\} + (0{\cdot}981)\left\{\frac{175\,T_z}{I_{zz}}\right\} + (0{\cdot}15)\{V_R\}$$

$$\{3R\} = \int\{3\dot{R}\}\,dt$$

$$\{2{\cdot}5\dot{\psi}\} = (0{\cdot}834)\{3R\}\cos\phi + \{2{\cdot}5Q\}\sin\phi$$

$$\{2{\cdot}5\psi\} = \int\{2{\cdot}5\dot{\psi}\}\,dt$$

FIG. C4 COMPUTER DIAGRAM FOR YAWING MOTION



EQUATIONS

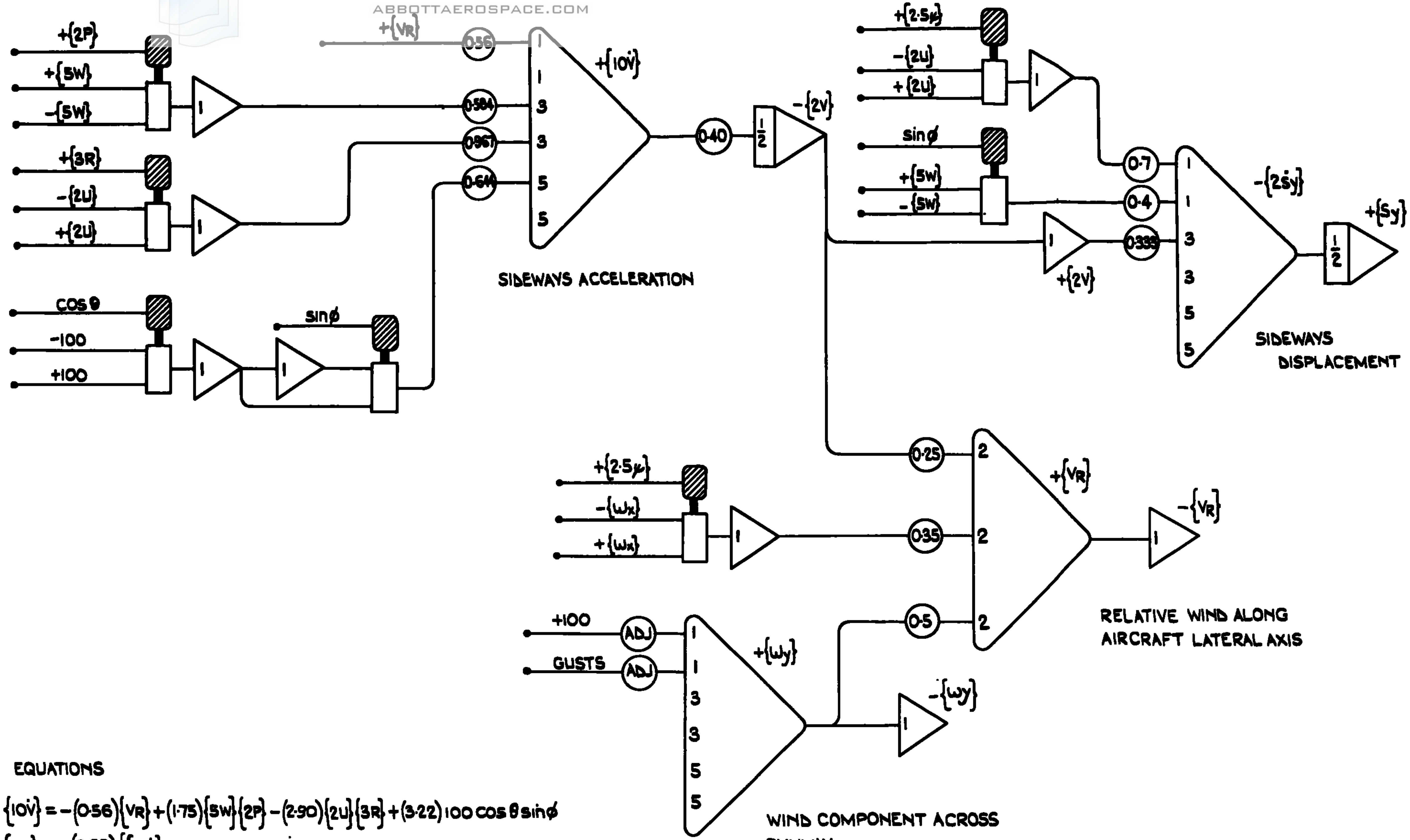
$$\{10\dot{U}\} = (0{\cdot}21)\left\{\frac{2{\cdot}5T_E}{m}\right\} - (0{\cdot}327)\{U_R\} - (1{\cdot}4)\frac{1}{100}\{5W\}\{2{\cdot}5Q\} + (2{\cdot}9)\frac{1}{100}\{2V\}\{3R\} - (3{\cdot}22)100\sin\theta + 18{\cdot}7$$

$$\{2U\} = (0{\cdot}20)\int\{10\dot{U}\}\,dt$$

$$\{2\dot{S}_x\} = \{2U\} - (0{\cdot}70)\frac{1}{100}\{2V\}\{2{\cdot}5_x\} + (0{\cdot}40)\{5W\}\sin\theta$$

$$\{U_R\} = -(0{\cdot}5)\{2U\} - (0{\cdot}70)\frac{1}{100}\{\omega_y\}\{2{\cdot}5_x\} - \{\omega_x\}$$

FIG C5 COMPUTER DIAGRAM FOR FORWARD TRANSLATIONAL MOTION



EQUATIONS

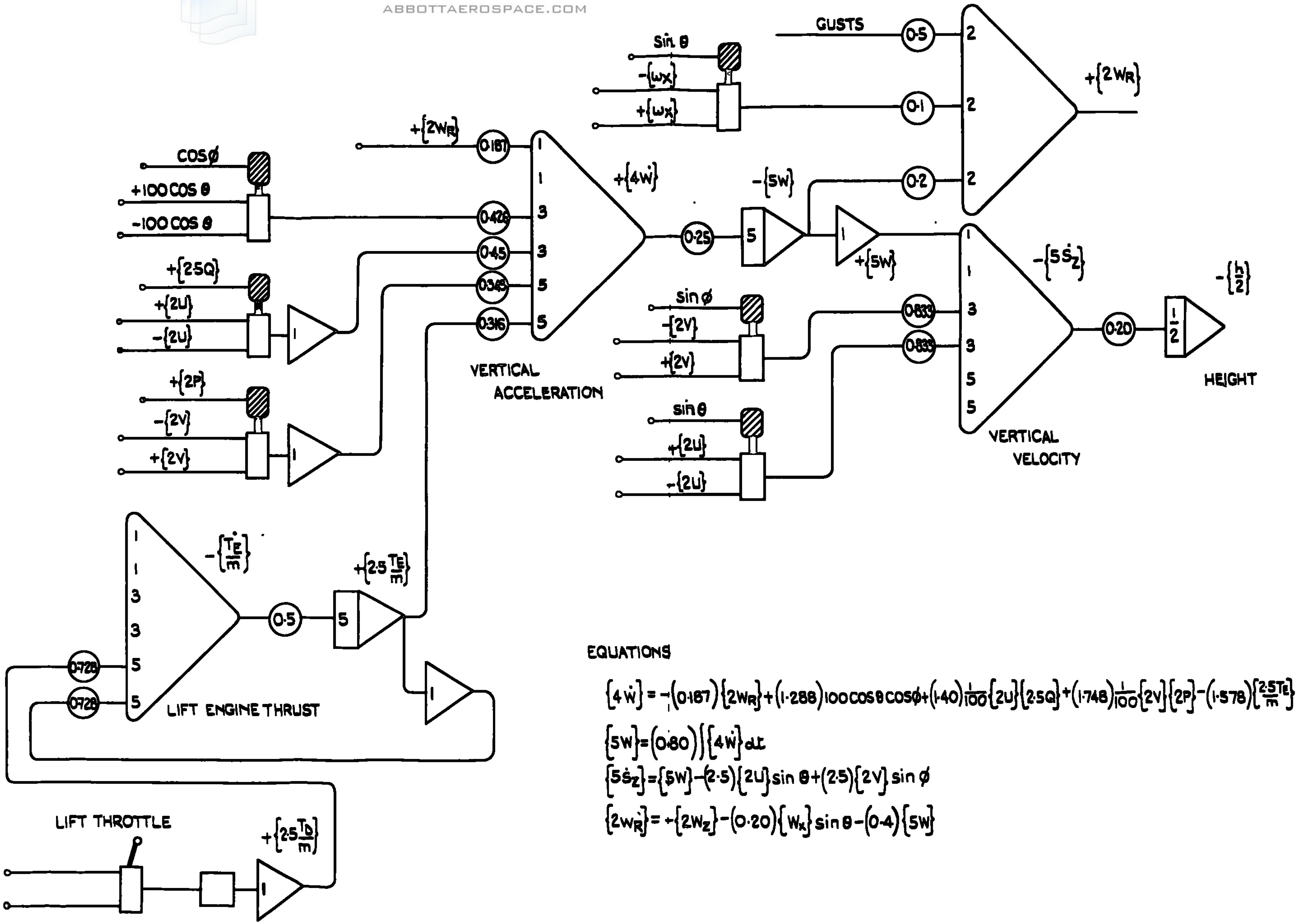
$$\{10\dot{V}\} = -(0.56)\{V_R\} + (1.75)\{5W\}\{2P\} - (2.90)\{2U\}\{3R\} + (3.22)\,100\cos\theta\sin\phi$$

$$\{2V\} = (0.20)\int\{10\dot{V}\}\,dt$$

$$\{2\dot{s}_y\} = \{2V\} + (0.70)\tfrac{1}{100}\{2U\}\{2.5\psi\} - (0.4)\{5W\}\sin\phi$$

$$\{V_R\} = -(0.50)\{2V\} + (0.70)\tfrac{1}{100}\{W_x\}\{2.5\psi\} - \{W_y\}$$

FIG. C6 COMPUTER DIAGRAM FOR SIDEWAYS TRANSLATIONAL MOTION



EQUATIONS

$$\{4\dot{W}\} = -(0{\cdot}187)\{2W_R\} + (1{\cdot}288)\,100\cos\theta\cos\phi + (1{\cdot}40)\tfrac{1}{100}\{2U\}\{2{\cdot}5Q\} + (1{\cdot}748)\tfrac{1}{100}\{2V\}\{2P\} - (1{\cdot}578)\left\{\tfrac{2{\cdot}5T_E}{m}\right\}$$

$$\{5W\} = (0{\cdot}80)\int\{4\dot{W}\}\,dt$$

$$\{5\dot{S}_Z\} = \{5W\} - (2{\cdot}5)\{2U\}\sin\theta + (2{\cdot}5)\{2V\}\sin\phi$$

$$\{2\dot{W}_R\} = +\{2W_Z\} - (0{\cdot}20)\{W_x\}\sin\theta - (0{\cdot}4)\{5W\}$$

FIG. C7 COMPUTER DIAGRAM FOR VERTICAL TRANSLATIONAL MOTION

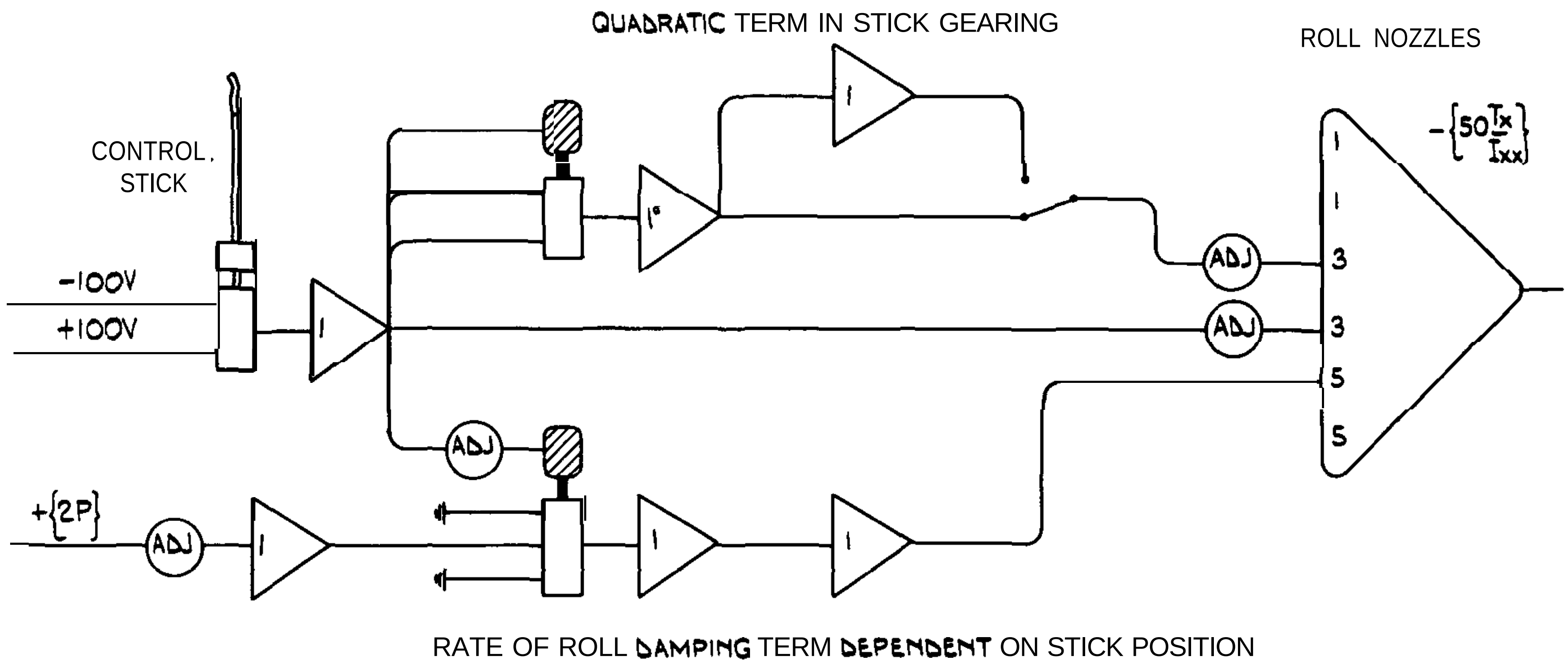


FIG. C8 MODIFICATIONS TO ROLL CONTROL COMPUTATION TO REPRESENT NON LINEAR STICK GEARING AND VARIABLE DAMPING

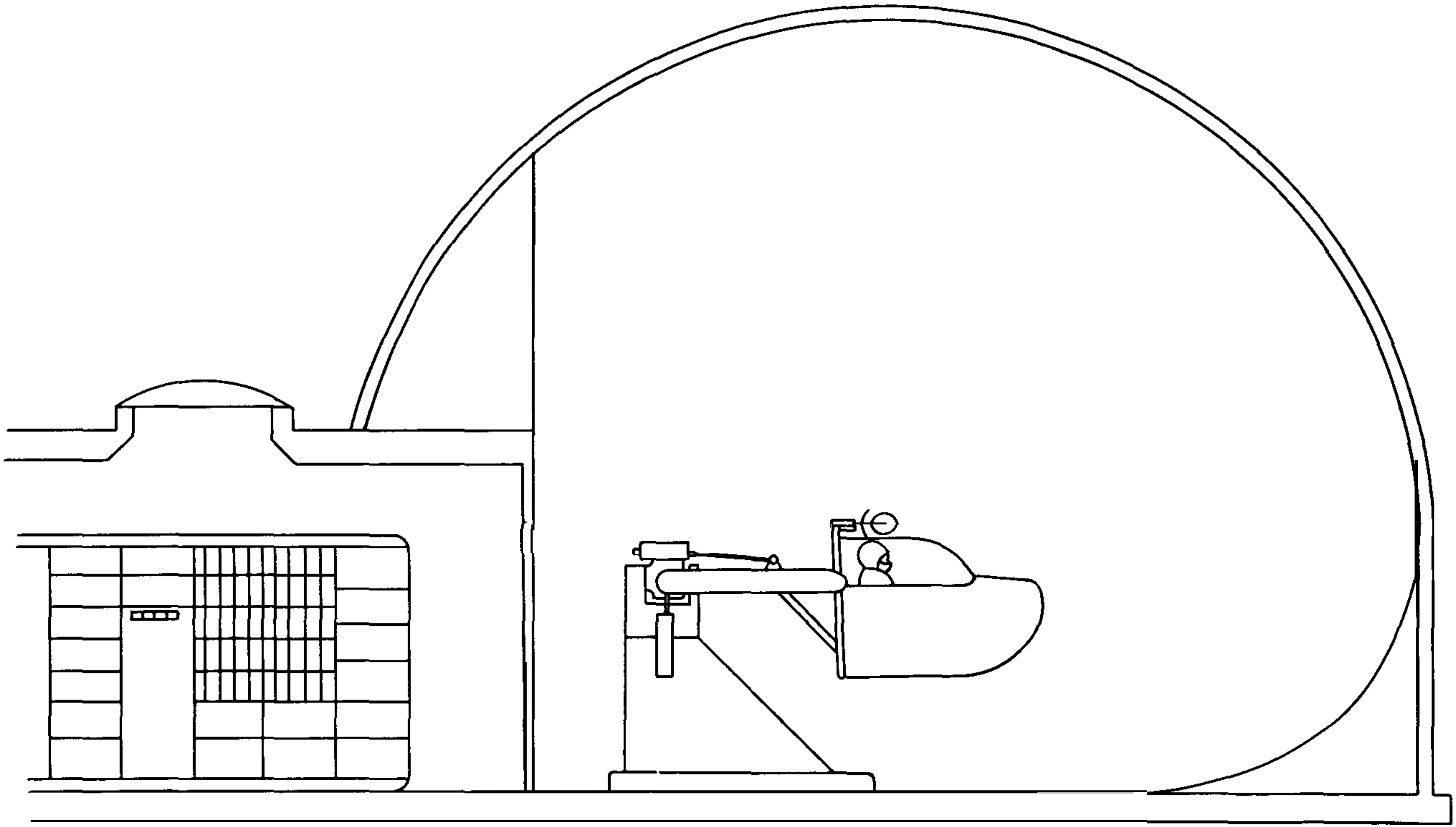
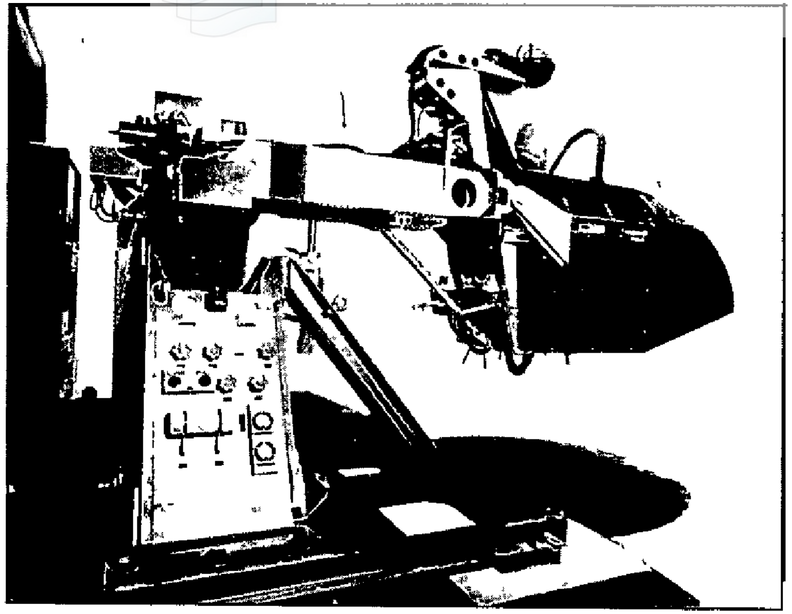
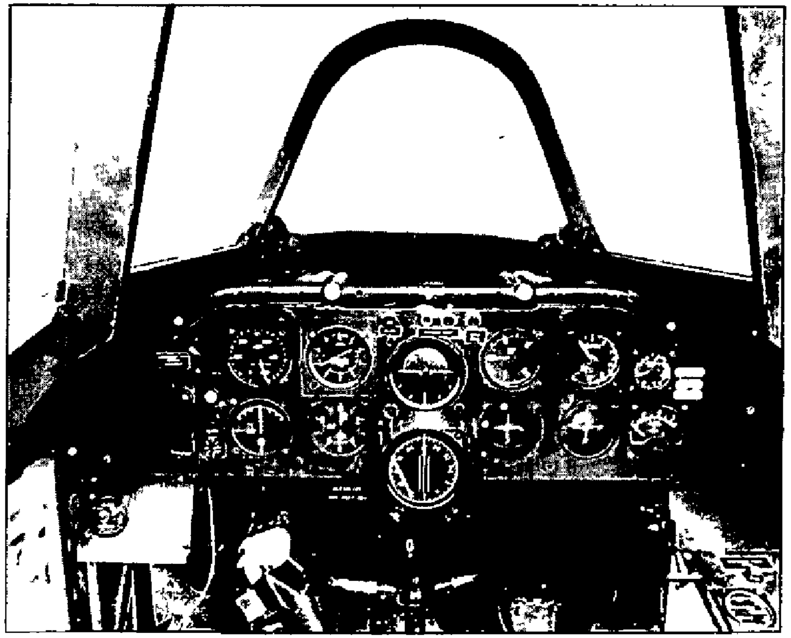


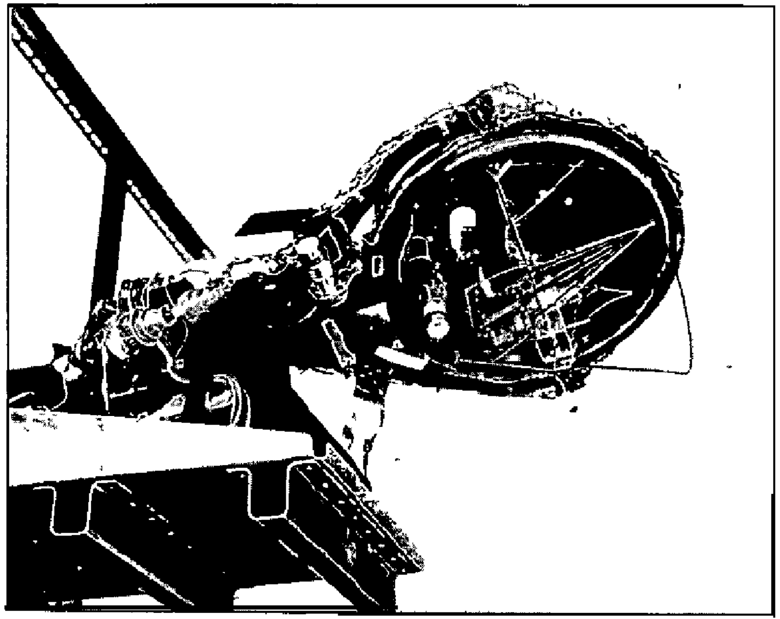
FIG.1. GENERAL LAYOUT OF THE SIMULATOR



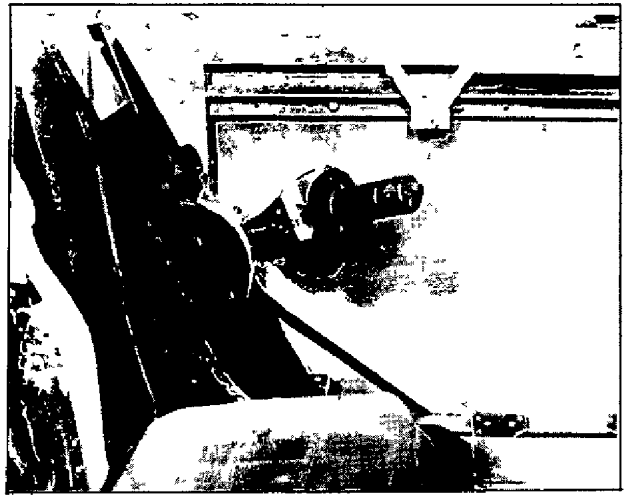
(a) Cockpit and moving mechanism



(b) Flight instrument panel



(c) Shadowgraph projector



(d) Lift engine throttle

Fig.2. Details of the simulation equipment

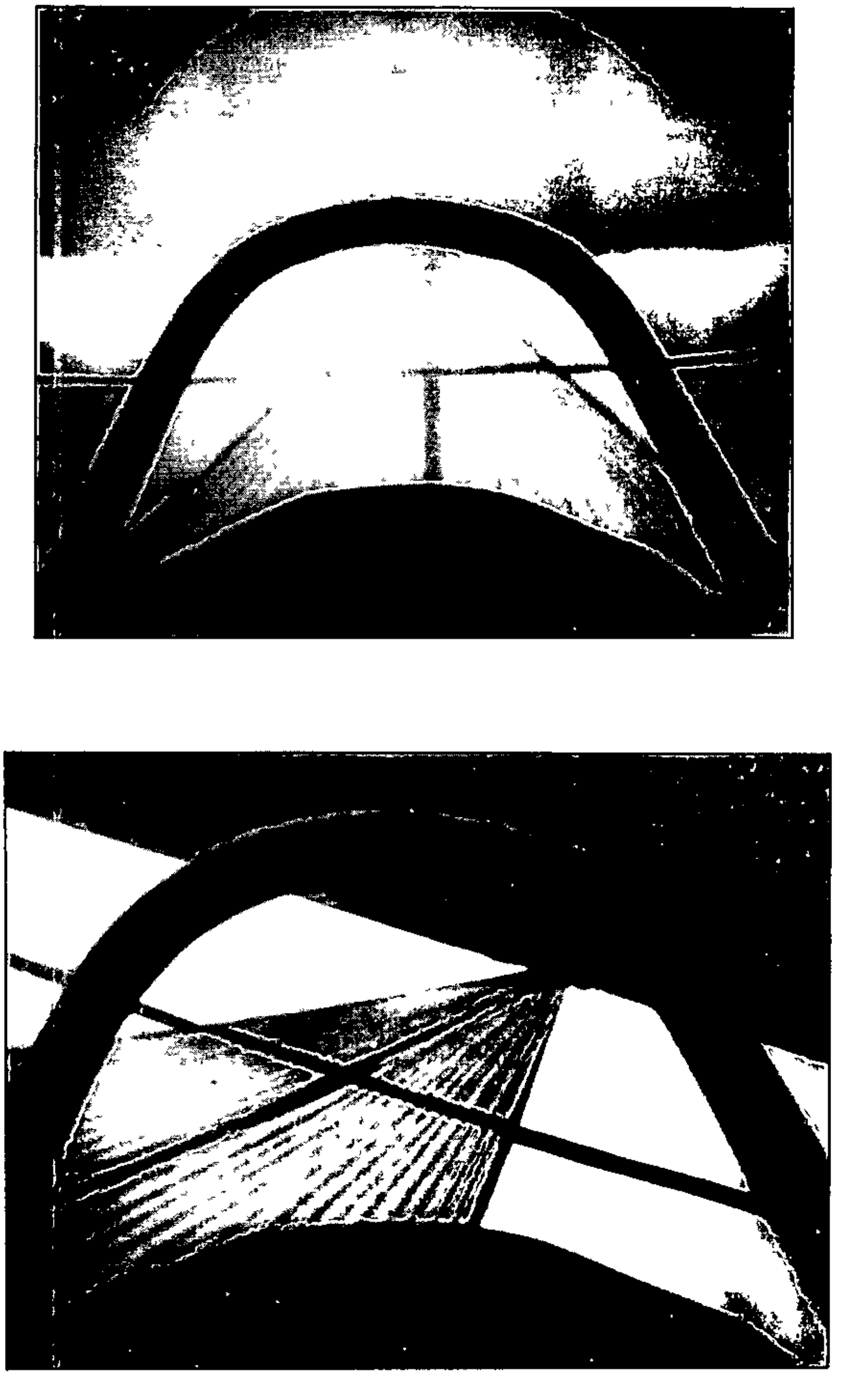


Fig.3. Two views of the simulator visual background as seen by the pilot

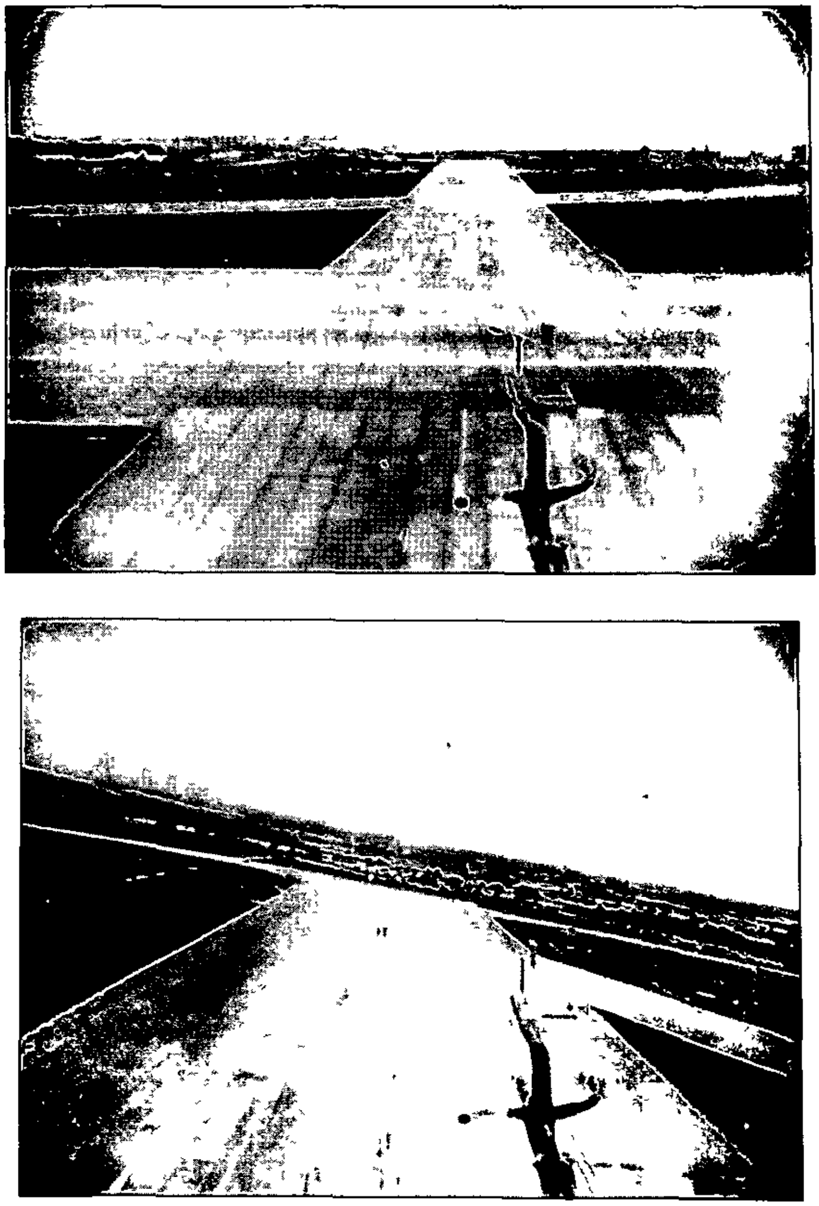


Fig.4. Two views of the runway taken by a camera attached to the S.C.1. aircraft

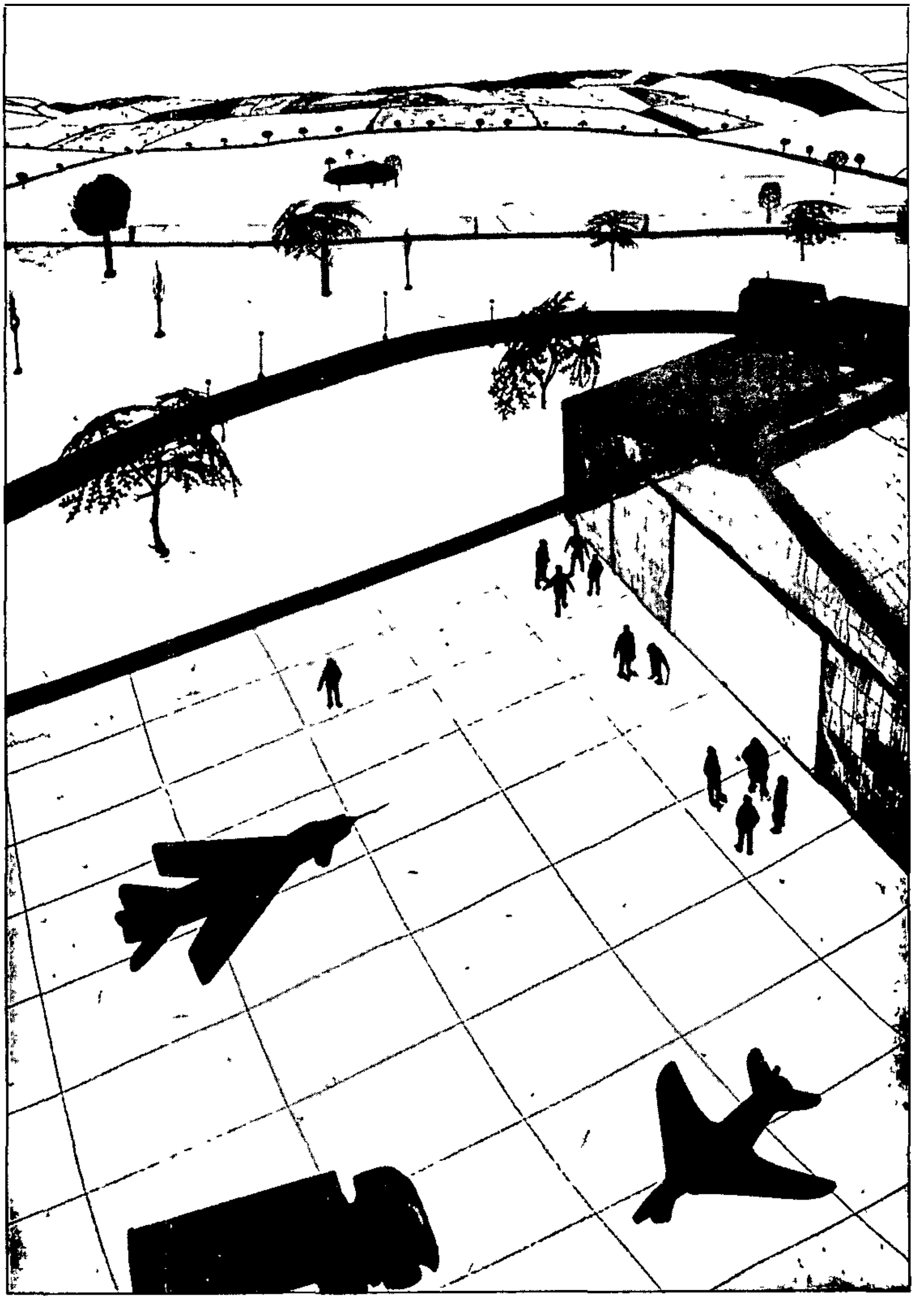
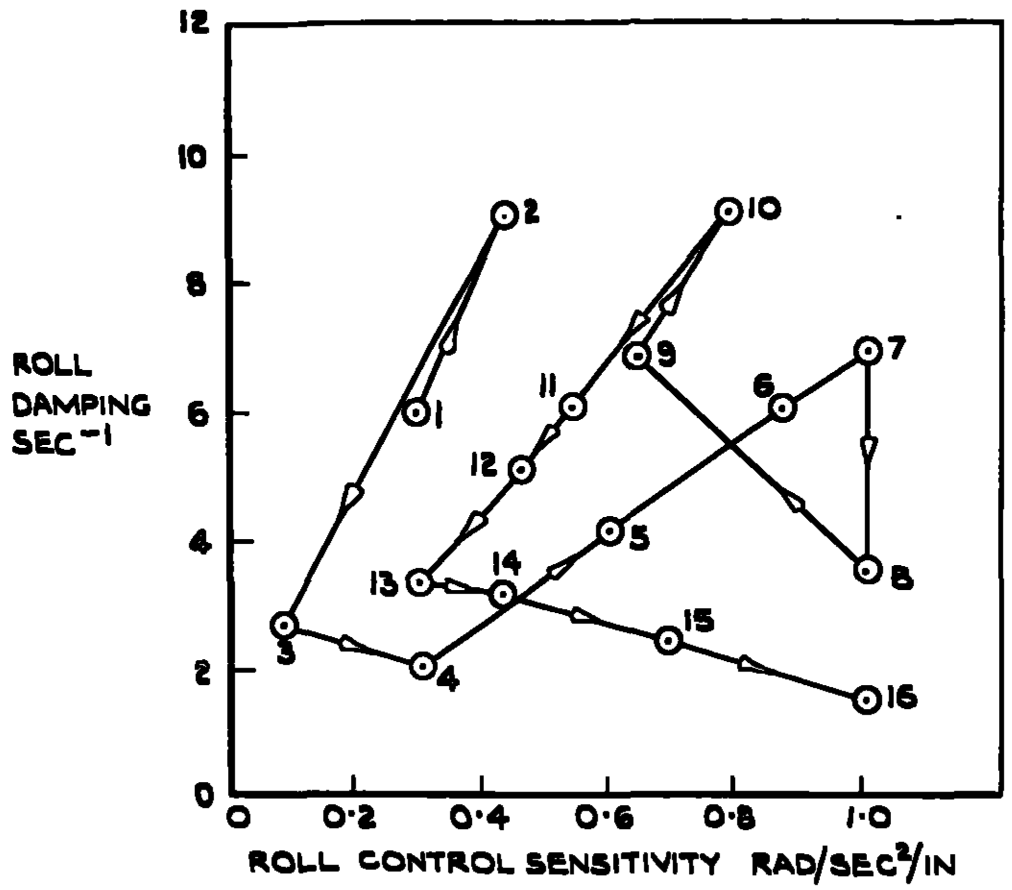


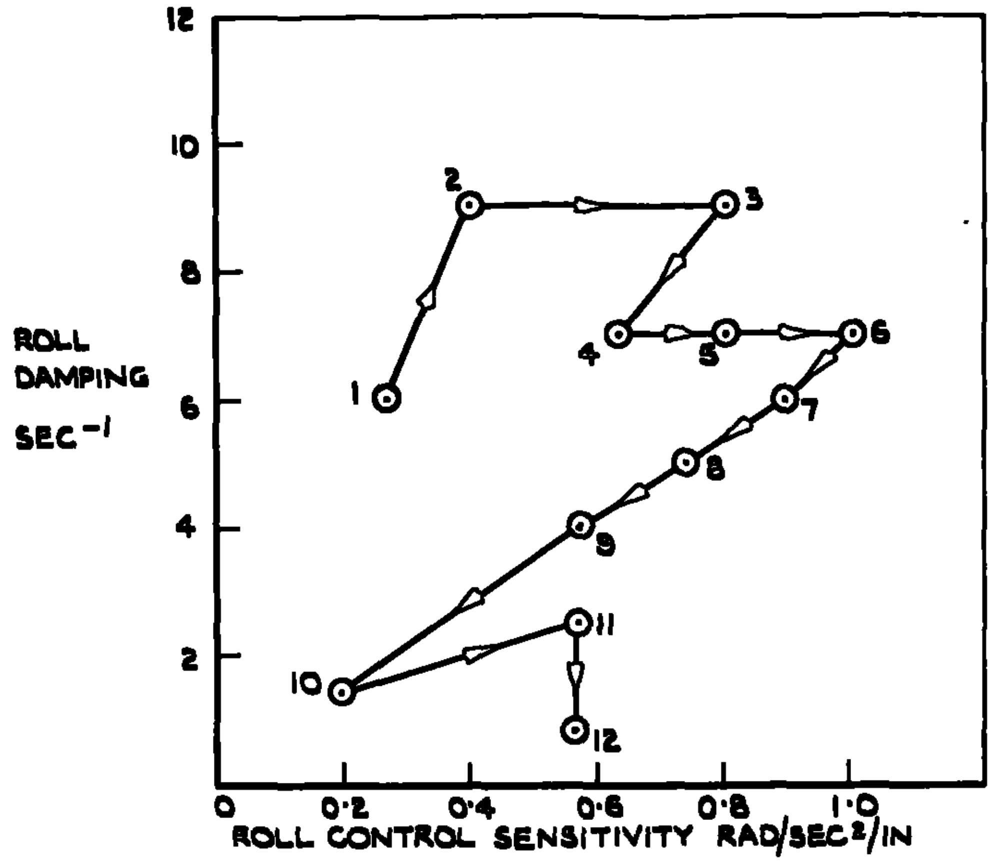
Fig.5. Type of visual simulation achieved with improved shadowgraph projector now being developed



CASE	SENS. RAD/SEC^2/IN	DAMPING SEC^{-1}	PILOT COMMENT.
1	0·29	5·9	
2	0·43	9·0	MORE SLUGGISH THAN 1. RATE OF ROLL NOT TOO BAD, BUT DIFFICULT TO STOP A LATERAL TRANSLATION PRECISELY, PARTICULARLY IN ROLLING WINGS LEVEL FAST ENOUGH AT THE END OF THE MANOEUVRE TO AVOID RESIDUAL SIDEWAYS VELOCITY
3	0·09	2·6	MUCH TOO SLUGGISH. USING FULL CONTROL TRAVEL ALL THE TIME BUT TAKES AGES TO ATTAIN A GIVEN BANK ANGLE. UNWILLING TO USE LARGE TRANSLATIONAL VELOCITIES BECAUSE OF DIFFICULTY IN STOPPING THEM QUICKLY
4	0·30	2·0	MUCH LIVELIER THAN 3. ATTITUDE CONTROL NOW QUITE COMFORTABLE. SOME STICK REVERSAL NEEDED TO STOP AT A CHOSEN ATTITUDE, OTHERWISE AN OVERSWING IN ATTITUDE OCCURS. QUICK AND PRECISE STOPS CAN BE MADE IN TRANSLATIONAL MANOEUVRES. NEVER NEEDED MORE THAN 2" OF STICK TRAVEL
5	0·60	4·1	VERY SIMILAR TO 4, PERHAPS SLIGHTLY BETTER ACCELERATION. LIKES THE WAY THE WINGS CAN BE LEVELLED RAPIDLY AT THE END OF A MANOEUVRE

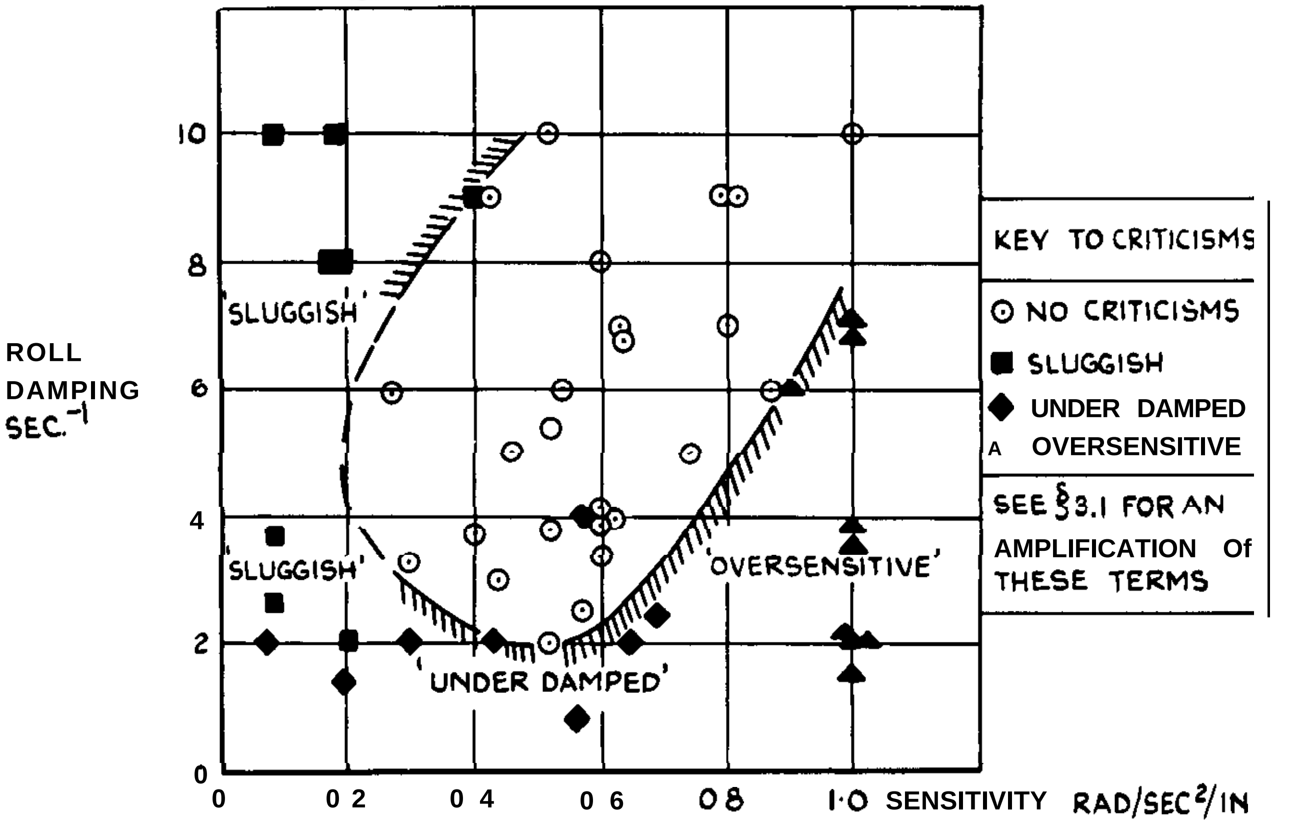
CASE	SENS RAD/SEC^2/IN	DAMPING SEC^{-1}	PILOT COMMENT
6	0·87	6·0	A GIVEN STICK DISPLACEMENT SEEMS TO PRODUCE A STEADY ROLL RATE ALMOST INSTANTANEOUSLY- THE TRANSIENT IS SCARCELY DETECTABLE. THIS IS THE SLIGHT DIFFERENCE BETWEEN THE LAST TWO CASES (5,6) AND THE PREVIOUS ONE (4), MAKING THEM SLIGHTLY PREFERABLE
7	1·0	6·9	THIS CONDITION SLIGHTLY WORSE THAN 5 AND 6. AIRCRAFT HAS RAPID RESPONSE NEEDING CONTINUOUS ATTENTION WHEN HOVERING
8	1·0	3·5	NOW VERY LIVELY. A VERY DELIBERATE STICK REVERSAL IS NEEDED TO PREVENT OVERSWING WHEN CHANGING BANK ANGLE. TRANSLATIONAL MANOEUVRES CAN BE STOPPED VERY PRECISELY BUT THERE IS A TENDENCY TO BUILD UP SMALL OVERCONTROLLING MOVEMENTS WHEN HOVERING
9	0·64	6·8	SEEMS VERY SLUGGISH, REMOVING ALL TENDENCY TO OVERCONTROLLING. TIME TO ACHIEVE A REQUIRED BANK ANGLE A BIT TOO LONG
10	0·79	9·0	DIFFICULT TO DETECT ANY DIFFERENCE BETWEEN THIS AND PREVIOUS CASE
11	0·54	6·0	AGAIN, VERY LITTLE DIFFERENCE. PERHAPS A SLIGHTLY MORE IMMEDIATE FEELING OF RESPONSE
12	0·46	5·0	NO DETECTABLE DIFFERENCE FROM PREVIOUS CASE
13	0·30	3·3	THIS FEELS DEFINITELY MORE SLUGGISH THAN THE PREVIOUS CASES. CONTROL AT THE HOVER IS STILL FINE, BUT THE TIME TAKEN TO CHANGE ATTITUDE MEANS THAT ANTICIPATION IS NEEDED IN CONTROLLING TRANSLATIONAL MOVEMENTS
14	0·44	3·0	INCREASED SENSITIVITY MAKES CONTROL OF LATERAL TRANSLATIONS EASIER. COMING BACK TOWARDS OPTIMUM AFTER PREVIOUS CASES. SLIGHT OVERCONTROLLING TENDENCIES AT THE HOVER
15	0·69	2·4	EXTREMELY RESPONSIVE, GETTING CLOSE TO BEING TOO SENSITIVE. DELIBERATE STICK REVERSAL NEEDED TO PREVENT OVERSWING IN ATTITUDE CHANGES. A DEGREE OF OVERCONTROLLING AT THE HOVER
16	1·0	1·5	CONTROLLABLE BUT UNDESIRABLE. CONTINUOUS LATERAL OVERCONTROLLING AND SEVERAL STICK MOVEMENTS NEEDED TO PHASE OUT ANY DISTURBANCE

FIG. 6 TEST DATA FROM ROLL CONTROL INVESTIGATION PILOT D

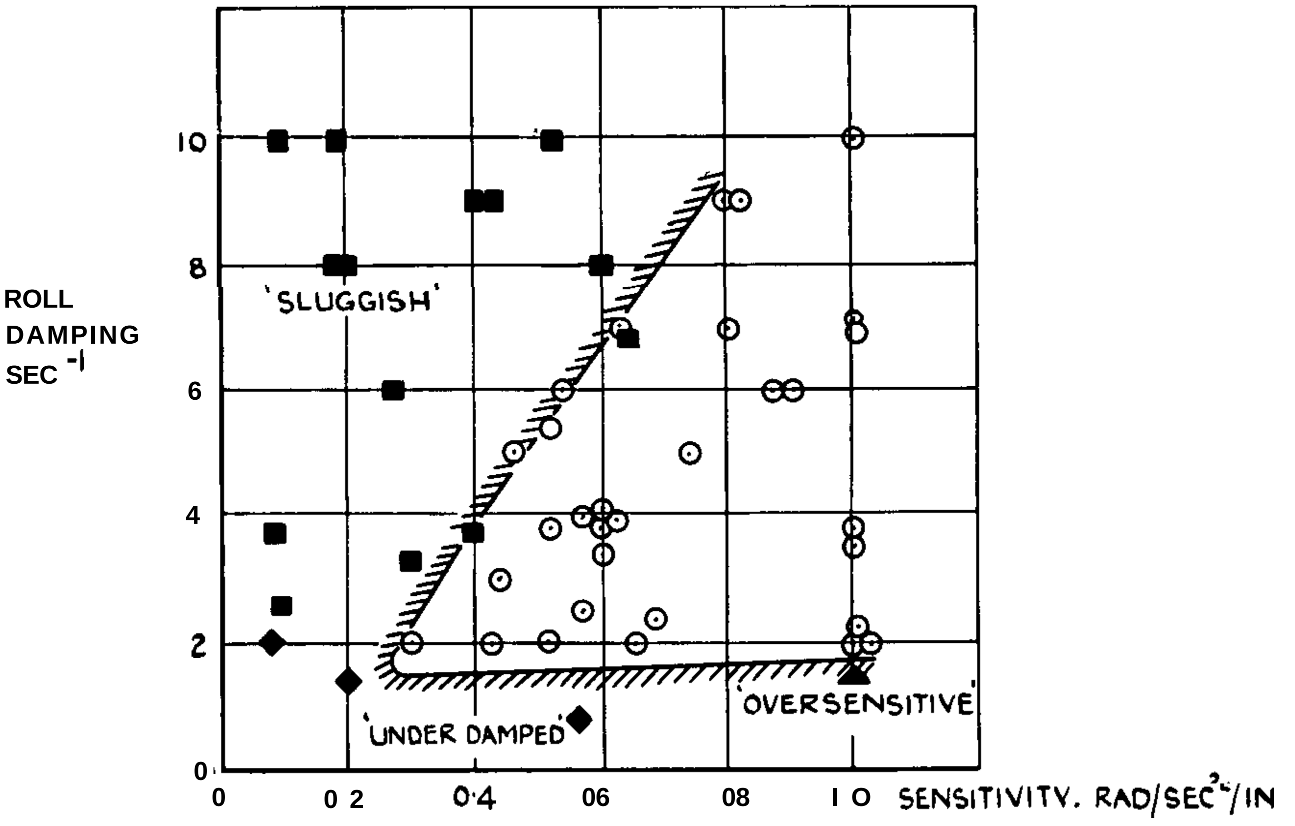


CASE	SENS RAD/SEC^2/IN	DAMPING SEC^{-1}	PILOT COMMENT
1	0·27	6	ROCK STEADY AT THE HOVER BUT NEEDING FULL CONTROL FOR MANOEUVERING AND WOULD LIKE THE ABILITY TO REVERSE BANK ANGLE A LOT MORE QUICKLY. TENDENCY TO OVERSHOOT ON LATERAL TRANSLATIONS BECAUSE OF TIME NEEDED TO APPLY BANK AND REMOVE IT. RESPONSE IN HOVER O.K. PROVIDED ONLY SMALL MOVEMENTS ARE NEEDED
2	0·40	9	CANNOT NOW CONTROL ATTITUDE QUICKLY ENOUGH TO AVOID SLOW TRANSLATIONAL WANDERING AT THE HOVER. INABILITY TO ROLL RAPIDLY AT THE END OF A TRANSLATION RESTRICTS THE MANOEUVRES ONE IS PREPARED TO MAKE. TENDING TO USE SMALLER BANK ANGLES AND SLOWER MANOEUVRES
3	0·80	9	A BIG DIFFERENCE OVER PREVIOUS CONFIGURATION. AIRCRAFT VERY MUCH LIVELIER. CAN MAKE ALL THE ATTITUDE CHANGES NEEDED FOR HOVERING WITH ONLY SMALL STICK MOVEMENTS. IN MANOEUVERING, FEELS VERY MUCH IN CHARGE OF THE AIRCRAFT AND CAN ADJUST ATTITUDE PRECISELY AT EACH STAGE AS THE MANOEUVRE PROGRESSES. POSSIBLE SLIGHT TENDENCY TO OVERCONTROL IF VERY LARGE CONTROL MOVEMENTS ARE MADE
4	0·63	7	NO GREAT DIFFERENCE FROM PREVIOUS CONDITION. NOT QUITE AS LIVELY. LIKES IT SLIGHTLY BETTER THAN THE LAST CONDITION BECAUSE CONTROL IS STILL CRISP BUT WITHOUT THE TENDENCY TO OVERCONTROL
5	0·80	7	AGAIN NO GREAT CHANGE FROM PREVIOUS CONDITIONS BUT NOT SO TIDY AT THE HOVER BECAUSE OF SLIGHT OVERCONTROLLING TENDENCY. GOOD AUTHORITY FOR MANOEUVERING
6	1·0	7	FURTHER DEGRADATION IN STEADINESS AT THE HOVER WHICH FEELS LIKE A REDUCTION IN DAMPING. RESPONSE FOR MANOEUVERING GOOD, NEEDING ONLY AN INCH OR SO OF STICK TRAVEL
7	0·9	6	LITTLE CHANGE FROM PREVIOUS CONDITION
8	0·74	5	AN IMPROVEMENT OVER THE PREVIOUS TWO CONDITIONS BECAUSE THERE IS STILL PLENTY OF AUTHORITY FOR MANOEUVERING BUT CONTROL IS TIDIER AT THE HOVER. USING ABOUT HALF THE AVAILABLE STICK TRAVEL FOR MANOEUVERS — THIS IS NOT EXCESSIVE AND THERE IS LESS TENDENCY TO OVERCONTROL AT THE END OF A TRANSLATION
9	0·57	4	SLIGHTLY MORE CONCENTRATION NEEDED TO MAINTAIN THE SAME ACCURACY AT THE HOVER, VERY REASONABLE FOR MANOEUVERING AND CONFIDENT THAT HE CAN MAKE SMALL DISPLACEMENT CORRECTIONS EASILY
10	0·2	1·4	A BAD CONDITION. ANTICIPATION WHEN CHANGING ATTITUDE IS NEEDED TO AVOID OVER ROLLING. HAVE TO DO THINGS SLOWLY AND AVOID LARGE BANK ANGLES
11	0·57	2·5	MUCH PREFERABLE TO PREVIOUS CONDITION. CAN NOW CONTROL SMALL TRANSATIONAL MOVEMENTS CONFIDENTLY
12	0·57	0·8	NOW TOO LITTLE DAMPING. EASY TO GET INTO AN OVERCONTROLLING TENDENCY NEEDING SEVERAL CYCLES TO DAMP OUT

FIG.7 TEST DATA FROM ROLL CONTROL INVESTIGATION PILOT A



(a) HOVERING OVER A GIVEN POSITION



(b) SIDEWAYS TRANSLATIONAL MANEOUVRE

FIG 8 PILOTS CRITICISMS OF ROLL CONTROL CHARACTERISTICS DURING HOVERING AND SIDEWAYS TRANSLATIONS

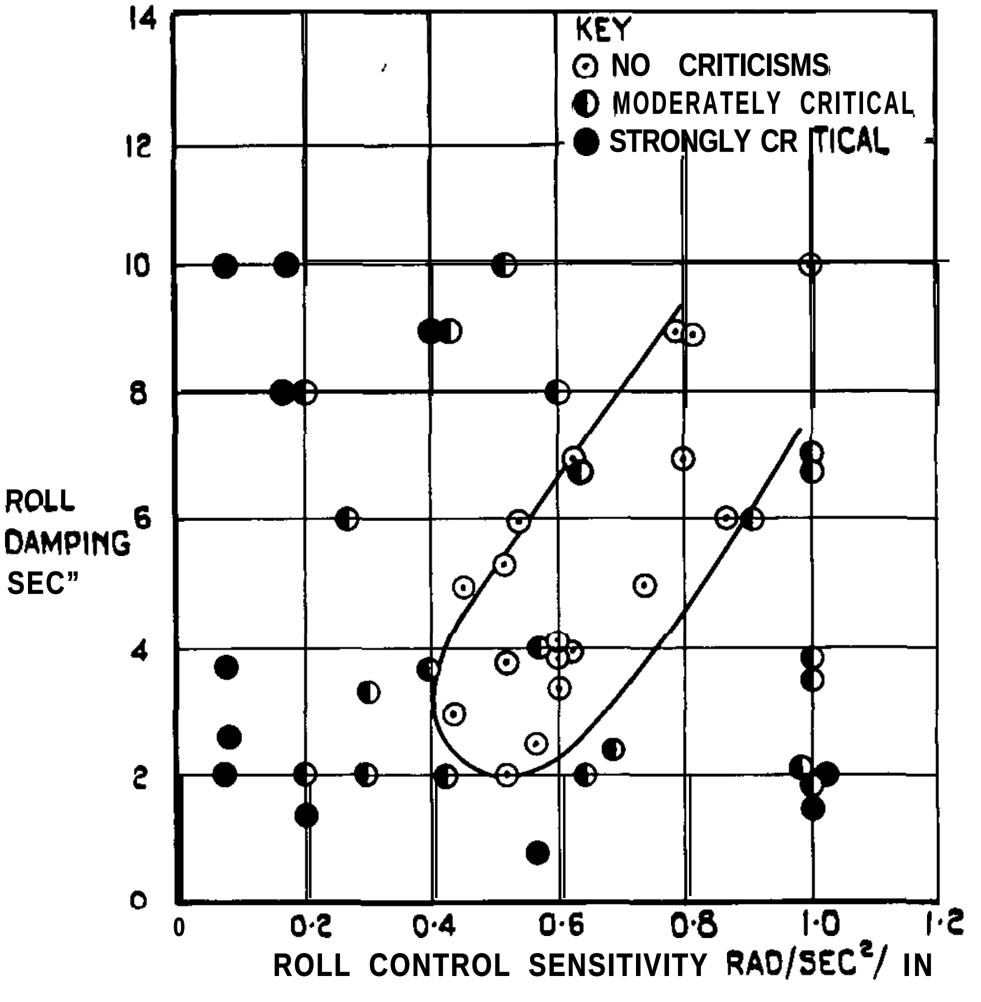


FIG. 9. ROLL CONTROL CHARACTERISTICS WHICH WERE FREE FROM CRITICISM FOR BOTH HOVERING AND MANOEUVERING. (FROM DATA IN FIGS. 8a AND 8b)

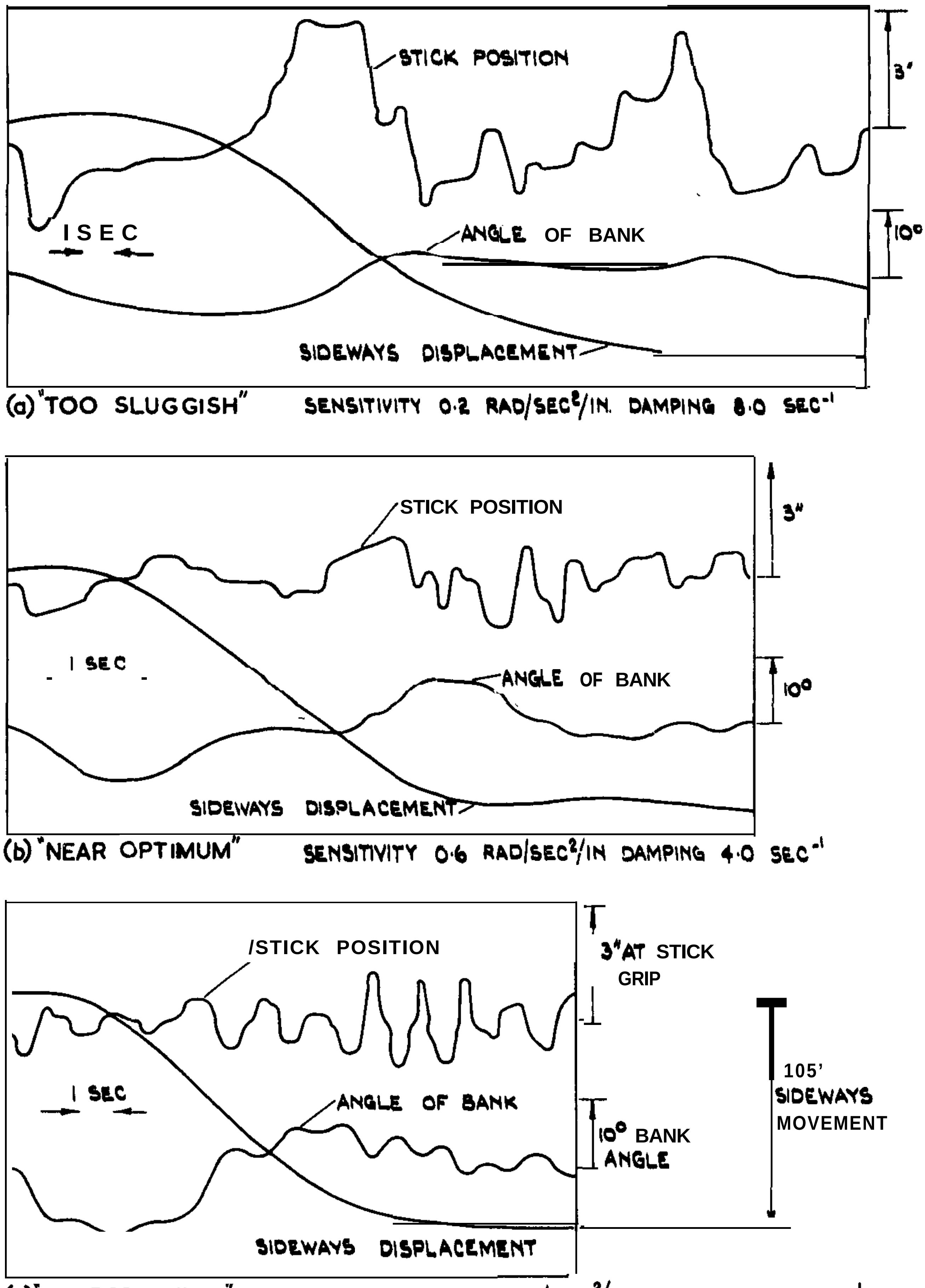
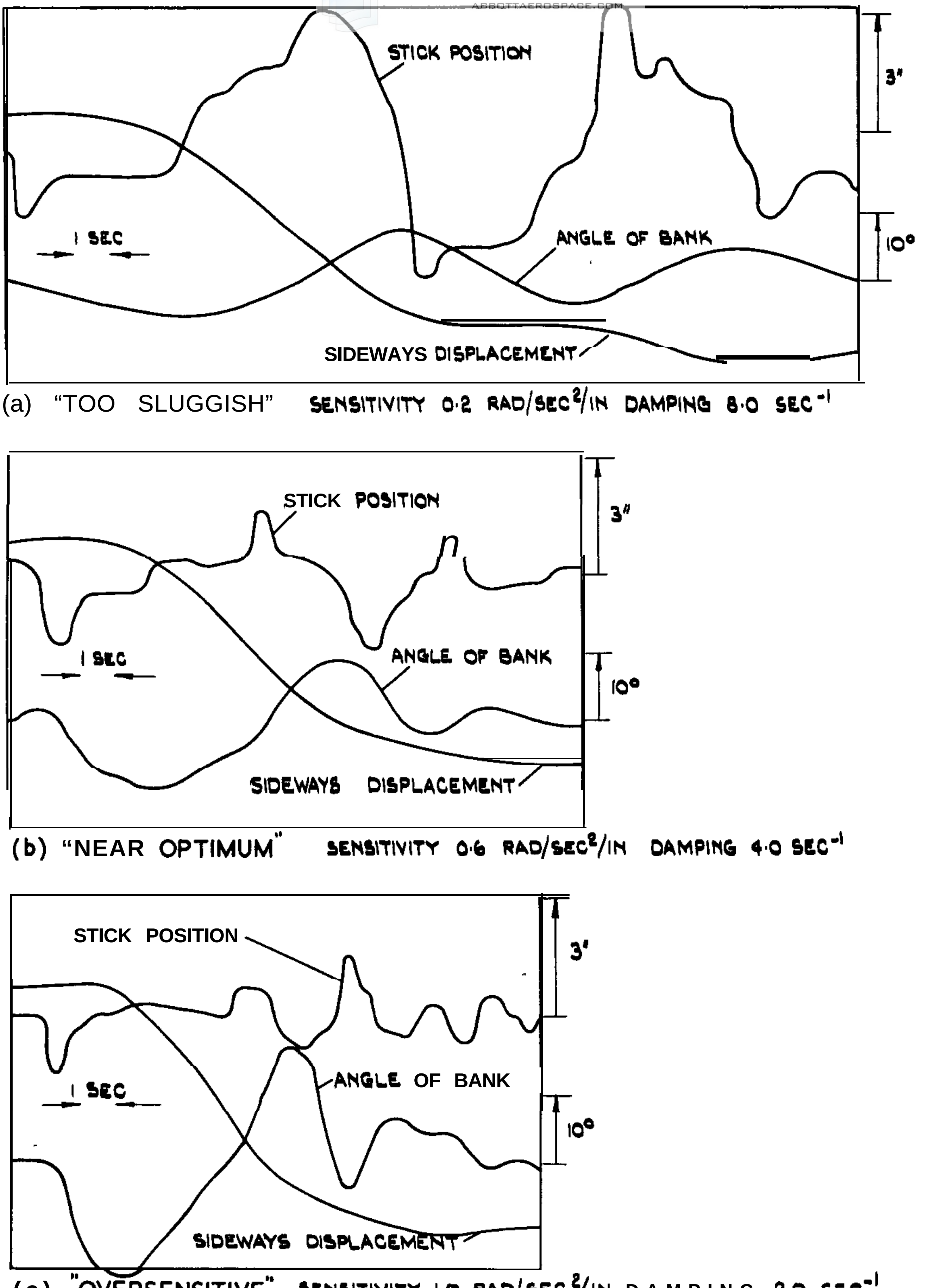


FIG. 10. TIME HISTORIES OF SIDEWAYS TRANSLATIONAL MANEOUVRES WITH DIFFERENT ROLL CONTROL CHARACTERISTICS PILOT D



(a) "TOO SLUGGISH" SENSITIVITY 0·2 RAD/SEC^2/IN DAMPING 8·0 SEC^{-1}

(b) "NEAR OPTIMUM" SENSITIVITY 0·6 RAD/SEC^2/IN DAMPING 4·0 SEC^{-1}

(c) "OVERSENSITIVE" SENSITIVITY 1·0 RAD/SEC^2/IN DAMPING 2·0 SEC^{-1}

FIG. II 'TIME HISTORIES OF SIDEWAYS TRANSLATIONAL MANOEUVRES WITH DIFFERENT ROLL CONTROL . CHARACTERISTICS PILOT B

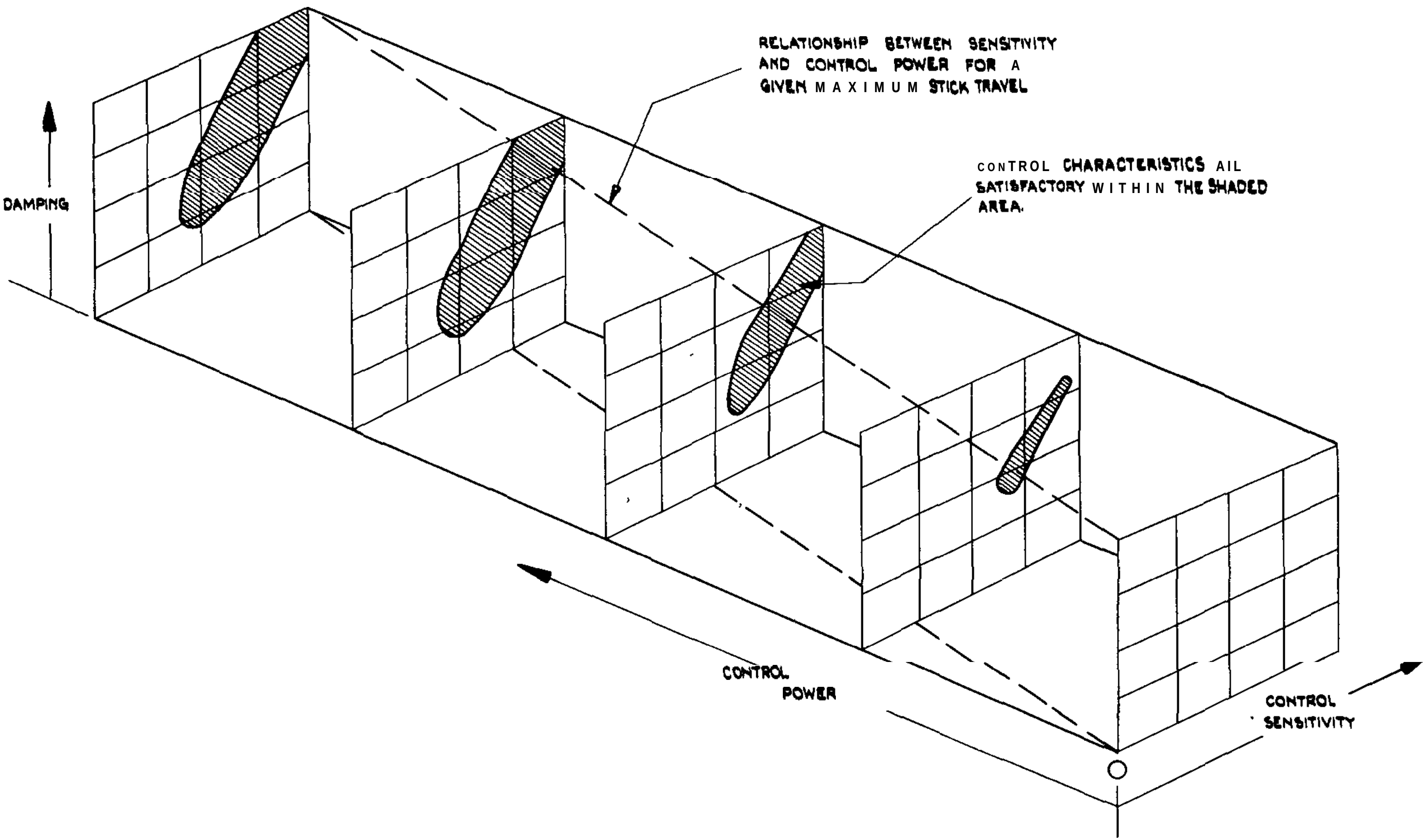


FIG.12 A HYPOTHETICAL MODEL OF THE RELATIONSHIP BETWEEN CONTROL POWER, CONTROL SENSITIVITY AND DAMPING FOR SATISFACTORY CONTROL CHARACTERISTICS

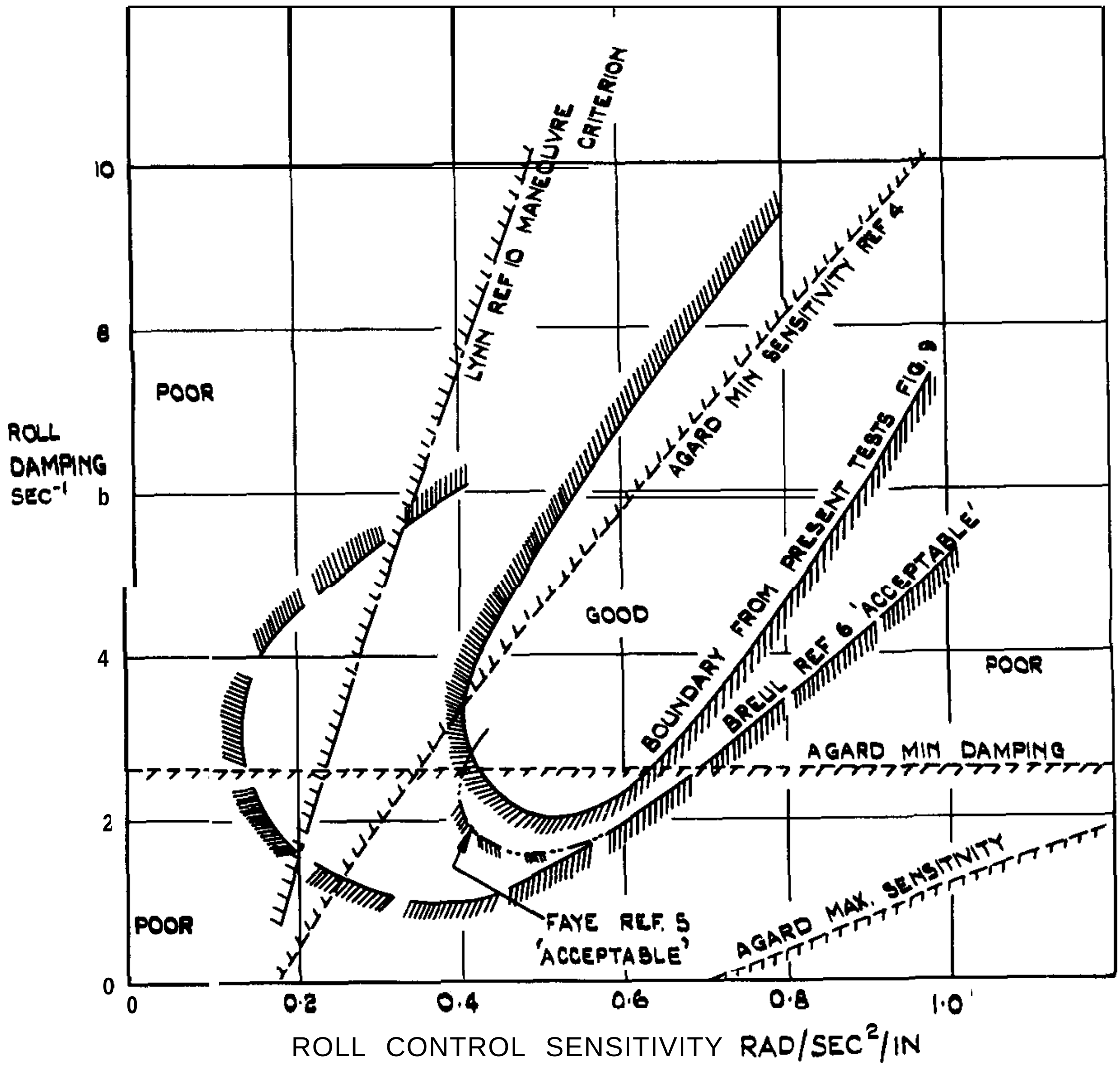


FIG.13. COMPARISON OF VARIOUS ROLL CONTROL CRITERIA AND TEST RESULTS. DAMPING AND CONTROL SENSITIVITY AS PARAMETERS

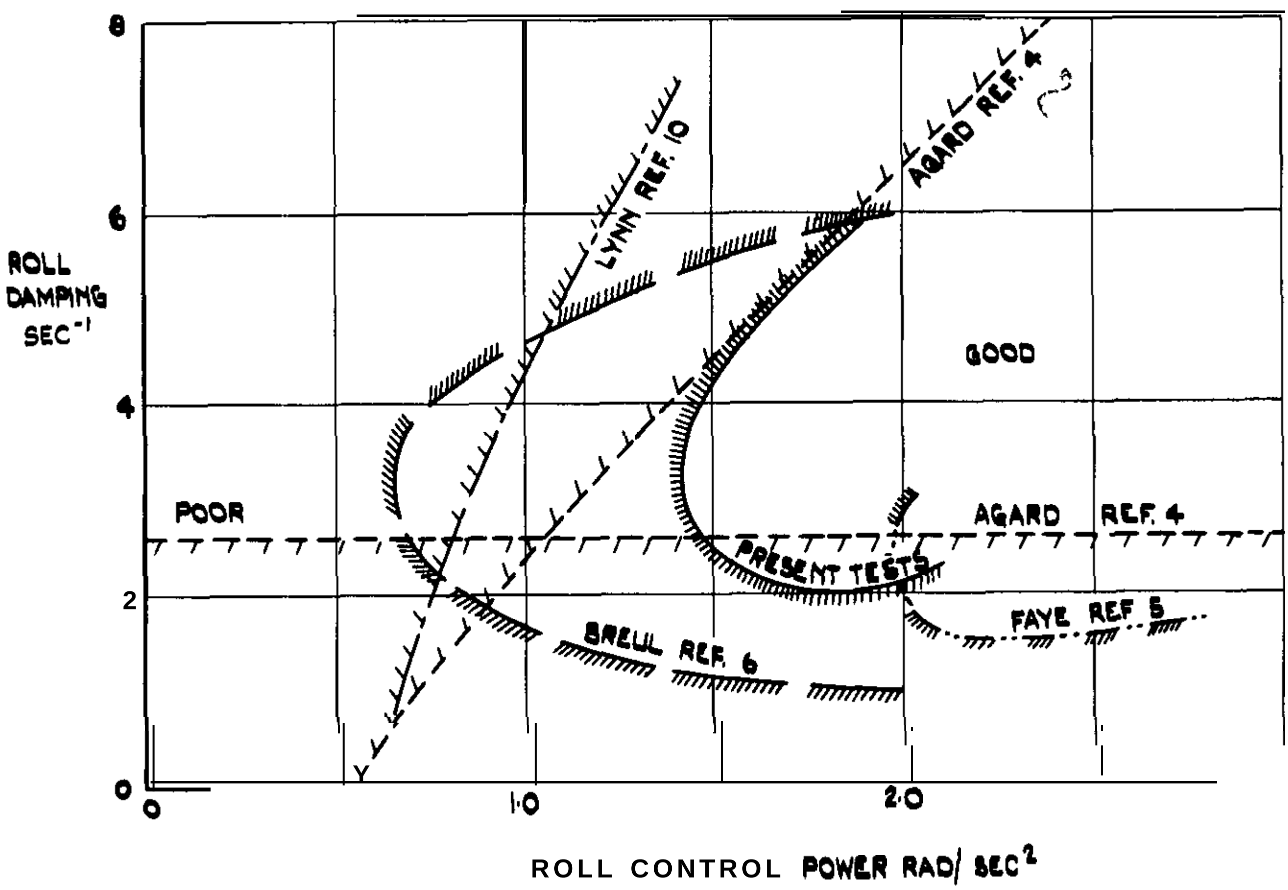
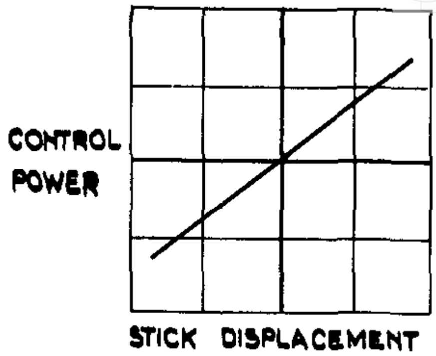
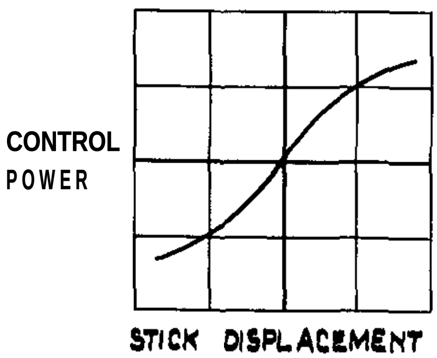


FIG 14 COMPARISON OF VARIOUS ROLL CONTROL CRITERIA AND TEST RESULTS. DAMPING AND CONTROL POWER AS PARAMETERS



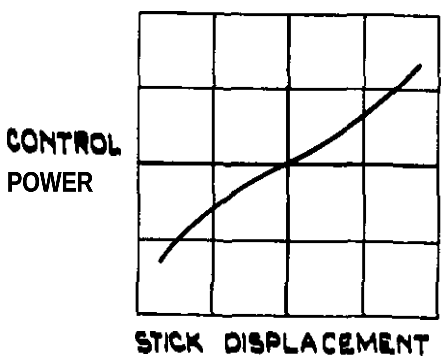
(a) LINEAR CONTROL GEARING.

STICK THROW ± 3½″
MAX. CONTROL POWER 1·3 RAD/SEC^2
CONTROL SENSITIVITY 0·37 RAD/SEC^2/IN.



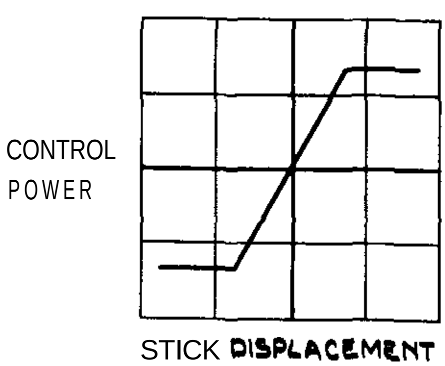
(b) NON LINEAR CONTROL GEARING (QUADRATIC LAW)

STICK THROW ± 3½″
MAX. CONTROL POWER 1·3 RAD/SEC^2
CONTROL SENSITIVITY FOR STICK NEUTRAL
0·75 RAD/SEC^2/IN



(c) NON LINEAR CONTROL GEARING (QUADRATIC LAW)

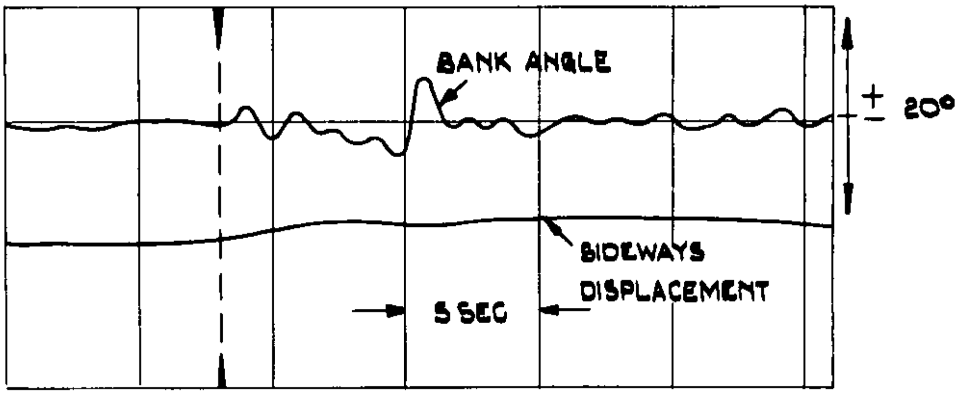
WICK THROW ± 3½″
MAX. CONTROL POWER 1·3 RAD/SEC^2
CONTROL SENSITIVITY FOR STICK NEUTRAL
0·19 RAD/SEC^2/IN



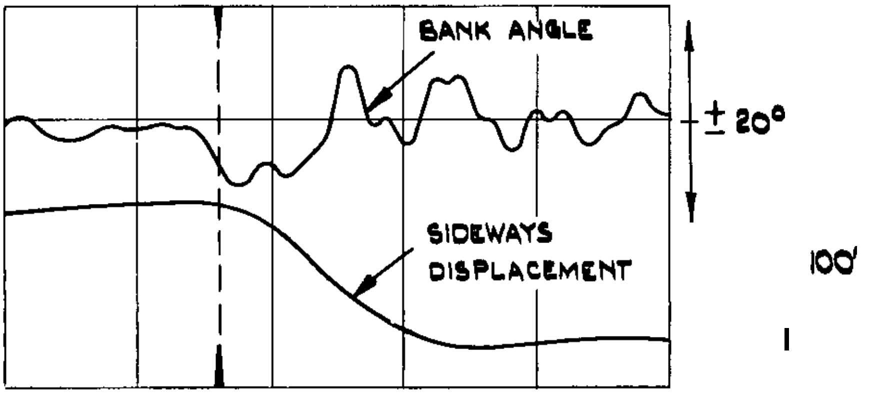
(d) SATURATION TYPE GEARING

STICK THROW ± 3½″
MAX. CONTROL POWER 1·3 RAD/SEC^2
CONTROL SENSITIVITY
0·86 RAD/SEC^2/IN FOR FIRST 1½″ OF STICK TRAVEL ZERO FOR LARGER MOVEMENTS.

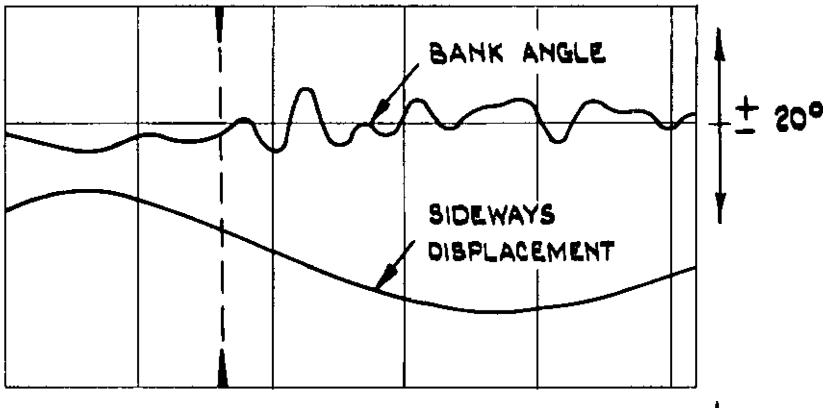
FIG.15 NON-LINEAR ROLL CONTROL GEARINGS TESTED



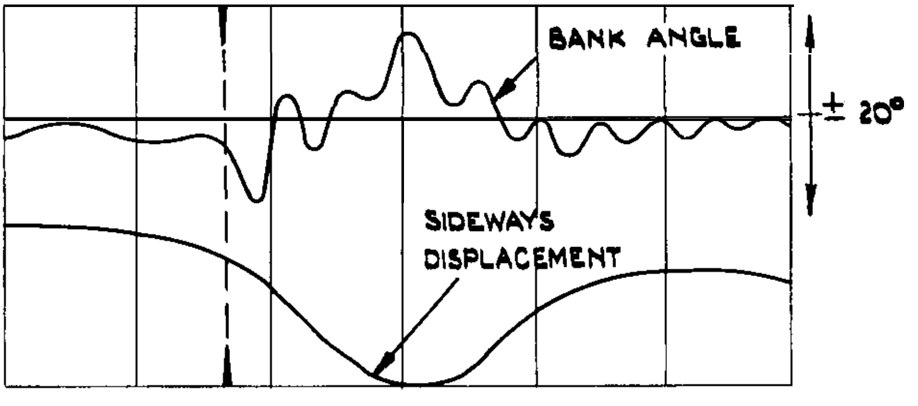
(a) FAILURE DURING HOVER REDUCING DAMPING SUDDENLY TO ZERO



(b) FAILURE AT THE START OF A SIDEWAYS TRANSLATION REDUCING DAMPING TO ZERO



(c) MALFUNCTION REDUCING DAMPING TO ZERO AND NEEDING 12½% CONTROL TO TRIM



(d) MALFUNCTION REDUCING DAMPING TO ZERO AND NEEDING 25% CONTROL TO TRIM

FIG 16 TIME HISTORIES OF AIRCRAFT BEHAVIOUR FOLLOWING VARIOUS FAILURES OF THE ROLL AUTOSTABILISER DURING PILOTED SIMULATION

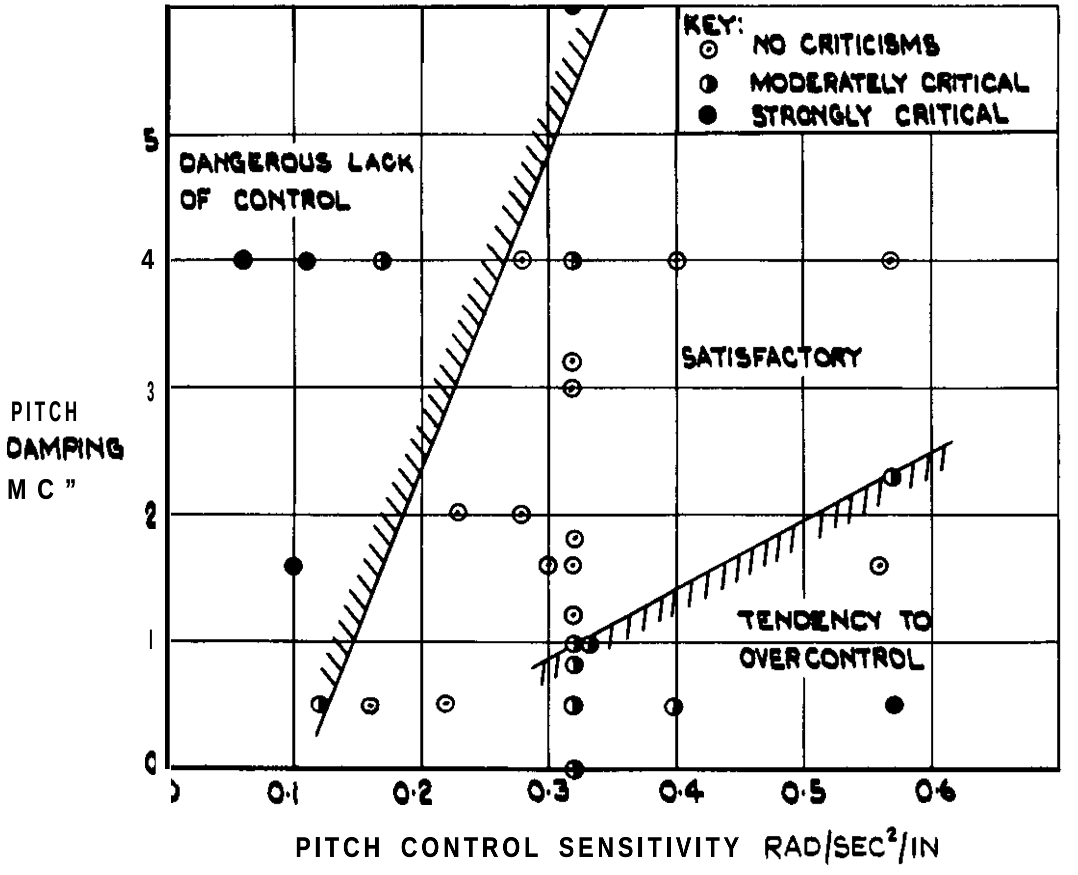


FIG. 17 PITCH CONTROL CHARACTERISTICS WHICH WERE FREE FROM CRITICISM

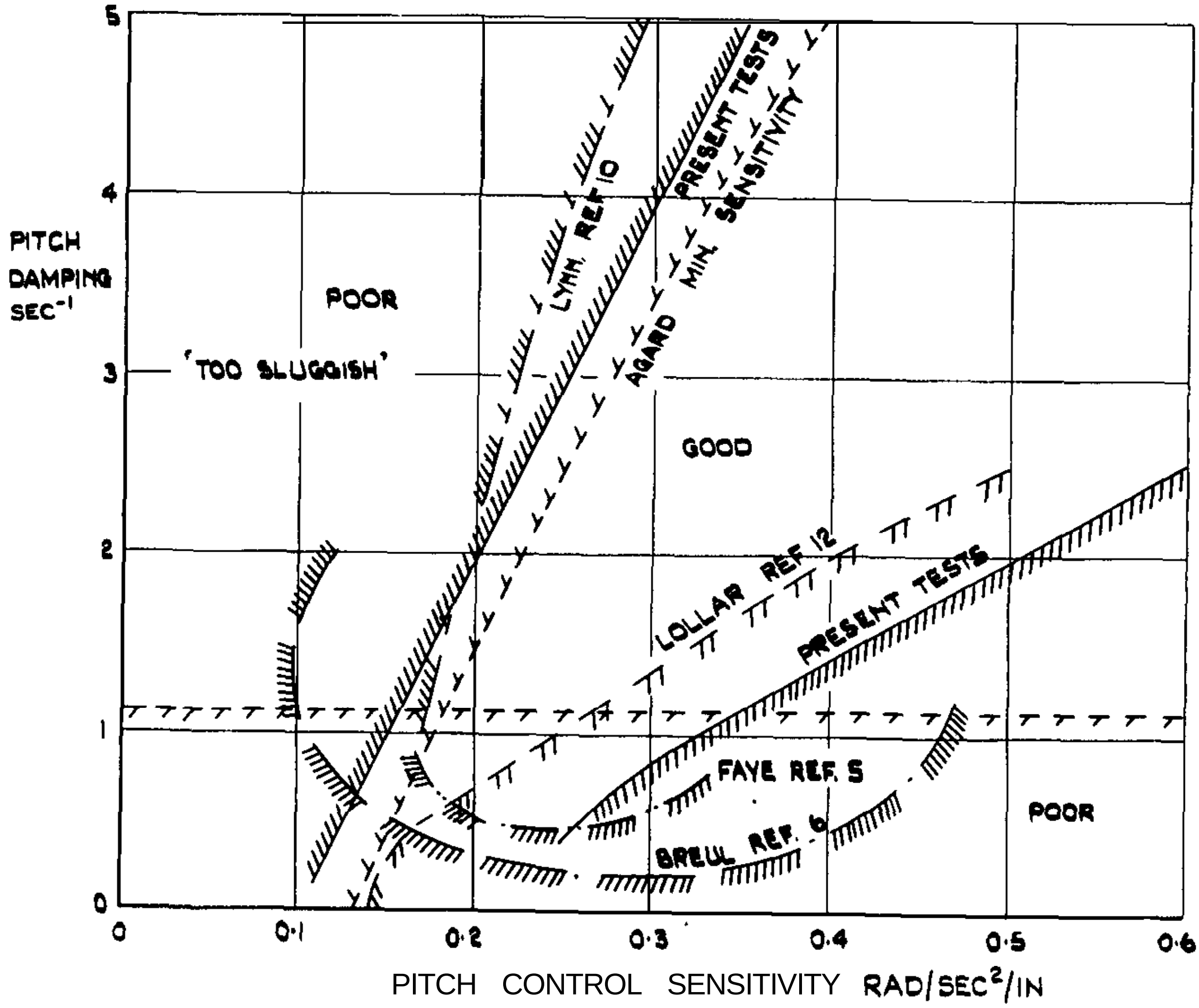


FIG 18 COMPARISON OF VARIOUS PITCH CONTROL CRITERIA AND TEST RESULTS. DAMPING AND CONTROL SENSITIVITY AS PARAMETERS

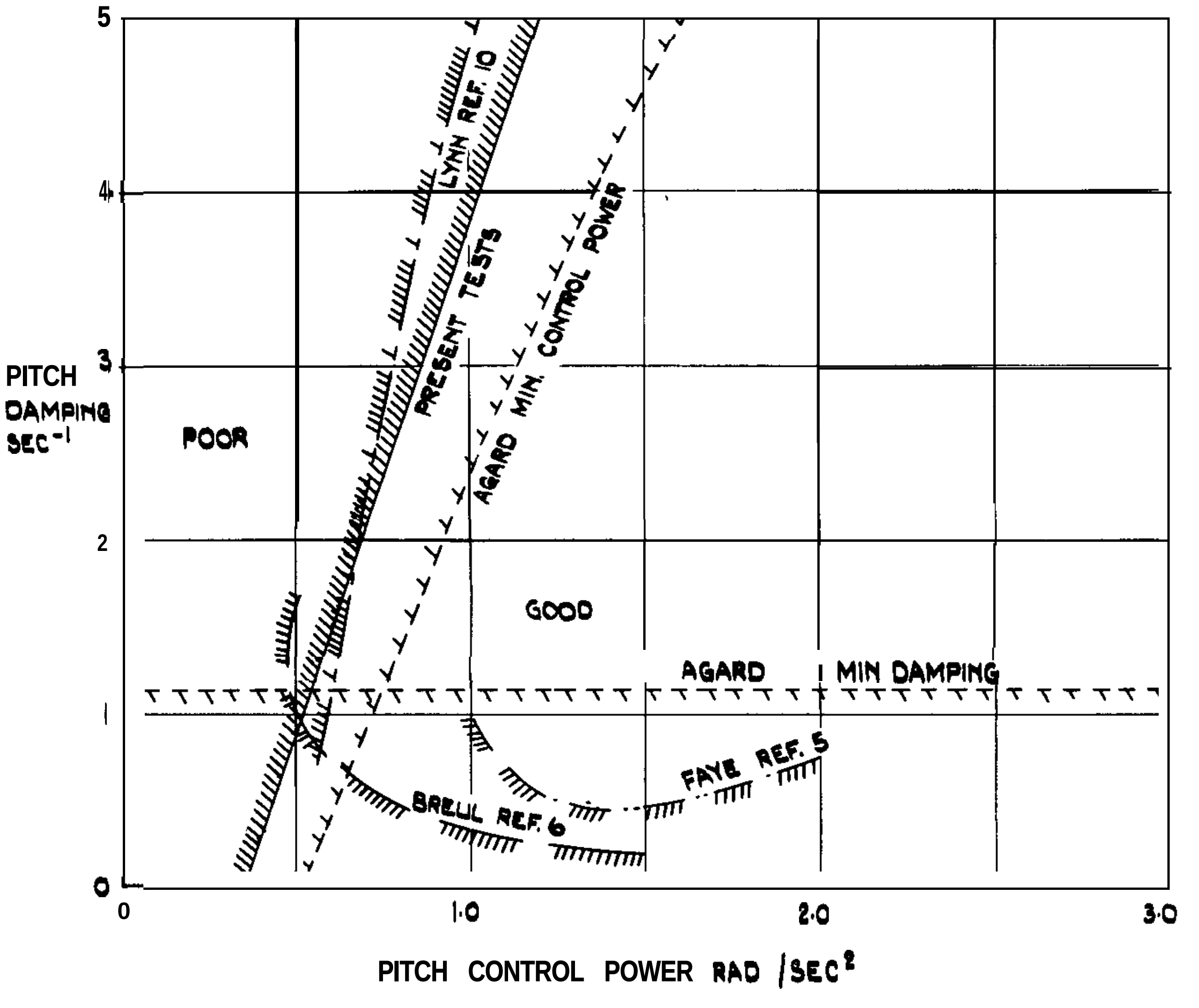


FIG.19 COMPARISON OF VARIOUS CRITERIA AND TEST RESULTS FOR PITCH CONTROL POWER

Printed in England for Her Majesty's Stationery Office by
the Royal Aircraft Establishment, Farnborough. Dd.125875.X.Y.

A.R.C. C.P. NO.902
June 1965
Perry, D. H.
Chinn, H. w.

5.001.58 :
629.136-118 :
629.13.014.6 :
533.6.013.67

A PRELIMINARY FLIGHT SIMULATION STUDY OF JET-BORNE V.T.O.L. AIRCRAFT HANDLING QUALITIES

A pIloted flight simulator, having cockpit motion In pitch and roll. together dth a simplified visual representation of the outside world, has been used to study attitude cmtml requirements for jet-borne V.T.O.L. aircraft in hovering f light and low speed manoeuvring. Values of control effectiveness and aircraft rate damping which were found to give satisfactory control characteristics in roll and pitch are presented and compared with the results of previous studies and with V.T.O.L. control criteria. Brief studies of some non linear control gearings, and tests or pilots' cmtml following autostabiliser failure, are also reported.

A.R.C. C.P. No.902
June 1965

Perry, D. H.
Chinn, H. w.

5.001.58 :
629.136-118 :
629.13.014.6
533.6.013.67

A PRELIMINARY FLIGHT SIMULATION STUDY CF JET-BORNE V.T.O.L. AIRCRAFT HANDLING QUALITIES

A pIloted flight simulator, having cockpit motion in pitch and roll, together with a simplified visual representation Of the outside world, has been used to study attitude control requirements for jet-borne V.T.O.L. aircraft lo hovering flight and low speed manoeuvring. Values of control effectiveness and aircraft rate damping which were found to give satisfactory control characteristics in roll and pitch are presented and compared with the results of previous Studies and with V.T.O.L. control crlterla. Brief studies of some non linear control gearings, sod tests of pilots' control following autostabiliser failure, are also reported.

A.R.C. C.P. No.902
June 1965

Perry, D. H.
Chinn, H. W.

5.001.58 :
629.136-118 :
629.13.014.6 :
533.6.013.67 .

A PRELIMINARY FLIGHT SIMULATION STUDY OF JET-BORNE V.T.O.L. AIRCRAFT HANDLING QUALITIES

A pIloted flight simulator, having cockpit motion in pitch and mll. together with a simplified visual representation of the outside world. has been used to study attitude control requirements for let-home V.T.O.L. aircraft in hovering flight and low speed manoeuvring. Values of control effectiveness and aircraft rate damping which were found to give satisfactory cmtml characteristics in roll and pitch are presented and compared with the results of previous studies and with V.T.O.L. control criteria. Brief studies of some non linear control gearings, and tests of pilots' cmtml following autostabiliser failure, are also reported.

DETACHABLE ABSTRACT CARDS

C.P. No. 902

Published by
HER MAJESTY'S STATIONERY OFFICE

To be purchased from
49 High Holborn, London w c 1
423 Oxford Street. London w 1
13A Castle Street. Edinburgh 2
109 St Mary Street. Cardiff
Brazennose Street, Manchester 2
50 Fan-fax Street, Bristol 1
35 Smallbrook, Ringway, Birmingham 5
80 Chichester Street. Belfast 1
or through any bookseller

C.P. No. 902

S.O. CODE No. 23-9017-2