ICAS Paper No. 70–41

FLIGHT SIMULATION AS A DESIGN TOOL ESPECIALLY WITH RESPECT TO THE GERMAN ACTIVITIES IN THIS FIELD

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**The Seventh Congress
of the
International Council of the
Aeronautical Sciences**

CONSIGLIO NAZIONALE DELLE RICERCHE, ROMA, ITALY / SEPTEMBER 14-18, 1970

Price: 400 Lire

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Abstract

The first part of the paper describes the present state of the simulation technique both for ground and inflight simulations and deals with the advantages and difficulties of both simulation methods. In the second part the German acitivities with inflight-simulators are described.

Introduction

The significance of the simulation technique as an aid for research and development in the field of aviation has constantly intensified as a result of the increasing complexity of the flight vehicles and of entering new fields of activity such as VTOL and STOL techniques. We can say that it is presently one of the primarily discussed subjects and is holding the most capable spellbound. And yet, for a long time its utilization has not been restricted to research and development, however, is in an ever increasing extent entering the training functions of the aircrews. Our present contemplation which is preferably to revolve on the special inflight simulation methods would be incomplete if we would not comprehend it as part of an over-all problem and exactly define its position in this problem. As a matter of fact, the inflight-simulation is one of the methods involving the highest financial and time expenditures, and its use is therefore requiring an especially careful substantiation.

A. Present state of knowledge in the field of simulation

The first reason requiring the use of simulations in aircraft design is certainly based on the necessity of having to develop and ensure the functional capability of a complicated system of components or subsystems well-known and tested in itself. To begin with, the system can be simulated by means of a mathematical model, however, at utilization of already available real components it must be subject as soon as possible to continued studies of the everywhere occurring interface-problems. Aside from these interface-problems, further functional interference problems are, however, existing which must thoroughly be simulated at e.g. the existence of redundancies or emergency systems.

First of all those studies will be concerned for the present contemplation which are dealing with questions resulting from the pilot's activities with the vehicle. The pilot in the servo-loop must cope with the characteristics of the vehicle, he must obtain a clear survey of all conditions of his present situation by the readings displayed to him, and he must dispose of a sufficient number of intervention and control possibilities easy to survey in order to be able in all situations to safely and economically reach the destination of his flight. Not before engaging the pilot in the simulation the difficulties are forthcoming with which we must occupy ourselves in this report.

An outstanding simulation feature is the reproducibility of certain flight tasks or manoeuvres. The pilot has the possibility of repeating the actions so long as required for his safe judgement whether the method to be accomplished by him for the solution of a certain flight mission can be learned and safely be carried out. Due to the large number of tests which the pilot can accomplish in a ground simulator, the method is getting cheap and the pilot is acquiring a great many experiences. It can, however, not be completely guaranteed at plain ground-simulations if the possibility of test repetition will not as well represent a risky simplification of his task which will not any longer occur at the later flight testing.

A further excellent chance of simulation use is existing in the possibility to largely vary the parameters at the tests in order to eventually elaborate a solution being the optimum for the function concerned, by means of which the pilot can achieve the best results. This possibility is of course systematically utilized both in the design and development phases of a flight vehicle and during aircraft flight testing, too.

The test reproducibility on a simulator has as well the further advantage that it is possible to let a great many pilots test the designed flight vehicle on the same conditions and thereby to be able to exclude individual opinions or capabilities of the test persons at forming a judgement on the optimum.

It is generally well known that the pilots all over the world have a fairly conservative opinion as to what can be flown and what cannot be flown. If, however, the design of a new aircraft type has the task to enter into completely new fields of operation - as this is e.g. the case at the VTOL technique - the pilot can be prepared for his unusual new work by way of the simulation of hovering flights and transitions, etc., and by discussions with the design engineer he can on time assist in optimizing the handling qualities, before it is too late for essential modifications of the vehicle.

In general we can say that any attempt whatsoever at departing in any direction from the field the pilot is used to must proceed over detailed simulations, since only here learning new techniques of flight vehicle operation can be hoped for prior to first flight tests. The experience gained in ground - simulation can also contribute essentially to arrange the later flight test program in such suitable manner that the results can promptly be achieved at minimum risks.

At the end of this review it may be mentioned that simulations are an excellent means, too, of testing emergency systems of the flight vehicle and the change over to their use, and to optimize these latter according to the pilot's viewpoints.

A.1. Ground simulations and their problems

It has not been entered into as yet in this description that simulations can be accomplished in a very different manner. Although we are here restricting ourselves to simulations being accomplished at activity of a pilot, there must, however, be distinguished two essentially different categories, i.e.

1. Simulations at instrument flight conditions,
2. Simulations at visual flight conditions.

The substantial difference of these two manners will be evident at considering that, at instrument flight conditions, the pilot is bound to make his decisions exclusively on the basis of his instrument study, consequently to disregard all other information, particularly all sensations of motion. This manner of flying the aircraft can obviously easily be simulated thereby that the pilot is seated in a cockpit in which the indicating instruments are reproducing by computer control the IFR-information which, in a real case, would be at disposal of the pilot. This task can on principle be solved and is causing difficulties only in so far as a complete consideration of all degrees of freedom and flight vehicle characteristics being conditioned by the configuration is sometimes necessitating an extraordinary computer expenditure. As a present rule hybrid computers are put into operation for this problem.

The real difficulties at setup of a simulation are occuring not before the change to visual flight conditions since these difficulties are of an inherent nature and can be overcome only with methods of approximation. This inherent difficulty is applicable both to ground-simulations and to inflight-simulations, although naturally in a very different manner. A more detailed explanation of these difficulties and the presently available methods of approximation will show in which of the cases inflight-simulations are preferable to ground - simulations.

The mentioned inherent difficulties are, in the case of ground-simulations, connected with the fact that the three sensations - by which the pilot is receiving his information at visual flight conditions, i. e.

sensations of motion
visual sensations
audible sensations

cannot be simulated in complete trueness in a ground installation.

In order to explain this fact in more detail, we are firstly considering the pilot's activity with the elevator control. As far as the pilot does not leave the aircraft control to the autopilot, he is continually operating the elevator control. In doing so he is not influenced only by the visible result of his work, however, mostly by the occurring accelerations upon which he can react much quicker. It is selfevident that the application of these vertical accelerations in a ground simulator is approximately possible only, since only a limited height for cockpit up- and down motion is existing. The application must therefore be realized in such manner that vertical accelerations in one direction, lasting for a longer while, are reduced and a cockpit resetting is accomplished at accelerations possibly being lower than the threshold of perception. It has appeared that a good compromise is possible here in many cases and that the anticipated improvement as compared to a fixed seat simulator can absolutely be achieved. This will be noticeable among other things thereby that the pilot will quicker get accustomed to the simulator with vertical movement, to such a degree that the fixed seat simulator is being judged as difficult to fly. Application of the accelerations in correct phase relation is of course important, particularly then when the simulator communicates visibility sensations, too, e.g. by TV pictures of a flown-over ground surface model, and the pilot can make a comparison between the sensation of motion and the visibility sensation. It has, by the way, turned out at the tests with moving simulators that the pilot, at instrument flight too, reacts upon sensations of acceleration, at least as a sort of danger signal, and is feeling a considerable facilitation of his control work by the approximately correct application of these sensations. In order to explain a little more clearly the type of ground simulator being discussed here, we are showing in fig.1 a project of a simulator such as is presently under development at the company VFW-FOKKER in Bremen.

If we are, moreover, restricting ourselves to the pitching motion, it must unfortunately be said that the application of a landing at moving system and TV picture does not necessarily turn out realistically. At simulations for the CONCORDE it was e.g. observed that the lack of perspective visibility in simulation was resulting in delayed pull-out manoeuvres and thus in unnecessary hard aircraft touch down on the runway. Not insignificant is in some cases, too, the visual field being essentially reduced by the TV projection as compared with the actually existing conditions, and as a result the pilot may apply unnecessarily rolling motions at simulation.

A general characterization of the sensations with respect to their significance for the pilot is of use for correctly considering the coordination at simulation. It appears that due to their speed and the fact that they are perceived independently of the pilot's concentration, these sensations of motion have a great significance for his handling. On the other hand, the visual sensations are important on account of a considerable extent of redundance which must not be suppressed in all directions if optical illusions are to be avoided. Simulation of noises in the aircraft has a great importance in some cases, i.e. then when a change of the environmental noises signifies a warning. It is again decisive here that the acoustic warning is functioning without an anticipated concentration of the pilot. Simulated noises have proved to be disadvantageous if the pilot is to execute intellectually difficult work at the simulator, as e.g. the study of the parameter variation effect. On the other hand, it is necessary in some cases to simulate real noises in order to suppress hereby the simulator noises.

Particularly important subjects having to be studied at an early stage on the simulator for the benefit of the project development are the cases which result from a failure of the stability augmentation system and necessitate the change to a form of the flight control system making higher demands on the pilot's skill and attention. Realistic acceleration information on the directions of the yaw and pitch axes are of great importance here, as these information are permitting the quickest reaction of the pilot and as only they are able to perform the actual servo loop with the pilot.

The same applies to the search of areas in which the pilot can,by his control measures, bring about oscillations with ineffective damping. The pilot cannot give reliable information on the aircraft characteristics in this respect without a sufficiently exact simulation of the lateral and vertical accelerations.

A.2. Inflight-Simulators and their problems

It will be noted from the foregoing that the simulation of flight phenomena at sufficiently realistic application of all facts being essential for the pilot's activities is involving many difficulties and that an elusion of these difficulties by simulation of a new aircraft type by means of an already existing type is fairly interesting. It can be assumed that the sensations of visibility and motion can at least be applied in a manner which is more corresponding with reality than in a ground-simulator.

If it is to fulfil its purpose it must now be possible to modify an inflight-simulator in the flight range concerned in such manner that it will adopt the characterstics of the new aircraft type. It must further be rendered capable of allowing a certain parameter variation in order to enable the pilot to optimize his parameters at flight tests.

There are on principle two different methods by which a given aircraft can be madified to an inflight-simulator. The first method with the designation "Response Feedback System (RFS)" derives suitable control commands from the aircraft reactions, by means of which the desired quick or slow aircraft reaction can be enforced (fig. 2). The "closed loop" attitude of this simulator is then adapted to the new aircraft so that it will be exactly like the real aircraft in e.g. turbulent air, too. This method can be used if the stability derivatives of the basic aircraft are exactly known; this necessitates, however, at flight attitude changes to engage again in the feedback line and to change the gains so long until the true derivatives have been adjusted to the new ones. The variation of a single parameter is frequently moreover necessitating a series of variations in the individual feedback lines, and subsequent reviews during flight so that the parameter variation is fairly complicated here.

The second method is much easier in this respect since here a parameter variation requires only one variation at a single point. It is the question here about a "Model Controlled System (MCS) " (Fig. 3) at which the pilot's signals are not only applied to the basic aircraft but also put into a computer for the model aircraft. The real aircraft reaction is compared with the model values and a correcting command is derived from the difference in such manner that the simulation aircraft is, to a large extent, similar to the model aircraft. In comparison with the mentioned ease of the MCS there is the fact that only aircraft can be simulated which have a slower response than the basic aircraft. The basic aircraft including the used stability augmentation system must in general have natural frequencies being higher by about the factor 1,5 than the aircraft to be simulated.

A mixture of both methods can be used, too, in such manner that a basic aircraft at higher natural frequencies is firstly produced by means of the response feedback method and subsequently the adjustment to the desired project is enforced by means of the model method.

Mention may be made that an MCS simulator has, in general, a very low or even wrong reaction upon air turbulence since the model is conditioning behaviour. This simulator is thus on principle acting differently from the RFS simulator. Gust effects can of course be studied, too, at the MCS simulator by artificial application to the model. Although at quiet air this has the advantage of the reproducibility, the theoretically anticipated reactions are, on the other hand, only supplied hereby.

It must at any rate be kept in mind that an inflight-simulator can be put into operation in limited flight ranges only, as any exceeding the validity range of the linear theory of the flight characteristics' derivatives could have no similarity with the model aircraft to be simulated.

A further very important advantage of an inflight-simulator - beyond the abilities of the true applications of sensation - is based on the possibility to simulate certain emergency conditions on this simulator, arising at failure of certain details of the control system or other applied real systems. Such tests require, however, that a safety pilot will be on board and that a clearly understandable warning system will be available enabling the safety pilot at danger cases to take counter-measures.

It is self-evident that limits are existing here which frequently necessitate to leave the really dangerous emergency and boundary conditions to the ground-simulation. Especially aerodynamic boundary conditions are certainly not to be studied on inflight-simulators since they can neither be represented at sufficient reality nor without danger. The rule is therefore applicable that the model aircraft can be simulated only within the limits of the basic aircraft.

Whilst the use for many and very different projects is possible at the ground-simulation system, this is not normally the case at the inflight-simulators. We can, until now a larger number of inflight-simulators has been constructed which had the task to imitate or supply the peculiarities of an individual flight vehicle or a very limited field of flight conditions. This is firstly influenced by the fact that the range of application of a simulator which in itself was intended for a certain range of parameters is much more limited than a ground-simulator. In addition hereto the intended simulator utilization is not only limited to the characteristics which the pilot must estimate or optimize, but the equipment parts of the new aircraft should frequently be pre-tested, possibly on the inflight-simulator which consequently is simultaneously the test vehicle for equipment subsystems. A third fact leading to this specialization is the frequently determinative peculiar engine configuration which e.g. at VTOL projects is resulting in a large part of the interesting phenomena.

For this reason it will not be surprising that 3 vehicles having had this double-function of inflight - simulator plus subsystem test vehicle are designated in the description of the German experiences with inflight - simulators.

The inadequacies which can occur at simulation of a high-performance weapon system by a known basic aircraft at variable stability are very convincingly demonstrated in fig. 4 which has been given by J.T. GALLAGHER (14). It will be noted that at all essential phases certain differences either in the flight altitude or in the flying speed or even both are existing; the differences are especially great at high-speed flight at ground level or at interception of the enemy.

The ground-simulator is in any case superior with respect to its universal flexibility, in particular also concerning the cockpit outfit.

Finally it is easy to study in a ground-simulator the effects of thrust reversal devices and air brakes on the accuracy at release of weapons as well as the characteristics of VTOL vehicle controls at transition and hovering flight, since this requires only the input of a mathematical description of their mode of operation into the computer, whilst the corresponding equipment on the inflight-simulator has largely to be constructed in conformity with the original. In many cases the major obstacle for an inflight-simulator is the fact that the safety of special installations can hardly be achieved or at insupportable expenditure only.

Critical examinations of an inflight-simulator are known of a practical case. This concerns the attempt to simulate the handling qualities of the CONCORDE in the cases landing and Mach 2 flight on a Mirage III B. It has appeared here that the dissimilarity of the cockpit outfit, e.g. the simulation of the control forces proved to be disadvantageous and that the pilot in the Mirage was seated much too close to the center of gravity so that at rotations around the center of gravity there were not the realistic translational accelerations of the CONCORDE at the pilot's position.

As an example of the distribution of simulations to different simulator types, the program for the CONCORDE may be compiled here:

1) Fixed seat simulator at visual simulation - Examination of general problems (roll coupling, directional stability)

2) Three-dimensional motion system at colored visual simulation - Examination of handling qualities

3) Mirage III B at adjusted control forces at landing and Mach 2 configurations - Examination of handling qualities at two major flight conditions

4) Same as 2), however, at prototype cockpit and possibility of realistic accident simulation in the systems - Examination of the workload on the pilot, preparation of the acceptance flights, training of line crews.

In summarizing we can say that the inflight-simulator has great advantages in the limited fields in which it can simulate the original . The useful scope is, however, in scarcely a single case adequate to make a ground-simulator with moving system and visual application superfluous.

B. German tests with inflight-simulators

It is generally known that the German aircraft industries have very intensely been engaged in problems of the VTOL technique since the late 1950ies. The many questions with respect to obtaining good handling qualities at take-off and landing and also at transitions from and to wing-borne flight gave sufficient rise to firstly study and construct, prior to the development of VTOL aircraft, hovering rigs which were moreover to furnish as well first criteria with respect to the engine configuration effect on the recirculation phenomena at variable wind conditions. We are going to describe hereafter three different activities in this field and give a summary of the most important test results. A fourth work being described, too, in more detail in this paper dealt with the use of a multi-purpose inflight-simulator, a BELL 47 G helicopter of the Canadian Air Force on which the possibility of simulation of the hovering rig of the company VFW-FOKKER has been tested.

B.1. The hovering rig of the company MESSERSCHMITT-BÖLKOW-BLOHM

The company MBB, at that time still under the name of ENTWICKLUNGSRING SÜD GmbH, constructed a hovering rig for the simulation of its VJ 1o1 project shown in fig. 5 which was lifted by 3 vertically installed RB 1o8 engines. Following is a brief description of this flight vehicle:

The control moments in the roll axis were applied by differential thrust between left-hand and right-hand engines, and in the pitch axis by differential thrust between the front engine and the two rear engines. The yaw control moment was generated by decalage of the rear engines and thereby their thrust directions against each other, at Y-axis as decalage axis. The altitude variation was effected by simultaneous variation of the total thrust of all of the engines with the aid of the main trust lever. A mechanical linkage connected the stick or pedal respectively, and the FCU levers of the engines or rotatable cylinder respectively. The signals of an autopilot with 3 axis (one channel design) were admixed by way of electro-hydraulic servos to these direct control signals. The autopilot had the purpose to change the primarily given angular acceleration rating into an angular rate control or angular position control respectively (roll and pitch axes). Only a damper had been provided in the uncritical yaw axis.

The hovering rig was pivoted on a telescopic mast for first testing and adjustment of the hovering autopilot. The flight characteristics could be measured and adjusted without danger in 4 degrees of freedom - the 3 axes of rotation and the altitude. Due to the blast deflectors, a fairly good approximation of the free flight conditions could be achieved. The corresponding proof is the substantial conformity of the telescopic and free flight test results determined later on. By swinging the hovering rig out of the deflector zone, the influence of the ground effects could be examined, too, without danger.

Fig. 6 respect. fig. 7 shows several intermittent transition functions for different response adjustments at rate or attitude control respectively. Fig. 8 shows the typical response at a larger disturbance of moments in case of attitude control. As the control was realized by thrust modulation, the slow response of these engines had a decisive effect on the optimum handling qualities to be achieved.

The hovering rig was flown up to 4o knots. Several tests were accomplished at the rate control mode of operation. During this test the pilot was able to change from the rate control to the attitude control and vice versa. He thereby had a very good possibility of comparison for both stabilization systems.

Take-off did not prove to be a serious problem at these tests. The ground effect zone was quickly flown through at full throttle, so that no disadvantageous effects occurred. During hovering at rate control, the pilot had to concentrate on holding the required attitude. Since the pilot received rather late low angular rates and thus slow attitude changes, it was fairly difficult for him to follow a certain flight direction at rate control or to hover over a predetermined spot. At use of the attitude control however, this manoeuvre presented no problem. In the case of the rate control, the pitch axis proved to be especially critical since the visibility in the hovering rig was insufficient for an exact estimate- Any small deviation of the attitude from zero results in a path acceleration. For this reason relatively heavy oscillations of the hovering rig occurred close to the determined hovering spot. Typical values for this attitude change were $\pm 3^{\circ}$ in the pitch axis, and $\pm 2{,}5^{\circ}$ in the roll axis.Such angles are required of the attitude control for initiation of manoeuvres over ground.

In the case of hovering over a predetermined spot in the ground effect zone, maximum attitude deviations at attitude control occurred close to $\pm 0{,}2^{\circ}$ without having to require the pilot's control applications.

Since any motion is consuming energy, the fuel consumption at the rate control mode of operation is higher than at the attitude control mode of operation.

Flight testing was eliberately not carried out during bad visibility conditions. At a flight test the visibility was, however, suddenly reduced considerably by snow blown up from the runway, so that the pilot was forced to bring the stick into zero position and to avoid any interference in the stabilization by the controller.

A landing was possible by means of the rate control, however, the pilot had to concentrate more, and the determined spot of landing could not quite exactly be met. When a spot landing was required, the pilot had to change to attitude control.

Since the attitude control proved to be superior as compared to the rate control, the two test airplanes VL lol CX-1 and X-2 were equipped with plain attitude control system and exclusively flown in this manner.

The consequences drawn from these tests were the following:

An aircraft equipped with a rate control system can be flown by any well trained pilot. A higher concentration is, however, required since the pilot must handle a larger integration over ground than at application of the attitude control. The pilot cannot satisfactorily and safely execute spot landings or additional tasks.

Concerning the energy, too, the attitude control is superior to the rate control in case of thrust modulation control. The system's reaction is much quicker than the human reaction. As a result of the quick reaction, any error is corrected sufficiently early before it has become significant, and any requested attitude change is accomplished at a much higher accuracy and requires a control moment which is lower than at rate control. The thrust reserve required for lifting is considerably reduced thereby, and the permissible useful load is increasing.

All pilots having flown the hovering rig until now - not only EWR pilots - preferred the attitude control system since it is largely taking pattern from the reactions and habits of pilots for fixed-wing aircraft at least in pitch axis. Qualified jet airplan pilots will not require helicopters- or any other special training - in order to be able to fly an attitude controlled aircraft.

As demonstrated above, the insignificant additional expenditure at the attitude control system by the additional attitude reference as compared to the rate control system results in a considerable reliability increase of the total operation system.

B.2. The Control and Stabilization Augmentation System (CSAS) Test Rig of the company DORNIER

The company Dornier has also built a hovering rig for the study of control and stabilization augmentation problems of its DO-31 project, the lift having been generated by 4 RB lo8 engines. Fig. 9 shows that the engines had been installed on the traverse. Roll control was accordingly effected by thrust modulation of the inner engines, whilst bleed-air of the engines at the tail was blown out upward and downward. Control around the yaw axis was effected by rotating the outer engines around the pitch axis.

An attitude control system had been provided in the pitch and roll axes of the hovering rig whilst the yaw axis had been equipped with a rate control system. All three axes could also be flown with direct hand-operated control,i.e. acceleration control; and lastly a damper instead of an attitude control system could be used in the roll axis. Later on the set-up of the control system in the roll axis was such that normally the attitude control system and the damper were simultaneously connected, however, that at a fault in the att tude control system, this system could be disconnected by the control stick limit switch. It turned out that an improved changing to the simple damper operation could be achieved by this manner.

The tests made with these different control methods have shown several very interesting results. On the one hand it was determined that the hovering rig can safely be flown in all 3 axes at hand-operated control, too, although in a very unpleasant manner.

But the flight at attitude control in the pitch and roll axes was more plesant and safer, too, if the pilot had some training in this mode of operation. It was felt that the use of a damper in the roll axis in the event of an attitude control fault is very advantageous.

It resulted moreover that various possibilities of CSAS operation proved the necessity of the pilot's constant training in these modes of operation.

It appeared that learning plain hand-operated CSAS in the pitch and roll axes will succeed most quickly if the pilot is working with brief impulses and deflections not too large, and is always waiting for the result of such impulse. Later on it will be possible, too, to continuously operate the hand-operated control. Difficulties in separating the axes have therefore not been discovered.

A further observance refers to tests at reduced control moments. It was proved in this case that the pilots went about their manoeuvering tasks with great care and also patience, and, as in the case of normal control moments, were avoiding commands exceeding 5o% of the feasible values (fig. lo). It can be called in question here if in case of actual fact each of the pilots will behave in a similar careful manner.

B.3. The SG 1262 Hovering Rig of the company VFW-Fokker

The company VFW-Fokker constructed an SG 1262 hovering rig as simulator for the VAK 191 B at take-off, landing and hovering which was lifted by 5 RB lo8 engines grouped in series in the roll axis (fig. 11).

The control moments around jaw, and roll axes were generated by bleed-air of the 5 engines in such a manner that one pair of nozzles each at the lateral booms and in front and at the rear could blow air downwards. Whilst pitching and rolling moments could be generated in a corresponding manner by bleed-air distribution, yawing moments were generated by laterally blowing out engine bleed-air. The control system was constructed electro-hydraulically as fly-by-wire-system, however, a mechanical pitch and roll control system up to the hydraulic actuators of the corresponding nozzles was at disposal in an emergency. An additional thrust modulation of the most forward and most rearward engine had been installed for trimming stationary moments, in particular, however, for the generation of large pitching moments in the event of an engine failure; this thrust modulation started, however, not until deflections of more than 2o% of the maximum value occurred, and then also with a time lag only.

The control system for pitch and roll axes was equipped with an attitude control system comprising a triplex system in both axes, supervising each other in pairs and, in the event of diverse results, deciding - according to the principle of majority - on the faulty unit which was disconnected with slight delay at exceeding a thresthold value. One of the two intact units was simultaneously connected as stand by system so that the pilot was flying with one unit only subsequent to the first controller fault. 4 limit switches had been installed in the control stick which, subsequent to the occurrence of a first controller fault, could serve to switch over from the switched-in control system to the emergency system. The reason for this step was to save the pilot any search for the proper emergency switch at a second controller fault, and to make the remaining faultless system accessible to him by way of the most direct reaction at the control stick.

The controller was a linear PD controller designed according to the operator augmentation principle, and at which any required response of the control and stabilization could be adjusted by mere variation of two resistances. Optimization of the attitude controller was accomplished thereby that the hovering rig, tethered on a pylon, was firstly moved around three axes and the networks of the controller amplifier - placed in a measuring compartment and connected by wire - were modified until the pilot was satisfied with the response of the hovering rig.

The yaw control was a plain damper control and designed without redundance.

The test accomplished with the hovering rig were built up on three hypotheses on which the VAK 191 B control conception has been based.

1. The pilot had to fly the aircraft exclusively with the attitude control system in order to ensure the same conditions of operation in all cases at good and bad weather, at no, one or two controller faults in one or two axes.

2. For this reason the mechanical emergency control was intended for the time of testing only, however, was to be removed completely by the installed redundance subsequent to testing.

3. The attitude control system was considered to be the most suitable control mode for hovering and slow transitions, and, notwithstanding the arguments initially still being opposed to the work, its suitability was to be substantiated.

From the beginning there was no doubt that it would be useful subsequent to one or two controller faults to completely adjust the aircraft response to the normal one. As a result, the pilots had to fly the hovering rig in one single control mode only and their training period has therefore been very brief. It became apparent that it was by no means difficult to fly the attitude control system, however, that pilots with short preparatory training were absolutely qualified for flying within 1 or two flights lasting less than lo minutes each. lo pilots have flown the hovering rig, each pilot having been made well acquainted with the operation of especially the 5 engines, firstly in a fixed-seat simulator and subsequently on the pylon.

The only difficulty which has occurred at the training of the pilots was the correct engine operation requiring a certain practice due to the risk of overheating by recirculation. It turned out at free flight that the pilots with no practice on similar equipment have, in the beginning, applied unnecessarily many and hasty control stick commands till they discovered that the attitude control actually effected vehicle balancing and that merely manoeuvering in the air was left to the pilot.

One characteristic of the linear attitude control system is the fact that the hovering rig is moving towards the new attitude (fig. 12) in response to a certain jump command irrespective of the size. We found that the pilots considered approximately 1,4 sec in the pitch axis and 1,1 sec in the roll axis to be sufficiently quick for reaching 95% of the final attitude angle without the existence of dangerous oscillations being induced by the pilot. For a long time nobody took exception to the fact that this response time was of the same magnitude for small stick commands,too. For theoretical considerations we came, however, to the assumption that a response such as indicated in fig. 13 would come up more still to the demands of the pilot. We constructed the corresponding nonlinear controller and tested it out on the hovering rig. It appeared that the pilots were fully satisfied of its response and valued the new characteristic as a real progress as compared to the linear controller.

In the arguments, by which especially American pilots wanted for a long while to convince us of the advantages of a rate control system as compared to an attitude control system, the term of equipment inertia at manoeuvering had been used. Although we had already succeeded with the linear attitude controller in demonstrating the mobility of the vehicle by a series of flights, we do believe that this argument is no longer significant by the realization of the nonlinear controller.

Among the further tests at the hovering rig, we may mention the following:

Firstly it became apparent that no unexpected effects were procured in the pitch axis by the superimposition at a modulation of the outer engine thrusts.

In comparison herewith, considerable difficulties at higher lateral velocities were noticed. The location of the 5 engine intakes over the center of gravity resulted in a roll moment at lateral motions which had the effect to raise the hovering rig and to reduce the lateral velocity. If at maximum lateral velocity the control stick was quickly pushed into the other extreme position relative to aileron control, the hovering rig rolled - due to the assistance of the engine intake impulses - to the other side at an essentially larger angle of bank, and any attempts to again stabilize the hovering rig in the horizontal line resulted in induced oscillations, if the pilot did not simply push the stick into the mid-position, but tried to dampen the motion. These pilot induced oscillations were caused by the fact that the roll moments were too low for these extreme angles of bank and the roll rates, and that the nozzles lay much too long time at the stops (fig. 14).

Remedial measures were taken by roll moment increase and limiting the lateral velocities to 40 kts. It turned out that the controller was now capable at restoring to pull out the rig at a much earlier time. Moreover, the pilot induced the oscillations had disappeared since the nozzles were now reaching the stops for a short time only. Summarizing we can say that the available control roll moments must be selected about 4 times as high as the external disturbing moments if the mentioned effectes are to be avoided and the handling qualities are to be preserved.

Hovering rig testing at acceleration control in the pitch and roll axes was accomplished. The control was though possible, but unpleasant. A landing at acceleration control in both axes could be accomplished, too. Changing from attitude control to acceleration control was made during flight, the changing over being controlled by the pilot even during some or the other manoeuvre. The control moments required were considerably higher than those at attitude control (fig. 15). Furthermore, changes of nozzle opening from one extreme position to the other occurred more frequently.

Attitude control system optimization has proved that the maximum pitch angles to be brought into a steady position by the control stick should be ± 12° , maximum roll angles ± 15°.

Simulation of a second controller failure has beentested only on the pylon since a safety pilot cannot be taken along. The studies in flight were postponed to the tests with a helicopter as simulator described in the next paragraph.

The tests on the pylon have turned out to be a very effective aid for achieving optimum flight characteristics. Although various free flight effects are not occurring, emergency flight conditions at extensive parameter variations could in particular be studied, and an opinion on the probability of overcoming these cases could be formed. Moreover, it was very useful to be able to make the controller optimization for the entire range of weights and moments of inertia, and by droping unsymetric loads to study the effect of external disturbances.

B.4. Helicopter as multipurpose simulator

An intensive and very pleasant cooperation with the National Research Council of Canada has enabled the company VFW-FOKKER to simulate the SG 1262 hovering rig with all its data on a Bell 47 G helicopter and thus to test the helicopter for its suitability as multipurpose simulator (fig. 16).

For power reserve increase at hovering, the Bell 47 G was equipped by a turbo-supercharged engine. The available control moment generators supplied a maximum of

pitch axis $\ddot{\vartheta}_{max} = 1{,}2 \text{ rad/sec}^2$

roll axis $\ddot{\varphi}_{max} = 2{,}2 \text{ rad/sec}^2$ Bell 47G

yaw axis $\ddot{\psi}_{max} = 2{,}4 \text{ rad/sec}^2$

Consequently in all 3 axes more than required for the hovering rig:

$\ddot{\vartheta}_{max} = 0{,}98 \text{ rad/sec}^2$

$\ddot{\varphi}_{max} = 1{,}6 \text{ rad/sec}^2$ SG 1262

$\ddot{\psi}_{max} = 1{,}17 \text{ rad/sec}^2$

For application of the model controlled system (MCS), position and rate gyro were at disposal reporting the actual helicopter movements to an analog computer which calculated the rated movements.

The simulator is on principle flown by two pilots, the test pilot on the right-hand seat flying his tests, whilst the safety pilot on the left-hand seat is constantly supervising the vehicle motions and in case of danger disconnects all the simulator equipment and, at use of its normal control system, restores the helicopter's safe attitude.

All parameters of interest could be varied to a large extent during flight by way of potentiometers in the cockpit.

Variations at the elevator control had been made, too, procuring the helicopter with an acceleration control in the yaw axis. The motion in altitude which the pilot is experiencing at his position in the hovering rig at changes of the longitudinal inclination was, however, not simulated. The visibility conditions of the hovering rig, having been adapted to those of the VAK 191 B, have not been applied.

Three facts have particularly irritated the pilot's report with regard to the simulator suitability for SG 1262 application, that is to say

1. the typical helicopter vibrations
2. the different conditions of visibility
3. the different stick and pedal forces.

But it appeared that after some practice the pilot got accustomed to these differences, so that he could fully concentrate on the peculiarities of the simulator operation. Simulation of the elevator control could largely be realized. Moreover, simulation of pitch control with and without thrust modulation, with and without skip zone, as well as with and without thrust modulation time lag, was successful. It was ascertained at these simulations that above mentioned too small distance of the pilot's seatin front of the center of gravity had become insignificant if the manoeuvres were flown at altitudes of more than 5 ms.

For reasons of time, the tests with the helicopter were limited to 9 flights. During these flights the SG 1262 pitch control could exactly be simulated as compared to an approximate simulation of the roll and yaw axes.It could be realized that it would have been possible without any trouble to eliminate the still existing deviations. On the basis of the experiences made with the pitch control being particularly complicated at the hovering rig and the very convenient possibilities of parameter variations, we can say that the inflight helicopter simulator is an excellent instrument for studying problems of operation. The tests made at boundary conditions have moreover shown, too, that the safety pilot had excellent possibilities for simulator supervision at conditions of danger. For this reason it was decided upon this year's realization of a thorough failure simulation together with studies on instrument-landing problems on the Bell 47.

Whilst, to be sure, the helicopter as simulator has a higher parameter flexibility as compared to the hovering rigs utilized in the Federal Republic of Germany, it must on the other hand be emphasized that for instance recirculation effects can by no means be simulated by the helicopter.

Especially in this field, a fairly large scope of practical information has been acquired by the hovering rigs of the companies Dornier and VFW-Fokker; for reasons of the limited extent of this paper, these information could not be described here. Furthermore, aforementioned lateral effects could not be simulated due to the missing engine intakes, respectively other replacing devices. It is self-evident that the component tests, too, having been made at large extent on the German hovering rigs, are not feasible on the helicopter.

It could thus be demonstrated by this example that inflight-simulators are usually limited to a certain range of application in which they are, however, capable to perform something very remarkable.

Finally, it should again be called to mind that the different ground-simulator models - according to aforementioned detailed description - have great advantages as compared to the inflight-simulators and are in many cases indispensable both for the development of new types and for the training of pilots for these types.

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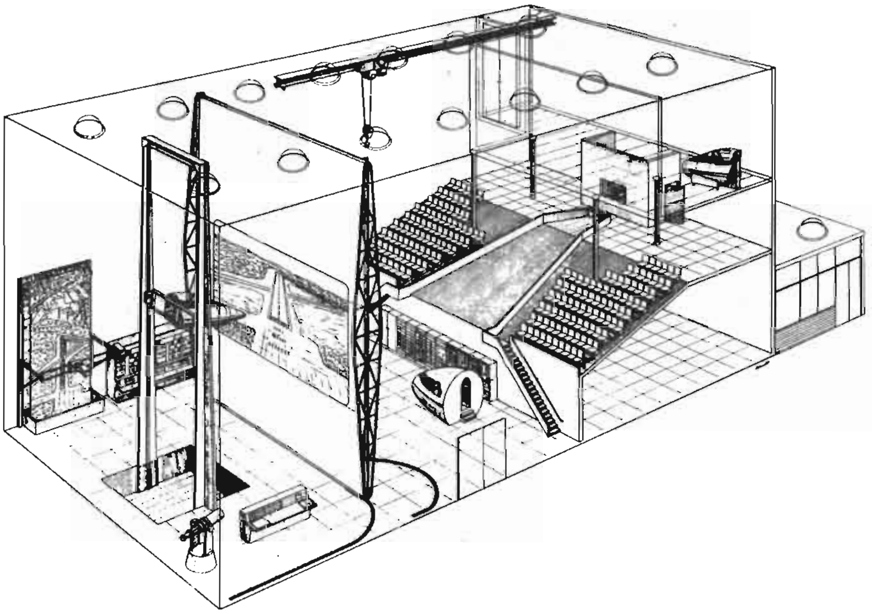

Figure 1 INSTALLATION OF A GROUND BASED SIMULATOR WITH MOVING COCKPIT AND VISUAL SYSTEM

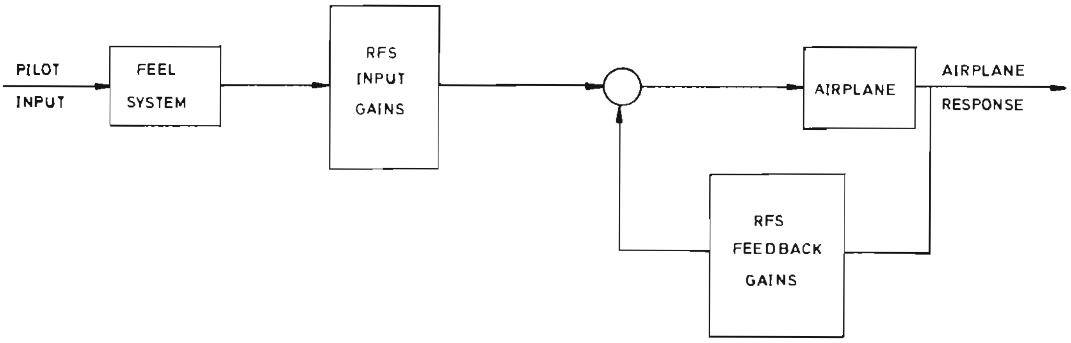

Figure 2 SIMPLIFIED BLOCK DIAGRAM OF RESPONSE FEEDBACK (RFS) VARIABLE STABILITY SYSTEM

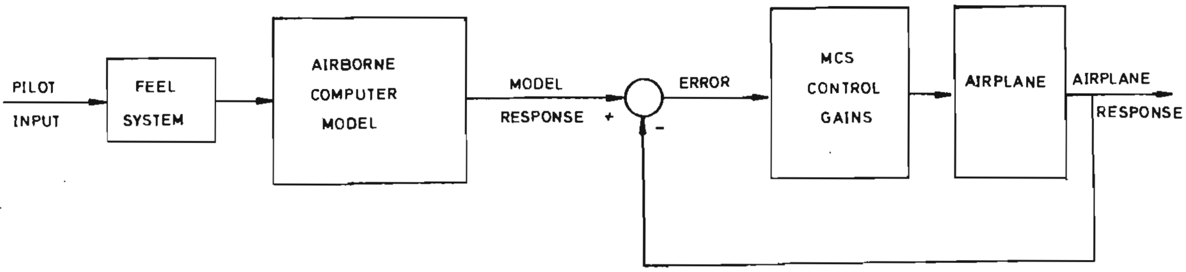

Figure 3 SIMPLIFIED BLOCK DIAGRAM OF MODEL CONTROLLED (MCS) VARIABLE STABILITY SYSTEM

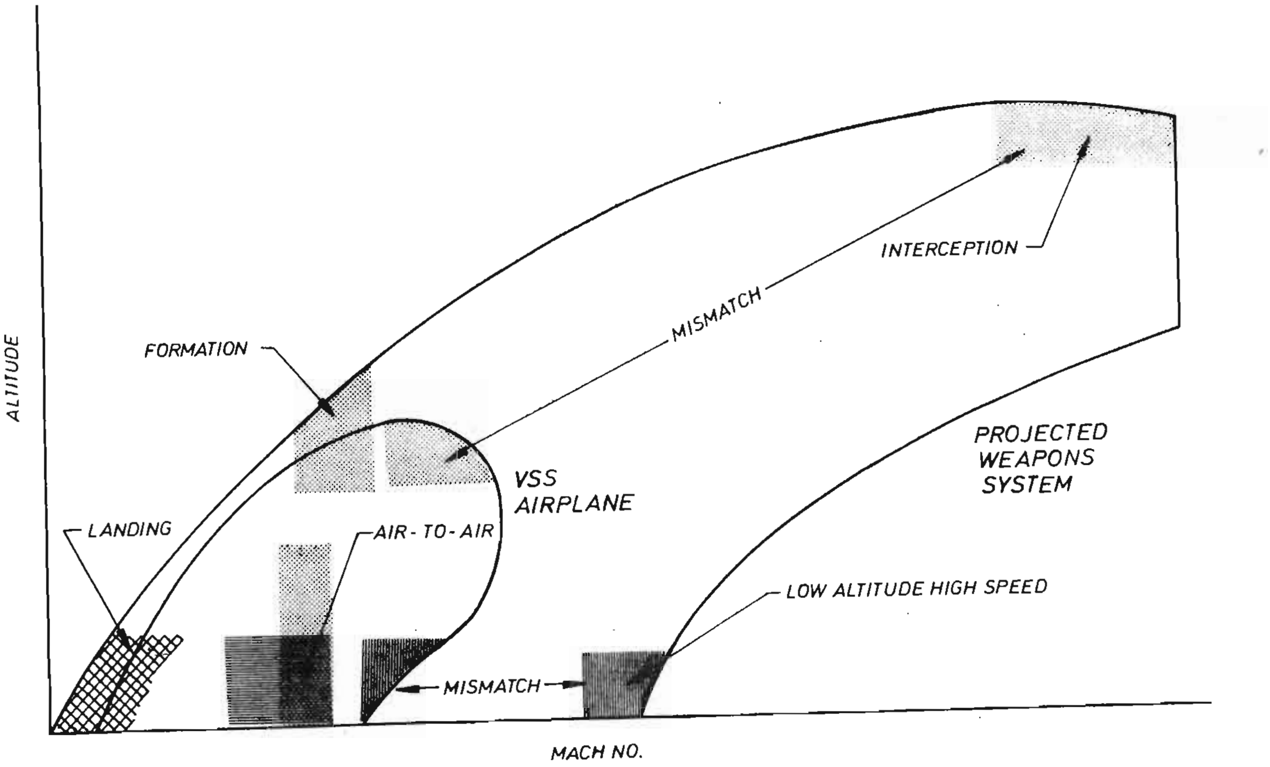

Figure 4 POSSIBILITIES FOR SPEED MISMATCH IN SIMULATION

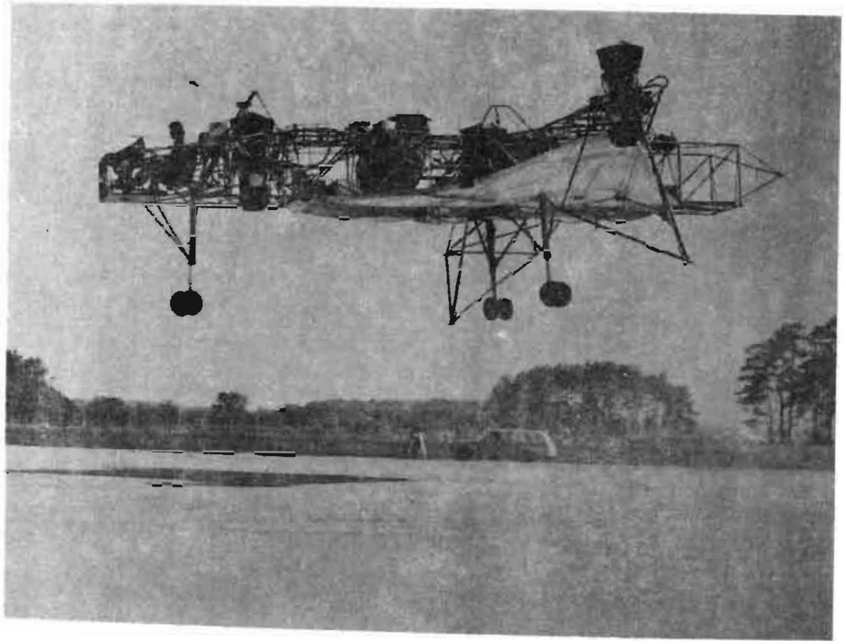

Figure 5 VJ 101 HOVERING RIG

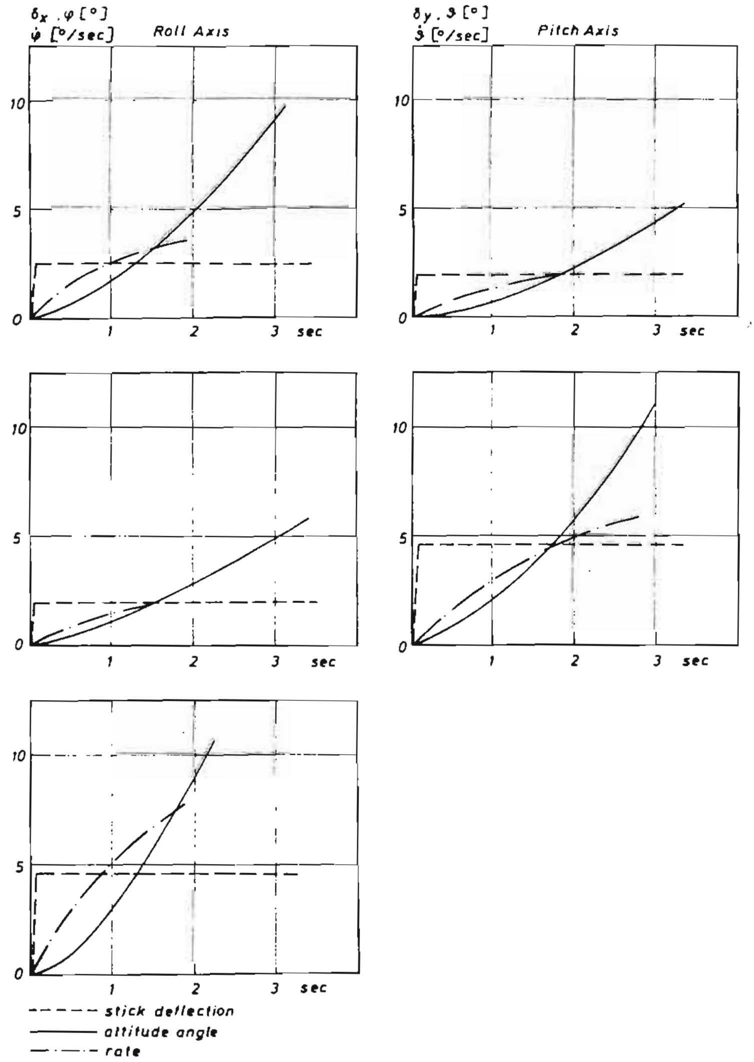

Figure 6 TRANSITION FUNCTIONS FOR DIFFERENT RESPONSE ADJUSTMENTS AT RATE CONTROL

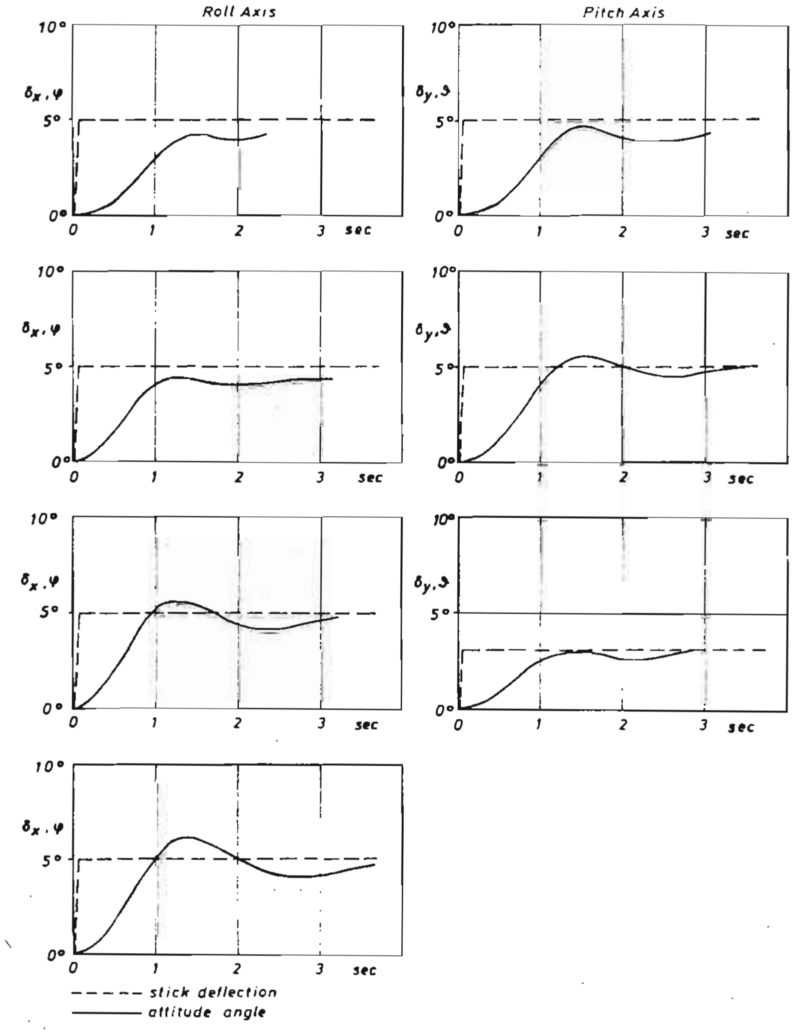

Figure 7 TRANSITION FUNCTIONS FOR DIFFERENT RESPONSE ADJUSTMENTS AT ATTITUDE CONTROL

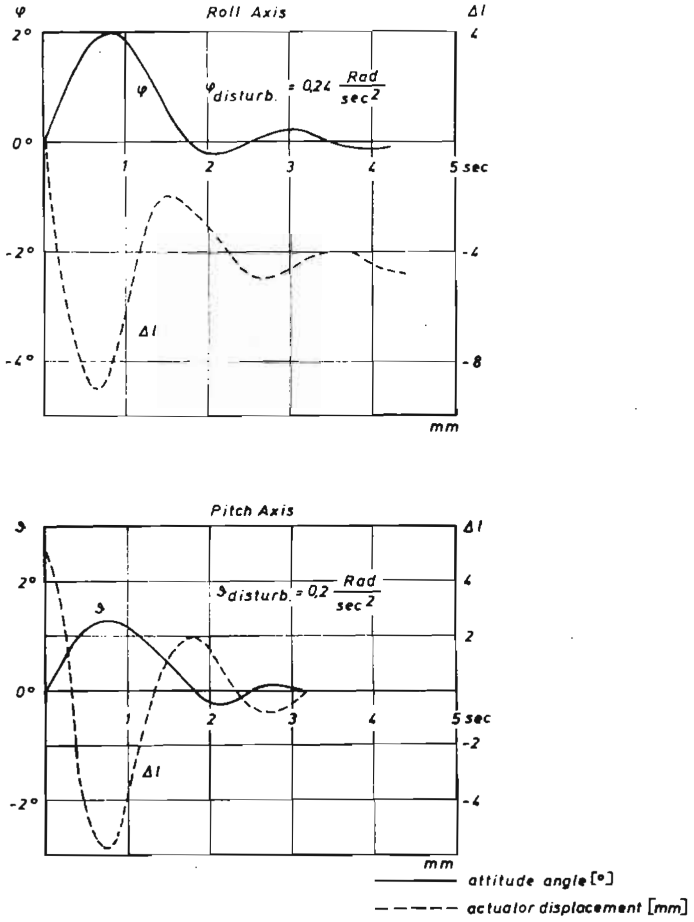

Figure 8 RESPONSE TO STEP DISTURBING MOMENTS BY DROPPING WEIGHTS AT ATTITUDE CONTROL

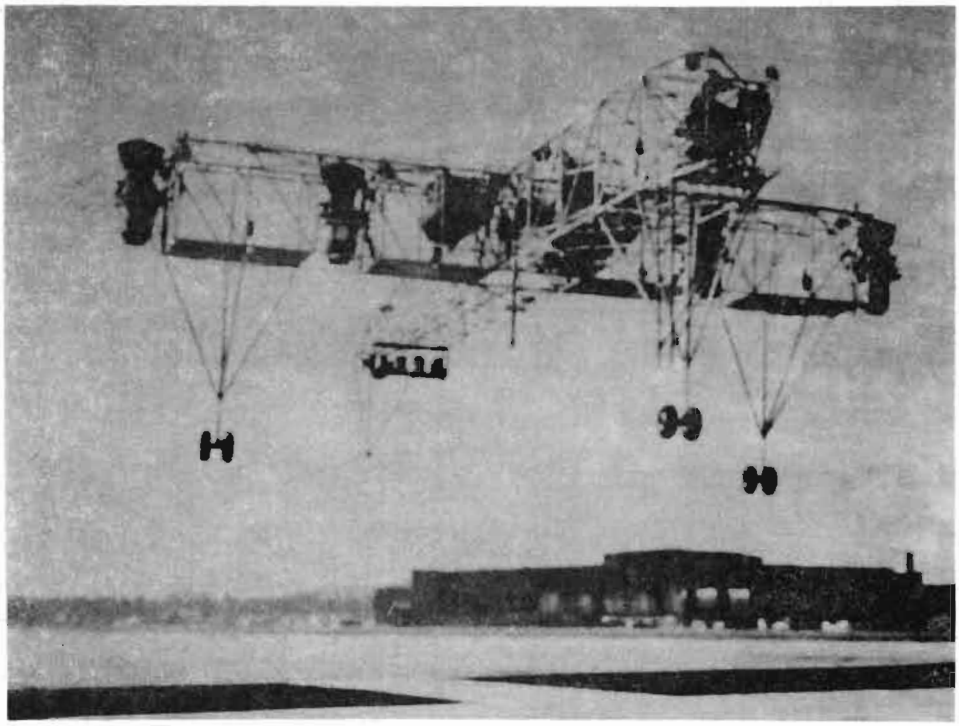

Figure 9 DO 31 HOVERING RIG

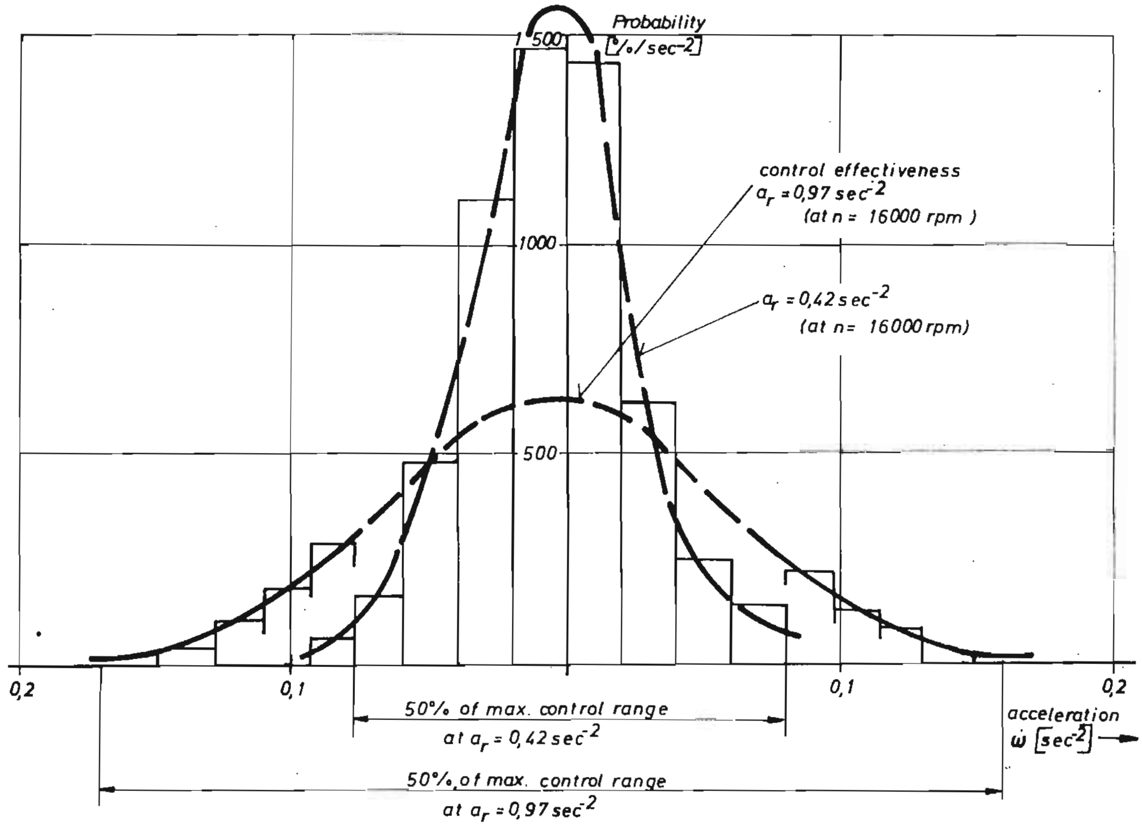

Figure 10 PROBABILITY DISTRIBUTION OF CONTROL DEFLECTIONS FOR TWO EXTREME VALUES OF CONTROL EFFECTIVENESS

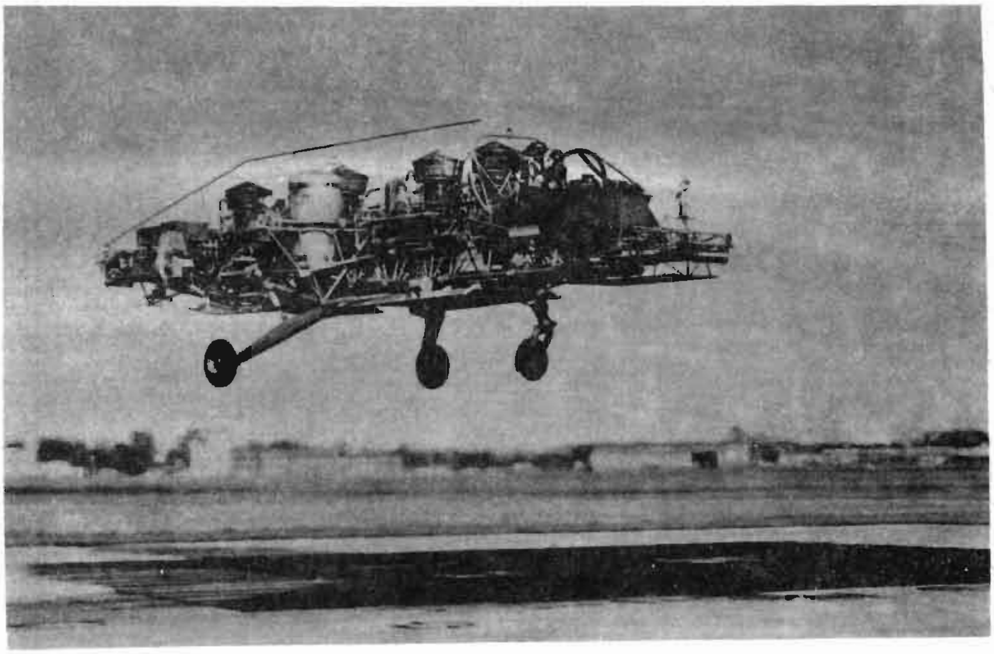

Figure 11 SG 1262 HOVERING RIG FOR THE VAK 191 B

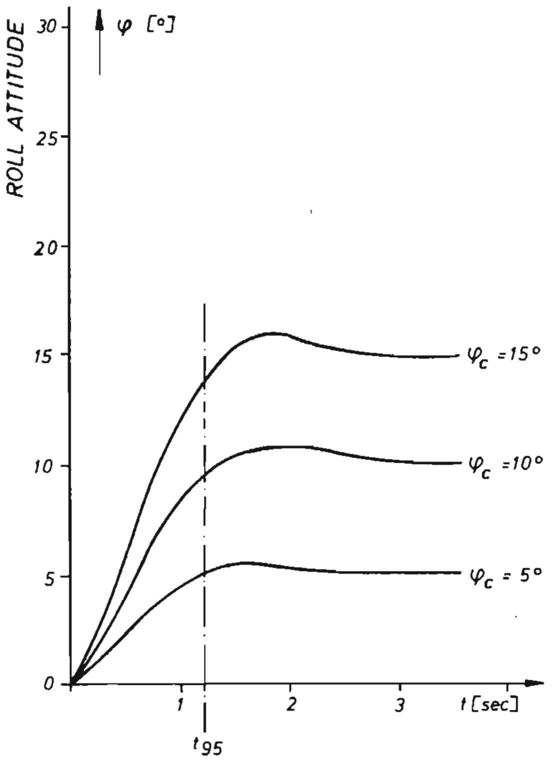

Figure 12 STEP RESPONSE,
LINEAR CONTROL SYSTEM

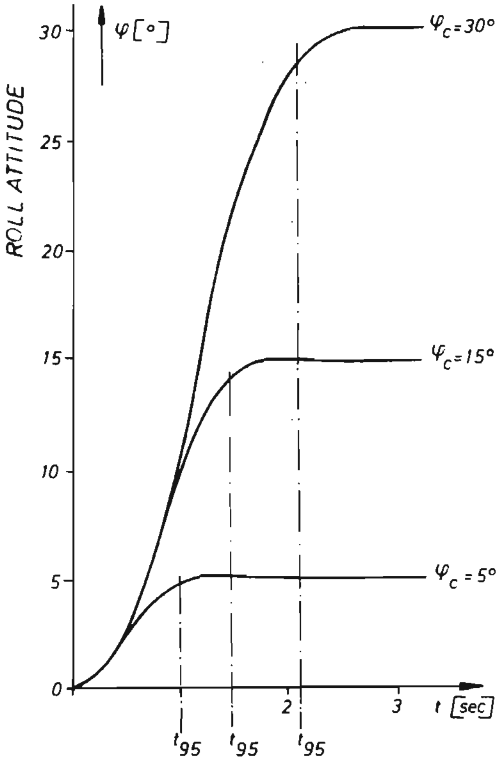

Figure 13 STEP RESPONSE
NONLINEAR CONTROL SYSTEM

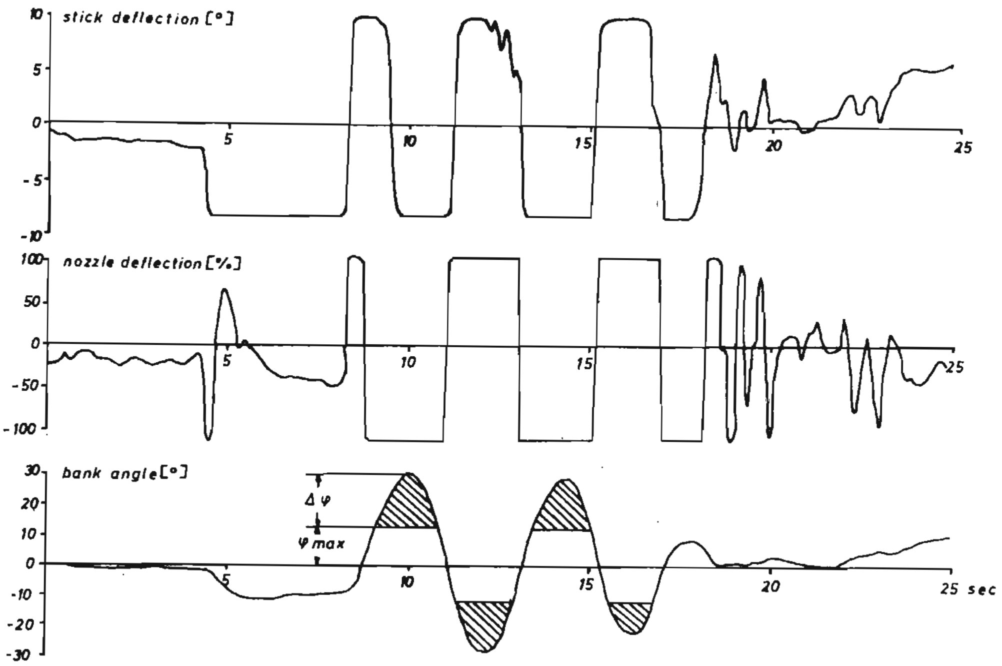

Figure 14 PILOT INDUCED OSCILLATIONS DUE TO INSUFFICIENT CONTROL EFFECTIVENESS

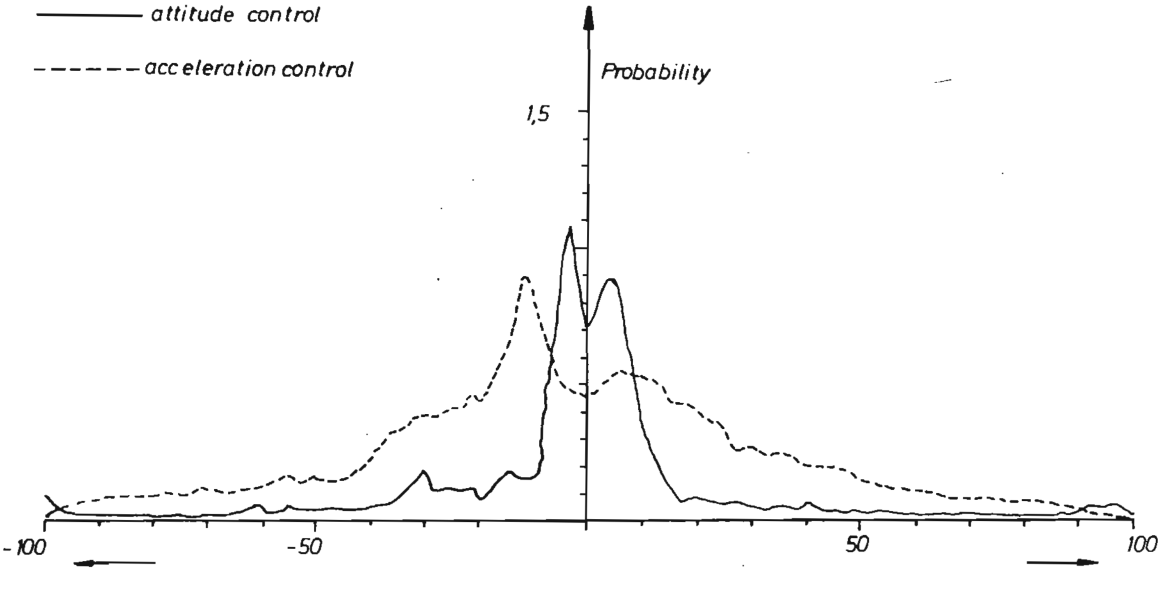

Figure 15 PROBABILITY DISTRIBUTION OF CONTROL DEFLECTIONS FOR ACCELERATION AND ATTITUDE CONTROL

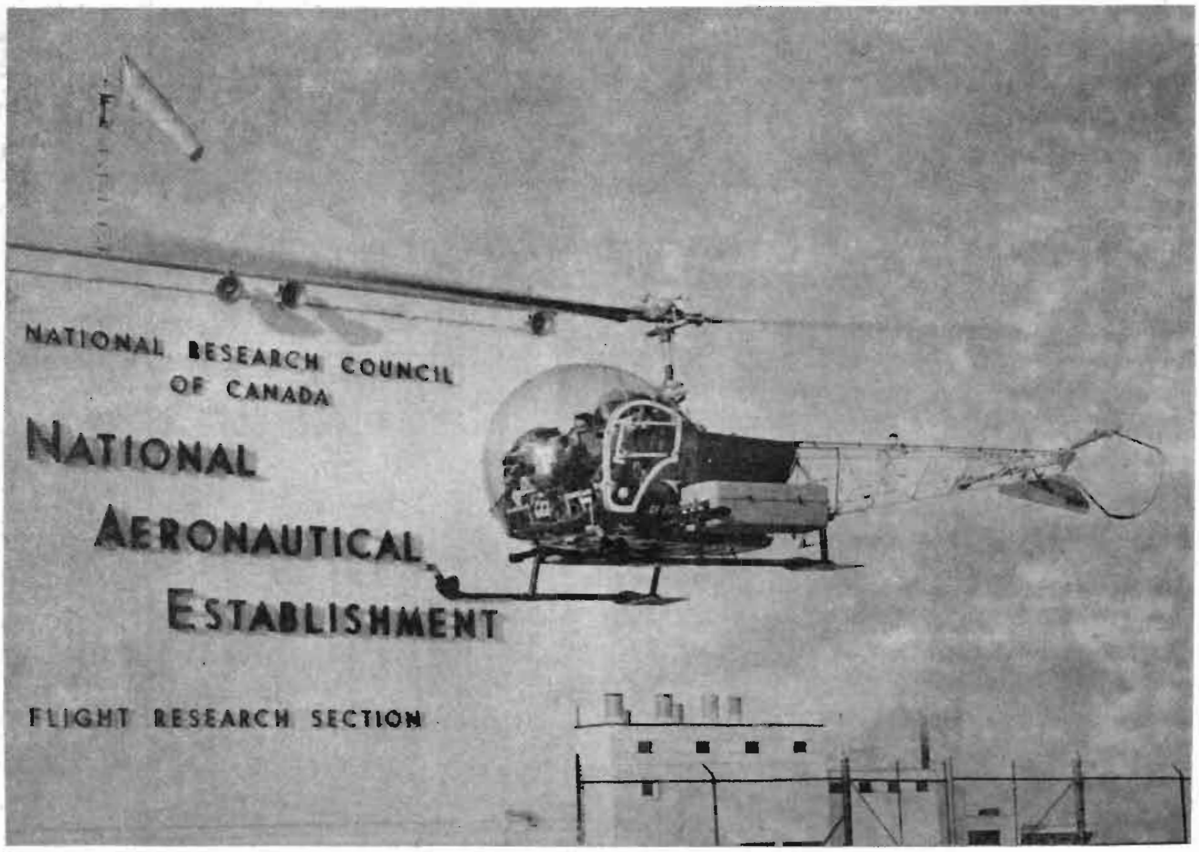

Figure 16 VARIABLE STABILITY HELICOPTER
BELL 47G OF NRC