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THE USE OF PILOTED SIMULATORS IN THE STUDY OF VTOL FLIGHT

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INTRODUCTION

The value of flight simulators in the study of control problems associated with piloted vehicles is widely recognized and their use is becoming more widespread. Simulation devices are useful not only in the area of research but are also applied to design and development work. General experience with simulators other than training devices is still relatively limited and their capabilities are not as well defined as is desirable. Thus, it appears that a continual review of the state of the art is necessary in order to assure proper and efficient use of the available equipment. This paper will describe some of the simulation studies done at the Ames Research Center and delineate some of the philosophy that is considered important in the planning and executing of flight simulation work. The discussion is illustrated by simulations applicable to VTOL aircraft performed on the cockpit with two degrees of freedom of motion described in the previous paper by Alan E. Faye, Jr.

Since the results of simulation depend on the interpretation of pilot opinion, the factors to be discussed which affect the simulation and the pilot are

(1) The experience of the personnel, particularly the pilot's ability to correlate and calibrate the simulation with recent flight experience

(2) Mechanization in which is covered the field of cockpit size and shape, control placement, and instrument panel

(3) Degrees of freedom represented by the mathematical equations used to define the motion of the airplane up to six degrees of freedom, which information is fed back to the pilot generally by visual means

(4) Cockpit motion with reference to providing real motion cues to the pilot, usually in rotation about the axes of pitch, roll, and yaw

DISCUSSION

In order to examine the process by which a simulation program is developed, figure 1 presents a block diagram of the components and information flow of a fully developed piloted simulator. The heart of the system is the analog computer which, using vehicle aerodynamic and mass characteristics, computes the vehicle motion resulting from input disturbances. The vehicle motion can be examined at the output of the computer to study the effect of the inputs.

The complication in obtaining a simulator capable of truly representing the flight vehicle in all aspects may be greater than that of obtaining the vehicle itself. The real value of the simulator lies in the ability to limit its capabilities to the study of important problems while ignoring the unimportant ones. Thus, unlike the aircraft, the complete system is unnecessary and great simplification can result with no significant loss in the success of the study.

In all cases, use should be made of the full capability of the computer to examine the problem. Without undue complication, it is possible to examine the response of the vehicle to standard control commands. Such studies can be as simple as the response to a control surface pulse or as complicated, for instance, as response to a throttle pulse involving engine response, propeller governing response, and slipstream effect on the vehicle characteristics. The only limitation to such a study is the degree of detail of data applicable to the vehicle. If the vehicle were to be operated completely in the automatic mode such as with a space-vehicle control system, then the results obtained would suffice. However, if the piloting requirements or performance are to be studied then the outputs of the computer should be used to command visual motion displays as in the top loop or to command real motion feedback as in the bottom loop. (See fig. 1.) The visual cues and/or real motion can be presented to a pilot and he can supply the command inputs to the computer. In this manner, closed-loop operation with the pilot in the loop is achieved.

For the piloted vehicle the question to be answered is whether the vehicle response characteristics are compatible with the pilot's requirements. Examination of the responses obtained without the pilot in the loop may show cases which would be considered acceptable. For example, smooth subsidence of motion following a disturbance or absence of motion cross coupling between axes may be taken as evidence that the pilot will find the vehicle characteristics acceptable. In general, however, decisions based on the examination of analog-computer motion traces alone tend to be conservative. The human and particularly the skillful pilot is a highly adaptive control mechanism and can cope with many systems which might otherwise appear hopelessly deficient. To take advantage of this skill requires that the pilot be brought into the system to aid in studying critical areas to avoid penalizing the design unduly.

Since the simulation results are dependent upon the pilot's reactions to the vehicle characteristics and he has to voice an opinion, the pilot must bring to the simulation a basis of knowledge about the task and characteristics being studied. The simulator cannot duplicate all of the experiences of flight but it can provide hints of what the flight would be like and, from these hints, the pilot must extrapolate to actual flight. This requires mental gymnastics by the pilot and he should have recent flight experience in the task being performed or a related task to be successful in the mental correlation. The interpretation of the pilot opinion given is quite important and it is felt that the simulation engineer with an understanding of pilot opinion procedure enhances the reliability of the results.

Mechanization of the cockpit assumes importance as soon as the pilot is included in the loop. It is not necessary to duplicate everything; but the controls and instruments essential to the problem need to be placed correctly. With fixed-cockpit simulation, it must be realized that the pilot receives all his information visually from the instruments and they must be adequate. Control-system characteristics should be reasonable as far as the feel to the pilot is concerned. An unrealistic breakout force or dead band in the control stick, for instance, has been found to have definite influence on the pilot's opinion of given characteristics.

With the pilot in the loop and surrounded by a cockpit that appears to him to represent the airplane, it must be decided what information is to be given him through his visual cues, the instruments, to obtain useful data. It is obvious that these instruments could be used to present to the pilot information showing motion about all axes. Some of these instruments would be required to substitute for motion cues and thus would be of a type not generally necessary or familiar to the pilot. Generally it is the opinion that it is impossible to absorb and act on the six-degree-of-freedom information presented in this way. The pilot's visual capacity to absorb the information becomes saturated and even relatively trivial problems may not be handled. It then becomes necessary to reduce the simulation to fewer degrees of freedom and possibly to divide the problem into portions for study. Thus it may be necessary to include only one degree of rotational freedom and one or two degrees of translational freedom in the simulation. If the problem can be restricted in this way, then the pilot has a firmer basis for judging the vehicle dynamics. If the problem cannot be simplified and more degrees of freedom are required, it is the conclusion that the pilot opinion will be unduly conservative if the visual cues are in the form of instrument presentation.

A more recent and less explored form of visual presentation is that of using television or motion-picture projection to present the pilot with an outside world which moves in relation to the vehicle response as a result of his control commands. Such a presentation extends the ability of the pilot to absorb more visual information by allowing him to use his peripheral vision to pick up movement while concentrating on instruments or other objects. Although experience with these systems is limited, it is the opinion that this type of presentation will substitute for motion of the simulator cockpit where low accelerations are expected to be imposed on the pilot in the real vehicle. If this proves to be true, then certain six-degree-of-freedom cases can be studied without motion of the pilot.

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From studies made on a fixed-cockpit simulator, certain conditions will appear to be unacceptable or uncontrollable to the pilot and the question arises whether or not motion cues would supply information enabling the pilot to revise his opinion. In addition, some problems must be studied which require more degrees of freedom to be simulated than are acceptable in the fixed-cockpit case. In general, it can be stated that the degrees of freedom which can be analyzed by the pilot satisfactorily increase directly as degrees of freedom of real motion feedback are added and may add to those acceptable in a visual sense. For example, two degrees of angular motion freedom provided could enable the pilot to analyze three degrees of angular freedom (one by visual presentation) and two degrees of linear freedom (both by visual presentation). The nature of the problem will specify the particular motion freedom required in addition to the visual presentation. In VTOL aircraft the linear accelerations on the pilot are fairly low and rotary motions therefore will usually be more pertinent to the simulation.

In the foregoing discussion a rough guide has been presented of the procedure to decide what parts of the block diagram (fig. 1) will be included and how complicated they will get. Each step in increased sophistication is made only when an unacceptable flight condition is found which is suspected to be the result of inadequate simulation. Thus for each step, the number of problems to be studied tends to reduce and the sophisticated simulation becomes directed at specific problems. Consequently, the simulation may remain simpler than first thought necessary.

Now that some of the factors influencing piloted simulation studies have been discussed, their use is illustrated by some specific examples.

The first of these was the study of transition characteristics of the deflected-slipstream vehicle. In figure 2 is the range of flight conditions studied from 0 to 55 knots. From the wind-tunnel tests, the variation of angle of attack with airspeed was determined for several flap deflections. Any point on any of the curves represents a steady level flight condition. The upper boundary is fixed by the wing stall and control available to balance the pitching moments. The lower boundary is imposed by the structural limits of the flap. From wind-tunnel results alone, it would be concluded that the vehicle could operate in this region. Prior to flight the transition was studied using a fixed-cockpit simulation. The pilots found it very difficult or impossible to complete the transition. To check on whether the omission of motion cues caused this result, the simulation was repeated with pitch and roll motion of the cockpit added. With these motion cues, the pilots were able to explore the transition region and establish a comfortable transition boundary which with the flap limit boundary designated a corridor through which the aircraft could be flown by careful attention to flaps, speed, and angle of attack. The gray area was to be avoided because it was too near the upper boundaries to allow sufficient control. Subsequent flight experience supported the pilots' conclusions regarding this corridor.

In reviewing the results of this simulation, the need for cockpit motion was readily apparent. Without cockpit motion, it became very difficult to perform the transition, even in the limited three-degree-of-freedom case of longitudinal mode only, because of the multiplicity of quantities which had to be monitored. The addition of roll and yaw calculation to give six-degree-of-freedom simulation made the task impossible and it was necessary to add pitch and roll motions to the cockpit to achieve satisfactory pilot performance.

A second example of the effect of motion feedback can be illustrated in some results obtained from the simulation of a large tilt-wing vehicle in hover. The study was concerned with the roll control and the simulation was limited to three degrees of freedom including roll and vertical and lateral translation. The pilot was given the tasks of lifting off into hover, of landing, and of moving laterally. Some conditions were compared with the cockpit fixed and with it moving in roll. As the characteristics became worse, a definite difference appeared as shown in figures 3 and 4. Figure 3 presents representative time histories of the roll-control position, rolling velocity, and lateral velocity for fixed-cockpit simulation and figure 4 shows the same quantities for the moving cockpit. The erratic movements and larger lateral velocities of the fixed-cockpit simulation are compared with the more regular movement and lower lateral velocity with the roll motion feedback. Even in this simple case, the pilot found the added motion cues in roll to be an aid since they gave him a more realistic picture of the onset of lateral velocity. He remarked that he found it possible to remove his hand from the control stick for brief periods of time with the moving cockpit and still regain control - something he could not do with the cockpit fixed.

This example illustrates that fixed-cockpit studies alone tend to be conservative. It emphasizes that, when a pilot finds he can cope with a problem on a fixed-cockpit simulator, the problem can probably be considered unimportant. However, when he cannot cope with the problem even where visual saturation is not suspected, serious consideration must be given to increasing the realism of the simulation to obtain valid pilot opinion.

The next two examples are of the study of specific operational problems which demonstrate the ability of simulation to familiarize the pilot with new characteristics, help him to explore limiting or boundary conditions without endangering the aircraft, and aid in development of techniques to handle an unusual situation. Motion of the cockpit was used in both of these cases to give the pilot a truer picture of the flight problem and to provide a more realistic environment of simulator operation.

The first of these was the study of attitude control in hover of a deflected-jet airplane. The reaction control power of this aircraft is low about all axes and the rotary damping is negligible. The simulation, making use of the pitch and roll motion of the cockpit, served to help the pilots learn what to expect and how to handle this type of hovering; it is somewhat akin to balancing yourself on a ball on a smooth surface.

This airplane also has the problem of gyroscopic coupling due to the engine rotating mass causing cross coupling between the axes of motion. This coupling appears in the pitch mode due to yaw movement. Gyroscopic coupling can be predicted and was recognized as a possibility early in the program; early flight tests confirmed this. Because of the inadvisability of exploring the limits of this region with the airplane itself, the simulator was used. With the simulator the pilot could explore the coupling region, determine approximately what the airplane limit should be, and calibrate himself to avoid this limit. Figures 5 and 6 have typical simulation records of this coupling. It should be pointed out that the pilot must supply his own damping, for the vehicle has little of its own. Values of yawing velocity, pitch control, and pitch angle are shown. Figure 5 shows the results of an attempt to hold a rate of yaw of approximately 5° per second. It can be seen that the yawing velocity in the first part of the figure varies between 5° and 8° per second. At the same time the pilot finds it necessary to use 50 to 80 percent nose-up pitch control to keep the pitch angle near zero. As the pilot reverses yaw control he requires nose-down pitch control to keep the pitch angle at a reasonable value. Figure 6 shows an attempt to hold a higher yawing velocity and it can be seen that an average rate of around 12° per second was held. Here full pitch control was necessary. From this study, the pilot selected the values of yawing rate to which he would restrict himself depending on the reaction control available. Some amount of margin of control is required by the pilot to handle disturbances and for maneuvering. In a previous paper, L. Stewart Rolls discusses this particular problem.

An investigation involving another deflected-jet aircraft studied the control problems due to the longitudinal dynamic characteristics in transition. Since only the longitudinal mode was being studied, the simulation was limited to three degrees of freedom and the cockpit moved in pitch only. The pilots went through a typical familiarization with the characteristics which were representative of the unaugmented stability or emergency case. The solid lines on figure 7 represent the variation of engine thrust with speed at three values of angle of attack for steady level flight as determined from the wind tunnel. Steady flight should be possible in the area above and to the right of the curve for $\alpha = 15^{\circ}$. The pilots found on the simulator that steady flight was possible in this region. With the requirements that altitude for transition from forward speed to hovering be held constant and that it be performed expeditiously, the initial transitions were attempted with low engine thrust for deceleration into the region of higher angles of attack before increasing engine thrust for lift. This type of deceleration ended in an uncontrollable pitch-up as indicated by 1 (fig. 7). A second attempt with slightly higher thrust ended the same way. Eventually it was found that the only feasible way of performing the transition was to move the diverter full down at a high enough speed to obtain good aerodynamic control and immediately increase engine thrust to 100 percent to obtain maximum reaction control power. The angle of attack was held slightly negative through most of the speed range to balance the excess lifting thrust.

This example demonstrates the value of simulation studies in interpreting wind-tunnel results as applied to new types of vehicles. Only in this way is it possible for the pilot to experiment with new techniques for a new vehicle. Simulation studies of this type are required to obtain a clear definition of the maneuvering requirements of VTOL vehicles as set by dynamic conditions rather than by static conditions.

The pilot still considers these simulation devices to be poor substitutes for flying but they can be a powerful tool in the investigation of flight problems. The simulator will become more important in the future when flight testing may not be available and most or all of the problems will have to be solved before the vehicle leaves the ground.

CONCLUDING REMARKS

This paper has discussed some of the factors affecting piloted flight simulation and the use of simulators in the study of flight techniques. Related pilot flight experience and engineer simulator experience enhance the reliability of simulation data. Proper cockpit mechanization is an important aid to the pilot in his correlation with the flight vehicle and with the task or problem being studied. Increased degrees of freedom in computation add to the realism of simulation but may be superfluous. Cockpit motion is an aid to the pilot in providing him with cues that otherwise must be interpreted visually.

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BLOCK DIAGRAM OF PILOTED SIMULATOR

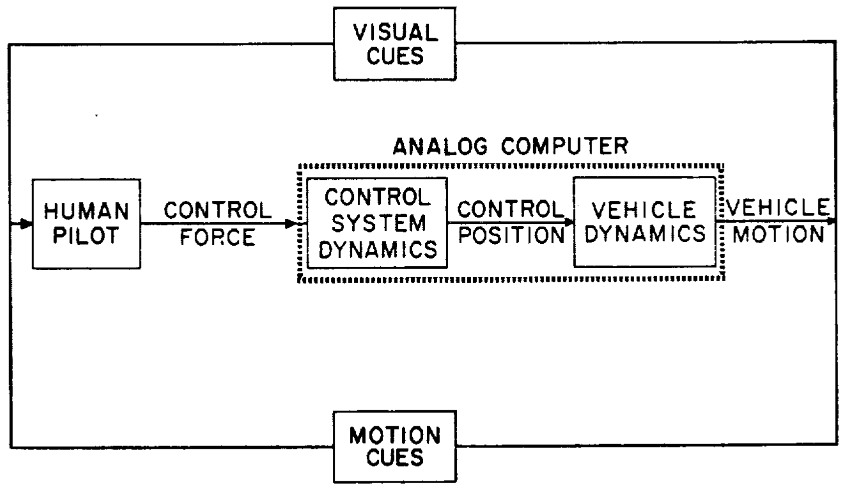

Figure 1

TRANSITION BOUNDARIES OF DEFLECTED
SLIPSTREAM AIRCRAFT FROM SIMULATOR STUDIES

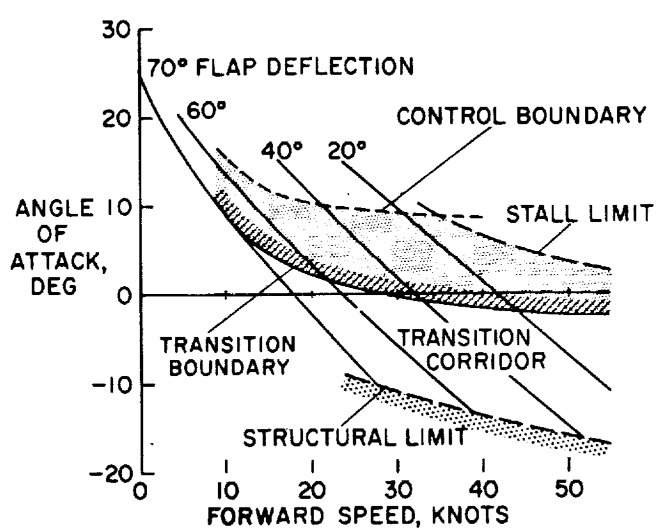

Figure 2

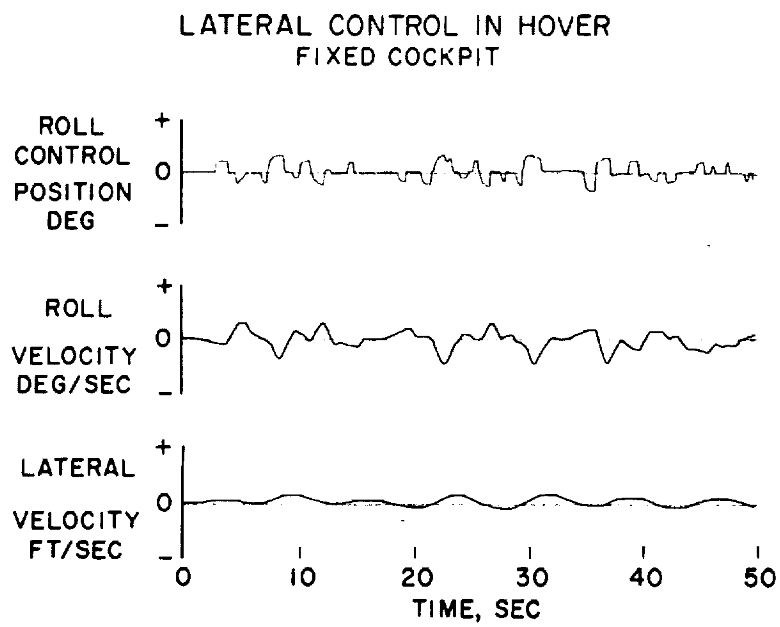

Figure 3

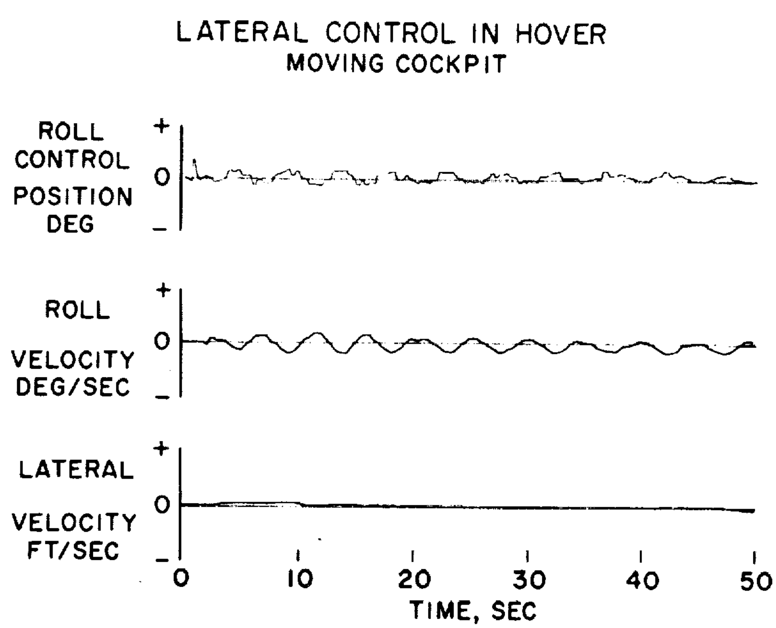

Figure 4

TIME HISTORY OF GYROSCOPIC COUPLING
SIMULATION AT LOW YAW RATE

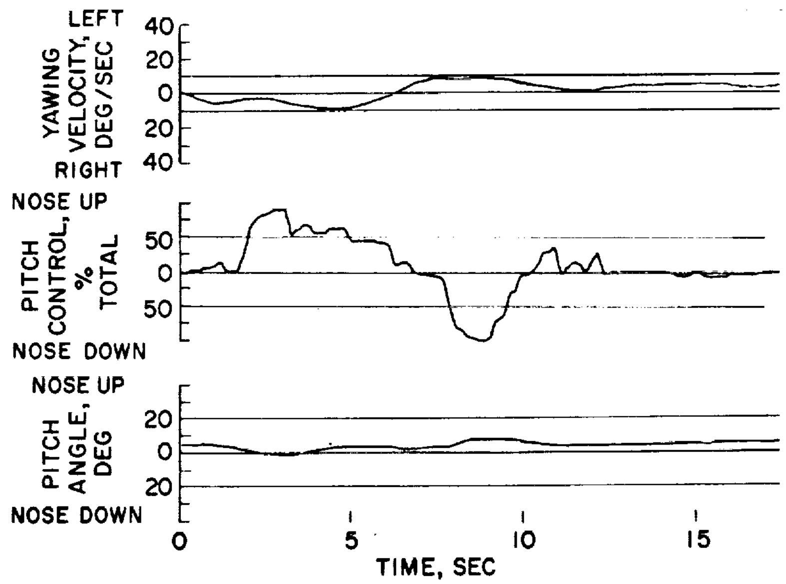

Figure 5

TIME HISTORY OF GYROSCOPIC COUPLING
SIMULATION AT HIGH YAW RATE

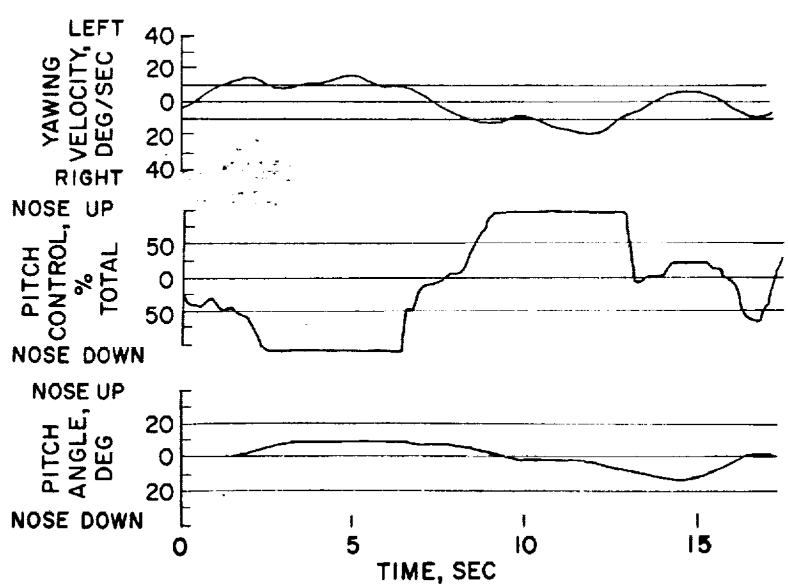

Figure 6

SIMULATOR TECHNIQUE IN TRANSITIONS
FROM FORWARD SPEED TO HOVER

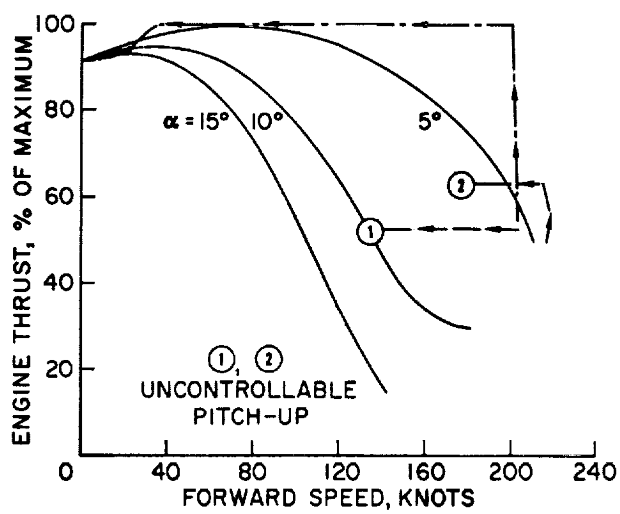

Figure 7