DETERMINATION OF HELICOPTER SIMULATOR TIME DELAY AND ITS EFFECTS ON AIR VEHICLE DEVELOPMENT*

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ABSTRACT

McDonnell Douglas Helicopter Company recently undertook a study to determine the actual simulator hardware time delay in all the simulators. It also investigated the effect of time delay on pilot performance and his aircraft evaluation in an engineering design environment. This paper describes the system architecture, techniques of measuring thruput delays, and initial study results. The average simulator delay was 87 milliseconds for the simulator with conventional flight control with the host computer running at 60 Hz. The average simulator delay was 101 milliseconds for the simulator with digital flight control system with the real time host executing at 30 Hz. The first value is less than those reported in the open literature for most of the engineering and training simulators while the second value is on par with the state-of-the-art systems in the industry. The second phase of the study involved systematically varying the simulator delays so that data on the effect of time delay could be collected and used as a useful parameter in aircraft/simulator design. Pilot performance was recorded and subjective evaluations in the form of Cooper-Harper ratings were also obtained. Analysis of pilot performance did not provide any dramatic changes due to increased simulator delays but did show that the pilot control activity increased in the low speed, high gain tasks. It was found that with increased time delay the Cooper-Harper rating increased indicating degradation in perceived handling qualities. However, for the type of helicopter simulated, there was not a definite time delay at which the ratings changed abruptly. This indicates that for engineering design purposes while it is desirable to keep the delay to the absolute minimum, there may be sufficient flexibility in the design of the simulator to permit cost/capability trade-offs. However, this needs to be further validated by additional tests that introduce pilot distractions (such as gusts) and force the pilot to increase his closed loop gain.

ABBREVIATIONS

A/D	Analog to digital
CIV	General Electric CompuScene IV
COMM	Communications
CPU	Central processor unit
DIST	Distribution
ETSD	Engineering and Training Simulation Department
HMT	Helmet mounted tracker
HSD	High Speed Data Interface
Hz	Hertz
IAT	Image auto-tracker
IHADDS	Integrated Helmet and Digital Display System
IPU	Internal processor unit
I/O	Input/output
MFD	Multifunctional display
mm/Sec	Millimeters per second
msec	Milliseconds
RTIO	Real-time input/output
SCS	Systems control station
SOPS	Servo Optical Projection System
VSM	Video/Switcher Mixer

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With the advances in simulation technology, simulators have come to play a very important role in the design and development of aircraft [References 1-4]. While the use of simulators for fixed wing design has been more common, engineering simulation as a design tool in rotorcraft development is a fairly recent application [References 5-16]. The simulation fidelity is very much dependent on a number of factors and there have been a number of research articles on this [References 17-23]. One of the important factors that influences simulation fidelity and pilot's perception as well as his ability to control and fly the air vehicle is simulator time delay. A number of researchers have examined this issue predominantly from a fixed wing aircraft aircrew training perspective [References 24-26]. The Naval Training Systems Center (NTSC) has conducted several studies on helicopter simulation fidelity [References 27-30]. These papers have examined in general terms the influence of visual system delay, among other factors, in hover/landing training tasks. The simulators used in these studies were, of necessity, limited in capability especially in visual cues and had somewhat large simulator system delays. Much more advanced helicopter simulators with superior visual simulation realism have been recently developed by several helicopter manufacturers. These simulators have come to play a very important role in the design of helicopters. These considerations make it necessary to examine in depth what role simulation time delay plays in an engineering design environment.

McDonnell Douglas Helicopter Company had recently set up a multi-ship simulation capability in support of its rotorcraft design and development [References 9, 14, 16, 31]. This facility currently has three twenty-foot diameter dome, fixed-base simulators. The facility employs state-of-the-art computational and visual systems with head-tracked, very large field-of-regard display systems. Modular crew stations simulating the appropriate air vehicle configurations are set up in the domes for engineering evaluations. As a part of simulation validation, the simulation department undertook efforts to determine the magnitude of simulator system delay. It was also desired to assess what impact the simulator system delay plays in a new aircraft design where the actual aircraft has not yet been flown and whose actual flight characteristics are unknown to the pilot. It may be noted that to date there has been no definitive study to establish system delay requirements for helicopter simulators and the helicopter manufacturer has to use engineering judgment in the simulator application for design.

The first part of the paper discusses the determination of actual system delay in the McDonnell Douglas Helicopter Company simulators. It briefly describes the simulator system, the test set-up and methodology and test results. The second part describes piloted simulator evaluation of a generic, high performance, combat helicopter with varying simulator time delays. It describes the test maneuvers, the test pilots' background and their assessment of aircraft handling characteristics.

SYSTEM DELAY MEASUREMENTS

Scope

The simulator system delay is defined here as the time interval between a step input at the crew station flight controller and a resultant change in the visual sensory cue output. Two sources contribute to the total system delay. First is the finite time delay (thruput delay) involved in hardware implementation of simulation of the aircraft and its system/subsystems, and the aircraft's relation to its environment. The second source is model inexactness arising from approximating a complex physical process for ease of real-time simulation. If a perfect model is used, this delay will be zero and the system delay will be just the hardware thruput. This study assumed a perfect model because of the generic nature of the simulated aircraft. Hence, the system time delay measured is strictly the hardware delay.

The study made the following additional assumptions:

1. Frames were not overrun [later verified].

2. Transmission times were small in magnitude with respect to the total thruput delay, i.e., for hardware interfaces, electrical signals and light propagation.

Description of the System

The systems used for the study were a known, managed configuration of hardware and software modules. The thruput studies were conducted on two separate simulation systems in isolated domes: one system for conventional flight controls, and the other system for digital flight control laws. Both systems utilized duplicate computing and digital image generation hardware, the same aero model and similar interface control. The simulator delay effect study was conducted only on the system configured with conventional flight controls. Fig. 1 illustrates the simulator hardware architecture. This system is hosted on a Gould Concept 32 Series 9780 computer system that runs the simulation in several internal tasks in two separate processors: 1) a Central Processor Unit (CPU), and 2) an Internal Processor Unit (IPU). This study concentrated on three specific tasks: 1) the control loader interface task (running in the CPU), 2) the IPU task, and 3) the CPU task. The control loader interface task accepts the control stick inputs from the HSD link and places the control positions into DATAPOOL common memory locations. The IPU has responsibility for running the flight model and control laws. The IPU cannot do I/O and shares memory with the CPU through DATAPOOL. DATAPOOL is a feature of the Gould operating system similar to a FORTRAN common with a nonrelocatable memory partition assigned during system configuration. In the IPU task, the control positions are retrieved from DATAPOOL, scaled and offset, and then used by the aero model to compute and update the aircraft position and attitude, which are then stored in DATAPOOL memory locations. The CPU does all I/O tasks. Specifically, the CPU task is responsible for: 1) digital image generation system interface, 2) avionics interface, 3) systems control station (SCS) interface, 4) environment control, 5) initialization, 6) data collection, and 7) mission record/ playback. All tasks in the IPU and the CPU communicate through DATAPOOL common memory. The simulator is configured with a conventional flight controls system.

The embedded microprocessors in the modular crewstation perform aircraft systems and avionics simulation, and display processing, thus providing considerable computational relief to the real-time host. This permits the flight simulation to be run at 60 Hz.

The system configured for digital flight controls [not shown] is also hosted on a Gould Concept 32 Series 9780 computer system that runs the simulation in three internal tasks. The significant difference in the tasks from the conventional controls system is that the control loader interface task is replaced by a simpler digital controller interface task. Hardware architecture differences are found in the Adage Graphics system driver for the multifunctional displays (MFD), a Chromatics moving map display, and sound system drivers.

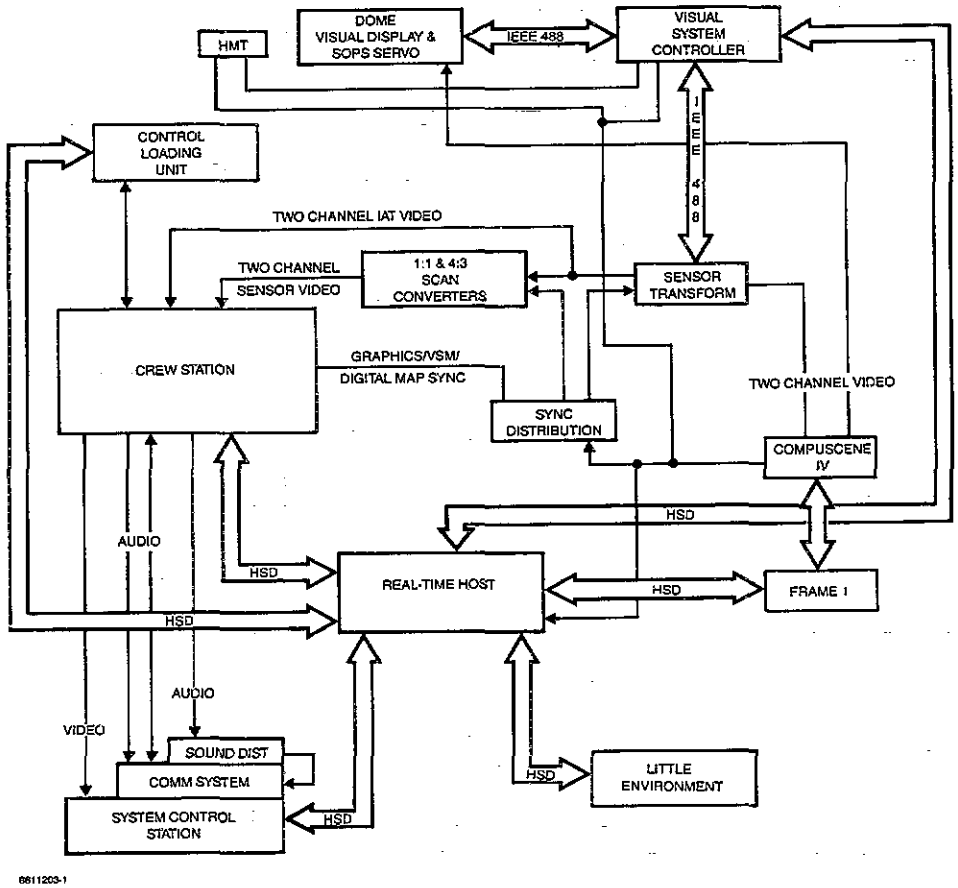

Fig. 1 System Block Diagram

Both systems interface to separate General Electric CompuScene IV (CIV) digital image generation systems, hosted on a Gould Concept 32 Series 9780 computer system, referred to as a Frame I. The output of the visual system is routed through a video matrix switcher/mixer to the background and inset General Electric light valve projectors. The projector images are routed through a Servo Optical Projection System (SOPS) that optically combines the images, and positions the projection lens through servo control in either a fixed forward mode or in head-tracking mode.

The conventional flight controls system consisted of a McFadden hydraulically driven, control loading system with a digital interface to the real-time host. The force versus displacement feel characteristics model replicated the feel characteristics of a generic rotorcraft.

Fig. 2 illustrates the conventional flight controls system data flow for the three tasks with respect to cockpit control signals in and the FRAME I signal out. We have not included secondary flow paths used for monitoring, external control or environment control such as those related to the audio/communication link, the system control station/instructor inputs, and the sensor channel control.

The diagram does not show that the CPU, IPU, and CIV tasks are running synchronously and that each task is complete inside of its frame respectively. The three main tasks ran at a 60 Hz frame rate on both systems. In the case of the simulator with digital controls, the flight control task is run in the IPU at 40 Hz, while the CPU task runs at 30 Hz. The CIV only displays attitude and position. The CIV does not extrapolate position or attitude based on rate.

The other routines that should be mentioned are real-time data save to tape and the strip recorder output. On digital tape, we collected data for raw stick (digital) input, shaped and filtered stick inputs, aero forces and moments, position, accelerations, CIV interface buffered data, and a limited number of performance variables and system control flags. This is done from the CPU at 30 Hz. The strip recorder data included the analog stick position and force. The data collected on both the strip chart recorder and save tape are asynchronous.

Thruput Test Cases

The total thruput delays are relative to step inputs made at the cockpit [or controller card] and to the response of the CIV monitor. The normal path of data flow for the conventional flight control systems is identified in Fig. 2: controller input, through the A/D, through the control loader interface task, through common memory, through stick scaling and offset, through the IPU task, through common memory,

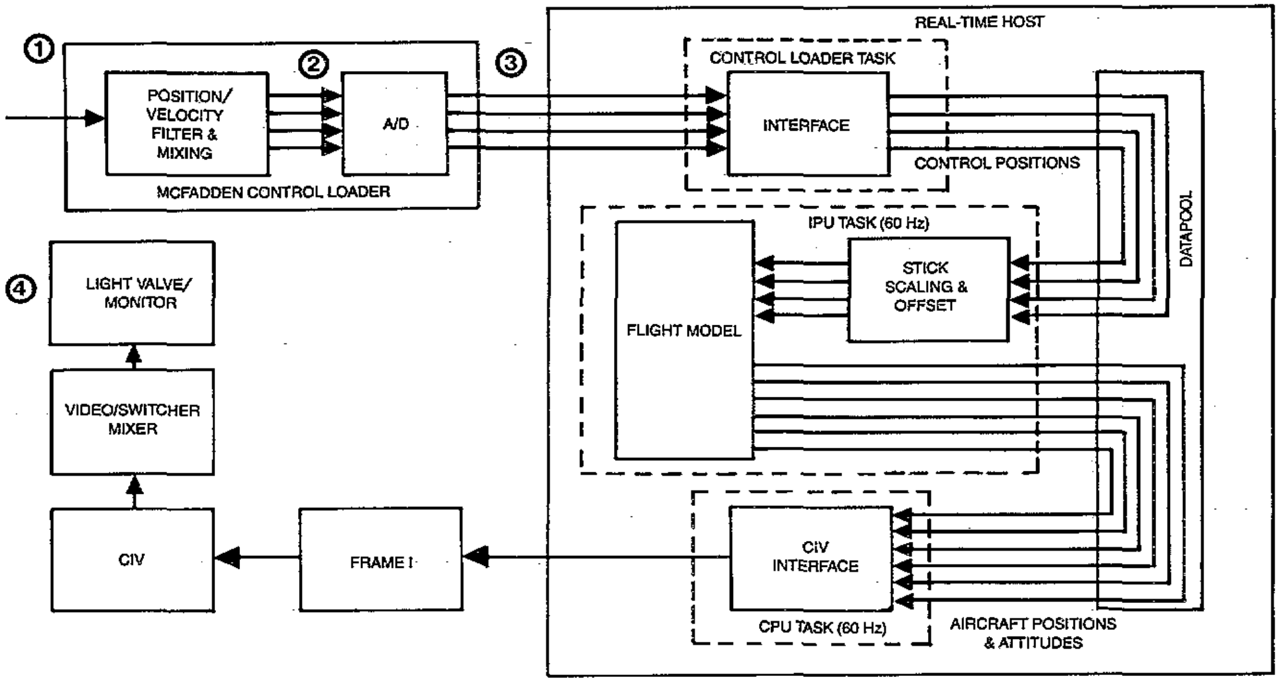

Fig. 2 System Data Flow for Conventional Flight Control System

through the CIV interface task, through the Frame I and CIV computing systems, and output video for projection to the dome and repeat on a monitor. A similar path through digital flight control system consists of: controller input, through the A/D and real-time I/O (RTIO) equipment, through the CPU task which samples the RTIO and computes stick zero shift and scaling, through common memory, through the IPU task, through common memory, through the CIV interface task, through the Frame I and CIV computing systems, and output video for projection to the dome and repeat on a monitor.

For the purposes of testing the hardware thruput delay, the output from the IPU task of the normal data flow was ignored. Values of the flight control stick position placed into DATAPOOL by the interface task were used as direct inputs to the CIV interface task. The CIV interface task monitored the flight control stick position variables for change and responded immediately in response to the stick position change. Modifications were made to the CIV interface task on each system for each test of a commanded axis, specifically pitch, roll, yaw, and lift.

Test Methodology for System Thruput Measurement

For each test case identified by input /response, a total thruput delay and a series of partial thruput delays (delay between simulator subsystems) were measured. Partial thruput delay was measured by trapping on changes to a preselected and identifiable memory locations via DATAPOOL common memory, line signal or generated interrupt. Digital data was collected from common memory and written to an on-line file and later dumped to tape for off-line processing. The digital data was collected at the CPU frame rate. Line signals were collected on strip charts running at 500 mm/Sec.

Total thruput delay was measured using defined pixel(s). A sensitive photo sensor was built to detect response of the visual system by sensing the change in pixel brightness. Analog output from the photo sensor device was assigned to a strip chart recorder channel along side the controller analog signal channels. The defined pixel(s) for the test cases were chosen to be located in objects of dark, high contrast value, and in specific areas of the database such that rotating 90 degrees in the plane of the tested axis locates another pixel of bright, high contrast value, specifically the change in brightness must be detectable by the photo sensor. Objects selected were dark pylons that contrasted well with the light blue sky.

For the total hardware thruput measurement, the CIV interface task was modified so that any detected change in the stick input resulted in an in-plane rotation of the visual by 90 degrees. The aero model would continue to integrate a response, but the output was ignored since the model delay was not being measured as part of the hardware delay. Thus, for example, during the yaw axis test, the aircraft was initialized in front of the pylon. The photo sensor was then placed on the display to detect the dark pylon. When the stick input was detected, the CIV was sent an immediate (within one frame of detection) 90 degree heading change, which now placed the bright sky in view of the photo sensor.

Response of the photo sensor was found to be less than approximately 0.25 msec, and was considered insignificant. Response was also measured across the controller and was found to be less than 1 msec, highest resolution of the strip chart recorder being used. We were unable to intercept electrical signals from within the control. We decided to monitor the output signal and monitored those signals at output test connections on the controller card. Another feature of the controller card allowed us to step the input voltage, similar to the result achievable to a square wave generator. We used the voltage step as our input for the conventional flight controls system once the aircraft was in position.

Total Simulator Response Test

These tests measured visual response time with respect to a step input. The flight model response is bypassed so that pure hardware delay can be measured. The tests were conducted as two sets. The purpose was to spike the visual as soon as a control input was detected. One set of tests was completed with the pilot activating the controls in the cockpit. The second set was activated by switching input voltage to the card representing the control input. This technique is similar to the one used by NTSC [Reference 32]. A modification was made to the real-time host software which responded as soon as the input was detected. The response rotated the model position 90 degrees. The position change sent to the Frame I resulted in a visual change from the CIV.

The aircraft was positioned in a reproducible location in front of a vertical bar at the runway in the visual database. Once the correct position was established, the test engineer placed the photocell on the high resolution monitor in the most sensitive position then directed the pilot or engineer to make the appropriate step input in the directional axis using the control for one set of tests and the voltage switching for the second set of tests. The input control position signal and the photo sensor output signal were recorded at a rate of 500 mm/Sec. The time delay between reference points 1 and 4 (Fig. 2) was measured on the strip chart recorder.

RESULTS

Fig. 3 summarizes the end-to-end results for simulator with conventional flight controls and shows an approximate total delay of 87 msec. This corresponds to path from reference points 1 to 4 in Fig. 2. Fig. 4 summarizes the results for the simulator with digital flight controls and the delay is approximately 101 msec.

EFFECTS OF SIMULATOR TIME DELAY

Having determined the simulator time delay, the next phase of the study was to investigate how the time delay affects pilot's performance and his perception of the aircraft. The simulator with conventional control was chosen for this study since the test pilots were more familiar with similar aircraft. This also avoided the digital control laws smoothing or masking the finer effects due to the time delay.

Test Method

The study required the pilots to fly three different types of courses/maneuvers; narrow slalom/dolphin, serpentine, and longitudinal quickstop. These three courses/maneuvers cover most of the helicopter's flight envelope; high speed, low speed-hover, and transition.

The Narrow Slalom/Dolphin course, Fig. 5, required the pilot to fly through pylons while maintaining constant speed and an altitude below 25 feet except when maneuvering over the two 50 foot obstacles within the course. Prior to each run the aircraft was initialized in a hover some distance out away from the course, the pilot then accelerated to his test speed of 70-85 knots. He entered the course at this speed and negotiated the pylons and 50 foot obstacles. This task heavily taxed his lateral, directional, and vertical controls while attempting to maintain constant velocity. The Serpentine course, Fig. 6, was a low speed maneuvering task of 10-20 knots. The pilot was required to start from a stabilized hover then follow the centerline of the closed course for one lap. The pilot must follow the course, stay below 25 feet, and maneuver over two 25 foot brick wall obstacles. The run was complete after one lap. This course required precise control in all axes.

The longitudinal quickstops were done along a road next to the Slalom/Dolphin course. This is visible on either side of the course (Fig. 5). From a stabilized hover the pilot accelerated to 60 knots, then decelerated back to a hover while maintaining constant altitude. He was required to maintain his alignment over the road, constant heading, and altitude. The run was complete when a hover was again established.

The helicopter crewstation, as mentioned earlier, was conventionally configured with cyclic, pedals, and collective with an integrated helmet and digital display system (IHADDS) for heads up flight symbology. The flight symbology displayed ground speed, heading, radar altitude, torque, and rate of climb simultaneously. Below 20 knots, an acceleration cue and velocity vector were displayed, while above 20 knots, a pitch ladder appeared showing pitch and roll attitude.

Delay was added to the pilot inputs in the real-time host software at the point the stick scaling and offsets were calculated [see Fig. 2]. The input data for all axes from the McFadden control loader task was stored in separate arrays along with 2 seconds of past data which was constantly updated, similar to pushing data onto a stack. The software control was written such that the simulation operator could select 0 to 10 frames of delay to the control law inputs, which determined the point at which data was pulled from the stack. The delay was added equally to all axes of control: longitudinal cyclic, lateral cyclic, pedal position, and collective.

The pilot was exposed to 0, 2, 4, 6 and 10 frames of delay to input; at 60 Hz this is 16.7 msec/frame. Prior to taking data the pilot was allowed to practice the course

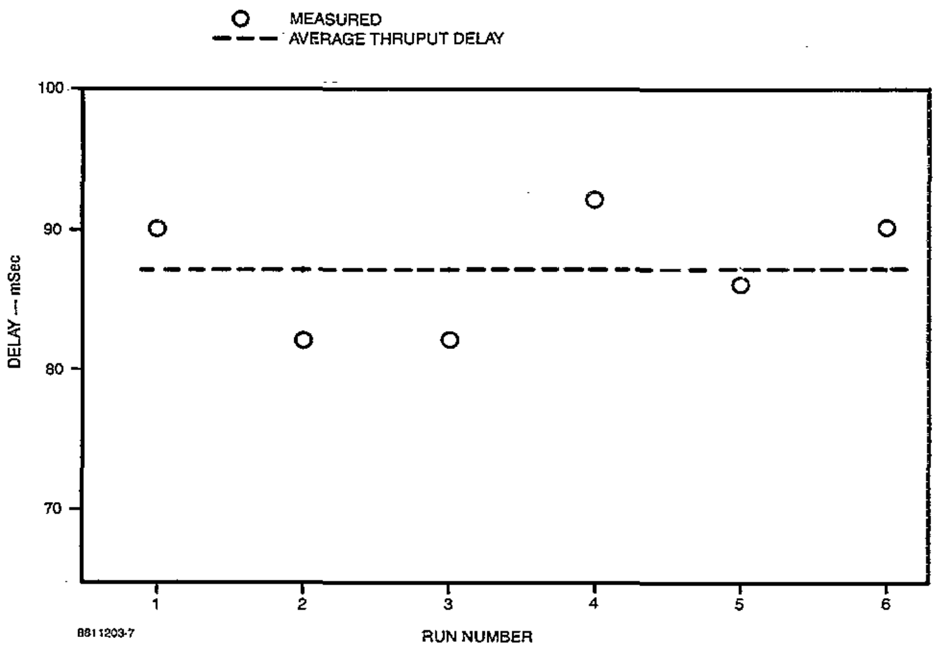

Fig. 3 Total Hardware Thruput Delay for Simulator with Conventional Flight Controls

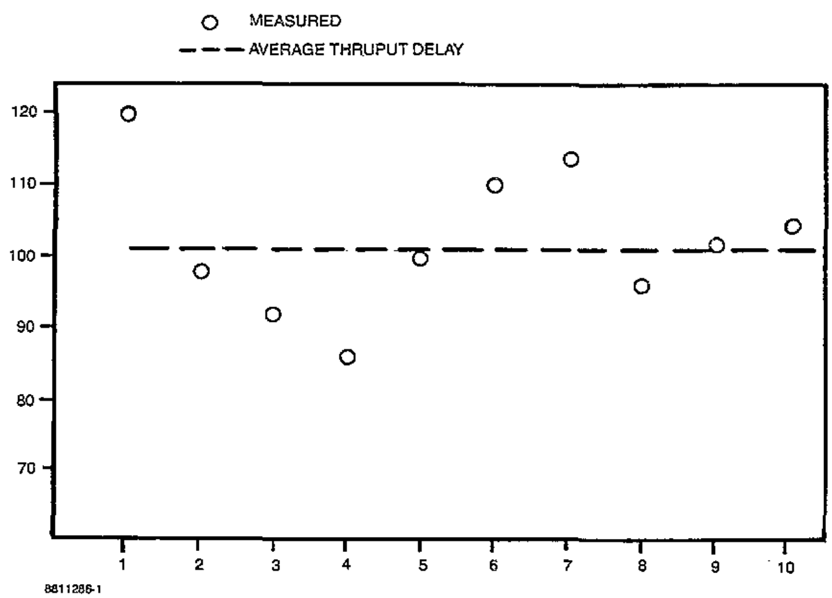

Fig. 4 Total Hardware Thruput Delay for Simulator with Digital Flight Controls

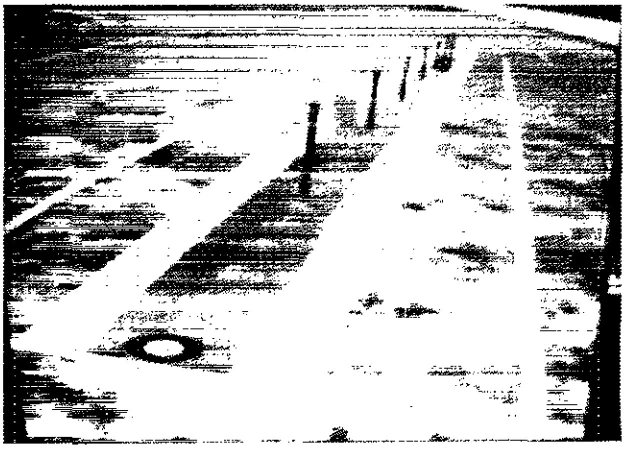

Fig. 5 Narrow Slalom/Dolphin Course

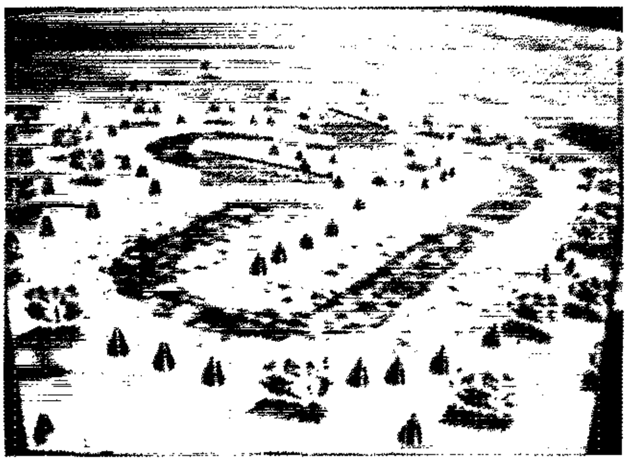

Fig. 6 Serpentine Course

until he was comfortable with the task. When ready he was initialized at the start point and proceeded to fly the run. He flew each delay 3 times in a somewhat random order for a total of 15 runs. The tests on each course took approximately 40 minutes to complete. During each run, performance data was recorded on magnetic tape and analyzed at the end of the session for controller activity. At the end of each run, the pilot was asked to evaluate the task with Cooper-Harper ratings (Fig. 7) [Reference 33]. Sessions were limited to one and one half hours per day per pilot, and only one course was flown each day to alleviate pilot fatigue.

Pilot Backgrounds

We selected four pilots as subjects for the delay study. Total flight time for each pilot ranged from a low of 2650 to a high of 7300 hours, Pilots A, C, and D were former U.S. Army pilots. Pilot B was a former U.S. Marine Corps pilot. All pilots are present employees of McDonnell Douglas Helicopter Company. Pilots A and B are company experimental test pilots. They had test pilot school training and were well versed in conduct of similar studies. Pilot C is a flight controls engineer and a current instructor pilot with the Army National Guard. Pilot D is a simulation pilot/engineer.

Pilot A has 5300 hours of total rotary wing flight time, Pilot B 1950 hours, Pilot C 2950 hours, and Pilot D 3250 hours. Their backgrounds included nap-of-the-earth flight experience and scout/attack mission experience.

Each of the pilots had expressed concern for and the importance of duplicating the real vehicle delay and minimizing the simulation delay. They felt that this fidelity factor of simulation was critical to any development program or study of handling qualities and performance.

Each pilot was briefed about the control input delays during the study. The sequence of delays would be random, but would remain constant for each run of the course. They were asked to evaluate the task using the Cooper-Harper rating scheme, and not to try to guess the delay length.

RESULTS

Fig. 8 is a graphic presentation of the ratings plotted against the delay for each course. From the median of the ratings, a slight trend moving from "deficiencies warranting improvement" to "deficiencies requiring improvement" is indicated with increased time delay. While the vehicle was still controllable, the pilots could not estimate the number of frames at which the simulation would become uncontrollable. The subjective Cooper-Harper ratings confirm their impressions.

Reviewing the plotted digital data, we found that the delay was more significant in the low speed, high gain task. During the high speed task, we found that as the delay increased, the stick activity increased only slightly, but the flight path became slightly tighter past the pylons. An example plot is shown in Fig. 8. The data also confirmed that the tasks were still controllable with only a slight increase in activity as the delays were increased from 0 to 10 frames.

CONCLUSIONS

McDonnell Douglas Helicopter Company had recently set up an advanced rotorcraft simulation facility. As a part of the simulation validation process, the simulator time delay was measured. The test consisted of applying pilot control input at the stick and measuring time delay to obtain the visual system response. Measurements showed that the average thruput delay was 101 msec for the helicopter with digital flight controls and 87 msec for the helicopter simulator with conventional flight controls. These are significantly less than the time delays reported in the literature for other simulators. As a second part of the study, piloted evaluations were done to ascertain the impact of time delay on pilot's performance and their evaluations of the aircraft. A generic high performance helicopter was simulated and typical maneuvers covering important regions of the flight envelope were flown. Four pilots with high helicopter flight time served as study subjects. Varying time delays (up to 253 msec) were introduced in a random fashion during different runs. Pilot performance was recorded and subjective evaluations in the form of Cooper-Harper

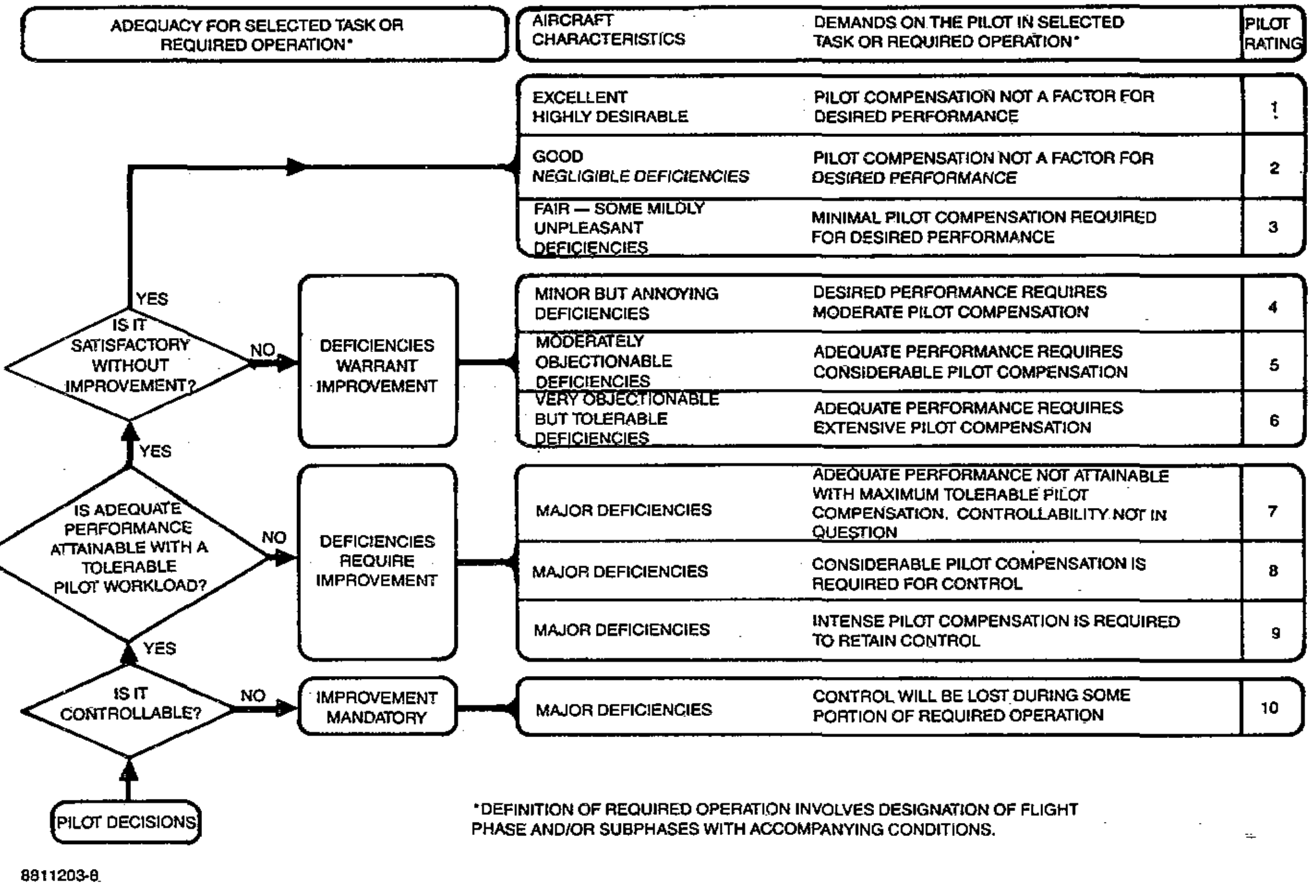

Fig. 7 Cooper-Harper Rating (from Reference 33)

ratings were also obtained. Analysis of pilot performance did not provide any dramatic changes due to increased simulator delays but did show that the pilot control activity increased in the low speed, high gain tasks. It was found that with increased time delay the Cooper-Harper rating increased indicating degradation in perceived handling qualities. However, for the type of helicopter simulated, there was not a definite time delay at which the ratings changed abruptly. This indicates that for engineering design purposes, while it is desirable to keep the delay to the absolute minimum, there is sufficient flexibility in the design of the simulator to permit cost/capability trade-offs.

However, this judgment has to be validated by further studies based on the findings of Smith and Bailey for fighter aircraft in-flight simulation [Reference 34]. Their study cites instances where, with high initial time delay, the pilot performance degraded significantly when high stress level was introduced. It will be important to find out whether such performance degradation will be true for helicopters also and whether such effects can be reproduced in ground based helicopter simulators.

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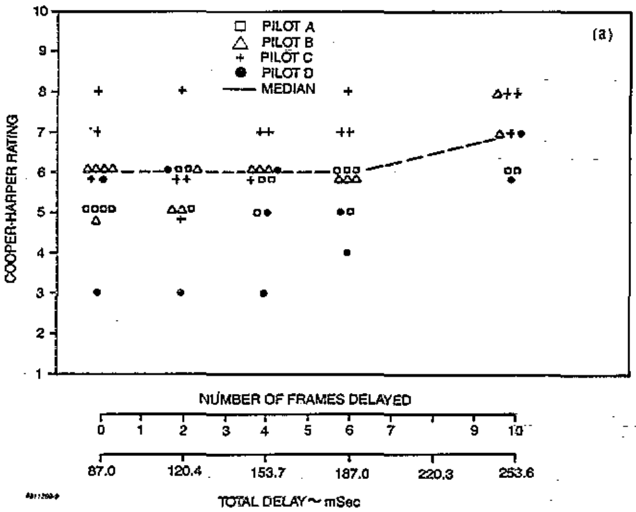

Fig. 8

Fig. 8 Effect of Time Delay on Cooper-Harper Ratings: a) narrow slalom course, b) serpentine course, and c) longitudinal quick stop.

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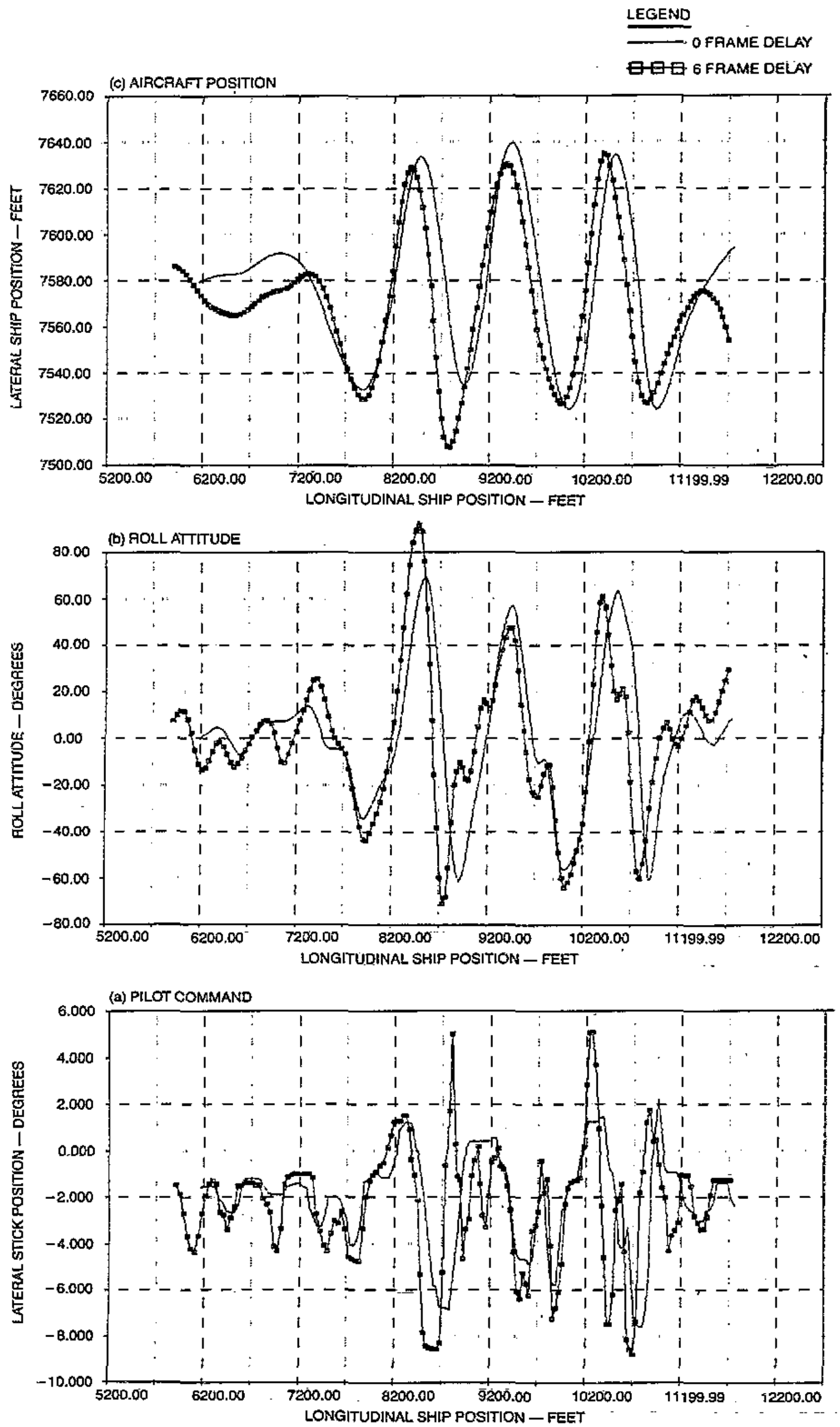

Fig. 9 Example of Effect of Time Delay on Commanded Input and Response

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