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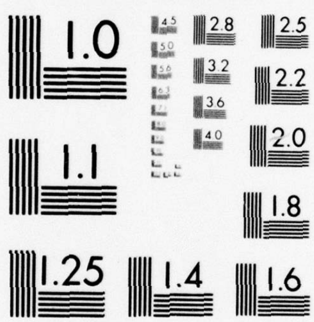

LEVEL II

Technical Report: NAVTRAEQUIPCEN IH-297
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COMPENSATION FOR TRANSPORT DELAYS PRODUCED BY COMPUTER IMAGE GENERATION SYSTEMS

June 1978

NAVAL TRAINING EQUIPMENT CENTER
ORLANDO, FLORIDA 32813

AIR FORCE HUMAN RESOURCES LABORATORY
BROOKS AIR FORCE BASE, TEXAS 78235

COOPERATIVE STUDY SERIES

Technical Report: NAVTRAEQUIPCEN IH-297/AFHRL-TR-78-46

COMPENSATION FOR TRANSPORT DELAYS PRODUCED BY COMPUTER IMAGE GENERATION SYSTEMS

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June 1978

This report was submitted by the Naval Training Equipment Center, Orlando, Florida 32813, under Project 4781, and by the Flying Training Division, Air Force Human Resources Laboratory, Williams AFB, Arizona 58224.

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This report describes a cooperative Navy/Air Force effort aimed at the problem of image-flutter encountered when visual displays that present computer-generated images are used for the simulation of certain flying situations. Two experiments are described that extend laboratory work on delay compensation schemes to the simulation of formation flight in a research device -- the Advanced Simulator for Pilot Training. The scheme used was one where low-pass filters were added to the lead-generation software of the visual display system. Both studies were geared to determining break-points for those filters (Cont'd)

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that would allow adequate flying control performance and provide an acceptable display. These experiments were based on the notion that a trade exists between the suppression of the visual image's flutter and the removal of the low frequency information necessary for flight control. One experiment represented a factorial combination of settings of the display filters and the non-visual cues of aircraft motion provided by the ASPT's g-seat and motion platform, and the second represented a simple comparison of filter settings. Both studies indicated that, at least for formation flight, there is a range of filter settings which will not adversely affect flight control and will adequately suppress visual flutter. This range represents half-power settings for the filters of 3/4 to 1 Hertz.

PREFACE

This is the first of a series of cooperative interactions in which the Naval Training Equipment Center and the Air Force Human Resources Laboratory can share their resources for research on the development and use of simulation devices and training systems. In this study, the unique capabilities of the Advanced Simulator for Pilot Training (ASPT) at Williams Air Force Base were used to address a problem of interest to both the Air Force and the Navy, namely the means of extending simulation-based training to the difficult-to-fly tasks for which, to date, devices equipped with computer image generation systems have not been used. Several of the capabilities of the ASPT were used in ways that make this study unique. For instance, this is the first study concerning the problems of formation flight performed on the ASPT, or for that matter on any device equipped with a computer generated visual scene; it is probably the first use of instructor-pilot observers in a repeater cockpit; and this is the first time that it has been possible to collect frequency-domain summary information in real-time using the ASPT.

The efforts of many people made the study possible. Captain Dan F. Cataneo, Airman Randy G. Cline, and Thomas R. Farnan, all of the Air Force Human Resources Laboratory, and Robert A. Greenland of Singer-Link served as simulator operators at the control console; Major G. Myers, Captain R. C. Brenneman, Captain J. G. Dunbar, and Captain B. D. Ott of the 97th Flying Training Squadron served as subjects in the first experiment; and Major S. P. Hannan, Jr., Major J. G. Paulsen, Jr., Captain E. B. W. Chun, and Captain J. W. Penland of the Air Force Human Resources Laboratory were the subjects in the second one.

For success, cooperative research requires attention to a great number of details, both before and after the data are collected. Captain William C. Mercer, the Chief of Naval Education and Training Liaison Officer at Williams Air Force Base energetically provided such attention and was an invaluable help, for which we thank him.

Also, a number of people helped by proofreading the report. They are Walter S. Chambers, Stanley C. Collyer, Paul E. Van Hemel, Elizabeth C. W. Ricard, and Dennis C. Wightman.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF ILLUSTRATIONS (Cont'd)

SECTION I

INTRODUCTION

A flight simulator is a complicated set of systems that can sense pilot control inputs, calculate a given aircraft's responses to them, and then present this information to the pilot. During real flight, information about the state of the aircraft comes from several sources so that, to a cockpit with its instruments and controls, today's simulators have attached a variety of cue-providing subsystems that form an interface for the human controller of the device. Their task is to provide visual, auditory, or proprioceptive signals which pilots can learn to use to control the flight of their aircraft. During the past 20 years, we have seen a dramatic increase of the number and complexity of these attachments paralleling the development of more sophisticated weapons systems that are used with more complicated tactics. Visual display systems, for example, have evolved from prerecorded films that allowed little freedom for simulated flight, to model board representations of the visual world that are presented to the pilot via a movable television camera, to the present computer image generation (CIG) visual display systems that allow limitless maneuvering by presenting visual scenes that are stored and changed by digital computer. The techniques for providing other cues for aircraft motion and of simulating an assortment of sensors have undergone a similar progression of development, and even the training systems that use flight simulators are becoming automated.

Modern flight simulators use digital controllers, and each of the developments cited above has placed a burden on the computational capacity of a device's computer. For the most part, digital computers perform calculations serially, with additional calculations requiring additional time. The CIG display processing adds perhaps the greatest number of calculations to those needed to operate the basic flight simulator. When CIG visual systems were used on Navy Device 2F90 and the Air Force's Advanced Simulator for Pilot Training (ASPT), problems of controllability caused by the addition of this type of display became apparent (O'Conner, Shinn, and Bunker, 1973; Larson and Terry, 1975). These problems of device control were usually seen during the simulation of flying situations where the aircraft had to be flown within quite narrow tolerances, such as on the last leg of a carrier approach or during formation flight.

A temporal gap between input and output is expected in systems that use digital processors as controllers. The simulator's computer must sample the inputs to the system and then calculate its responses, and in the case of a CIG visual system, a second computer usually controls the displaying of those responses. For a flight simulator equipped with a CIG display, this delay of visual feedback can be broken into two parts -- that related to the sampling rate of the flight dynamics processor and that due to the processing time of the visual display system. Current flight simulators sample pilot activity at 15 to 30 Hz so that the time interval from the calculation of one set of positions for the simulated aircraft until the next is rarely greater than 66.6 milliseconds, and the calculations needed to create each true-perspective image take about 100 milliseconds. The actual total transport delay may be less than the sum of these two values, depending upon when within the computation cycle the values for the aircraft's new position are passed to the CIG system. In the ASPT, these two computers operate at different sampling rates, with the result that the total transport delay for its visual scene varies between 126 to 193 milliseconds (Larson and Terry, 1975). Other cueing devices of a flight simulator, such as model board visual systems, motion platforms, or g-seats, produce lags due to the inertias of their mechanical components and can produce delays a good deal longer than those of the computer-generated visual displays.

One of the most difficult tasks to simulate in a device equipped with a CIG visual system is formation flight. Unlike most flying tasks, formation flight closely approximates pursuit tracking in that an image of a lead aircraft is displayed to a pilot, and he has knowledge of where he should be in relation to that craft. One might then expect that, with its visual reference, formation flight would be easier than ground-controlled approaches or instrument landings that more closely approximate compensatory tracking; but pilots do make rather high frequency control movements -- up to 3 Hz (Cyrus, 1976) -- during formation flight and we feel it is this tendency, along with the phase lag produced by delays in the system, that makes flying formation so difficult in simulators with delays. The phase lag produced by a transport delay is linear with frequency, causing the high frequency components of control inputs to be more out of phase than the low frequency ones. When facing such a situation, the tendency of human controllers is to force the system to a lower gain-crossover frequency by trading response frequency for amplitude. In a sense, it is the pilot's willingness to tolerate high-frequency error that enables him to keep the system stable, yet the requirements of flying formation are such that displayed errors must be reacted to quickly and kept small. From descriptions of the operation of flight simulators with CIG visual display systems, it appears that flying tasks with those requirements of accurate control of the aircraft and quick response to error are most affected by display delays. This is supported by discussions of the experimental literature of manual control of systems with delays (Muckler and Obermayer, 1964; Poulton, 1974; and Ricard and Puig, 1977).

Past attempts to compensate for dead-time delays in simulation systems have, for the most part, been concerned with reducing the response lags of motion platforms. At the National Aeronautics and Space Administration Langley Research Center, Parrish, Dieudonne, Martin, and Copeland (1973) used a linear projection of a simulated aircraft's rotational axes positions to adjust the signals sent to the motion platform of their device. Later a filter with a "notch" centered at 32 Hz was added to remove vibration caused by the 32 Hz iteration rate of the device's processor. Motion platforms respond slowly compared to the ability of a computer-driven visual display, and when the same technique for compensating for time delays is applied to the software that creates the signals for a CIG visual system, the displayed image can contain an annoying "jitter" or "flutter." This happens because the linear projection scheme amplifies the high frequency components of the signals sent to the display. More accurate prediction would produce less jitter, but some would occur whenever pilots make high frequency control inputs. One would think that software schemes that provide a phase-advance for the pilot would help his control of systems with delays, and indeed some work at the Naval Training Equipment Center has indicated that following a linear projection scheme with a low-pass filter (which allows a low frequency phase-advance while attenuating high frequency jitter) would help piloting control and would potentiate the acquisition of control skill (Ricard, Norman, and

Collyer, 1976). The main purpose of this study is to test further the usefulness of the predict-then-filter notion by observing trained pilots asked to fly formation in the ASPT.

Figure 1 should provide a context for our changes to the computer software. Each of the cue-providing subsystems of a simulator has as its input the updated position of the aircraft as calculated by the aerodynamic model. Each subsystem then provides its own set of cues to the pilot with their fidelity determined by that subsystem's capability. When, for a given task, control of the device must be made easier, several options are available. One is modifying the aerodynamic model to make the device more "flyable," and another is tinkering (in one manner or another) with the particular subsystem that seems to be causing the difficulty. This latter approach is the one we have taken. In the ASPT, aircraft parameters are adjusted for calculation times in the flight dynamics software; and then a filter is inserted before the calculation of the simulated visual scene to allow those predicted values to be modified without affecting ones for the other cue-providing systems. Our basic experiment then is to measure flying performance while setting the time constant of this filter to different values so that differences of piloting control can be related to the spectral content of the signals sent to the CIG display system.

A second goal of the study was to assess the usefulness of the proprioceptive cueing provided by the g-seat and motion platform of the ASPT. Few data exist concerning the advantages offered by these systems when the visual scene is a computer-generated one and the flying task is difficult. This is partly because CIG displays are a new technology that has not been used long, and partly because attempts to use CIG displays for tasks such as formation flight have not been particularly successful, usually because the delay compensation made control difficult or visual flutter annoying. Using pursuit tracking tasks very similar to formation flight, Miller and Riley (1976, 1977) have shown some benefit gained by adding the cues provided by a simulator's motion base, at least for long delays of the display. Generally they found that the more difficult a simulation was to fly, the shorter was the delay that could be tolerated, and that activation of their device's motion platform extended the delay that was tolerable for the simulation of a given aircraft. No data exist on the effect of adding a g-seat to a simulation of flight, but we felt that if its cues were timely, then they might be shown to be helpful.

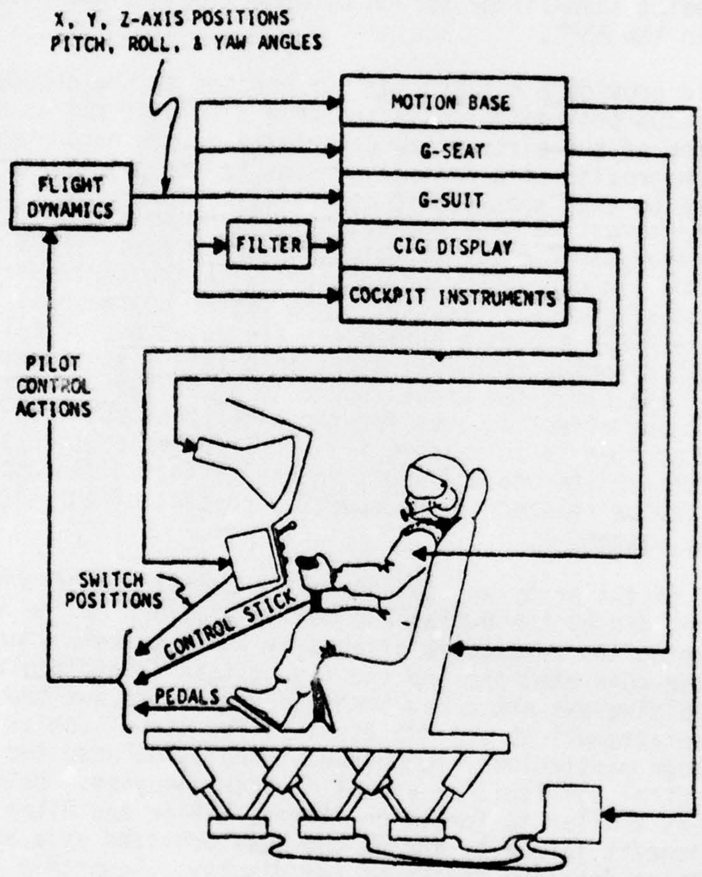

Figure 1. The cue-providing subsystems of a modern flight simulator (Arrows indicate the direction of the flow of information).

SECTION II

EXPERIMENT I

METHOD

SUBJECTS. The four volunteers who served as subjects in this experiment were Air Force instructor pilots -- members of the 97th Flying Training Squadron at Williams Air Force Base, Arizona. All were instructors for advanced jet training in the T-38 aircraft and had accumulated between 1200 and 4200 individual hours of flying time with a group average of over 2400 hours.

EQUIPMENT. This study used the ASPT -- a flying training research device located at Williams Air Force Base. It consists of two simulator cockpits with Systems Engineering Laboratories Model 86 computers driving the motion bases, g-seats, and computer-driven visual displays for each. An advanced instructor/operator console was used for controlling experiments via keyboard-entered codes and for monitoring the progress of individual trials. The simulator cockpits were configured to represent the T-37B aircraft -- a two-seat jet trainer. They were mounted on six-post, six-degrees-of-freedom synergistic motion platforms that are capable of 60-inch strokes which can provide cues of at least 0.6g for the aircraft's vertical, lateral, and longitudinal accelerations and of $50^{\circ}/\text{second}^2$ for pitch, roll, and yaw angular accelerations. The cues of steady-state acceleration also were simulated by appropriately inflating the 31 cells of the pilot's g-seat and by varying the tension on his seatbelt.

The simulator's CIG system presented external visual cues with 36-inch cathode ray tubes and display optics equipped with mirrors, polarizers, and beam splitters to provide infinity-focused images. Each cockpit was partially surrounded by a mosaic of seven of these pentagon-shaped display channels that provided a 300° horizontal, 150° vertical field-of-view that essentially duplicated the field-of-view of the T-37 aircraft. After transmission losses through the pancake window optical system, this display system could present the computer-generated visual scenes with highlight brightnesses of up to six foot lamberts. The entire visual display system is capable of displaying 2500 edges and of allocating them over the 14 channels of the two cockpits. In this study, identical visual scenes were presented to each cockpit so that each seven-tube mosaic was assigned 1,000 edges for its representation of a T-37 aircraft in the lead position of formation flight. A capacity of 500 edges was retained as a buffer to be used when the system was overloaded, as occasionally, when parts of the lead aircraft crossed from one channel to another, the edge-handling limits of the system would be exceeded and parts of the CIG picture were momentarily absent from the display. Priorities were assigned so that the nondisplayed elements were usually fields placed near the horizon to supply ground texture, but occasionally an element of the lead aircraft would drop from the scene. When the two aircraft were in their correct relative positions, these conflicts did not arise.

The advanced instructor/operator console used to interface the experimenters to the simulator's computer system contained a keyboard, two seven-color and two black and white cathode ray tubes (all under program control), three closed-circuit television channels, a control stick, plus a number of switches and dials. Codes for the conditions of the experiment and commands to continue or abort a trial were entered with the keyboard, and the results were verified over the color alphanumeric displays. The achromatic displays were used to present information concerning the state of the two aircraft, including a graphics representation of their relative positions. One of the closed-circuit television channels was used to view the pilot in the cockpit, and the other two were used to display selectable channels of his computer-generated visual scene.

TASK. The flying task used for this study was to maintain the "fingertip" position off the right wing of a lead aircraft (a T-37). This is a visually guided task that requires the pilot to hold a position 30° back from the lead aircraft while maintaining a three-foot wing tip clearance. When this position is obtained, the lead aircraft appears as in Figure 2 (copied from Air Training Manual 51-4) which is a fair representation of the high fidelity image of the lead aircraft used by the ASPT. Several of the visual references that pilots are trained to use to hold the fingertip position have been indicated in the figure: (1) the lead pilot's head is kept aligned with the outside flap hinge and the radio antenna of the lead aircraft, (2) the top 1/3 and bottom 2/3 of the lead aircraft's right wing are visible, (3) the trailing edge of the lead aircraft's opposite elevator is barely visible, as is (4) the top part of an inverted triangular ejection warning sign located on the fuselage of the lead aircraft just forward of the pilot. For straight-and-level flight, the fingertip position can be maintained with a constant throttle setting and small movements of the control stick, but during maneuvers like turns, throttle changes must be made in order to maintain the position.

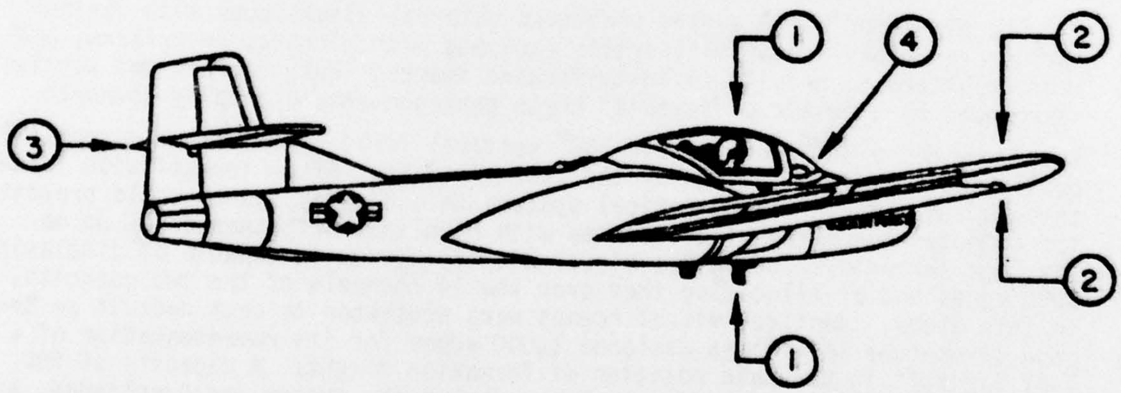

Figure 2. Pilots' view of the T-37 aircraft in the lead position when flying the finger-tip position off its right wing (Taken from ATCM 51-4).

EXPERIMENTAL DESIGN. Our intention was to examine the effect of selectively filtering the drive signals sent to the CIG system processor and the effects such filtering might have on a pilot's use of the nonvisual cues of aircraft motion available in modern flight simulators. To that end, this data collection was designed as a three-factor, mixed-effects factorial experiment where differences due to subjects were considered a random effect and the effects produced by the types of motion cueing and settings of the display signal filters were considered fixed. Three conditions of motion cueing were selected -- corresponding to the presentation of just the visual scene, or to the addition of the proprioceptive cues provided by either the g-seat or the motion platform of the ASPT. Six settings for the signal filters were included; these represented half-power points for the low pass filters of 1/4, 1/2, 3/4, 1, and 2 Hz, and an unfiltered condition. Thus was formed a three-by-six-factorial whose 18 combinations of motion and filter conditions were block randomized with a different order of presentation for each subject. Each subject completed three of these 18-trial blocks during the experiment.

Despite the fact that our subjects were expert instructor pilots, they experienced considerable difficulty in adjusting to the characteristics of the simulator. This was partly because the presence of the transport delay made the formation flying task difficult, partly because the computer system failed several times during the first day or two of the experiment, and partly because the pilots were not accustomed to the math models for certain subsystems of the device, particularly the one that calculated changes of airspeed in response to small, quick changes of the throttles. For this reason, we expected performance to improve throughout the experiment and our analyses of variance included a "trials" effect to remove this variability from the error terms.

A secondary objective of the study was to compare ratings obtained from both the pilot flying a maneuver and an observer in the second cockpit. While both raters saw the visual display of the lead aircraft, only the pilot had his g-seat or motion base activated, so that comparison of the pilots' and observers' ratings would measure the contribution that nonvisual cues of motion had on the pilots' judgments of the adequacy of a simulated flight. For these comparisons, we used the same analysis-of-variance model mentioned earlier. These rating data were collected as the experiment progressed and for the pilots at least, they fit the block-randomized design.

EXPERIMENTAL VARIABLES.

Filter Settings. Previous work (Ricard, Norman, and Collyer, 1976; and tests at the Air Force Human Resources Laboratory) has established that an optimal setting for the filters for the CIG display signals would be in the range 1/2 to 1 Hz, so for this test of the utility of the signal filtering notion, a single-pole Butterworth filter (see Sterns, 1975 or Oppenheim and Shafer, 1975) routine was developed. To be consistent with previous work performed at the Naval Training Equipment Center, we used a first-order, low-pass filter with the Butterworth configuration selected for its smooth amplitude and phase response. Only three degrees-of-freedom of the simulated aircraft were filtered -- roll angle, pitch angle, and z-axis -- because the preliminary analysis of other work performed at the Air Force Human Resources Laboratory (Cyrus, 1976) indicated that only the responses along these axes contained enough high frequency energy to create problems of "flutter" in the visual display. When the filter routine was integrated into the ASPT's software, it was placed after the visual prediction algorithm (see Larson and Terry, 1975), and it therefore affected only the visual display, not other aspects of the simulated flight dynamics. All translational and rotational variables were time-adjusted for the transport delay in the ASPT CIG visual system, then those mentioned were filtered, and finally all were processed by the CIG system. Specifically, each variable was predicted according to the following: $x_{n+1} = x_n + {}^h/_2(3\dot{x}_{n+1} - \dot{x}_n)$ where x is the variable being adjusted, $\dot{x}$ its derivative, the subscript refers to a value at a point in time, and h is the integration interval. To accommodate different iteration rates for the processing of the flight dynamics and the visual image, the prediction span h is variable in the ASPT. We deemed it premature to try to select individual settings for the filter for each axis, so for this test, the three aircraft parameters that were adjusted were passed through identical filters. The method developed to accomplish the integration and filtering for these axes has been presented by Cyrus (1977) as a general technique for compensating CIG system transport delays. Its advantages are that the calculations it requires can be performed simply and quickly, and it would be easy to implement either in hardware or software. The technique does require that constants be set that may be a function of the type of flying task being simulated, hence the need for studies like this one.

In evolving this approach to compensation for transport delays in visual display systems, we assumed that the information used by the pilot for controlling the aircraft and the noise generated by software prediction schemes are different functions of frequency. More specifically, we assumed that both are monotonic functions somewhat similar to those depicted in Figure 3, in that most of the useful information in the signal is low frequency and that the more annoying noise is high frequency. The manipulation of the break frequencies of the signal filters, then, is an empirical attempt to find the signal-to-noise crossover point of Figure 3. By setting the break frequency of the filters there and removing the high frequency components from the signals sent to the CIG display processor, we should be able to improve the "quality" of the visual information presented to the pilot, and presumably, his flying performance also.

Motion Cues. Because the two aircraft were in their correct positions at the start of a trial and because we used instructor pilots for the formation flying task, we expected that our subjects would have to produce only small changes of piloting control and aircraft state parameters in order to control the simulator, and that such a situation would enhance the usefulness of those subsystems of flight simulators that provide nonvisual cues of aircraft motion. If a trial was flown well and the simulated aircraft was kept in its proper fingertip position, the expected motions of the cockpit would be small and the relative scaling of the signals sent to the actuators, while normally less than unity so that effective cueing can be provided for large g-forces, could for this test be set one-for-one. To that end, the mathematical model for the signals sent to the motion platform was changed. The "gravity align" subroutine -- which keeps the resultant simulated external force vector aligned with the normal earth vector -- was kept active, but no additional cues for the translational motions of the aircraft were provided. Together these changes of the software for the motion platform were designed to optimize the simulation of small rotational responses. That they were successful was indicated by the ability of instructor pilots assigned to the Air Force Human Resources Laboratory to identify correctly the direction of small ($<10^{0}$) platform inclinations and by their agreement that indeed the motion platform was perceived to move before the CIG visual display responded when small control inputs were entered from the cockpit. Details about the ASPT motion system are provided by Kron (1975a).

To increase the ability of the g-seat to act as a signaling device, its software was changed to provide a nonlinear signal for the position-following bellows system. This was accomplished by creating as the forcing function for the bellows, a weighted average of aircraft velocity and acceleration values. The amount of lead which the g-seat could be provided was thus controllable, and for this study was subjectively set. As in the case of the adjustments to the action of the simulator's motion system, the cues of rotational motion were considered to be more important than those of translational motion. Kron (1975b) has also described the g-seat of the ASPT.

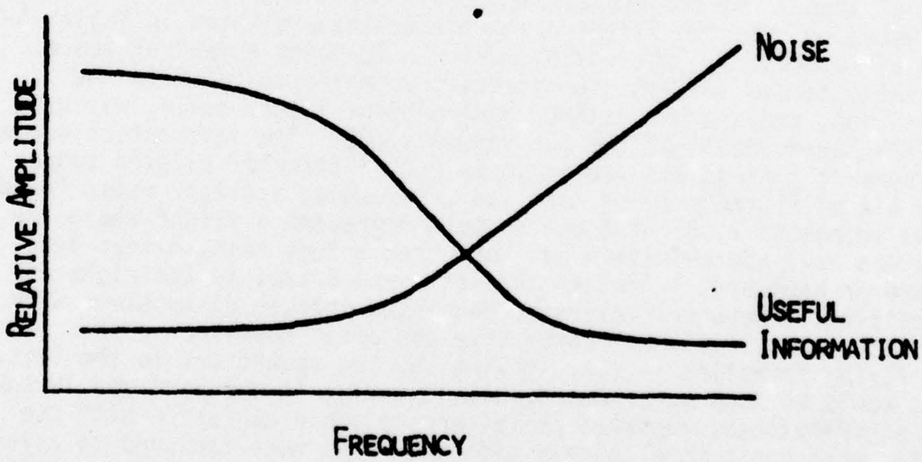

Figure 3. Hypothesized relation of information useful for flight control and prediction scheme noise in the computer-generated image as a function of signal frequency.

PERFORMANCE MEASUREMENT. We collected two types of data: objective measures of the pilot's performance of the flying maneuver, and subjective impressions both of his performance and of the jitter of the CIG display. The latter measures were ratings collected from both the pilot and an observer after each trial. For the formation flying task, the objective data included measures of the translational motions of the aircraft (x-, y-, and z-axis errors measured as differences of position of the two aircraft), measures of its rotational motion (pitch, roll, and yaw angles, again measured as differences), and measures of the position of the aileron and elevator control stick, and the positions of the rudder pedals and of the left and right throttles. The measures of the lag aircraft's absolute position in space were obtained relative to the position of the lead aircraft; to adjust them to be errors from the ideal position for the lag craft, the following constants should be added: x-axis = -21.25 feet, y-axis = 36.78 feet, and z-axis = 3.00 feet. After the first 20 seconds of a trial, these eleven parameters were sampled 15 times per second and recorded for 137 seconds. The performance measurement routine developed for this study obtained both time-history and frequency-domain summary information for these eleven variables. These summaries represent linear transformations of the information contained in the time histories, and for each parameter sampled, we calculated its mean and variance. Each variable was also passed through five single-pole Butterworth filters with half-power points of 1/8, 1/4, 1/2, 1, and 2 Hz to obtain a crude estimate of its power spectral density function. At the end of the day's testing, all of these records were stored on magnetic tape along with the information needed to identify each pilot, trial, and factor combination.

Ratings provided the subjective assessments of the flights and of the CIG system's visual scene. At the end of each trial, both the pilot and the observer were asked to rate the flight using the scales presented in Tables A-1, A-2, and A-3 of Appendix A. One rating, using a 12-point numerical scale, was used to indicate how well the lag aircraft appeared to maintain the fingertip position, and another rating, a nine-point letter scale, was used to appraise the "usefulness" of the CIG visual scene. The information needed to make the numeric ratings was presented on each instructor pilot's score sheet (Table A-4 of Appendix A) so that, as an example, a flight rated "good" would receive scores of 7, 8, or 9 which would represent a flight where the lag aircraft was held approximately not more than 2 feet high, 4 feet low, 3 feet forward or backward, 1 foot to the left, and 5 feet to the right of the ideal position. These criteria were developed through discussions with instructor pilots at Williams Air Force Base and after considering the geometry of flying formation -- i.e., moving the lag upward and to the left, for example, would be much more hazardous than moving it downward and to the right. The other ratings, recorded as letters to avoid confusion with the numeric scale, were a bit more loosely defined. They were included to assess the annoyingness of the "flutter" in the CIG system's visual display. Initially the instructor pilots were ignorant of the purpose of varying the settings of the display signal filters, but after the first 18 trials, they were informed that it was the visual flutter that we were trying to remove from the display and they were requested to direct their ratings to that aspect of the visual scene.

PROCEDURE. Several events took place before the experiment proper began. One of these was to make flightpaths for the lead aircraft with which the instructor pilots could fly formation. The instructor's console of training simulators is often equipped with a control stick which can be used to change the position of the pilot's aircraft or to "fly" the image displayed to him. Usually there is no throttle for this control and the aerodynamic model that generates responses to inputs from the instructor's station is simpler than the one that responds to inputs from the cockpit of the simulator. Because the ASPT is equipped with two cockpits, each with its own CIG visual display mosaic, we decided to prerecord flights for the lead aircraft and thus be able to use both cockpits for real-time data collection. An instructor pilot assigned to the Human Resources Laboratory flew a number of flights during which he performed gentle climbs, dives, and turns. These flights were recorded and then used to drive the CIG visual system to create the flightpath for the lead aircraft for our formation flying task. During the data collection, the prerecorded flight controlled the image of the pilot's view of the lead craft for both cockpits. In this way, the lead aircraft could be made to fly realistically while freeing the second cockpit for an observer. Twelve such flights were recorded, and from this set, six were chosen for use during the experiment. Two criteria were used for their selection: first, that the instructor pilots assigned to Air Force Human Resources Laboratory judged that the particular flightpath was not too difficult for formation flight, and second, that the selected flights presented fewer synchronization problems than the rejected ones. If a trial was started at an inopportune time, the calculation of the position for the lead aircraft was begun before that for the lag aircraft and the CIG system's image "jumped" ahead. It was for this reason that a 20-second dead-time was included at the start of each trial. It gave the subjects time to catch-up to the lead aircraft before data were recorded. Some of the prerecorded flights seemed to magnify this synchronization problem, and these were the ones we deleted. The advantage gained by using prerecorded flights was the improved dynamic response of the lead aircraft which the better math model allowed. However, a simulator with two "active" cockpits has a disadvantage. The effective delay from control input in one cockpit to display and then response from the other cockpit would now be doubled. A 100 to 200 millisecond visual system transport delay becomes a 200 to 400 millisecond total system delay, and the problems of piloting control are made even more difficult. We might note that this was not the case in this study as only the pilot's cockpit could provide inputs to the CIG visual system.

Personnel at the Air Force Human Resources Laboratory also performed the tasks of software integration, i.e., of developing and inserting into the simulation program the filtering and performance measuring routines, and of setting the lead times and gains for the g-seat and motion platform of the ASPT. They also developed the rating scales specifically for the formation flying task and created the block randomized orders of experimental conditions for each pilot. This last task was performed on a Wang computer at the Human Resources Laboratory using programs developed there.

Prior to the collection of data, the instructor pilots were briefed about the nature of the experiment and of what would be required of them, and on normal operating and safety procedures for the ASPT. Along with viewing a safety film, they had an opportunity to "fly" the ASPT for a while to see how it operated.

The experiment consisted of ten four-hour testing sessions with two instructor pilots present each session. Each served as pilot and then observer for about half of each session, with each serving as observer for every other at least twice during the five days of testing. Initially we had hoped to complete one block of 18 trials per day, but this proved to be overly optimistic so that only three such blocks were finished by the end of the data collection. At the beginning of a testing session, the simulator was checked to see that it was set appropriately for this experiment, and then, while the device was being prepared, the pilot and observer were given their data sheets and asked to enter the cockpits. Radio contact was established with each pilot and was the means of pilot-experimenter communication used during all of the tests. Each trial included a one-to-two minute period while experimental condition codes were entered at the instructor/operator console, and then, when the operator judged the pilot ready, a key press actuated the trial program, starting a 157-second trial with data recorded during the last 137 seconds. All trials were started with the fully-fueled T-37 flying at an airspeed of 190 knots at an altitude of 15,000 feet. At the end of each, one of the instructor pilots assigned to the Air Force Human Resources Laboratory made the judgment of whether or not the flight should be considered controlled enough to produce reasonable data, and then the recordings were either entered into the data file for this study or were deleted. Conditions under which control was lost were repeated immediately. Trials for which the motion platform had to be activated took a bit longer than others as the walkway to the cockpit had to be retracted and the motion platform had to be raised to its starting level. All of these events allowed an average time-per-trial of five to ten minutes, a time that was gradually reduced throughout the experiment. Until it was time to switch places, the pilot and observer remained in their cockpits, resting between trials.

As performance data were collected, they entered a disk-file that was stored on magnetic tape at the end of each day. After the experiment was completed, a listing was made of this file, and the magnetic tape was taken to the Naval Training Equipment Center for analysis.

At the end of the experiment, we discovered that a total of 13 trials had been omitted because of human errors while entering the condition codes and trial numbers at the instructor console. The analysis procedures we used required a complete set of data from each subject, so that each subject's missing information was estimated using measures of his performance under similar conditions. For no subject was one of the 18 different experimental conditions skipped more than once, so that we always had two sets of measures with which to estimate the third.

RESULTS AND DISCUSSION

To keep this discussion simple, the details of each analysis of variance are presented at the end of the report and will be discussed only generally. Based on our results, it may be desirable to make similar adjustments to other flight simulators; so for this reason, all of the statistically significant effects related to the main variables of the study are presented graphically for reference.

OBJECTIVE MEASUREMENTS. Tables B-1 to B-11 of Appendix B present the results of the analyses of variance performed on the means and variances of the 11 parameters we measured. Each table presents the analysis of the average value of the measure and then the analysis of its variance. In these tables, the variables we manipulated are designated by A, B, and C and each subject's data were considered a "block," so to decode the tables: A = conditions of motion cueing, B = settings of the filters, C = trials, and a block effect reflects differences due to the pilots. For an effect significant at the $p<.05$ level of confidence or above, these tables give the probability of the occurrence of its F-ratio and its proportion of the total sum of squares, η^2 (Eta Squared). To provide some perspective, η^2 for each residual variance term is also given. Generally speaking, an advantage was gained by structuring the data collection as a blocked randomized factorial experiment with trials as a factor. Often both the blocks and trials effects produced significant F-ratios, and as we were able to remove this variance from the residual terms, the other tests were undoubtedly made more sensitive. Several observations can be made.

First, the residual (error) variances of these analyses, that variance which could not be parsed into any of the effects, were often quite large. For the average values of the measures, for example, the error terms accounted for 67 percent of the total sums of squares, and for the variances, the residual variances accounted for 59 percent. *Typically none of the effects we* could analyze were statistically significant if the residual term had an η^2 greater than 0.70. Usually those analyses of variance that produced significant F-ratios had error terms for which η^2 was in the range 0.50 to 0.65. In only three analyses (the ones of the variances of the positions of both throttles and of the mean position of the left one) were we able to reduce the residual term to less than 50 percent of the total sum of squares, so that obviously a good deal of the variability of our pilots' performances was not accounted for by the conditions of the study.

Related to the large amount of unaccounted variance is the presence of a trials effect in the analysis of many of the measures. This was seen in the analyses of the lag aircraft's attitude (relative to the lead craft) and in the measures of piloting control. While the trials effects were statistically reliable, they were not large, with η^2 values of only 0.10 to 0.12. Usually this difference of average performance was seen between the first set of 18 trials and the next two sets. Our instructor pilots were naive to the ASPT so that an effect due to sequential testing was quite expected. It was included in the analyses, as was the blocks effect, to reduce the size of the error terms. Usually the effect due to progressive trials was quite reliable, with small probabilities of occurring by chance, yet some measures, as the difference of translational position of the two aircraft did not show this trend.

The lack of a trials effect in the analyses of the measures of the position in space of the lag aircraft leads to a third observation: that those measures were relatively insensitive to the manipulations of this study. On only one test -- that for the effect of different filter settings on the variance of the x-axis difference of position of the two aircraft -- was a significant result obtained (shown in Figure 4), and this was probably spurious. This was not one of the variables we filtered, and it also is one where we would expect little or no such effect to be found. Our impressions during the collection of the data were that the actual flightpaths taken by the lag aircraft were a bit too variable for the measurement of any differences of the pilots' ability to control the simulator, and the analyses of variance confirmed these. Having the lead aircraft undergo climbs, dives, and turns and requiring the pilots to maintain their aircraft in a given position relative to the lead brought to the fore their unfamiliarity with the simulation system.

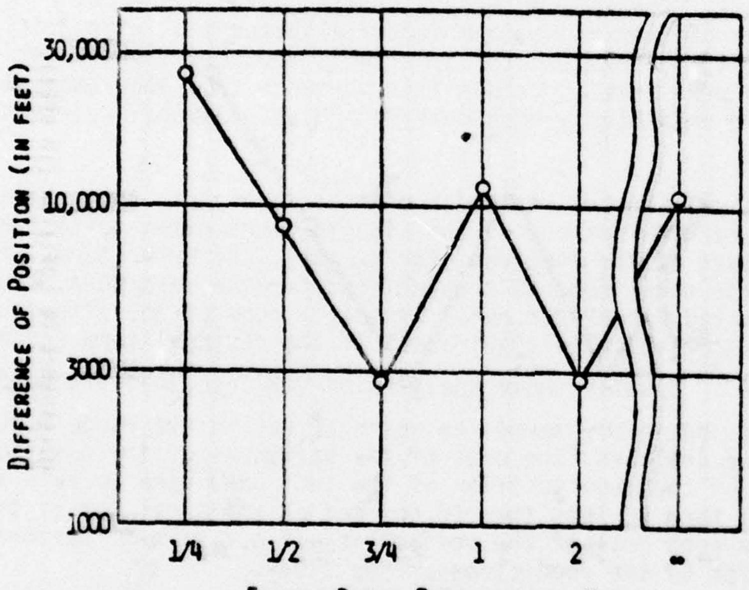

Figure 4. Variance of the x-axis difference of position of the lead and lag aircraft as a function of filter setting. In this and the subsequent figures, the ∞ symbol represents the break frequency of the unfiltered condition, although for this simulation, the Nyquist frequency of the ASPT CIG system is 15 Hz.

Along with the z-axis difference of position, we filtered the differences of the aircrafts' pitch and roll angles, and of these, the variance of the pitch angle measure showed an effect of this filtering. The variability of the lag aircraft's pitch angle was reduced, and so was the variability of the pilots' longitudinal and lateral movements of their control stick. That our manipulations of the display actually affected piloting control is comforting, given the adaptation to the simulation system required of the pilots. These measures presented as a function of the break frequency of the display signal filters are depicted in Figures 5 and 6. All of these functions display a reduction of variance as the break frequency of the filter is increased up to about 3/4 to 1 Hz. For the variance of the differences of pitch angle, there is a hint that the variance then increases under the no-filtering condition, although that value does not reliably differ from those produced by filtering in the range of 3/4 to 2 Hz. The difference is not statistically significant, but it does hold the possibility that more sensitive measurements may find that the measures of aircraft attitude display a U-shaped function across filter settings. Those for the variances of the positions of the control stick definitely appear to reach an asymptote at about 1 Hz with no indication of a high frequency elevation. Our filtering of the display signals not only encouraged the pilots to use the aircraft's control stick differently, but also led to differences of their use of the throttles. The average positions of the left and right throttles are presented in Figure 7. Although the significant differences of throttle position were seen in the average values, not in the variance, of these positions, these functions appear similar to the previous ones where variances were reduced as the display was made more responsive until a filter setting of 3/4 to 1 Hz was reduced.

Most of the significant results we obtained were with measures of the differences of aircraft attitude or of pilot control inputs. The majority of these results were effects due to differences between pilots or blocks of trials, but some were relatable to the variables of the study. Of the 22 analyses of variance performed on the means and variances of our measures, five effects were found to be significant but difficult to interpret. One was the effect of filtering on the variance of the x-axis difference of aircraft position mentioned earlier. Another was the only effect that the conditions of motion cueing produced -- this was on the variance of the differences of yaw angle. Again why the filtering we did should affect this measure is not clear. In addition to these two main effects, three interactions produced significant F-ratios that seemed arbitrary. These were a motion cueing by trials interaction of the mean of the roll angle measure, a motion cueing by filter setting by trials effect seen in the variance of the differences of yaw angle, and a motion cueing by filter setting interaction of the variance of the position of the rudder pedals. None of these effects would have been predicted nor are they particularly interpretable.

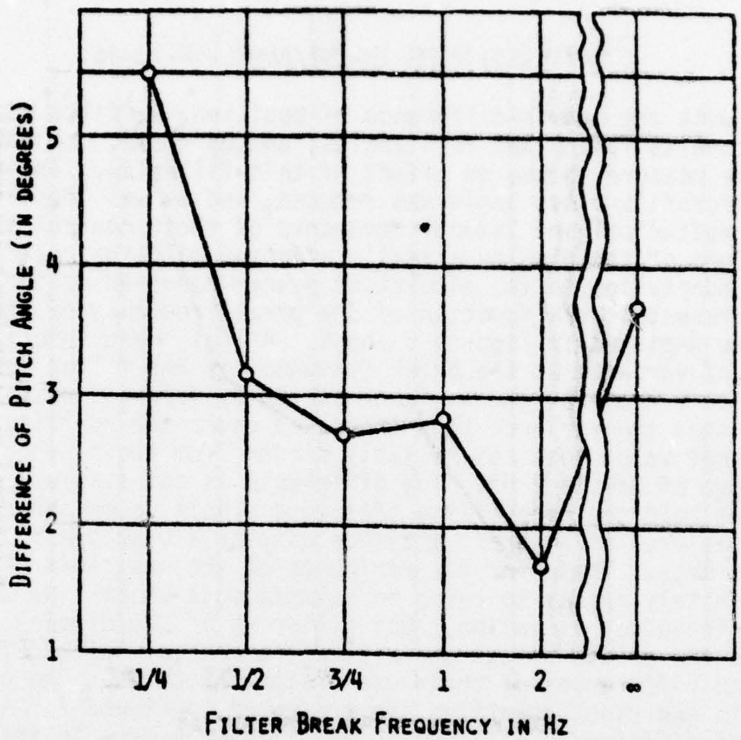

Figure 5. Variance of the difference of pitch angle of the lead and lag aircraft as a function of filter setting.

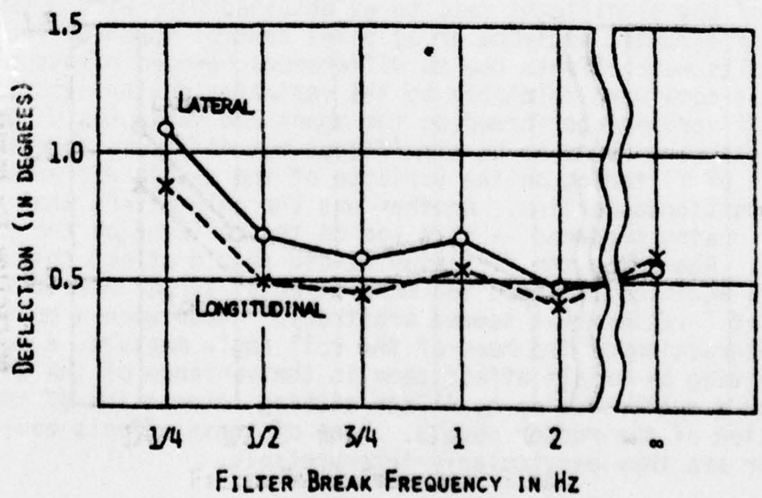

Figure 6. Variance of the pilots' longitudinal and lateral-axis movements of their control stick as a function of filter setting.

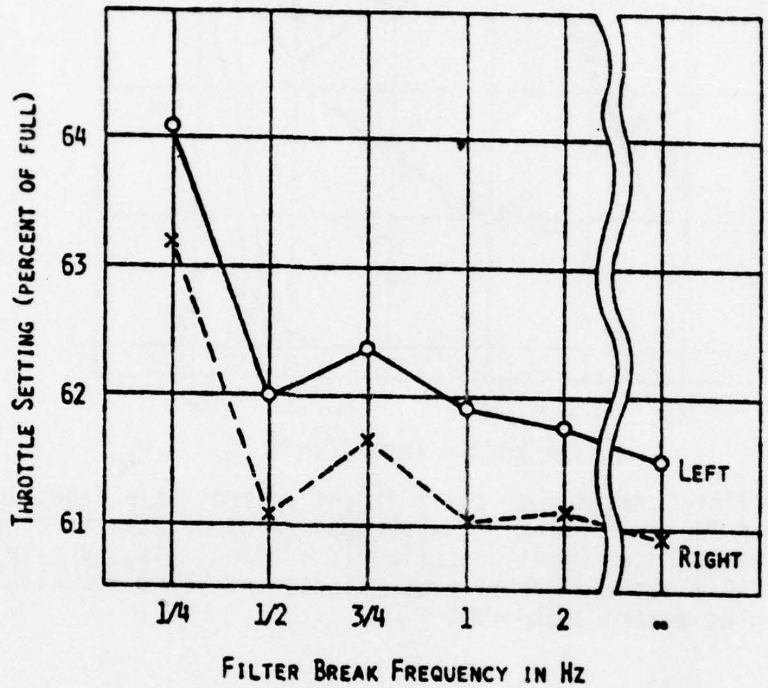

Figure 7. Average position of the left and right throttles as a function of filter setting.

RATING MEASURES. The subjective ratings of the flights provided by the pilots and observers were analyzed in the same manner as the objective measures and these results are presented in Tables B-12 to B-15 of Appendix B. In all four of these analyses, the blocks and trials effects were significant, indicating that the pilots and observers not only differed in their ratings, but tended to give higher ratings during the last two sets of trials. Of the two sets of ratings, those based on the flights were more sensitive to the variables we manipulated in this study than were those based on the noise of the visual image. The ratings of flight control given by the pilots are depicted in Figure 8, and those made by the observers in Figure 9. In these ratings, effects of both filter settings and conditions of motion cueing were found. For the ratings of a flight made by the pilot, there is no difference between the subjective impressions obtained from the visual display alone and with the g-seat added. Both conditions displayed their highest ratings at a break frequency of 3/4 Hz with a slight trend toward lower ratings as the display was made more responsive. The ratings for the condition with the motion platform activated were on the average lower and displayed less of an effect of changing the filter setting. For the ratings of these flights made by the observers, similar trends are evident. They judged flights to be most controlled when the pilot's g-seat was activated and least controlled when the motion platform was used. While the differences due to conditions of motion cueing are significant, the ones across display filter settings were not significant in this set of ratings provided by the observers.

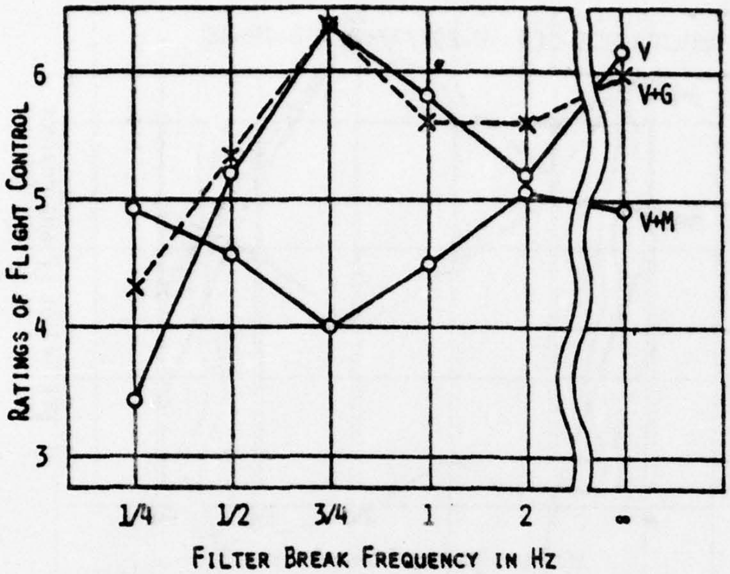

Figure 8. Pilots' ratings of their flight control as a function of filter setting. The parameter represents the different conditions of motion-cueing (V = visual display only, V+G = visual display plus g-seat, and V+M = visual display plus motion platform).

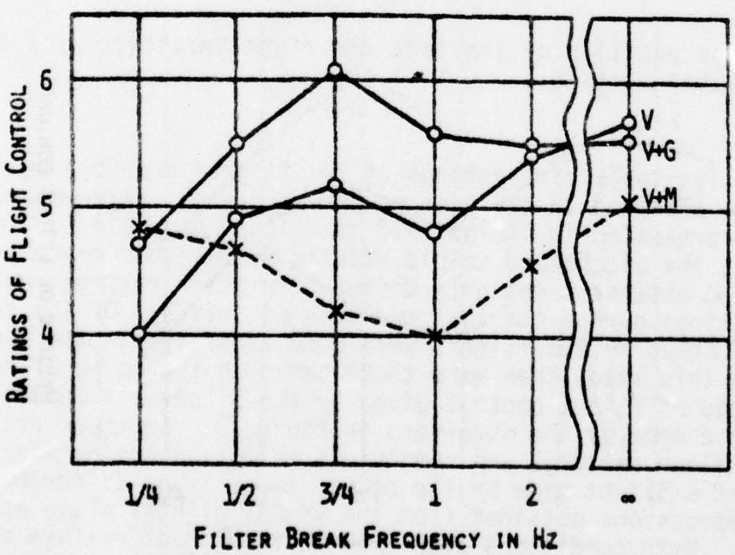

Figure 9. Observers' ratings of flight control as a function of filter setting. The parameter is the same as in Figure 8.

The other sets of ratings (of the noisiness of the CIG display) were a bit disappointing in that no differences related to the variables of the study were found. The subjects were not really informed about the nature of the problem of jitter in CIG displays, and it took them some time to become sensitive to it. This learning is reflected in the significant trials and blocks effects in these data. Most of the complaining about flutter or noise in CIG visual systems comes from people quite familiar with a particular display, so we suspect that some training would have made these ratings more useful.

Because some of the flying control data indicated that an optimal filter setting could be found that would allow better flying control performance than an unfiltered display would, and because the ratings of the noisiness of the computer-generated image showed no effect of filtering -- an effect that obviously should be there -- we decided to perform a second experiment to see if more definitive results could be obtained.

SECTION III

EXPERIMENT II

INTRODUCTION AND METHODS

The second experiment was a simplified repetition of the first except there were some changes which made this study more sensitive to the effects of filtering the signals sent to the CIG display processor. For instance, this time subjects familiar with the ASPT were used. They were instructor pilots for the T-37 aircraft who had between 1,000 and 4,500 hours of flying time with a group average of over 3,200 hours. They had been assigned to the Air Force Human Resources Laboratory to act as advisors and subjects for experimental and development work on the ASPT and had "flown" the device under a variety of conditions.

The flying task was made easier and emphasis was placed on the problems caused by flutter of the visual image. Rather than have the lead aircraft perform climbs and dives, the formation flight software was changed to have the lead craft fly straight-and-level. To emphasize the effects of noise propagated forward through the visual system, the maximum buffet that the ASPT software could provide was added for the duration of each trial. This did make controlling the simulator more difficult than just flying it straight-and-level, but the buffet affected the translational positions of both aircraft similarly, so that to this buffet, we added "noise" by randomly varying the position of the lag aircraft's ailerons. This created differences of attitude of the lag aircraft relative to the lead that our pilots had to correct in a compensatory manner. This noise was then scaled to where the instructor pilots agreed that it plus the buffet forced the formation flying task to be moderately difficult.

To simplify the experimental design, the conditions of nonvisual motion cueing used in the first study were eliminated. The same filter settings as in Experiment 1 were tested and repeated trials were used, making the data collection a simple block-randomized design with six levels of a single variable. All six settings were tested in each block of trials with all subjects receiving the same random order of conditions. The testing was done within a single three-hour session of five six-trial blocks.

Piloting control performance was measured using the software developed for the first experiment, except that we estimated an additional summary measure. This was σ_{ω} (see Sterns, 1975) -- the standard deviation of a frequency domain representation of a time series. It is a measure easily accumulated in real time, and is proportional to the bandwidth of a signal. For pilots' control activities, it provides an indication of the structure of the changes that different settings of the display filters encourage. This time also the measures of the x-, y-, and z-axis position were adjusted to represent error from the ideal position for the lag aircraft.

Again ratings were used for the instructor pilots to quantify their reactions to our changes of the visual display. The two scales developed this time were both nine-point scales, one for the noise of the CIG system and one for the controllability of the simulation. In constructing these scales, attention was given to dividing each dimension into describable sections that might enable the raters to be consistent. Descriptions of the two scales given to the pilots are presented in Tables A-5 and A-6 of Appendix A. For this second study, more time was available for briefing the pilots so that they were aware of the nature and purpose of the study and had been instructed on the use of the rating scales. Some problems of interpretation occurred as testing started, so we used the first block of six trials to indicate to the pilots what we felt were the worst and best cases of each dimension.

To remove the problem of edges being deleted during a flight, the ASPT CIG system was operated at 75 percent of full capacity this time. The result was an image of the lead aircraft without all of the detail of the ones used in Experiment I, but with all of the cues shown in Figure 2 that pilots use to maintain the fingertip position. As in the first experiment, the first 20 seconds after the device was activated (but before data were collected) were used for the pilot to recover the fingertip position, and in this study the display filters were not active till the end of that period. We felt that allowing the pilots an interval to observe the no-filtering condition before each trial would also help to make their ratings more stable. To that end, the instructor pilots were asked to observe this "worst" case of jitter of the visual image and use it for comparison to the behavior of the display during the rest of the trial. During the pilots' briefing, they were reminded that at the altitude and airspeed of this simulation, the longitudinal axis of the T-37 aircraft was more responsive than the lateral one and that the greatest jitter would appear on the horizon line directly ahead. When flying in the fingertip position, the pilots attended to the position of the lead aircraft to their left, so as part of the experimental instructions, they were asked to notice the behavior of the forward horizon and to take this into account as they rated the jitter of the display.

Because of the subject and trials effects of Experiment 1, differences attributable to those sources were removed by expressing each measure collected within a block of six trials as a z-score -- i.e., the six observations of each measure were normalized, forcing the effects due to different subjects and blocks of trials to be zero and leaving the effect due to different settings of the display filters as the only one analyzable. This effect was then tested with a simple one-way analysis of variance performed on the subjects' average performances. The means of repeated trials were used in these analyses so that the findings of this experiment apply only to average performance and do not reflect typical trial-by-trial variability.

RESULTS AND DISCUSSION

Tables B-16 to B-26 of Appendix B present the results of the analyses of variance performed on the objective measures of this second study. Each table presents the one-way analysis of the average value, variance, and bandwidth for a given measure. This time η^2 for all significant effects was 0.66. Averaging repeated trials also reduces the error variance of experiments -- somewhat unfairly in the sense that information about subjects' trial-by-trial variability is lost -- but in this case the interest was in device design, not human performance.

OBJECTIVE MEASURES. The results of this experiment can be divided into three categories: those most likely related to our filtering (in general) of the signals sent to the CIG system, those related to our filtering in the context of the formation flight task, and those that seem a bit arbitrary and that probably are spurious. Effects in the first category are changes of the pitch and roll angles of the lag aircraft and the changes of piloting control that produced them. As the display was made more sensitive by raising the break frequency of the filters, the pilots responded by controlling their aircraft so as to reduce the variance of its pitch and roll angles and to change the bandwidth toward its value for the no-filtering condition. This required an increase of bandwidth along the aircraft's longitudinal axis and a slight reduction along the lateral one. These functions are displayed in Figures 10 and 11. These changes of aircraft response were accomplished by parallel changes of the pilots' use of their control stick. On both the longitudinal and lateral axes, pilots reduced the variance of the position of the control stick, shown in Figure 12, and its bandwidth, shown in Figure 13. Their use of the throttles also changed as a function of the filtering break frequency, paralleling the pattern of results seen in their use of the control stick. As the setting of the filter allowed more high frequency information to the display, lower average settings for the throttles were used, and the variance of these settings was reduced. These trends are shown in Figures 14 and 15. As in Experiment 1, the variance of a measure seemed the datum most likely to be affected by our manipulations, a finding similar to that of Cooper, Harris, and Sharkey (1975). Clearly when the display was filtered strongly, so that it appears too sluggish, our pilots worked more to control the simulated aircraft. Contrary to the data of Experiment I, there is no indication that the pilots will control more poorly without the filtering than with it. This may reflect our use of pilots familiar with a given device or merely human controllers' willingness to ignore the annoying high frequency activity in an unfiltered display.

Changes of aircraft position and of related piloting control that were placed into the second category were similar to some seen in Experiment I. These were the reduction of the variance of the difference of the yaw angle of the lag aircraft presented in Figure 16, and the reduction of the variance of the rudder pedal position shown in Figure 17. These changes probably reflect the tactic the instructor pilots stated they used to fly formation during our simulation -- which was that they would "crab" into the fingertip position and then maintain a yaw angle to counter the effect of the lead aircraft's backwash. Whenever a large gust upset the lag aircraft, the pilots' response was to move laterally (to the right) and then carefully maneuver back into position. It was probably these responses that caused significant effects in the variances of the yaw angle and rudder pedal positions. Another flying task, like aerial refueling or air-to-ground weapons delivery, may not show similar effects on these measures.

Probably related to the above technique was a tendency to keep the average position of the control stick a bit off-center (to the right) that was accentuated at low break frequencies of the display filters. This was probably used to counteract the tendency of the backwash to roll the lag aircraft to the left, and when the display was sluggish (relatively), the instructor pilots were conservative and tended to keep their craft prepared to roll to the right. This use of the control stick is documented in Figure 18.

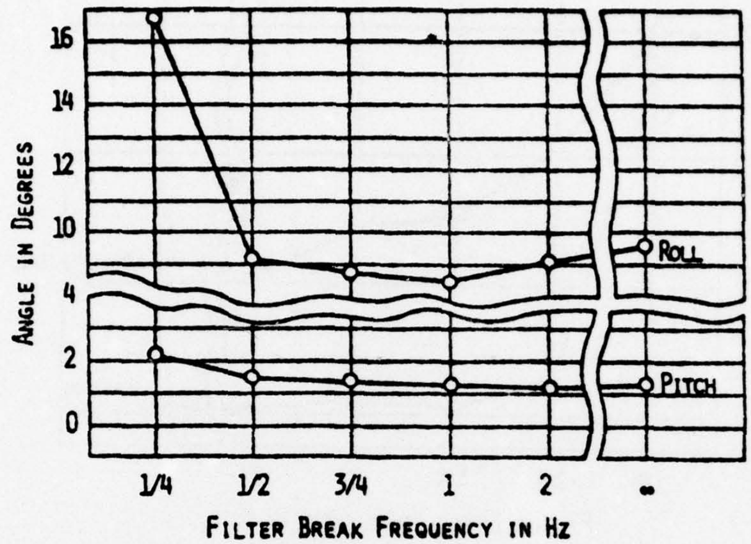

Figure 10. Variance of the difference of pitch and roll angle of the lead and lag aircraft as a function of filter setting.

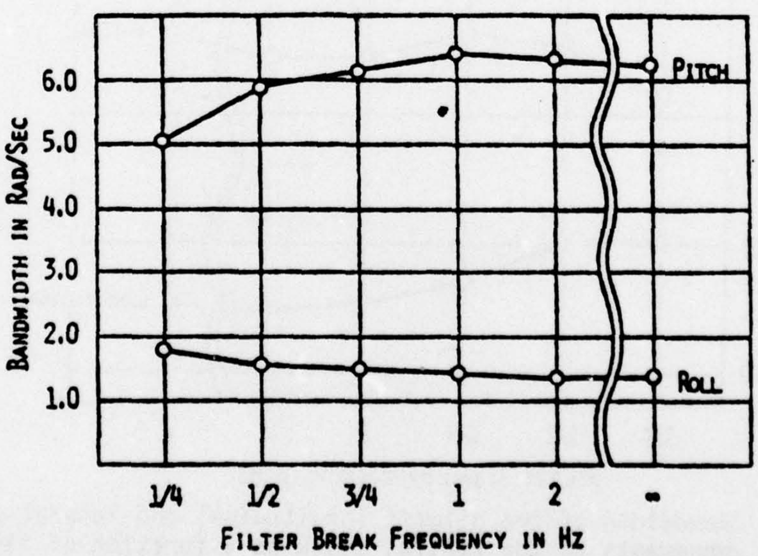

Figure 11. Bandwidth of the pitch and roll angle differences of the lead and lag aircraft as a function of filter setting.

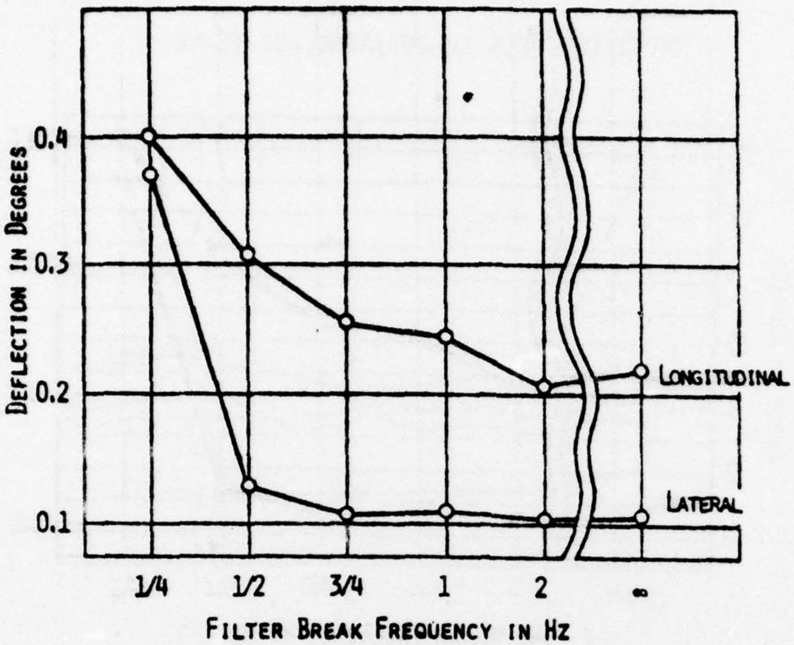

Figure 12. Variance of the pilots' longitudinal and lateral-axis movements of the control stick as a function of filter setting.

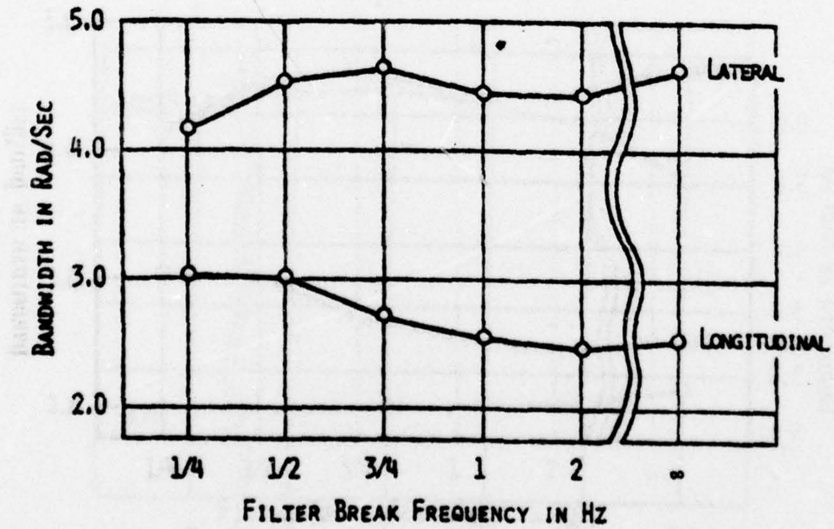

Figure 13. Bandwidth of the pilots' longitudinal and lateral-axis movements of the control stick as a function of filter setting.

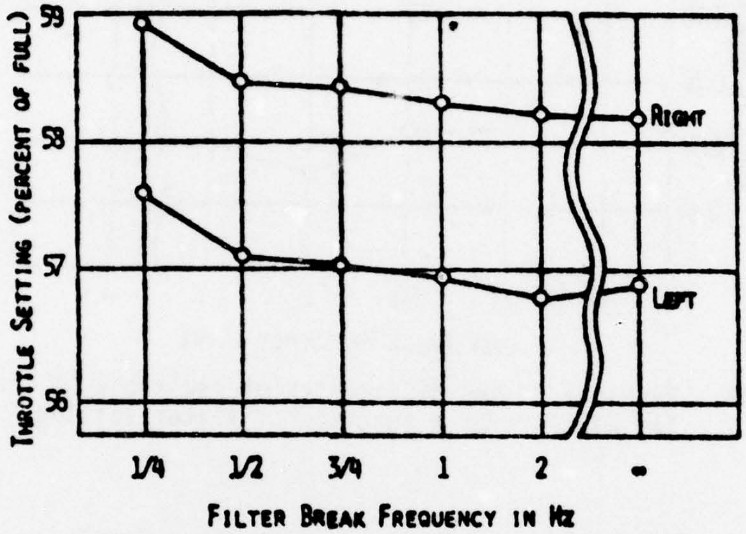

Figure 14. Average position of left and right throttles as a function of filter setting.

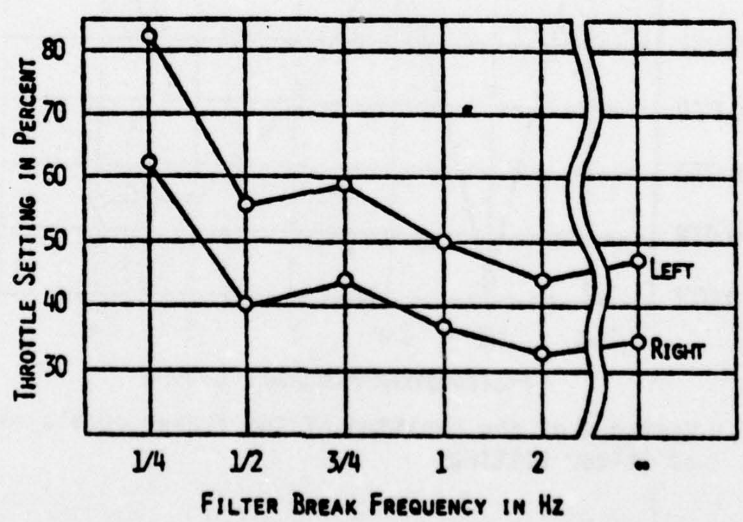

Figure 15. Variance of the position of the left and right throttles as a function of filter setting.

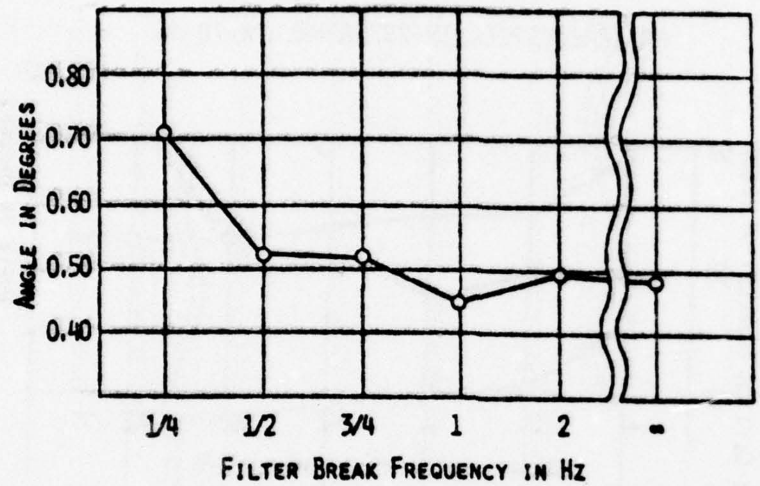

Figure 16. Variance of the differences of yaw angle of the lead and lag aircraft as a function of filter setting.

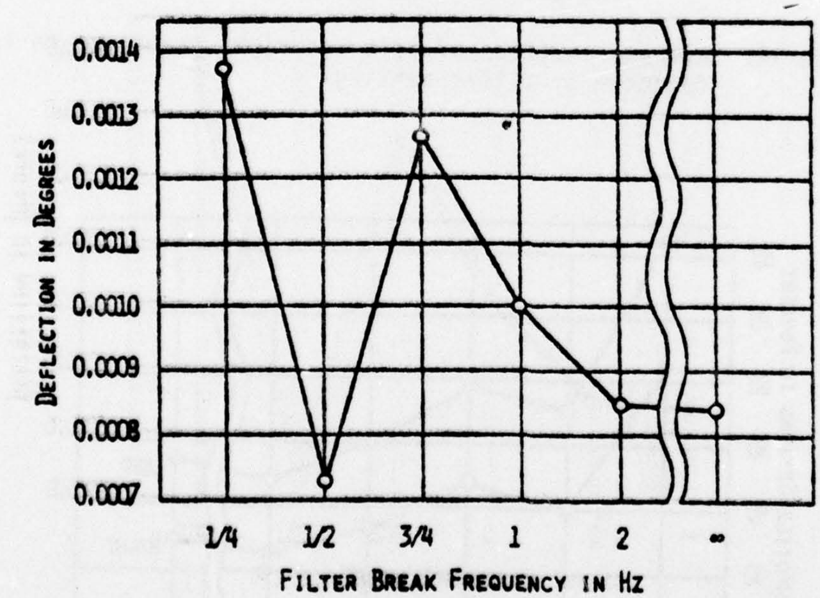

Figure 17. Variance of the position of the rudder pedals as a function of filter setting.

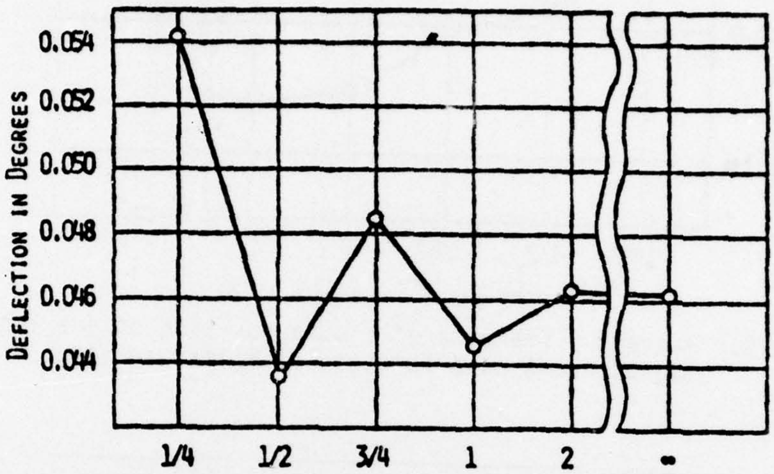

Figure 18. Average lateral position of the control stick as a function of filter setting.

More firmly in the odds and ends category are the changes of the average z-axis position and its variance shown in Figures 19 and 20. Our instructor pilots tended to fly the ASPT simulation a little too high at low filter settings, and this height along with its variance was reduced as the filter setting was increased to 1 Hz. Again, little change was seen beyond that point. The z-axis information to the CIG display system was filtered because of peculiarities of the simulation of formation flight in the ASPT. Undoubtedly this effect on the measure of position along the z-axis reflects this aspect of our simulation.

Finally, Figure 21 presents the bandwidth changes seen in the x-axis difference of position of the two aircraft. Unless it reflects the pilots' changes of their use of the aircraft's throttles, we do not know why this measure showed the effect that it did. Statistically the effect is quite large, but the spectral content of this particular time-series is quite low frequency, so the changes of position may well reflect the changes of engine thrust used by the pilots.

RATING MEASURES. The subjective ratings collected this time were more useful as they consistently differed with changes of the filter settings. The ratings of both the flutter in the visual display and the controllability of the simulation fit the one-way analysis-of-variance design, and after the ratings were converted to z-scores, they were so analyzed. While the ratings of noise in the CIG display were made on a nine-point scale where high numbers represented a stable display and low numbers a jittery one, the ratings of flight control were made on a scale with the most controllable point at its center. The extremes of this scale -- high or low numbers -- were used for aircraft responses that seemed too sluggish or too responsive. Our pilots had great difficulty assigning consistent ratings to the flights

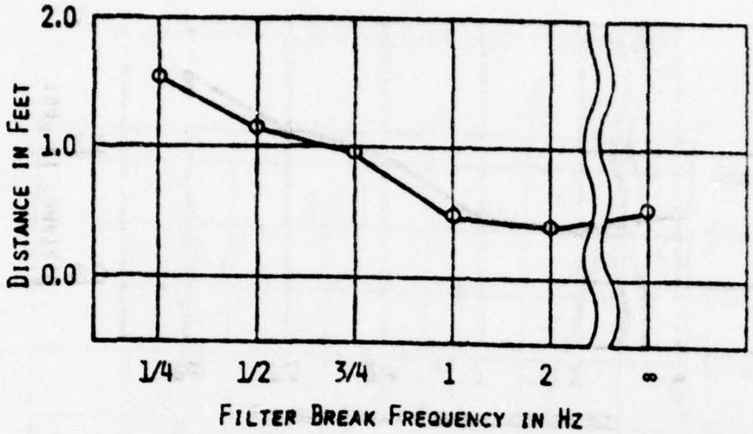

Figure 19. Average difference of z-axis position of the lead and lag aircraft as a function of filter setting.

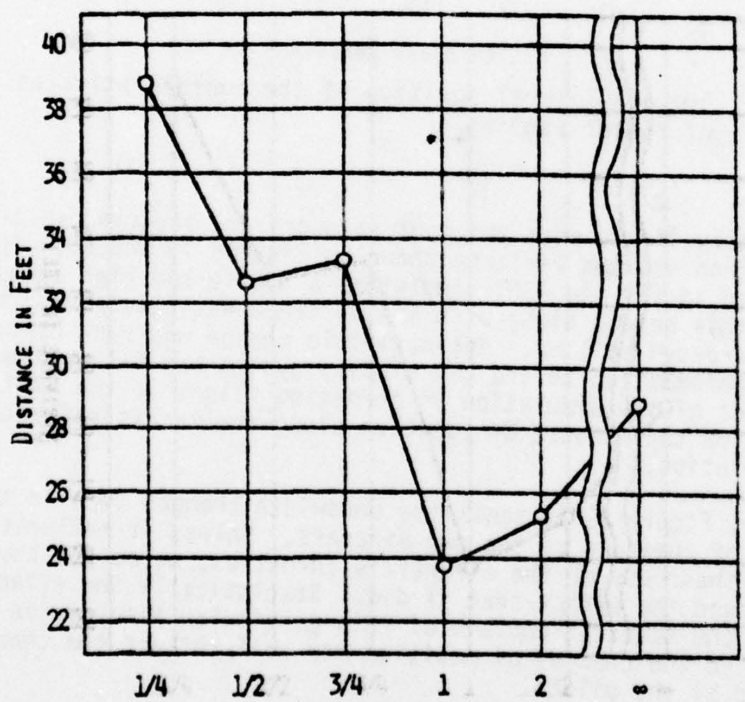

Figure 20. Variance of the z-axis difference of position of the lead and lag aircraft as a function of filter setting.

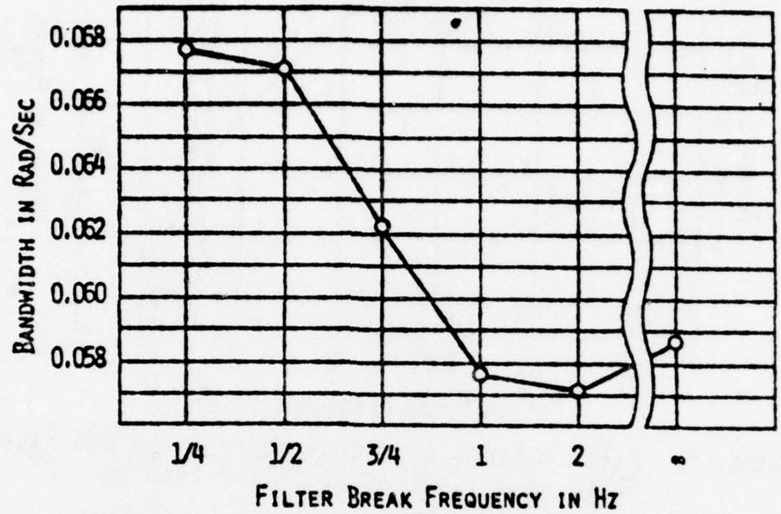

Figure 21. Bandwidth of the x-axis difference of position of the lead and lag aircraft as a function of filter setting.

where the filter was set to a break frequency of 1/4 or 1/2 Hz. Particular events during those trials seemed to be selected for the rating and the result was that the ratings for these low-frequency settings of the filters were quite variable. The pilots pilots agreed that those settings were not desirable, but they could not consistently extract from the behavior of the display just what it was that they did not like. Occasionally a gust would sum with a control input and the condition was judged too responsive, and just as frequently, the same filter setting was judged too sluggish. So to remove this ambiguity, the ratings of flight controllability were "folded" to become a one-to-five scale (ratings of six, seven, eight, and nine became ratings of four, three, two and one). Now high numbers on the scale represent control that was easy and low numbers represent difficult control, regardless of the reason.

The results of the analyses performed on the rating data are presented in Table B-27 of Appendix B and are depicted in Figure 22. The pilots judged the flights to be significantly less well controlled under the 1/4 Hz setting, with the other conditions judged about equally well controlled, but perhaps most significant in a practical sense, their judgments of display jitter show a monotonic decrease with filter setting with the no-filtering condition felt to be the worst case. Although the relative scaling of the two ratings is immaterial, we can see that a mid-range of filter settings is preferable to either a low-frequency setting or a no-filtering condition. Their ratings of system controllability parallel objective measures of flight control -- i.e., as the pilots changed their control activity so that the variance or bandwidth of a measure approached its value under the no-filtering condition, the controllability of the simulation was felt to increase, while at the same time they judged the jitter of the computer-generated visual image to become more and more annoying with the unfiltered image judged as containing the most noise.

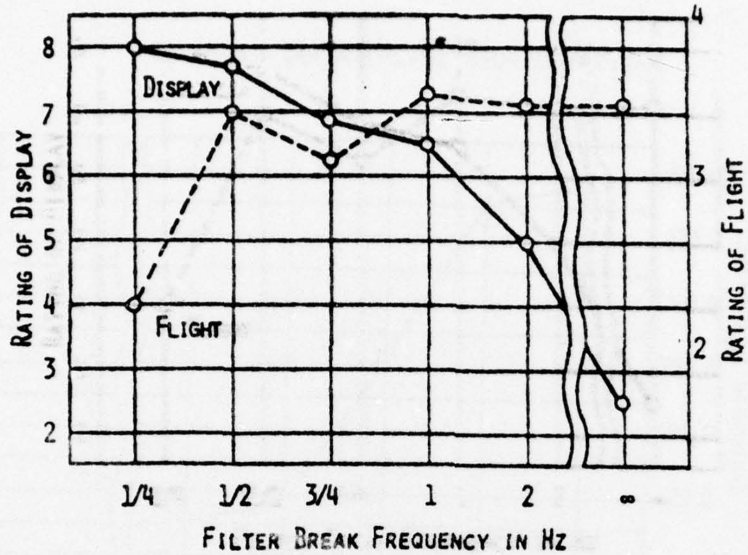

Figure 22. Pilot ratings of flight control and CIG system noise as a function of filter setting.

So that the main finding of this study can be displayed more clearly, we have plotted in Figure 23 the normalized ratings of the noisiness of the visual image and the average of the normalized pitch and roll errors -- both as a function of the break frequency of the display signal filters. Both sets of data are expressed as z-scores to indicate where a particular measure was above or below its experimental average of zero. Here we can see that as the break frequency of the filters was raised, aircraft control became more and more accurate until a "best" setting of 1 Hz was reached, while at the same time, the ratings of the visual display were not drastically reduced until a setting above 1 Hz was reached. Clearly a relatively "safe" setting for the filters can be defined where the changes to the CIG system's inputs will not degrade piloting control and pilots will feel the display has acceptable stability. This is the shaded range in the figure.

We feel that some factors of flight simulations should determine where the break point of display filters should be. Should this sort of delay compensation be used for a simulation of air-to-air combat using high performance aircraft, a setting near the upper end of the safe range would be preferred, and conversely, a task that requires the display of only low rates of angular acceleration may well benefit by using a low frequency setting. Along with the sort of flying task, the type of aircraft simulated will determine the filter setting, as obviously, a simulation of an aircraft that can have high frequency components in its responses should have those components reach a visual display. The trade that filtering allows is one of preference for a particular amount of display stability vs. flying performance. For the T-37 aircraft and the simulation of formation flight used for this study, there clearly was a range of settings that allowed the degree of flight control normally found in the ASPT and that also removed most of the annoying jitter in the CIG system's image. From these two experiments, we suggest that this range is from 3/4 to 1 Hz.

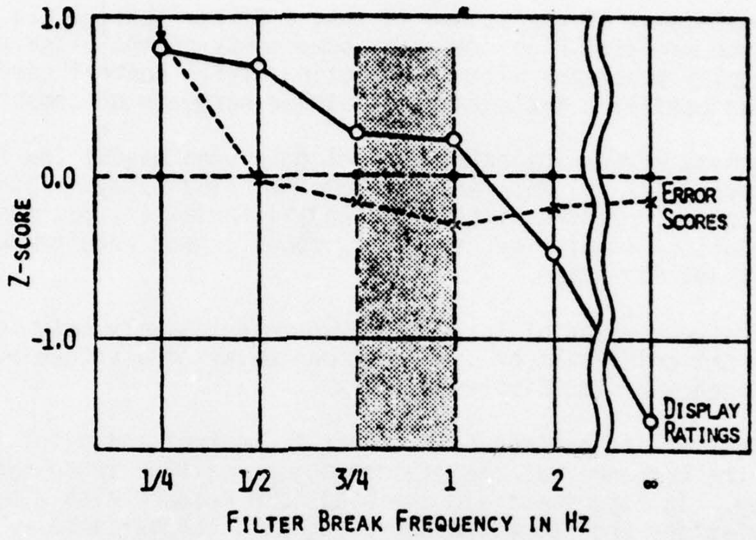

Figure 23. Average flight control and opinion of the computer-generated image as a function of filter setting. The measure of flight control is the average of the variances of the differences of pitch and roll angle, and both sets of data are normalized.

SECTION IV

CONCLUSIONS

a. The predict-then-filter scheme implemented on the ASPT is useful for delay compensation in operational flight simulators that have significant transport delays in the operation of their CIG visual systems.

b. The usefulness of the scheme is that a filter setting can be chosen that reduces the annoying high frequency components of the signals sent to the visual display processor without affecting flying control performance, and that it can easily be implemented as either hardware or computer software.

c. The scheme affects piloting control only when useful low frequency information (below 1/2 Hz) was removed from the CIG display. Tasks other than formation flight may require higher frequency information, but many of the flying tasks for which CIG displays are used probably have requirements similar to those of flying formation.

d. For a given amount of lead, it would be relatively easy to tailor this scheme for a particular task or device by manipulating a single parameter -- the break frequency of the display filter.

e. For most of the parameters of aircraft control and pilot input that we observed, the variance was the measure most sensitive to changes of the visual display. In Experiment II, the bandwidth measure also was sensitive to our manipulations and seemed to correlate with the variance -- in that changes of bandwidth were probably the activity reflected as significant differences of variance.

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APPENDIX A

FORMATION FLIGHT GRADING CRITERIA

TABLE A-1. 12-POINT SCALE USED FOR RATING FLIGHT CONTROL IN EXPERIMENT I

EXCELLENT

1. Excellent is characterized by exceptionally smooth control and small deviations from the desired position. Excellent position is maintained within deviations as follows:

   a. Fore-Aft (longitudinal): $\pm$ 2 ft.

   b. Side-side (lateral): from 1 ft closer in (tighter) to 3 ft further out.

   c. Vertical: from less than 1 ft high to not more than 3 ft low.

2. Good. Good is characterized by smooth control, with larger deviations and longer time out of position. Deviations must range within:

   a. Fore-aft (longitudinal) $\pm$ 3 ft.

   b. Side-side (lateral) from 1 ft closer in (tighter) to 5 ft further out.

   c. Vertical: from 2 ft high to 4 ft low.

3. Fair. Fair is characterized by rough control with large deviations, almost always out of position. Deviations range within:

   a. Fore-aft (longitudinal) $\pm$ 5 ft

   b. Side-side (lateral) from 2 ft closer in (tighter) to 8 ft further out.

   c. Vertical: from 4 ft high to 6 ft low.

4. Unsatisfactory. Unsatisfactory is characterized by the inability to maintain even fair position. Aircraft control is rough.

TABLE A-2. DESCRIPTION OF 12-POINT SCALE VALUES OF TABLE A-1 USED FOR EXPERIMENT I

EXAMPLE GRADES

12 Perfect position maintained, control use smooth, accurate.

11 Only small deviations seen. Control use smooth. Errors quickly corrected.

10 Deviated from desired only within the excellent area; however, did not remain "on" desired position, but passed through it.

9 Remained tightly within the "good" area. Control use smooth. Nearly an excellent.

TABLE A-2. DESCRIPTION OF 12-POINT SCALE VALUES OF TABLE A-1 USED FOR EXPERIMENT I (Cont'd)

8 A solid good. Normal use of controls. Was in position most of the time.

7 Stayed in good area, but control use was a little rough. Drifted constantly out of position.

6 Nearly a "good," but deviations somewhat too large. Correction time too slow, and control use too rough.

5 Kept aircraft in fair position but was constantly jockeying the controls. Almost always correcting errors. Somewhat behind the aircraft.

4 Barely stayed in the basic formation flight area. Aircraft control poor. Almost unsafe.

3 Able to move the aircraft into the "fair" area, but unable to keep it there. Constantly "behind" the other aircraft.

2 Did not crash or otherwise jeopardize life, but could not maneuver into position.

1 Crashed, passed under, over, or fell out of range.

TABLE A-3. DESCRIPTION OF CIG RATING SCALE OF EXPERIMENT I

ADDITIONAL RATING INFORMATION

We expect that some of the computer software changes that we will make between trials will affect the characteristics of the CIG visual display, and therefore after each trial, we would like you to rank the display's "goodness" or usefulness for formation flight. This will be in addition to the numerical score you will give the flight, and in order to avoid confusion, we would like you to use a letter scale where A = good, B = average, and C = poor, and where pluses and minuses are allowed. The ratings can thus go from A+ to C-, and for decisions like B- vs C+, you will have to do the best you can.

These letter scores can be entered on the flight scoresheet after the numerical score for a given trial, and the first entry might look like:
1 6, C+ .

TABLE A-4. SCORE SHEET USED BY INSTRUCTOR PILOTS IN EXPERIMENT I

IP or OBS

NAME____________________________

DATE____________________________

GRADING:

- U +			- F +			- G +			- E +		
1	2	3	4	5	6	7	8	9	10	11	12

OVER 4	4	2	1 HIGH
OVER 6	6	4	3 LOW
OVER 5	5	3	2 FORWARD
OVER 5	5	3	2 BACK
OVER 2	2	1	1 LEFT
OVER 8	8	5	3 RIGHT

DEMO #	TRIAL #	
	1	
	2	
	3	
	4	
	5	
	6	
	7	
	8	
	9	
	10	
	11	
	12	
	13	
	14	
	15	
	16	
	17	
	18	

TABLE A-5. RATING SCALE USED TO JUDGE AIRCRAFT CONTROL IN EXPERIMENT II

RATING	DESCRIPTION OF AIRCRAFT'S RESPONSE	JUDGMENT OF SIMULATOR	
9	Far too sensitive and difficult to control	Responsive +	Difficult to Control
8	Aircraft is sensitive and too responsive	Responsive	
7	Only a bit too sensitive for good control	Responsive -	
6	Controllable, but sensitive	Controllable +	Controllable
5	Perfectly Controllable - Responds as it should.	Controllable	
4	Controllable but sluggish.	Controllable -	
3	Aircraft response is only a bit slow for good control.	Sluggish +	Difficult to Control
2	Response is slow and sluggish.	Sluggish	
1	Aircraft is too sluggish and responds too slowly.	Sluggish -	

TABLE A-6. RATING SCALE FOR CIG SYSTEM IMAGE FLUTTER DURING EXPERIMENT II

RATING	DESCRIPTION OF JITTER IN DISPLAY	JUDGMENT OF DISPLAY
9	No flutter or jitter	Satisfactory +
8	Barely detectable jitter	Satisfactory
7	Jitter is noticeable but not annoying.	Satisfactory -
6	Easily noticeable jitter, but only barely annoying	Usable +
5	Jitter is noticeable and mildly annoying	Usable
4	Noticeable and annoying jitter	Usable -
3	Almost usable, but jitter is annoying	Poor +
2	Barely usable, very annoying jitter	Poor
1	Unusable - Jitter is far too annoying	Poor -

APPENDIX B

ANALYSIS OF VARIANCE TABLES OF EXPERIMENTS I AND II

These tables report the analyses of variance of Experiments I and II. In them, the exact probability of F-ratios significant at the p<.05 level or greater are given along with η^2 - the proportion of the total sum of squares attributable to each significant effect. The analyses for a given measure are grouped together -- those of the average value and variance for the data of Experiment I and of the average value, variance, and bandwidth for Experiment II. Occasionally rather large numbers were encountered as sums of squares and to conserve space, these were expressed in exponential or scientific notation. The value to four places is expressed as a decimal and the number following the E is an exponent of ten. For example, 0.1234E7, would represent 0.1234×10^7 or 1,234,000.

TABLE B-1. ANALYSIS OF THE AVERAGE VALUE (A) AND VARIANCE (B) OF THE X-AXIS DIFFERENCE OF POSITION OF THE LEAD AND LAG AIRCRAFT

(A)

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Blocks	169294.60	3	56431.53	0.42		
Treatments	7205487.50	53	135952.59	1.01		
A	255036.60	2	127918.30	0.96		
B	659077.61	5	131815.52	0.98		
C	191216.69	2	95608.34	0.71		
AxB	1233427.90	10	123342.79	0.92		
AxC	532276.81	4	133069.20	0.99		
BxC	1638471.70	10	163847.17	1.22		
AxBxC	2695180.30	20	134759.02	1.00		
Residual	21389720.00	159	134526.54			.744
Total	28764502.0	215				

(B)

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Blocks	.12936E+11	3	.43122E+10	1.05		
Treatments	.22196E+12	53	.41880E+10	1.02		
A	.78885E+10	2	.39442E+10	0.96		
B	.52143E+11	5	.10428E+11	2.55	.0295	.058
C	.17582E+11	2	.87914E+10	2.15		
AxB	.40799E+11	10	.40799E+10	0.99		
AxC	.17651E+10	4	.44129E+9	0.11		
BxC	.61820E+11	10	.61820E+10	1.51		
AxBxC	.39965E+11	20	.19982E+10	0.49		
Residual	.65047E+12	159	.40910E+10			.735
Total	.88537E+10	215				

TABLE B-2. ANALYSIS OF THE AVERAGE VALUE (A) AND VARIANCE (B) OF THE Y-AXIS DIFFERENCE OF POSITION OF THE LEAD AND LAG AIRCRAFT

(A)

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Blocks	1624517.20	3	541505.73	1.64		
Treatments	9734820.40	53	183675.86	0.55		
A	437389.08	2	218694.54	0.66		
B	1657612.60	5	331522.53	1.00		
C	932172.32	2	466086.16	1.41		
AxB	3687199.70	10	368719.97	1.11		
AxC	1375824.70	4	343956.18	1.04		
BxC	3264811.30	10	326481.13	0.99		
AxBxC	6378910.40	20	318990.52	0.96		
Residual	52635920.00	159	331043.52			.731
Total	71995257.0	215				

(B)

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Blocks	.32476E+9	3	.10825E+9	0.47		
Treatments	.11274E+12	53	.21272E+10	0.93		
A	.31673E+10	2	.15836E+10	0.70		
B	.13551E+11	5	.27102E+10	1.19		
C	.19453E+10	2	.97268E+9	0.43		
AxB	.28850E+11	10	.28850E+10	1.27		
AxC	.10965E+11	4	.27413E+10	1.20		
BxC	.23679E+11	10	.23679E+10	1.04		
AxBxC	.30584E+11	20	.15292E+10	0.67		
Residual	.36109E+12	159	.22710E+10			.757
Total	.47709E+12	215				

TABLE B-3. ANALYSIS OF THE AVERAGE VALUE (A) AND VARIANCE (B) OF THE Z-AXIS DIFFERENCE OF POSITION OF THE LEAD AND LAG AIRCRAFT

(A)

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Blocks	3035.96	3	1011.99	5.79	.0012	.076
Treatments	9298.42	53	175.44	1.00		
A	669.17	2	334.59	1.91		
B	728.01	5	145.60	0.83		
C	206.71	2	103.36	0.59		
AxB	2106.55	10	210.65	1.20		
AxC	1157.10	4	289.28	1.65		
BxC	1632.07	10	163.21	0.93		
AxBxC	2798.80	20	139.94	0.80		
Residual	27807.77	159	174.89			.693
Total	40142.15	215				

TABLE B-3. ANALYSIS OF THE AVERAGE VALUE (A) AND VARIANCE (B) OF THE Z-AXIS DIFFERENCE OF POSITION OF THE LEAD AND LAG AIRCRAFT (Cont'd)

(B)

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Blocks	.34581E+10	3	.11527E+10	1.59		
Treatments	.29356E+11	53	.55389E+9	0.76		
A	.10544E+10	2	.52723E+9	0.73		
B	.46242E+10	5	.92485E+9	1.28		
C	.27301E+10	2	.13650E+10	1.88		
AxB	.69328E+10	10	.69328E+9	0.96		
AxC	.27469E+10	4	.68675E+9	0.95		
BxC	.81067E+10	10	.81067E+9	1.12		
AxBxC	.13161E+11	20	.65804E+9	0.91		
Residual	.11532E+12	159	.72527E+9			.729
Total	.15813E+12	215				

TABLE B-4. ANALYSIS OF THE AVERAGE VALUE (A) AND VARIANCE (B) OF THE DIFFERENCE OF ROLL ANGLE OF THE LEAD AND LAG AIRCRAFT

(A)

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Blocks	93.99	3	31.33	2.98	.0325	.039
Treatments	636.12	53	12.00	1.14		
A	8.29	2	4.14	0.39		
B	35.50	5	7.10	0.67		
C	80.72	2	40.36	3.83	.0230	.034
AxB	137.90	10	13.79	1.31		
AxC	133.00	4	33.25	3.16	.0156	.055
BxC	100.57	10	10.06	0.96		
AxBxC	140.13	20	7.01	0.67		
Residual	1673.88	159	10.53			.696
Total	2403.99	215				

(B)

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Blocks	193812.92	3	64604.31	3.55	.0157	.045
Treatments	1199290.78	53	22628.13	1.24		
A	42240.93	2	21120.47	1.16		
B	65286.83	5	13057.37	0.72		
C	215488.60	2	107744.30	5.92	.0031	.050
AxB	215077.45	10	21507.75	1.18		
AxC	63066.01	4	15766.50	0.87		
BxC	162226.06	10	16222.61	0.89		
AxBxC	435904.88	20	21795.24	1.20		
Residual	2893975.20	159	18201.10			.675
Total	4287078.80	215				

TABLE B-5. ANALYSIS OF THE AVERAGE VALUE (A) AND VARIANCE (B) OF THE DIFFERENCE OF PITCH ANGLE OF THE LEAD AND LAG AIRCRAFT

(A)

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Blocks	0.84	3	0.28	1.14		
Treatments	13.60	53	0.26	1.04		
A	0.42	2	0.21	0.85		
B	1.13	5	0.23	0.92		
C	0.29	2	0.15	0.59		
AxB	2.91	10	0.29	1.18		
AxC	1.54	4	0.38	1.56		
BxC	3.33	10	0.33	1.35		
AxBxC	3.98	20	0.20	0.81		
Residual	39.13	159	0.25			.731
Total	53.56	215				

(B)

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Blocks	739.28	3	246.43	12.83	.0000	.130
Treatments	1884.06	53	35.55	1.85	.0021	.332
A	62.02	2	31.01	1.61		
B	294.63	5	58.93	3.07	.0114	.052
C	641.73	2	320.86	16.70	.0000	.113
AxB	269.75	10	26.97	1.40		
AxC	39.42	4	9.86	0.51		
BxC	216.05	10	21.61	1.12		
AxBxC	360.45	20	18.02	0.94		
Residual	3054.71	159	19.21			.538
Total	5678.04	215				

TABLE B-6. ANALYSIS OF THE AVERAGE VALUE (A) AND VARIANCE (B) OF THE DIFFERENCE OF YAW ANGLE OF THE LEAD AND LAG AIRCRAFT

(A)

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Blocks	203.00	3	67.67	0.24		
Treatments	17404.79	53	328.39	1.18		
A	206.74	2	103.37	0.37		
B	1666.96	5	333.39	1.19		
C	920.13	2	460.07	1.65		
AxB	3464.58	10	346.46	1.24		
AxC	1692.22	4	423.05	1.51		
BxC	3123.97	10	312.40	1.12		
AxBxC	6330.19	20	316.51	1.13		
Residual	44424.89	159	279.40			.716
Total	62032.68	215				

TABLE B-6. ANALYSIS OF THE AVERAGE VALUE (A) AND VARIANCE (B) OF THE DIFFERENCE OF YAW ANGLE OF THE LEAD AND LAG AIRCRAFT (Cont'd)

(B)

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Blocks	.18490E+8	3	61634E+7	1.92		
Treatments	.28419E+9	53	53620E+7	1.68	.0015	.034
A	.29195E+8	2	14597E+8	4.56	.0118	.027
B	.22152E+8	5	44304E+7	1.38		
C	.18699E+8	2	93496E+7	2.92		
AxB	.40013E+8	10	40014E+7	1.25		
AxC	.11393E+8	4	28481E+7	0.89		
BxC	.42749E+8	10	42749E+7	1.34		
AxBxC	.11998E+9	20	59993E+7	1.87	.0178	.148
Residual	.50866E+9	159	31991E+7			.627
Total	.81134E+9	215				

TABLE B-7. ANALYSIS OF THE AVERAGE VALUE (A) AND VARIANCE (B) OF THE LATERAL MOVEMENTS OF THE CONTROL STICK

(A)

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Blocks	0.038	3	0.013	6.38	.0007	.077
Treatments	0.145	53	0.003	1.36		
A	0.009	2	0.004	2.16		
B	0.016	5	0.003	1.62		
C	0.059	2	0.029	15.03	.0000	.119
AxB	0.016	10	0.002	0.79		
AxC	0.008	4	0.002	1.07		
BxC	0.006	10	0.001	0.31		
AxBxC	0.031	20	0.002	0.80		
Residual	0.312	159	0.002			.632
Total	0.494	215				

(B)

Blocks	13.12	3	4.37	7.99	.0002	.083
Treatments	58.01	53	1.09	2.00	.0007	.367
A	3.20	2	1.60	2.93		
B	12.30	5	2.46	4.49	.0010	.078
C	26.48	2	13.24	24.19	.0000	.167
AxB	4.73	10	0.47	0.86		
AxC	0.62	4	0.15	0.28		
BxC	5.70	10	0.57	1.04		
AxBxC	4.99	20	0.25	0.46		
Residual	87.01	159	0.55			.550
Total	158.14	215				

TABLE B-8. ANALYSIS OF THE AVERAGE VALUE (A) AND VARIANCE (B) OF THE LONGITUDINAL MOVEMENTS OF THE CONTROL STICK

(A)

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Blocks	0.0024	3	0.0008	0.08		
Treatments	0.3740	53	0.0070	0.70		
A	0.0032	2	0.0016	0.16		
B	0.0367	5	0.0073	0.73		
C	0.0003	2	0.0001	0.01		
AxB	0.0852	10	0.0085	0.84		
AxC	0.0173	4	0.0043	0.43		
BxC	0.0650	10	0.0065	0.64		
AxBxC	0.1683	20	0.0084	0.83		
Residual	1.6046	159	0.0101			.809
Total	1.9829	215				

(B)

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Blocks	7.35	3	3.45	14.68	.0000	.152
Treatments	14.61	53	0.28	1.65	.0094	.301
A	0.48	2	0.24	1.43		
B	2.40	5	0.48	2.88	.0161	.050
C	7.91	2	3.96	23.72	.0000	.163
AxB	1.20	10	0.12	0.72		
AxC	0.37	4	0.09	0.56		
BxC	0.63	10	0.06	0.38		
AxBxC	1.62	20	0.08	0.48		
Residual	26.52	159	0.17			.547
Total	48.48	215				

TABLE B-9. ANALYSIS OF THE AVERAGE VALUE (A) AND VARIANCE (B) OF THE POSITION OF THE RUDDER PEDALS

(A)

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Blocks	0.255	3	0.085	28.32	.0000	.258
Treatments	0.260	53	0.005	1.63	.0112	.263
A	0.015	2	0.007	2.48		
B	0.010	5	0.002	0.66		
C	0.116	2	0.058	19.31	.0000	.117
AxB	0.027	10	0.003	0.91		
AxC	0.009	4	0.002	0.78		
BxC	0.041	10	0.004	1.38		
AxBxC	0.042	20	0.002	0.69		
Residual	0.476	159	0.003			.481
Total	0.990	215				

TABLE B-9. ANALYSIS OF THE AVERAGE VALUE (A) AND VARIANCE (B) OF THE POSITION OF THE RUDDER PEDALS (Cont'd)

(B)

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Blocks	0.0006	3	0.0002	2.00		
Treatments	0.0066	53	0.0001	1.25		
A	0.0001	2	0.0000	0.46		
B	0.0006	5	0.0001	1.79		
C	0.0016	2	0.0008	11.40	.0001	.089
AxB	0.0014	10	0.0001	2.05	.0313	.079
AxC	0.0000	4	0.0000	0.09		
BxC	0.0009	10	0.0001	1.29		
AxBxC	0.0020	20	0.0001	1.48		
Residual	0.0109	159	0.0001			.606
Total	0.0180	215				

TABLE B-10. ANALYSIS OF THE AVERAGE VALUE (A) AND VARIANCE (B) OF THE POSITION OF THE LEFT THROTTLE

(A)

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Blocks	295.07	3	98.37	8.19	.0001	.091
Treatments	1030.41	53	19.44	1.62	.0118	.319
A	1.85	2	0.93	0.08		
B	164.57	5	32.91	2.74	.0208	.051
C	378.84	2	189.42	15.78	.0000	.117
AxB	93.86	10	9.39	0.78		
AxC	66.09	4	16.52	1.38		
BxC	127.26	10	12.73	1.06		
AxBxC	197.92	20	9.90	0.82		
Residual	1908.72	159	12.00			.590
Total	3234.20	215				

(B)

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Blocks	1823318.00	3	607772.66	22.19	.0000	.204
Treatments	2770875.00	53	52280.66	1.91	.0014	.310
A	25772.69	2	12886.34	0.47		
B	203935.01	5	40787.00	1.49		
C	1165862.20	2	582931.12	21.29	.0000	.130
AxB	273127.55	10	27312.76	1.00		
AxC	66815.78	4	16703.95	0.61		
BxC	403874.30	10	40387.43	1.47		
AxBxC	631487.55	20	31574.38	1.15		
Residual	4354020.20	159	27383.78			.204
Total	8948213.80	215				

TABLE B-11. ANALYSIS OF THE AVERAGE VALUE (A) AND VARIANCE (B) OF THE POSITION OF THE RIGHT THROTTLE

(A)

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Blocks	555.32	3	185.11	17.55	.0000	.177
Treatments	909.42	53	17.16	1.63	.0110	.289
A	2.13	2	1.06	0.10		
B	133.50	5	26.70	2.53	.0300	.042
C	334.15	2	167.07	15.84	.0000	.110
AxB	89.67	10	8.97	0.85		
AxC	58.80	4	14.70	1.39		
BxC	110.08	10	11.01	1.04		
AxBxC	181.10	20	9.05	0.86		
Residual	1676.76	159	10.55			.533
Total	3141.51	215				

(B)

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Blocks	1681344.0	3	560448.0	22.57	.0000	.205
Treatments	2591764.0	53	48901.2	1.97	.0009	.315
A	25939.5	2	12969.7	0.52		
B	187854.0	5	37570.8	1.51		
C	1111642.7	2	555821.4	22.38	.0000	.135
AxB	251001.7	10	25100.2	1.01		
AxC	62261.2	4	15565.3	0.63		
BxC	360865.3	10	36086.5	1.45		
AxBxC	592198.7	20	29609.9	1.19		
Residual	3948198.7	159	24831.4			.480
Total	8221305.2	215				

TABLE B-12. ANALYSIS OF THE PILOT'S RATING OF HIS FLIGHT

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Blocks	474.15	3	158.05	38.82	.0000	.296
Treatments	479.83	53	9.05	2.22	.0002	.299
A	29.36	2	14.68	3.61	.0284	.018
B	53.11	5	10.61	2.61	.0264	.033
C	207.25	2	103.63	25.45	.0000	.129
AxB	59.86	10	5.99	1.47		
AxC	19.14	4	4.78	1.18		
BxC	43.81	10	4.38	1.08		
AxBxC	67.31	20	3.37	0.83		
Residual	647.35	159	4.07			.404
Total	1601.33	215				

TABLE B-13. ANALYSIS OF THE PILOT'S RATING OF THE CIG DISPLAY

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Blocks	595.35	3	198.45	103.82	.0000	.572
Treatments	140.58	53	2.65	1.38		
A	2.01	2	1.00	0.52		
B	7.36	5	1.47	0.77		
C	52.84	2	26.42	13.76	.0000	.051
AxB	8.05	10	0.80	0.42		
AxC	9.44	4	2.36	1.23		
BxC	30.21	10	3.02	1.57		
AxBxC	30.68	20	1.53	0.80		
Residual	305.40	159	1.92			.293
Total	1041.33	215				

TABLE B-14. ANALYSIS OF THE OBSERVER'S RATINGS OF THE FLIGHTS

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	P	η^2
Blocks	460.80	3	153.60	33.42	.0000	.288
Treatments	410.33	53	7.74	1.68	.0075	.256
A	30.33	2	15.17	3.30	.038	.019
B	19.00	5	3.80	0.83		
C	176.78	2	88.39	19.23	.0000	.110
AxB	23.67	10	2.37	0.52		
AxC	15.72	4	3.93	0.86		
BxC	38.06	10	3.81	0.83		
AxBxC	106.78	20	5.34	1.16		
Residual	730.70	159	4.60			.110
Total	1601.83	215				

TABLE B-15. ANALYSIS OF THE OBSERVER'S RATINGS OF THE CIG DISPLAY

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Blocks	89.65	3	29.88	7.02	.0004	.96
Treatments	164.83	53	3.11	0.73		
A	3.25	2	1.63	0.38		
B	1.50	5	0.30	0.07		
C	35.11	2	17.56	4.12	.0000	.038
AxB	15.75	10	1.58	0.37		
AxC	8.56	4	2.14	0.50		
BxC	17.72	10	1.77	0.42		
AxBxC	82.94	20	4.15	0.97		
Residual	677.35	159	4.26			.727
Total	931.83	215				

TABLE B-16. ANALYSES OF THE AVERAGE VALUE, VARIANCE; AND BANDWIDTH OF THE X-AXIS DIFFERENCE OF POSITION OF THE LEAD AND LAG AIRCRAFT

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Average Value						
Between Groups	0.243	5	0.049	2.593		
Within Groups	0.338	18	0.019			
Total	0.581	23				
Variance						
Between Groups	0.722	5	0.144	1.283		
Within Groups	2.027	18	0.113			
Total	2.749	23				
Bandwidth						
Between Groups	0.469	5	0.094	3.869	.015	.52
Within Groups	0.436	18	0.024			
Total	0.905	23				

TABLE B-17. ANALYSES OF THE AVERAGE VALUE, VARIANCE; AND BANDWIDTH OF THE Y-AXIS DIFFERENCE OF POSITION OF THE LEAD AND LAG AIRCRAFT

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Average Value						
Between Groups	.124	5	.025	1.431		
Within Groups	.312	18	.017			
Total	.436	23				
Variance						
Between Groups	.337	5	.067	0.497		
Within Groups	2.444	18	.137			
Total	2.781	23				
Bandwidth						
Between Groups	.085	5	.017	0.780		
Within Groups	.393	18	.022			
Total	.478	23				

TABLE B-18. ANALYSES OF THE AVERAGE VALUE, VARIANCE, AND BANDWIDTH OF THE Z-AXIS DIFFERENCE OF POSITION OF THE LEAD AND LAG AIRCRAFT

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Average Value						
Between Groups	0.729	5	0.146	3.310	.027	.48
Within Groups	0.793	18	0.044			
Total	1.522	23				
Variance						
Between Groups	1.236	5	0.247	2.961	.039	.45
Within Groups	1.502	18	0.083			
Total	2.738	23				
Bandwidth						
Between Groups	0.186	5	0.037	1.700		
Within Groups	0.393	18	0.022			
Total	0.579	23				

TABLE B-19. ANALYSES OF THE AVERAGE VALUE, VARIANCE, AND BANDWIDTH OF THE DIFFERENCE OF ROLL ANGLE OF THE LEAD AND LAG AIRCRAFT

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Average Value						
Between Groups	0.753	5	0.151	2.110		
Within Groups	1.285	18	0.071			
Total	2.088	23				
Variance						
Between Groups	3.145	5	0.629	13.961	.000	.79
Within Groups	0.811	18	0.045			
Total	3.956	23				
Bandwidth						
Between Groups	0.958	5	0.192	11.171	.000	.76
Within Groups	0.309	18	0.017			
Total	1.267	23				

TABLE B-20. ANALYSES OF THE AVERAGE VALUE, VARIANCE, AND BANDWIDTH OF THE DIFFERENCE OF PITCH ANGLE OF THE LEAD AND LAG AIRCRAFT

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Average Value						
Between Groups	0.530	5	0.106	2.663		
Within Groups	0.716	18	0.040			
Total	1.246	23				
Variance						
Between Groups	3.783	5	0.757	66.842	.000	.95
Within Groups	0.204	18	0.011			
Total	3.987	23				
Bandwidth						
Between Groups	0.628	5	0.126	37.550	.000	.91
Within Groups	0.060	18	0.003			
Total	.688	23				

TABLE B-21. ANALYSES OF THE AVERAGE VALUE, VARIANCE, AND BANDWIDTH OF THE DIFFERENCE OF YAW ANGLE OF THE LEAD AND LAG AIRCRAFT

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Average Value						
Between Groups	0.230	5	0.046	2.072		
Within Groups	0.398	18	0.022			
Total	0.628	23				
Variance						
Between Groups	1.585	5	0.317	5.190	.004	.59
Within Groups	1.100	18	0.061			
Total	2.685	23				
Bandwidth						
Between Groups	0.233	5	0.047	1.833		
Within Groups	0.456	18	0.025			
Total	0.689	23				

TABLE B-22. ANALYSES OF THE AVERAGE VALUE, VARIANCE, AND BANDWIDTH OF THE LATERAL MOVEMENTS OF THE CONTROL STICK

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Average Value						
Between Groups	0.481	5	0.096	6.039	.002	.63
Within Groups	0.287	18	0.016			
Total	0.768	23				
Variance						
Between Groups	9.316	5	1.863	76.475	.000	.96
Within Groups	0.438	18	0.024			
Total	9.754	23				
Bandwidth						
Between Groups	0.148	5	0.030	4.337	.009	.55
Within Groups	0.122	18	0.007			
Total	0.270	23				

TABLE B-23. ANALYSES OF THE AVERAGE VALUE, VARIANCE, AND BANDWIDTH OF THE LONGITUDINAL MOVEMENTS OF THE CONTROL STICK

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Average Value						
Between Groups	0.000	5	0.000	0.226		
Within Groups	0.002	18	0.000			
Total	0.002	23				
Variance						
Between Groups	3.942	5	0.788	24.894	.000	.87
Within Groups	0.570	18	0.032			
Total	4.512	23				
Bandwidth						
Between Groups	0.517	5	0.103	3.516	.021	.49
Within Groups	0.530	18	0.029			
Total	1.047	23				

TABLE B-24. ANALYSES OF THE AVERAGE VALUE, VARIANCE, AND BANDWIDTH OF THE POSITION OF THE RUDDER PEDALS

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Average Value						
Between Groups	0.234	5	0.047	0.660		
Within Groups	1.275	18	0.071			
Total	1.509	23				
Variance						
Between Groups	1.365	5	0.273	6.420	.002	.64
Within Groups	0.765	18	0.043			
Total	2.130	23				
Bandwidth						
Between Groups	0.095	5	0.019	0.232		
Within Groups	1.479	18	0.082			
Total	1.574	23				

TABLE B-25. ANALYSES OF THE AVERAGE VALUE, VARIANCE, AND BANDWIDTH OF THE POSITION OF THE LEFT THROTTLE

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Average Value						
Between Groups	0.003	5	0.0006	3.530	.021	.60
Within Groups	0.002	18	0.0001			
Total	0.005	23				
Variance						
Between Groups	1.145	5	0.229	3.408	.024	.49
Within Groups	1.209	18	0.067			
Total	2.354	23				
Bandwidth						
Between Groups	0.540	5	0.108	1.641		
Within Groups	1.185	18	0.066			
Total	1.725	23				

TABLE B-26. ANALYSES OF THE AVERAGE VALUE, VARIANCE, AND BANDWIDTH OF THE POSITION OF THE RIGHT THROTTLE

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
Average Value						
Between Groups	0.002	5	0.000	3.035	.037	.40
Within Groups	0.003	18	0.000			
Total	0.005	23				
Variance						
Between Groups	1.184	5	0.237	3.493	.022	.49
Within Groups	1.220	18	0.067			
Total	2.404	23				
Bandwidth						
Between Groups	0.398	5	0.080	0.991		
Within Groups	1.447	18	0.080			
Total	1.845	23				

TABLE B-27. ANALYSES OF THE PILOTS' RATINGS OF THE CIG DISPLAY AND OF THE FLIGHTS

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-RATIO	p	η^2
CIG Display						
Between Groups	15.64	5	3.128	42.02	.000	.92
Within Groups	1.34	18	0.074			
Total	16.98	23				
Flights						
Between Groups	5.05	5	1.010	8.41	.000	.70
Within Groups	2.16	18	0.120			
Total	7.21	23				

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