SIMULATION REQUIREMENTS FOR ROTORCRAFT

Irving C. Statler
Director, Aeromechanics Laboratory

and

David L. Key
Chief, Flight Control Division
Aeromechanics Laboratory
U.S. Army Aviation R&D Command
Ames Research Center
Moffett Field, California

I. INTRODUCTION

Over the last 20 years or so, piloted flight simulation has emerged as a recognized and widely accepted training tool. Marked success is being claimed in cost savings by transfer of part of the training requirement from the real aircraft to the simulator. In the fixed-wing aircraft industry, the cost effectiveness of piloted flight simulation has also been demonstrated in research and development (Ref. 1). It has become a primary tool used in the fields of dynamics, control system development and human factors. The understanding of the flight characteristics of new aircraft, the development of certification criteria, the validation of aircraft control concepts, and the formulation of new approaches to air traffic control procedures are just a few examples of the many uses of the modern flight simulator. Recent emphasis on the control of development and training costs and on the conservation of fuel have enhanced the increasingly important role played by flight simulators.

While their value has been widely exploited by the fixed-wing industry for many years, piloted flight simulators have seen much less use by the rotary-wing industry. In 1971, the U.S. Army initiated an extensive program in the use of simulators for training helicopter aircrews with its introduction of the UH-1H Synthetic Flight Training System. Since then, training simulators have been developed for the CH-47 Chinook and AH-1 Cobra, and one is under development for the UH-60A Blackhawk. Similarly, the U.S. Navy introduced a Weapons System Trainer for the SH-2F Seasprite in 1976 and have systems under development for the CH-46E Sea Knight and SH-3H Sea King. However, in contrast with the fixed-wing aircraft industry, there has been limited exploitation of man-in-the-loop simulation during the research and development phases of rotary-wing aircraft. Some examples are the use of Northrop's capabilities during development of the Heavy Lift Helicopter (Ref. 2), simulations performed by Sikorsky and NASA-Langley in support of the Advancing Blade Concept (ABC) helicopter and the Rotor Systems Research Aircraft (RSRA) developments (Refs. 3 and 4), and NASA-Ames' support of the tilt rotor development (Refs. 5 and 6) and Stability and Control Augmentation System (SCAS) failure investigations on the Bell 214 (Ref. 7).

In 1975, a joint U.S. Army and NASA study was performed to review the functions, status and future needs for ground-based flight simulation of rotary-wing aircraft. Contacts were made with the U.S. helicopter industry and with the various U.S. agencies concerned with the development of rotary-wing systems to assess the needs for research simulation. In the course of this review, the deficiencies in current simulation capability relative to rotary-wing aircraft requirements were defined with consideration of all the special aspects of this problem including mission, task, aircraft characteristics, environmental conditions, instrumentation and displays, performance and workload. Many of these aspects impose requirements quite different from those met by even the most sophisticated fixed-wing piloted simulators. As a result of this review (Ref. 8), a program was initiated to develop a high-fidelity rotorcraft simulation capability that could be exploited by both government and industry in research and development. The simulation capability is being developed jointly by the U.S. Army and NASA at Ames Research Center. This paper is a status report of that program.

II. REQUIREMENTS FOR SIMULATION

Simulators can be used to train better pilots or to develop better helicopters. The latter application is addressed in this paper. The review performed by the U.S. Army and NASA pointed up the need to be able to study the interrelated elements of the rotary-wing aircraft system: the human pilot, the flight control system, the displays and vision aids, the navigation and guidance equipment, the weapons systems, and the ever-changing environment. Rotary-wing aircraft could be made easy to fly or to fly themselves but such benefits are not cheap. They can have significant impact on cost, complexity, reliability and maintainability. To be cost effective, the rotary-wing system must make full use of the pilot and his capabilities. He must not be overloaded so that his mission performance is degraded or his margins for error decreased to such an extent that there is an increased susceptibility to accidents. Ground-based flight simulation is the only practical way to investigate the tradeoffs systematically before hardware is developed.

The uses of an engineering R&D flight simulator extend through the life of an aviation system (Fig. 1) from development of the technology data base (from which design criteria and specifications can be developed) through all stages of system development. Uses also range from conceptual and system integration studies during initial design to product improvement efforts long after the aircraft has entered service.

To enable these many uses, an R&D flight simulator must be versatile, making it possible to change the simulation easily from one aircraft type to another and to perform the wide range of maneuvers appropriate to each type. Helicopters of interest to the U.S. Army range from small lightweight types such as the OH-58A observation through utility and attack, to medium and heavy lift such as the CH-47 and CH-54. Research configurations such as the Rotor Systems Research Aircraft, the Advancing Blade Concept and the XV-15 Tilt Rotor Research Aircraft also must be covered. The maneuvers performed by these helicopters range from high agility terrain flying to sedate instrument approaches or precision hover. These requirements for versatility affect the mathematical modeling capability both in capacity and ease of reprogramming. They also influence motion system performance and the cab-visual display interface.

The fundamental problem in the use of the piloted flight simulator for research or development is that the pilot, required to assess an unknown aircraft, is bound to be influenced by the qualities of the simulator itself. Most simulator problems arise in achieving stimulation of the pilot's auditory, visual and motion receptors sufficiently to allow him to appreciate the simulator as a flying machine and to draw valid conclusions on the behavior of the aircraft being simulated. Consequently, a primary characteristic required of an R&D flight simulator must be high dynamic fidelity so that the handling quality assessments can be taken at face value, not merely as indicating trends. Major contributors to dynamic fidelity are the mathematical model accuracy, the motion system response, and the visual display. The requirements for providing the pilot motion and visual cues have the biggest impact on simulator design and on cost.

Simulators must be effective yet economical. This assumes that we know what the minimum essential cue requirements are when, in fact, we know very little about the minimum cue requirements needed to achieve our desired outcomes. Moreover, it is important to remember that the desired outcomes are quite different when simulators are used for training and when they are used for research and development.

Ideally, the simulator should provide the pilot with all the cues that are normally available and used by him to control the aircraft in real life. However, in practice many of these cues must be degraded. Fortunately, pilots are very adaptable at synthesizing from limited or imperfect information what is required for control of the vehicle, and severe degradation of cues can frequently be tolerated. Advantage must be taken of this adaptability in simulation as long as we can be assured of a positive transfer of training or the correct prediction and evaluation of handling qualities. Unfortunately, little is known about the factors limiting a pilot's performance or the manner in which he synthesizes the information required for controlling the aircraft and, in particular, what criteria he uses for selecting, rejecting or weighting the sensations impinging on him. As a result, it is not known how much motion is required in what circumstances and for what tasks. Any change in control strategy due to imperfect cues must be shown not to affect the pilot's assessment of the vehicle and this is very difficult to do if the vehicle has no real-life equivalent. There have been adequate demonstrations of the fact that degraded or missing motion cues have resulted in either an unrepresentative handling task or, more seriously, a failure to predict the handling characteristics of the vehicle. It has been shown that false handling predictions can arise when visual cues in the simulator totally replaced the motion cues the pilot would use in flight (Ref. 9).

III. SPECIAL CONSIDERATIONS FOR ROTORCRAFT

There are many differences between fixed-wing aircraft and rotary-wing aircraft that imply different simulation requirements. Generally, fixed-wing aircraft fly high and relatively fast and are close to the ground only when landing or when taking off. In contrast, helicopters fly low and slow and, especially during military missions, are in close proximity to the ground during most of their flying time. The term nap-of-the-earth (NOE) (Fig. 2) has been coined by the helicopter community to describe operations in which they fly only a few feet above the ground and fly around obstacles rather than over them. The environment for the pilots flying these missions is rich in detail — full of trees and bushes, hills, and valleys, which, while offering protection from the enemy, are lethal to an unwary pilot. Terrain features, visibility factors of weather and darkness, and atmospheric characteristics of wind, turbulence and ground effect are all elements of the environment that may significantly affect the helicopter pilot's tasks. The helicopter crew must maneuver around and between obstacles and navigate, communicate, and proceed with the mission while maintaining awareness of threat weapons.

Fundamental differences in the environmental cues which have to be simulated for rotorcraft operations compared with fixed-wing aircraft result from these different flight conditions. The visual display is required to represent much more detail in the terrain and vegetation. Being close to the ground, terrain and vegetation discontinuities cause more complex atmospheric wind shear and turbulence characteristics. Slow flight speed and, in particular, the conditions in and around hover make assumptions of a non-time-varying turbulence model invalid, and satisfactory turbulence models more difficult to achieve. Slow flight and high maneuverability, especially of military helicopters, allows rapid changes of flight path to be achieved. This means that the field of view required for the pilot to see where he is going is wider than in a fixed-wing aircraft.

The basic control problems are more difficult too. In a fixed-wing aircraft with good handling qualities, the aircraft is stable, and control is largely a two-axis task with pitch and bank angles being used to direct the aircraft flight path. In a helicopter, especially at speeds approaching hover, pitch attitude becomes less effective in controlling flight path angles and a better control of speed, while an additional control, thrust, is required for rate of climb. In addition, heading is no longer controlled by bank angle but also requires an additional specific control through the yaw control. Thus, the pilot's control problem becomes much more complex; it now requires all four controls to be actively worked. In addition to this fundamental control problem, the basic helicopter is likely to be unstable and to have significant cross coupling between the various axes.

All these complications associated with helicopters and VTOL aircraft make the need for the additional cues provided by a simulator motion system greater than in the case of fixed-wing aircraft. Finally, the mathematical model required for a reasonable representation of a helicopter must contain some elements of rotor dynamics, the extent depending on the purpose and nature of the simulation. Thus, the requirements on the visual, motion and computational aspects are all different, and generally significantly more severe than those for a simulation of similar fidelity for a fixed-wing aircraft.

Studies are being conducted at the Aeromechanics Laboratory of the U.S. Army Aviation R&D Command in conjunction with NASA-Ames Research Center to address these issues as part of the preliminary definition phase of the joint Army/NASA program. In the following sections of this paper, each aspect of flight simulation — visual displays, motion systems, and computation — will be addressed and the general requirements will be defined from the viewpoint of adequate simulation of Army rotorcraft and their missions.

IV. VISUAL DISPLAY REQUIREMENTS

Setting requirements for an out-of-the-window visual system for a simulator and the tradeoff of these requirements with available visual system hardware is a vexing problem. The initial approach is usually to determine the gross performance of the human visual system and then to set the requirements of the ideal visual system to match the performance of the human eye. This approach results in impractical requirements. We can readily accept that duplication of motion cues is neither technologically nor economically feasible; it is less obvious but equally true that duplication of visual cues also is currently not technologically feasible. The requirement for a complete reproduction of the air crew's available visual cues will be compromised just as surely as a requirement that the pilot's available motion cues be totally duplicated.

Current visual simulation systems make several different kinds of compromises. Despite rapid changes in the technological feasibility, it is still impossible to assemble the perfect system usable for all aircraft and all missions. Tradeoff decisions will have to be made to provide a solution that is feasible both technically and economically. However, there are no clear guidelines on how to make the tradeoffs from aircraft mission requirements into human performance requirements and finally into simulator engineering specifications.

Table I from Reference 10 examines the alternatives by comparing seven existing and projected visual display arrangements on the basis of some factors which influence the success of the systems. (A more complete catalog of factors relating to visual information may be seen in Ref. 11.) The lesson from this table is that no one display concept has all the desirable features for a given task; one system is good in some respects but deficient in others. Moreover, the display configuration best suited for a training facility may be inappropriate for a research and development simulator. The five factors that appear to drive hardware cost and complexity are:

1. Field-of-view and its location; that is, placement of the field center relative to helicopter body axes.

2. Textural quality and level of detail; that is, the features of the simulated area presented to the crew members.

3. Resolution/contrast (including color)/luminance; that is, the parameters that govern detectability, recognition capability, and image quality.

4. Dynamic performance, thresholds, and all factors affecting image quality during periods of movement.

5. Range; that is, whether or not the optics are collimated.

<u>Field-of-View</u>

Maneuvering during air-to-air combat operations obviously dictates the critical (widest) field-of-view requirement. During one-on-one combat, the adversary helicopter can rapidly traverse to nearly any part of the top hemisphere of the field of view.

In conventional high-altitude air combat, the adversary's attitude and location relative to the attacker's body axes comprise the primary information required. With helicopter air combat, this is not true. The low-speed, low-altitude, and low-thrust/weight capability of these machines makes combat near the ground more attractive due to enhanced concealment. This means that a high-resolution, wide-field display of the adversary and the ground is required.

For NOE point-to-point flying and hover operations, the necessary area of display is significantly smaller than in air-to-air combat. For example, studies of obstacle avoidance during NOE flight yields a requirement for a horizon-stabilized 120°-wide by 60°-high area centered at a point directly forward. This requirement results when one calculates the azimuth of a point 3 seconds ahead during turning or sidestepping level flight. The value of 3 seconds is considered the minimum preview time for obstacle avoidance. What this means is that a display must be wide enough to show obstacles at least 3 seconds ahead in the projected flight path during turns or sidestepping. For example, a 2-g level turn (60° bank angle) requires that objects 3 seconds ahead be visible at an azimuth of 60° for a speed of 50 knots. It also means that the display might have to be horizon-stabilized if the vertical field is small (40° or less) or else the 3-second point (or objects) will lie out of the field when the aircraft is banked. This effect is illustrated in Figure 3 (from Ref. 12).

These considerations lead to an NOE field-of-view requirement of about 120° horizontally by 60° vertically that is horizon-stabilized in roll. Such a display can be centered directly forward. Hover at 15 meters altitude during a difficult low-visibility pinnacle approach requires a field of 40° by 50° centered downwards about 45° and to the side and rear. Flight at night introduces other considerations. Some preliminary tests at NASA-Ames suggest that while a helicopter can be hovered in daylight with a limited field of view, an increased field of view is required to provide the cues needed to control the aircraft in darkness. Hence, simulation of night out-of-the-window display puts considerable emphasis on providing peripheral cues.

Level of Detail

The recognition of ground features plays a part in the representation of NOE flying. The visual cues required for the simulation of the full NOE mission almost defy analysis. Good texture and parallax cues are a minimum requirement for the pilot. Scene detail is most easily achieved in a camera model image-generation system. A terrain board can be constructed with very high detail even with quite small scales. For example, Figure 4 shows detail of an NOE terrain board with a scale of 400:1 at Ames Research Center.

Detail presented in the visual scene is of critical concern with Computer Generated Imagery (CGI). With CGI, the field-of-view and resolution are limited only by the price one may be prepared to pay for the necessary computation capacity; however, the present practical problem is providing sufficient scene detail over a large area. Available techniques can achieve a highly detailed scene such as shown in Figure 5 which contains 1500 edges. Although current CGI picture generators are capable of producing sufficient polygons and lights to make a scene flyable, the scene that is presented to the pilot lacks one important feature — texture. The polygons calculated by present-day CGIs, although shaded to blend the edges, are of uniform color. It is very difficult to locate such a polygon in space by judging its size and perspective area. The addition of texture to the polygon surface facilitates the task of judging the distance between the observer and the object, thus enhancing the three-dimensional effect of the picture. If texture is added, the picture becomes richer and more realistic. The problem is to develop techniques that will allow the density of detail to increase as features, such as hillsides, are approached, so that scene content is maintained at some sufficiently high level to provide the necessary cues to the pilot. Figure 6 shows how the present situation runs out of detail as the ground is approached. Figure 7 shows a test terrain derived by Singer-Link under contract to the U.S. Army Aviation R&D Command to investigate what minimum scene detail and object realism a pilot will accept. Arranged in the flat valley, the scene shown provides adequate detail for precise low-altitude maneuvering; facets on the square-section posts, and angular rocks, become quite distinct at short range, and provide a good textural cue. Several test pilots were asked to evaluate their ability to maneuver in this area and they judged the cues and realism to be adequate. The next step must be to extend these kinds of scattered objects over non-planar areas such as on hills.

Several companies are predicting an ability to paint texture over scenes without comprising computation rate, though with increased computer capacity. Figure 8 shows a scene developed by non-real-time emulation by Marconi. When such texture is available in real time, a major problem of detail with CGI will have been resolved.

Resolution, Contrast (and Color), and Luminance

Because these parameters are interrelated from the viewpoint of human performance, they are treated together. It would seem that a moderate degradation in our visual resolving power would result in a moderate loss of performance in accomplishing tasks requiring visual cues, but this is not the case. A visual acuity of 3 arc-minutes (about 20/60 vision) will not result in a third of the performance (e.g., the speed at which a NOE course could be flown at a specified mean altitude) obtainable with 20/20 vision even though objects must be three times closer to be recognized or detected. This quality of the seeing mechanism results in relaxed requirements for uncorrected vision associated with many roles (such as pilots) and points up the fact that rarely in our lives do we really need the fine resolving power in our eyes.

These assumptions are in accord with a study performed by R. J. Milelli et al. (Ref. 13) to evaluate the pilot's ability to fly three tasks with closed-circuit TV providing different fields of view and different resolution. The tasks, which could be classified as contour flying, consisted of:

- Maintaining a minimum height over a rugged terrain course while flying at 85 to 90 feet altitude.
- Deceleration and descent to a hover at 75 feet.
- Hover hold at 75 feet.

The fields of view were 60°, 120°, and 180° in azimuth and 45° in elevation. Resolution values were varied by changing from 525 lines/frame to 1023 lines/frame (about 6 and 3.5 arc-minutes/line pair respectively). The conclusions were that the effect of resolution change was not significant. It should be pointed out, however, that the results might have been different if the pilot had been required to descend to a touchdown rather than hover at 75 feet.

The detection performance of the human eye is given in Figure 9, from Reference 12, in terms of threshold contrast, background luminance, and target size. The target for these tests was a circular gray dish on a darker background. The probable operating envelope of the research facility visual system is also shown for a minimum resolution of 3 arc-minutes. The dimension into the paper represents the inverse of resolution and, therefore, can be used to describe spatial frequency. This also permits the operating envelope to be described in terms of the modulation transfer function, although the boundaries shown do not reflect this. Most earth features have contrasts between 0.03 and 1. The probable worst point is at high-brightness, low-contrast, and design resolution. It is seen that, for the range of brightness shown, color is not always needed.

Terrain model board and closed-circuit TV are particularly limited with respect to resolution and field of view. For a given size of model board, small scale is required to maximize gaming area but optical probe clearance and depth of focus put lower limits on the scale and these limits are particularly severe in probes with wide field of view. In considering the wide-angle probe, it was concluded that in order to obtain reasonable resolution through the TV chain, the 140° field would have to be divided into three fields of 42° × 60°. Limiting resolution for such a system of probe and TV cameras is then estimated to be as shown in Figure 10. Further degradation and resolution can be expected due to registration errors in the projection of independent red, blue, and green and due to the probe depth of field as shown in Figure 11. If the probe is focused at 60 millimeters (15 meters at 250:1), the scene will have resolution from the probe of better than 6.7 arc-minutes per optical line pair, from 51 to 72 millimeters (12.8 to 18 meters) and will degrade below 20 arc-minutes per optical line pair for objects closer than 45 millimeters (11.25 meters) and further away than 105 millimeters (26.3 meters). For missions involving terrain flight where it is important to see close three-dimensional objects, these limitations are probably the most restricted aspect of camera model technology. As there seems to be a trend away from camera model systems towards computer-generated imagery (CGI), it follows that we are unlikely to see advances in conventional camera model technology that will result in a dramatic improvement in resolution or field of view.

With the advent of computers for generating the images, the presentation system becomes the limiting factor with regard to the visual display. Resolution with CGI is primarily determined by the image presentation system with which it interfaces. The CGI image generator can produce scenes for large viewing angles but the displays presently used to produce a collimated continuous wide-angle field of view (e.g., the ASPT, Ref. 14) are exceedingly complex, heavy and expensive. Candidate displays for real image displays such as the Scanned Laser Visual System and the 360 Degree Annular Visual System (Ref. 15) are high risk developments that will take several years to mature.

The digital nature of CGI systems would seem to make them likely candidates for use with the rapidly developing field of digital matrix array displays such as light emitting diodes, liquid crystals, and thin film electroluminescent displays. Currently, these displays cannot match even conventional television display devices in resolution. However, the resolution is constantly improving, the power densities are low, and very high brightness seem attainable. The greatest hope for meeting the resolution and field-of-view requirements lies in a good match between the computer image-generation hardware and the image-display hardware.

Dynamic Performance

The specification of simulator visual system dynamic performance is relatively straightforward if there are no delays due to computation. Unfortunately, there are significant computation-induced delays and we are currently studying the allowable tolerances. Some discussion of this point is to be found in Reference 12.

Collimated Versus Real Imagery

In a human, the perception of depth and distance is considered to arise principally from three characteristics of the eye: accommodation, convergence, and retinal disparity.

- Accommodation provides a sense of distance from the position of the focusing muscles of the eye, and is generally effective for distances up to about 2 meters.
- Convergence conveys a sense of relative distance from muscle forces involved in rotating the eyeballs about their vertical axes when viewing objects closer than about 20 meters. This characteristic relies on both eyes or, in other words, binocular vision.
- Retinal disparity is the result of each eye seeing a slightly different view of three-dimensional objects and the brain processing and interpreting these two images as depth information. Retinal disparity, which also obviously depends on binocular vision, is considered capable of conveying depth information for distances of up to several hundreds of meters.

Though very attractive, there are presently no simulation visual systems which provide stereo images and hence can reproduce the cues of convergence and retinal disparity. Accommodation, however, can be simulated by the use of collimating lenses. In choosing between a collimated or real image display, one has to consider several factors. For example, collimating lenses have two major disadvantages: they reduce the available luminance by factors as large as 50 and reduce the viewing volume to quite small values. This latter fact makes it very difficult to provide a wide field of view simultaneously to two crew members. Mirror-beamsplitter collimating devices are better in both of these respects, and a side display for the right seat pilot can provide some moving peripheral cues for the left seat pilot, but not of a quality that would allow him to make a right turn through a gap in some trees.

V. MOTION (PLATFORM) REQUIREMENTS

Motion and orientation perception integrates four sensory modalities including vestibular, visual, non-vestibular proprioceptive and tactile. The vestibular sensors — the semicircular canals and otolith — are perhaps the best understood with the visual sensors next and the tactile and proprioceptive sensors being the least well understood. While the sensors are largely physiological components, the biological control processor which integrates information from the various sensors is strongly influenced by psychological factors.

Just because certain motions and forces are present and perceived in flight does not necessarily mean that they are important in performing or learning certain flying tasks. On the other hand, motion cues in piloted flight simulation can be important even when adequate alternative visual cues are available and even for the study of head-up display presentations. For the prediction and evaluation of handling qualities using a piloted flight simulator, it is not always sufficient for the pilot to achieve a similar performance in the simulator as in flight; it is also necessary that he should adopt the same control strategy. To achieve this, it is often essential to provide motion cues, as no substitute in these circumstances has yet been found.

It is generally agreed that motion simulation is required to obtain the full potential pilot performance. In a more general sense, motion simulation is required:

1. When expected motions are above human sensory or indifference thresholds, <u>and</u>

2. Within the sensory frequency range; that is above 0.2-0.5 rad/sec

3. <u>If</u> full pilot performance (e.g., tracking) is desired

4. <u>Or</u> when a degree of face validity or realism is required to gain pilot acceptance of the total simulation.

The primary design characteristics that influence the cost and complexity of a motion system are:

1. The number of axes.

2. Excursions, velocity and acceleration.

3. Thresholds of the motion, or smoothness.

4. Dynamic performance.

Each of these topics is discussed in Reference 12 so only a few points of emphasis will be made.

The properties of the pilot's sensory process of motion cues are not perfect, and it is possible to take advantage of this imperfection to reduce the required simulator motions. The known limitations in human motion perception are used in motion simulation in two ways. First, only the onset of motion is simulated after which the simulator returns to its mid-position with a rate (or acceleration) below the human perception threshold. In frequency domain terms this means that only the high frequency part of rotational motion is simulated. High-pass washout filters are used for this purpose. Second, use is made of a component of gravitational force existing in longitudinal or lateral direction through angular tilt of the simulator cockpit to simulate forces due to longitudinal or lateral aircraft acceleration. The rotation to the desired pitch or roll angle must be carried out with a rate not perceivable by the pilot. In frequency domain terms this means that only the low frequency part of rotational motion is simulated. Low-pass filters are used for this purpose (Refs. 16, 17, and 18). Washout can be made compatible with sensory washouts so as to produce motion sensations in the simulator that are close to those of flight. Just how close is, of course, the central question.

The criteria adopted for these requirements are the result of researcher opinions supported by very limited test data. In essence, the criteria relate the maximum allowable distortion of angular velocity and apparent force in the simulator relative to that of the simulated aircraft. This distortion is considered at the discrete frequency of one radian per second which is the frequency where rotational sensing is best and is close to the frequency where sensory washout is placed. Figure 12 describes the fidelity of the motion in terms of the phase distortion and amplitude of the angular velocity and specific forces observed in the simulator relative to those of the helicopter cockpit that is being simulated.

Flight maneuvers resulting from fixed-base simulations of NOE flight operations were analyzed to define the platform excursion requirements. These time histories were played (off line) through a drive logic representing that of an advanced six-degree-of-freedom simulator, with the fidelity boundaries and selected operating points for each axis shown in Fig. 12. The results of the analysis, in terms of the maximum excursion, velocity, and acceleration of each axis, are presented in Table II. The requirement is for all axes to produce these quantities simultaneously. The simultaneous requirement is amplified by Table III, where the position of each axis at the instant one reached a maximum is presented. The data are from a typical maneuver case and the optimized drive logic. The significance of the data is that when one axis is at a maximum some of the others are at large values also.

The requirement to allow precision hover with external loads means that helicopter attitude motions are typically ±1° and ±2° per second, and ±4° per second^2 (Ref. 19). These values are above the human threshold by a factor of 2 to 10. Angular motion thresholds have been shown to be frequency dependent and all values are a function of pilot task loading. The values adopted are shown in Table IV and are approximations to the available data. The use of such data for specifying threshold performance insures a smooth device devoid of the bumps and jerks so characteristic of platform motion systems.

The speed of response or dynamic response of the motion base should be chosen on the basis of the fastest commands it must follow. If we knew the highest frequency at which a helicopter could ever be maneuvered, a natural frequency of the motion platform 7 to 10 times greater with adequate damping will result in good following performance. It turns out that roll reversals during high performance NOE flight can occur at frequencies of up to 3 radians per second, hence the requirement for a critical frequency of at least 20 radians per second for the motion platform.

VI. COMPUTER REQUIREMENT

Another area that poses problems considerably more severe than conventional aircraft is that of the mathematical model for real-time simulation of the helicopter. The aerodynamic forces and moments on a helicopter rotor depend on the radial distance from the hub and on the blade azimuth. The rotating blades are relatively flexible. In certain flight situations, parts of the blades enter nonlinear aerodynamic conditions such as stall or high Mach number flow. Additional aerodynamic complexities occur due to interference between the rotor blades and the rest of the helicopter or between the helicopter and the ground. Comprehensive math models such as C81 (Ref. 20) attempt to take all of these complications into account because they are important for analyzing blade loads and rotor dynamics. However, the programs take very large computation capacity and run much slower than real time. For real-time simulation many simplifications have to be made, but the extent to which this can be done depends on the application.

Table V, developed by R.T.N. Chen of NASA-Ames, indicates a matrix of possibilities for math models based on including different representations of the aerodynamics and rotor dynamics. Linear aerodynamics implies simplifications such as infinitely stiff rotor blades, small flapping and inflow angles, and simple strip theory with no consideration of stall or compressibility. With such a model, much useful work of a generic nature can be performed (Refs. 21 and 22). However, if it is desired to investigate boundaries of the flight envelope, then even in generic studies the effects of compressibility, stall and other nonlinearities must be included. In simulations of specific helicopters where special quirks of that particular configuration need to be investigated, nonlinear effects may have to be included even well within the flight envelope.

Considering the rotor degrees of freedom, Figure 13 from Reference 23 shows that the six-degree-of-freedom rigid-body modes are of low frequency and the rotor modes generally of higher frequency. The most important rotor root with regard to rigid-body motion is the flap regressing mode, but studies of high-gain feedback control concepts may also require inclusion of the rotor inplane degree of freedom. The inplane degree of freedom generally does not introduce a significant net reaction at the hub and is usually ignored for most flight dynamics studies.

A rotorcraft simulation capability to meet the needs of research and development must be able to represent the essential effects of nonlinear aerodynamics and at least the flap, lead-lag, and rotor speed degrees of freedom. To accommodate a mathematical model of this complexity without introducing a significant time lag, a very large general-purpose digital computer such as the CDC 7600, CYBER 175 or some of the larger IBM 360 and 370 models would be required. In view of the cost of such computers, a study was made to determine if there were any other ways to solve the problem more cheaply. It was concluded that a host digital computer of moderate size supporting a peripheral special processor is capable of meeting the computation requirements (Ref. 24). Several candidate peripheral processors were identified as potential candidates that could indeed perform the chosen baseline model computations sufficiently fast. They ranged from special-purpose array processors, through concepts using several processor modules combined into a parallel architecture, to a special hybrid digital-analog device.

The special-purpose array processors are widely used in the field, but this would be a new application for which little software support exists. Programming requires assembler and machine language which could be tedious compared with FORTRAN. Concepts using several processors combined into a parallel architecture seem feasible but are new and may take considerable development. Programming the multiprocessors would be complicated by the scheduling and cueing requirements. The hybrid concept that was considered was designed especially for real-time simulation of rotorcraft. It is hard wired and uses entirely integrated circuit technology. A flexible set of helicopter equations of motion are programmed into the computer and when changes to the model are required, coefficients can be reset. One example of the device has been delivered and two more are on order. The cost of these special-purpose processors are all in the range of $100,000 plus $200,000 for the associated host digital computer, a modest price compared with that of a large general-purpose digital computer. Further studies will be required to see if any of these devices are practical for a research facility where frequent model changes are routine. While the initial acquisition costs are considerably less than that of a general-purpose digital computer, the programming difficulties may make these approaches impractical.

In non real-time simulations, the rotor is represented by the actual number of blades, a sufficiently large number of blade segments is used to represent the spanwise loading distribution accurately, and only a small rotor azimuth advance angle is allowed between each computation. Simplifications for real-time operation have included reducing the number of blades, reducing the number of spanwise segments and increasing the azimuth advance angle. Cooper and Howlett (Ref. 25) and Houck (Ref. 26) present results of a detailed investigation into the effect of such simplifications on the overall simulation. For example, Figure 14a from Reference 25 shows how the forces and moments are affected by reducing the number of blades. While the moment, thrust and torque may be sufficiently accurate with less than the actual number of blades (n), the n per revolution variations in the rotor forces and moments are correct only when the correct number of blades is used in the computations. The artificial n-per-revolution oscillations can be filtered out, and Figures 14b and 14c show how reducing the number of segments and azimuthal spacing affects these filtered forces and moments. Unfortunately, even if a study is performed to determine the errors which result from such a series of simplifications, until the errors become extreme it is still difficult to predict what effect these errors have on the total response as felt by the pilot.

Apart from the difficulty of obtaining an adequate approximation of the complex math model that will run in real time with limited computer capacity, there is the basic question of how well the real helicopter is represented. The only check for this is to compare response time histories from flight tests with those from the simulator models; however, even this poses difficulties. To check the mathematical model, comparisons are made between the actual and predicted trim conditions (that is, speed, angle of attack, power, control positions, etc.) and responses to various control inputs. The problem is to decide whether the differences are sufficiently large to influence the simulation fidelity. This is the same problem we faced when judging the adequacy of a simplified mathematical model and there are no easy answers.

If the comparison between the experimental and theoretical responses are obviously inadequate, the problem becomes one of deciding how to change the mathematical model to improve the correlation. A few parameters, such as initial response to control, may be relatively uncoupled and identifiable. Generally, however, one has to delve deeper, and the application of parameter identification techniques should help in this regard. A program has been jointly funded by the U.S. Army and NASA to apply advanced techniques of state estimation and parameter identification to rotorcraft (Ref. 27). The model form is based on a Taylor's Series expansion of the forces and moments, including nonlinear terms, and the degrees of freedom include rotor coning, flapping and lagging. In applying these parameter identification techniques to improve the math model for real-time simulation, one technique is to compare the parameters derived from flight test with the same parameters extracted from the simulation math model. These can be extracted by perturbing each variable one at a time and determining the resultant changes in forces and moments, or by using a technique such as the flight test parameter identification technique on the simulator generated time histories. The question of how good a comparison is adequate must still be faced, this time in terms of model parameters which may be more difficult to assess than differences between time histories. There is the additional task of changing the simulator math model to achieve a better fit between parameters obtained from the simulator math model and those from flight test. This will require keen insight into the simulator model and the physical contribution of the various components in the model.

Despite the difficulty of this model development and verification task, it is a necessary element if we are to exploit fully the simulator potential for supporting the aspects of system development discussed earlier in this paper.

VII. SUMMARY AND CONCLUSIONS

Our studies have shown the need for flight simulation in research and development of rotary-wing aircraft and have defined some of the requirements for adequate fidelity in order to simulate the missions and tasks that are unique to rotary-wing and V/STOL aircraft. Helicopters and military missions in particular impose special requirements on flight simulation. Flight at very low altitude is in an environment requiring a highly detailed out-of-the-window display to be presented over a wide field of view. Use of a simulator for helicopter system development necessitates high dynamic fidelity for all components and especially for the most expensive components that provide the visual display, the motion cues and the mathematical modeling. We expect that the motion system fidelity requirements will be achieved with the planned modifications to NASA's Vertical Motion System. Visual display requirements for military mission simulation are the most critical limitation on environmental simulation. Hypothesized desirable performance levels for field of view, detail, resolution and dynamic response are unlikely to be realized in the near future. Computer-generated imagery offers the most promise for the field of view and resolution capabilities, and recent advances suggest that acceptable detail will be available soon. It is not clear at this time what image presentation system may be adequate. Candidate systems are those based on improved projection, laser scanning, and solid-state devices.

Little need be said about computers since, generally, this element of simulation represents no constraint except that of cost. However, the need for accurate input data is increased, and there will be increased pressure to provide, for development simulation purposes, a fully comprehensive set of aerodynamic, structural and system data very early in the life of a new project.

There is still room for considerable advances in the technology of simulation, particularly for visual systems and equally for improved understanding of the effects of deficiencies in motion and visual systems on the pilot's performance and subjective assessments. Inevitably, these further improvements in technology will be expensive, and compromise on the basis of cost effectiveness will have to be reached. It is already impossible for every organization to order the best available visual or motion system because the cost of a complete facility is now comparable with that of a medium-sized aircraft. Most users will have to accept something less than the best without (at present) much sound advice as to the effect of this or that compromise. Continuing effort is needed to collate and digest experience and future prospects so that limited financial resources may be used to best advantage.

Simulation has established itself as an important and relevant technology. It is to the flight dynamicist what the wind tunnel is to the aerodynamicist. With still rising costs of flying and flight testing, the cost savings represented by extended use of simulation, already large, will increase and the future of the art seems assured.

We expect that the current U.S. Army/NASA joint program will result in a unique capability at the Ames Research Center that will benefit the entire helicopter industry. Similar facilities in NASA have been used extensively by European as well as U.S. fixed-wing industries and we expect to see the same use of this new facility by the rotary-wing community. We are confident that the rotorcraft simulator will represent a major step forward in simulation capability and that it will prove as valuable to rotorcraft research and development as has its counterparts in the fixed-wing industry.

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TABLE I. VISUAL DISPLAYS EVALUATION
(from Ref. 10)

Group \ Factor	Field of view	Textural quality	Resolution	Response to inputs	Range	Flexibility	Installation overhead[a]	Capital cost
Raster TV/model	E[b]	B[c]	D	D	D	D	High	Moderate +
Film/Servo projector	E	B	A	D	D	E	Moderate	Moderate
Laser TV/model (predicted)	C[d]	B	A	D	B	D	High	High
Night CGI	C[d]	D[e]	B	B	B	D	Low	Moderate −
Night CGI with raster infill	C[d]	C	B	B	B	D	Low	Moderate
Day CGI	C[d]	D	C	B[f]	C	B	Moderate −	High
Contact analog	C[c]	E	C	A	E	D	Low −	Low

Scale: A (Excellent) — B — C — D — E (Barely acceptable)

Notes:
[a]Space, power consumption
[b]One window
[c]Modelling limit
[d]Three window
[e]No credit for neon signs and firework displays
[f]Subject to good cycle time

TABLE II. MOTION (PLATFORM) REQUIREMENTS FOR CRITICAL TERRAIN FLIGHT MANEUVERS (from Ref. 12)

Axis	Parameter: Position, rad, m	Velocity, rad/sec, m/sec	Acceleration, rad/sec^2, m/sec^2
Yaw	±0.4	±0.6	±1.0
Pitch	±0.3	±0.5	±1.0
Roll	±0.3	±0.5	±1.0
Surge	±1.3	±1.3	±3
Sway	±3	±2.6	±3
Heave	+7, -14	+8, -11	+14, -12

Notes:
The requirement is for simultaneous operation.
The rotational gimbal order is yaw, pitch, roll.
Translational axes are orthogonal; plus is forward, right, and down.

TABLE III. EXAMPLES OF SIMULTANEOUS EXCURSIONS (from Ref. 12)

Axis at maximum position	Simultaneous axis position, % maximum: ϕ Roll	θ Pitch	ψ Yaw	X Surge	Y Sway	Z Heave
ϕ	100	0	31	0	92	73
θ	60	100	6	83	46	14
ψ	67	22	100	28	54	41
X	33	33	19	100	0	59
Y	87	33	38	83	100	77
Z	47	33	0	56	69	100

TABLE IV. MOTION PLATFORM THRESHOLDS (from Ref. 12)

Angular: Position	Velocity	Acceleration	Linear Acceleration
$\frac{0.2}{\omega}$ deg	0.2. deg/sec	0.2 ω deg/sec^2	0.01 g
ω in rad/sec			

TABLE V. ROTORCRAFT MATH MODELS FOR PILOT-IN-THE-LOOP SIMULATION

Applications	Model complexity							
	Linear aerodynamics with simplifications					Nonlinear aerodynamics		
	Fuselage and quasi-static rotor 6 DOF	Fuselage and rotor flap 9 DOF	Fuselage and rotor flap/rpm 10 DOF	Fuselage and rotor flap/lag 12 DOF	Fuselage and rotor flap/lag/pitch/rpm 16 DOF	Fuselage and quasi-static rotor 6 DOF	Fuselage and rotor flap/rpm 10 DOF	Fuselage and rotor flap/lag/pitch/rpm 16 DOF
I. General flying qualities - well within flight envelope								
(A) Basic aircraft								
• Low freq. maneuvers	X							
• High freq. maneuvers		X	X					
(B) SCAS research								
• Fuselage feedback	X	X						
• Fuselage/rotor feedback		X	X	X	X			
II. General flying qualities - full flight envelope								
(A) Basic aircraft								
Envel. exploration and maneuv. perf.						X	X	X
(B) Boundary limiting and expanding SCAS							X	X
III. Specific aircraft flying qualities						X	X	X

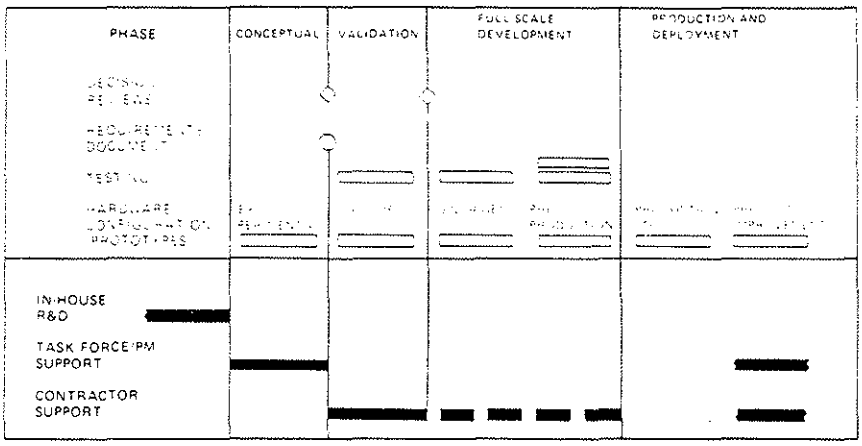

Fig. 1 Use of an engineering simulator through a typical aviation system acquisition cycle.

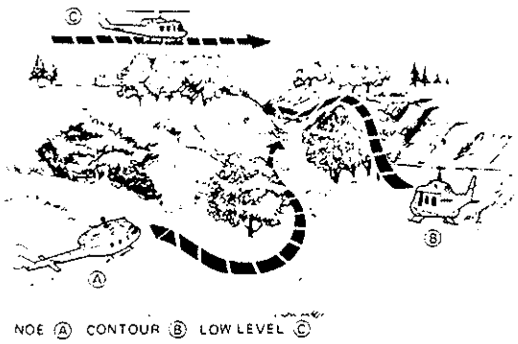

Fig. 2 Terrain flying regimes.

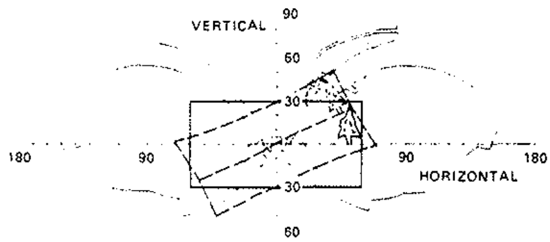

Fig. 3 Effect of display rotation on viewing area (from AH-1G - pilot's position).

Fig. 4 Terrain board detail at 400:1.

Fig. 5 Detailed CGI scene.

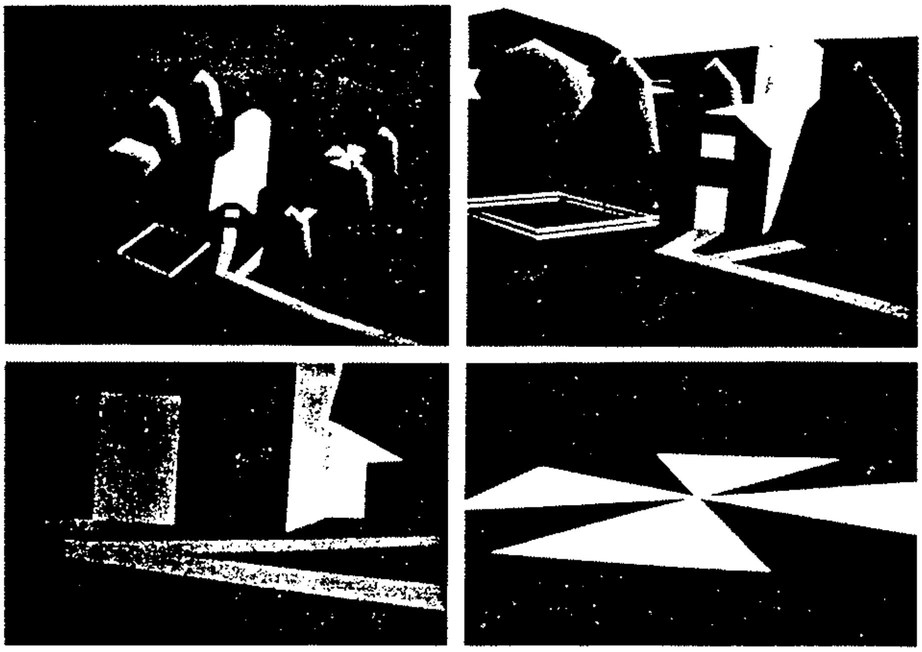

Fig. 6 Reduction in detail as surface is approached.

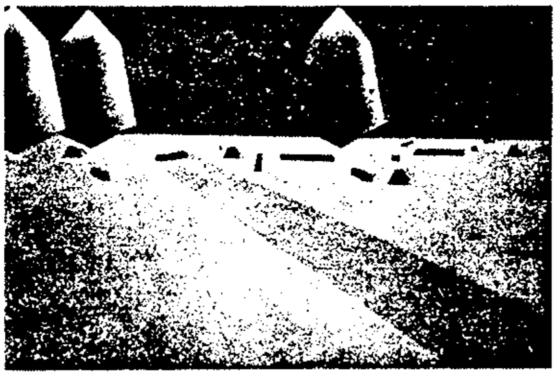

Fig. 7 CGI test terrain.

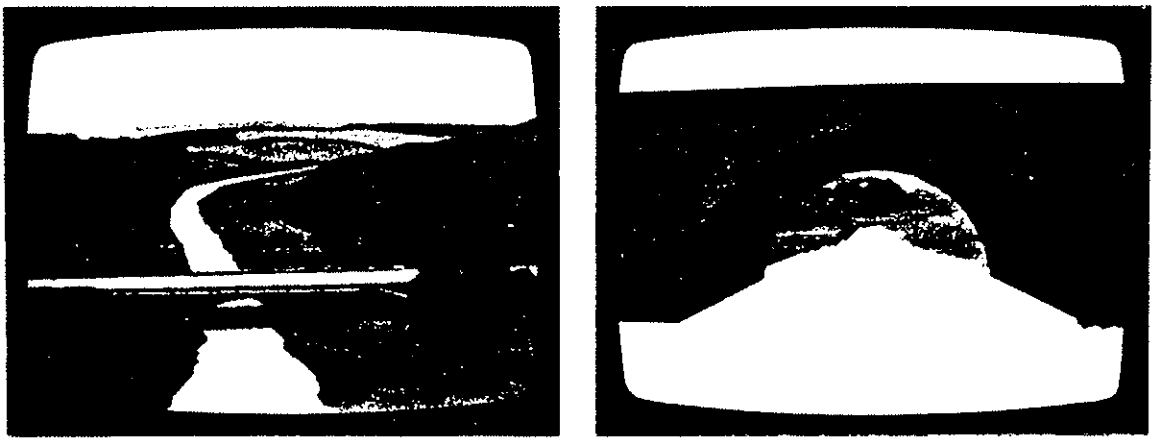

Fig. 8 Texture possibilities.
(Reproduced with permission of Marconi Radar Systems Limited.)

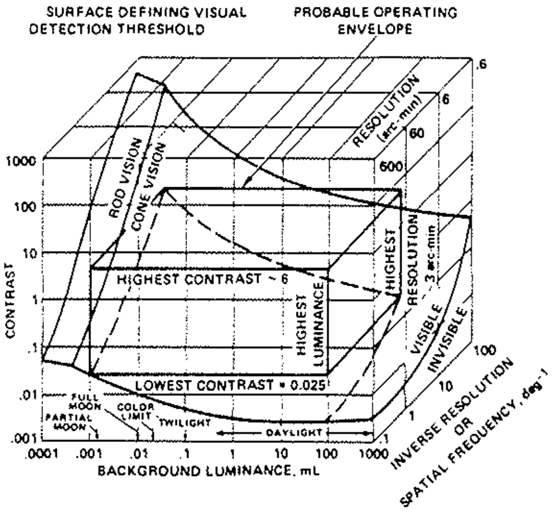

Fig. 9 Visual performance envelope (from ref. 12).

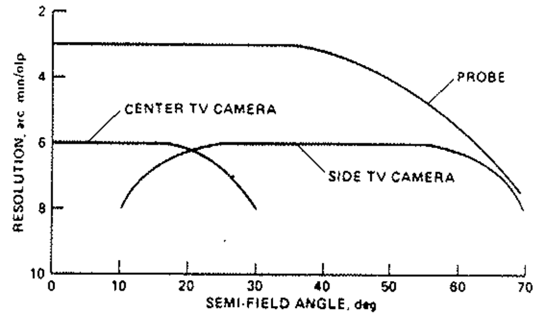

Fig. 10 Limiting resolutions vs field-of-view for probe and TV cameras (from ref. 12).

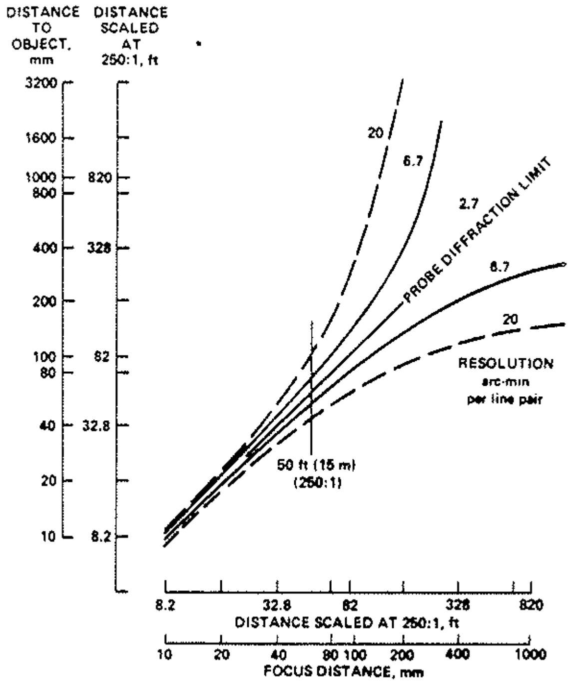

Fig. 11 Probe depth of field vs focus distance (from ref. 12).

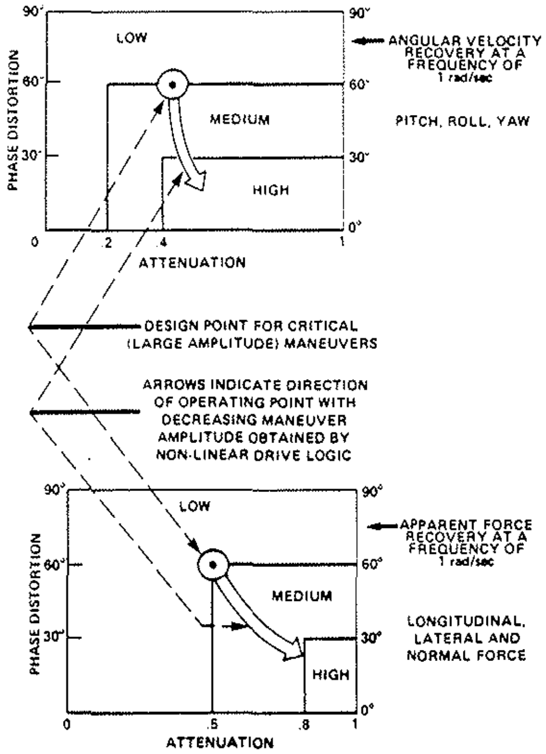

Fig. 12 Platform motion fidelity criteria (from ref. 12).

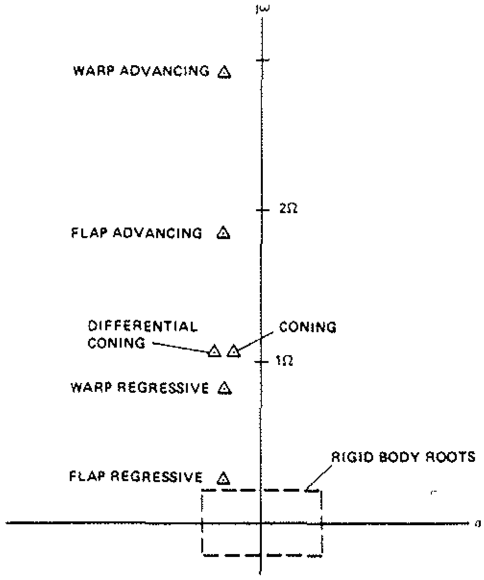

Fig. 13 Illustrative diagram plot showing typical characteristic root location for a six-bladed flapping rotor (from ref. 23).

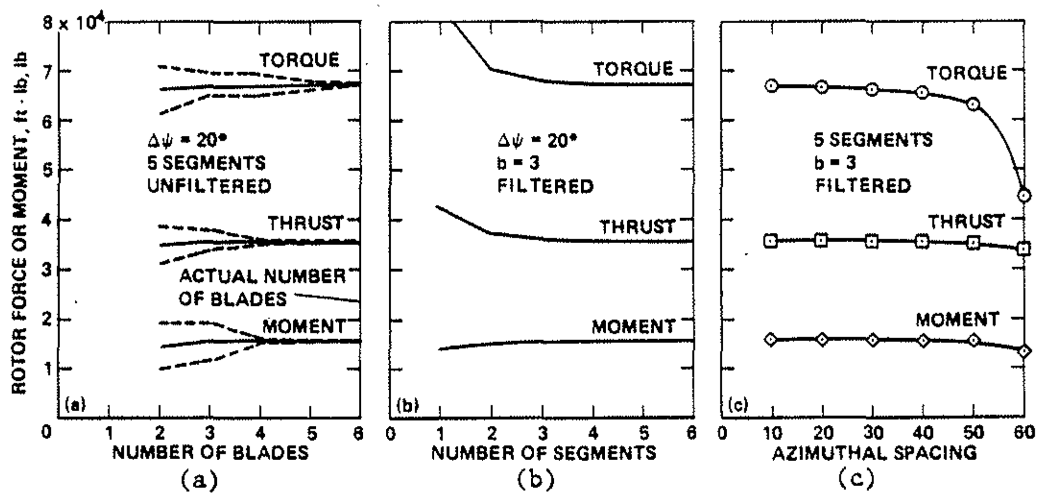

Fig. 14 Effect of blade truncation and azimuthal update on rotor force and moment output - 100 KTS (from ref. 25).