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TACTILE DISPLAY FOR AIRCRAFT CONTROL

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Nearly all flight parameter information is transmitted to the pilot visually and it is well known that instrument scanning during zero visibility flying conditions can be fatiguing. Displays using information from other modalities can alleviate the demands of this task and this program was directed towards the development of tactile displays for flight control.

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The data reported herein were taken with the tactile display providing pitch and, or roll attitude error in static tests; mach number deviation during high speed maneuvers, and angle of attack or ILS (2-axis) data during approach-to-landing in a simulator with 3 axis cockpit motion. Data were taken with and without an added visual task. Results proved performance of single axis tactile display of mach number error exceeded performance with analog mach number instrument. The utility of 2 tactile data channels is low because of masking and difficulty of simultaneous signal perception. The use of vibrotactors was preferred over electrotactors. All subjects were qualified pilots.

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SUMMARY

This program has surveyed several types of tactile transducers and tactile displays to determine their merit as a flight control instrument as a method to reduce the pilots' visual workload. Preliminary phases have been reported in References 1, 2 and 9.

The laboratory evaluation of the tactile displays, in which four instrument rated pilots acted as subjects, utilized difficult attitude tracking tasks to measure the subjects' performance over a reasonably wide frequency range. The tasks were single axis pitch or roll and 2 axis pitch and roll tracking. The simplified vehicle dynamics represented the response of a high-speed fighter aircraft having good handling qualities. The pitch and roll axes were perturbed by independent quasi-random inputs used to simulate first-order Gaussian noise having an upper break frequency of 2 rad/sec. In these difficult tracking experiments, tracking performance with the quantized tactile display was poorer than the performance with an analog visual display. When using the tactile display, the single-axis, average tracking standard deviation (SD) score was about twice that for the visual display. The two-axis tactile SD score was 3.6 times the visual score. Both the 1 and 2 axis scores were better than the scores obtained with the first tactile control display. The 2-axis scores were poorer than the 1-axis scores because of inter-axis masking and the difficulty in the differential perception of two simultaneous tactual signals.

The final evaluation of the tactile display was conducted with a simulator having F4 dynamics. To provide a more realistic experiment, the roll, pitch and heave axes of the cockpit were controlled by the simulation; and independent of the flight control, a visual monitoring task was added to burden the subjects' visual workload.

The experiments were run with two simulation models: high-speed flight, wherein the subjects were required to maintain constant mach number while executing prescribed maneuvers, and an approach-to-landing where either angle of attack or glide slope and localizer errors were controlled. Each experiment was completed by six subjects who were Navy Pilots.

In the high-speed flight experiments, the tactile display of mach number error consistently produced better SD scores than the use of a standard mach number indicator, and the relative improvement was greater when the visual monitoring task was added. No significant changes in either control or monitoring performance were found when the tactile display was used for angle-of-attack or path (ILS) error information in the approach-to-landing task.

Even when the visual mach number display was available, the pilots appeared to rely on the tactile display for mach number control, furthermore, all six pilots were willing to use the tactile display as a supplement to the visual display of mach number in actual flight.

It is apparent that under certain conditions, a single-axis tactile display can be utilized advantageously as an operational instrument.

SECTION 1
INTRODUCTION

1.1 OBJECTIVES

In current aircraft, nearly all the flight parameter information available to the pilot is transmitted to him visually, whether under visual contact or instrument flying conditions. It has long been recognized that during instrument flying conditions, the task of scanning just the essential instruments is a taxing, fatiguing one. It may be that displays using information from other modalities can alleviate the demands of this task. Furthermore, the importance of maintaining continuous attention to the visual scene outside the cockpit is being increasingly realized for a number of situations. Traditional panel - mounted visual instruments do not permit this, whereas display of information to other modalities could free the eyes substantially from tasks inside the cockpit. Tactual presentations possess considerable promise of being suitable substitutes for visual displays in flight-control applications. The goal of this program has been to develop a tactual display that can be utilized as a flight control instrument.

A systematic evaluation of a tactual display has been carried out in three separate phases:

a. initial design and laboratory evaluation,

b. evaluation utilizing full task simulation, and finally,

c. a flight test.

The program has encompassed the first two phases and has produced the following reports.

a. D. Ross, R. Sanneman, W. H. Levison, R. Tanner, and T. Triggs, "Tactile Display for Aircraft Control", Semi-Annual Technical Report, Sanders Associates, Inc., Nashua, N. H, (AD757-344) January 1973.

b. D. Ross, R. Sanneman, W. Levison, R. Tanner, T. Triggs, "Tactile Display for Aircraft Control", Final Technical Report, Sanders Associates, Inc., Nashua, N. H. (AD767-763), August 1973.

c. D. Ross, R. Sanneman, W. Levison, J. Berliner, "Tactile Display for Aircraft Control", Semi-Annual Report, Sanders Associates, Inc., Nashua, N. H. (AD783-690) June 1974.

The work accomplished during the first year was conducted in three parts and is reported in the first two references listed above.

a. Review and selection of elemental tactile transducers (tactors) for operation in arrays.

b. Development of tactile display configurations suitable for applications concerning aircraft control problems.

c. Evaluation of the man/machine tracking performance for single and multi-axis data utilizing the tactile displays together with a suitable dynamic tracking problem and an ancillary visual monitoring task.

Tactile displays using bimorph vibrators and electrotactors were evaluated. The electrotactors were driven by a short single polarity, constant current pulse which to some produced a sharp sensation, consequently further work was done on the evaluation of biphasic stimulation which could be made more comfortable. In the formal laboratory tests, two instrument rated pilots served as test subjects. The results of the evaluation showed that the tracking error scores obtained with the tactile display were a factor of three to four times greater than scores obtained with a continuous visual display. However, the results also indicated the inter-task interference effects are substantially less with the tactile display in situations imposing a high visual scanning workload. The single-task performance degradation found with the tactile display appeared to be a result of the display coding rather than the use of the tactual sensory mode per se.

The laboratory tests were done with broadband disturbance functions in order to obtain data for an "optimal-control" model for pilot/vehicle systems. The analytical effort expended on the model provides a valuable backup and extension of the display evaluation. It was shown in the August 1973 report that the state-variable model for pilot/vehicle systems can be used to obtain reasonably accurate predictions of tracking error scores when the vehicle dynamics are wide-band, despite non-Gaussian pilot response behavior.

With this encouraging start, the second year's goals were set as follows:

a. Redesign the tactile display to reduce time displays.

b. Evaluate the refined display under the same laboratory conditions as prevailed during the first year tests.

c. Evaluate the display utilizing a moving base aircraft simulator.

A full description of the display system and the laboratory tests have been presented in the third report listed above. In addition to the above program elements, a data fallout occurred which proved that coaxial electrotactors do not restrict skin current flow within the bounds of the tactor. The tactile display had four major improvements.

- A programmable tactor excitation code.
- Independent axis control.
- Automatic stimulus intensity control for the electrotactor display.
- Separate intensity controls for the x-axis and the y-axis segments.

The laboratory tests indicated the display performance was improved twenty-five to fifty percent referenced to the first year tests.

The final evaluation has been performed utilizing a moving base aircraft simulator with F4 dynamics, more specifically, the simulator and helicopter motion platform operated by the NMC Weapons Systems Simulation Branch at Point Mugu, California. The program has incorporated the tactual display as a flight instrument during typical flight problems.

1.2 EQUIPMENT DESCRIPTION

A detailed description of the tactile control system has been reported (9), however, portions of the description have been included for general information. Descriptions of the F4 simulation and the dynamic motion have been added to this section.

1.3 LABORATORY EVALUATION

The laboratory evaluation program utilized four instrument rated pilots as subjects to accomplish 3 goals; display optimization, electrotactor and vibrotactor performance comparison, and the performance measurements of the tactile display in single and double axis tracking problems.

The results of the display optimization, tactor comparison and the subject training data have been reported[9], as well as the performance measurements. Since the model analysis work based on this effort is now being reported for the first time, the performance measurement data has been included to provide a more comprehensive report.

1.4 SIMULATOR EVALUATION

The objective of these experiments has been the determination of the tactile display utility as an instrument for providing flight-control information in a moving base simulator having realistic aircraft dynamics. These tests were run with two operational models, high speed cruise and approach to landing. Motion in pitch, roll and heave were used to provide cockpit dynamics. In the high-speed cruise model, the tactile display indicated mach number error. The task required maintaining constant mach number while maneuvering through prescribed flight paths. The Tactile Display provided either angle-of-attack, or glideslope and localizer errors in the approach-to-landing model. Conventional instruments were also used to provide a performance reference. All flight tests were run with and without an added visual monitoring task that was independent of flight control.

SECTION 2
EQUIPMENT DESCRIPTION

2.1 GENERAL

The equipment used for this phase of the program consisted of the tactile display, the simulator and the visual monitoring task. The tactile display system has been discussed in fair detail in the June 1974 Technical Report (9), however, for convenience, portions of the report are repeated in this section.

2.2 TACTILE CONTROL SYSTEM

The Tactile Control System presented in Figure 2-1 consists of the following parts.

a. Tactile Control Unit (TCU), left in the figure, contains the logic circuitry and all the controls necessary for the functional operation of the system. The visual display in the middle of the panel is removable for remote viewing. The front panel is illustrated in Figure 2-2.

b. Tactile Power Supply (TPS), right in the figure, contains the system power supplies and the power control switches.

c. Two electrotactor displays, both of which have the same configuration and incorporate silver, coaxial electrotactors.

d. One vibrotactor display employing bimorphs as the electromechanical vibration transducers.

e. Two cutaneous display belts, one of which is shown under the vibrotactor display.

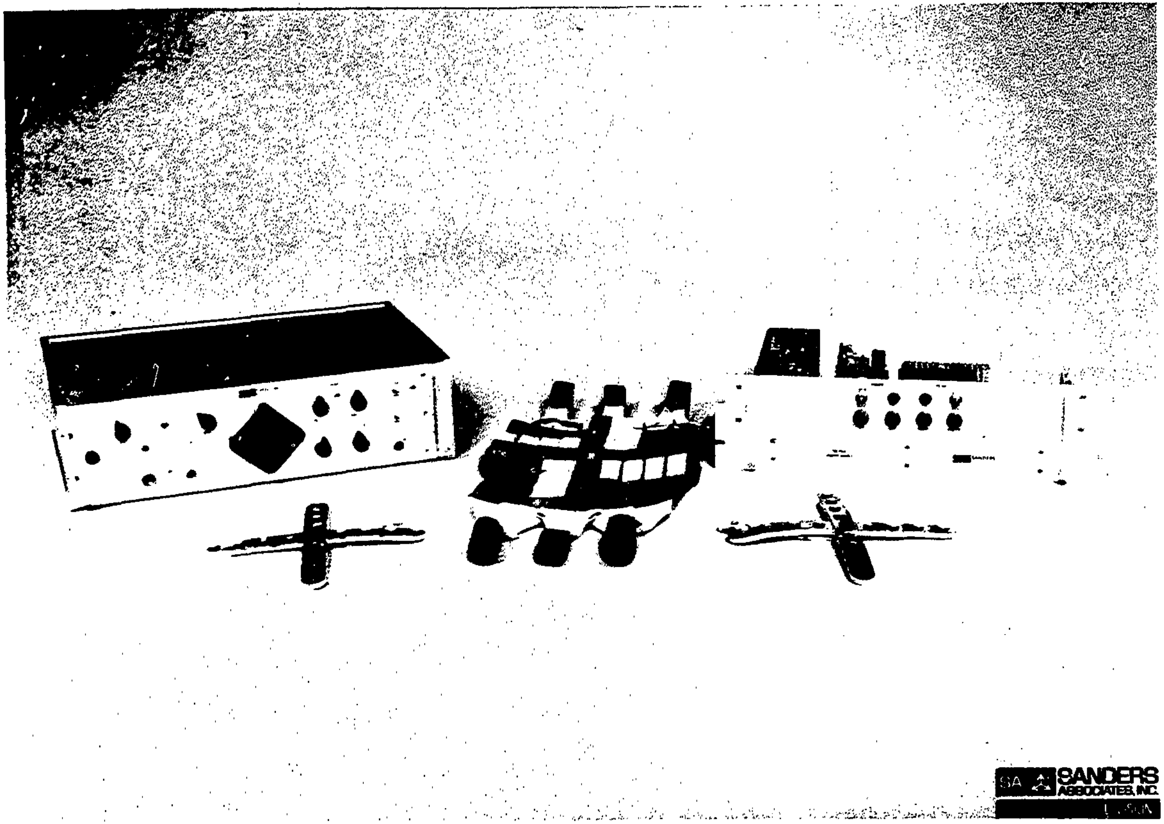

Figure 2-1 Tactile Control System.

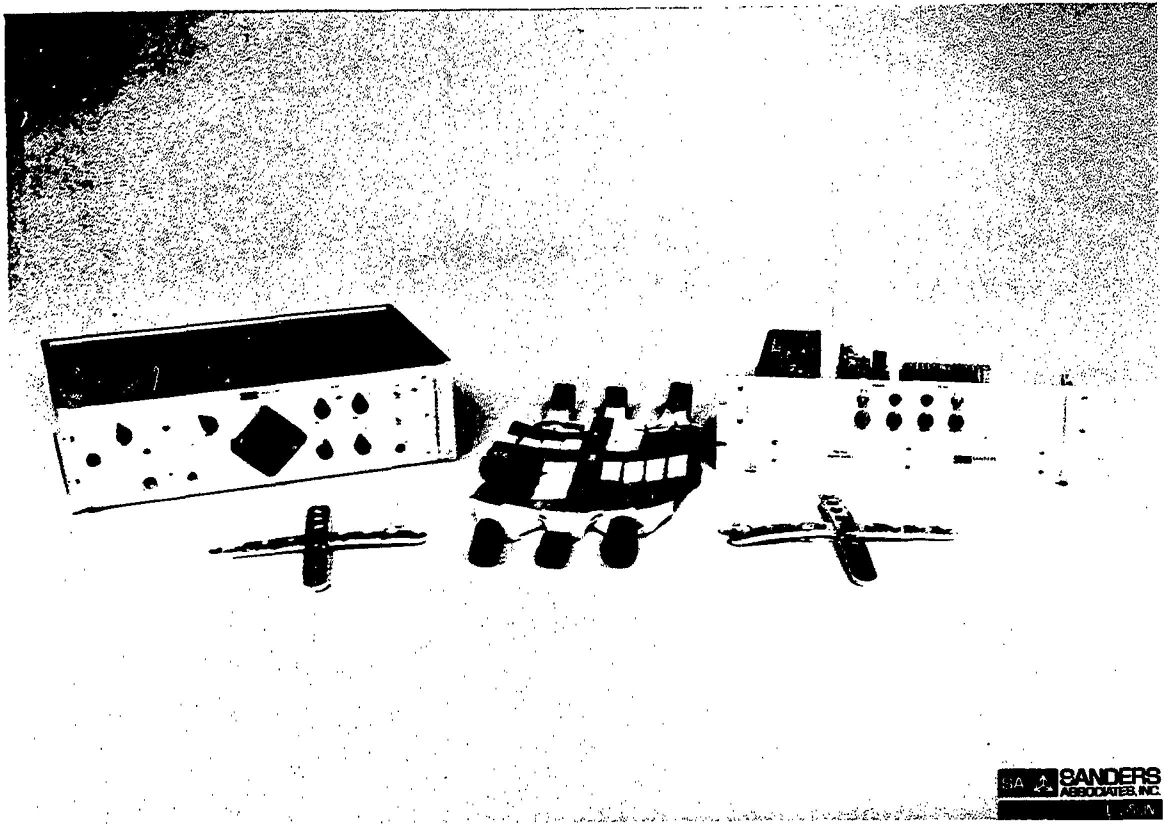

Figure 2-1 Tactile Control System.

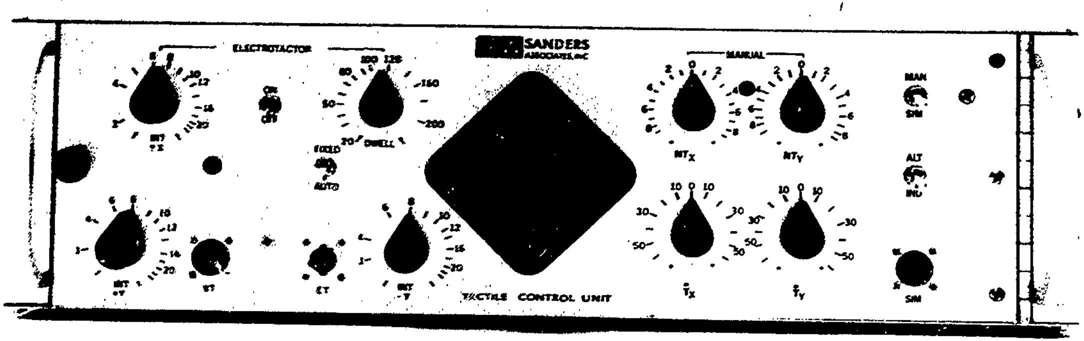

Figure 2-2 Tactile Control Unit, Front Panel.

For this phase of the program, one display format has been selected; it is an array using eight tactors per axis, four for each axis polarity and no central, common tactor. Each axis is a complete, independently controlled channel to allow simultaneous data presentation to both axes. In order to increase the versatility of the system, a switch is available to allow either independent data display for each axis, or an alternate-axis display sequence. A number of tactor excitation codes are available and, if desired, each axis can have a different code.

2.2.1 Display Format. Only one format has been fabricated for the displays, it is an X-Y array having no central tactor and with 4 tactors in each leg as illustrated in Figure 2-3. The size of the array is fixed, i.e., the tactors are not movable. It is well known that tactile spatial resolution is generally not high, thus it is advantageous to separate the tactors as much as possible; however, for convenience, the tactile display should be small. Therefore, a compromise has been made by fixing each axis length to 9 inches. This allows 1-1/8 inches between tactors in each axis leg and 2 inches between the central tactors.

One of the final electrotactor displays is shown in Figure 2-4. The electrotactors are coaxial and have silver electrodes. The OD is 11 mm with an inner electrode area of 17 mm^2 and an outer electrode area of 57 mm^2.

Figure 2-5 is the vibrotactor display resting on one of the belts used to apply the display to the body. The 1 mm diameter probes used to vibrate the skin is driven with a piezoelectric crystal (bimorph) held as a cantelever and is capable of providing a peak force of 30 grams at 150 volts. A one-inch square pressure pad surrounds the 0.25 inch probe clearance hole in order to minimize the effects of skin wave propagation.

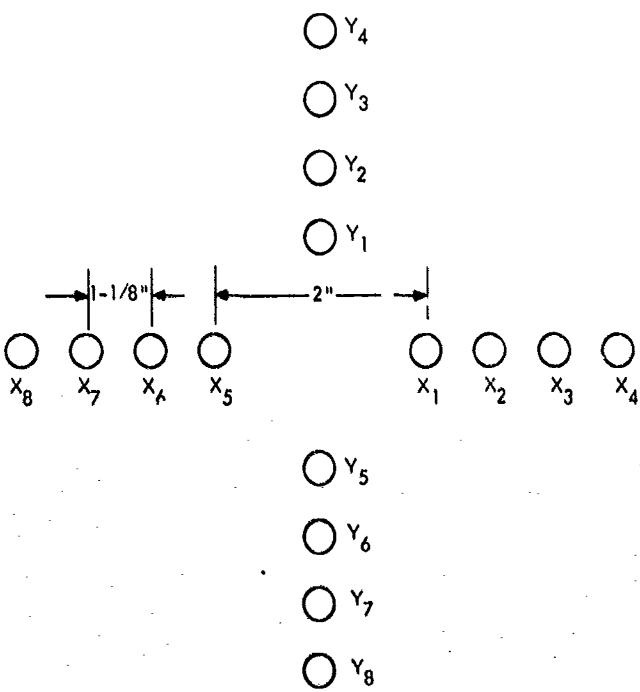

Figure 2-3 Tactile Display Geometry.

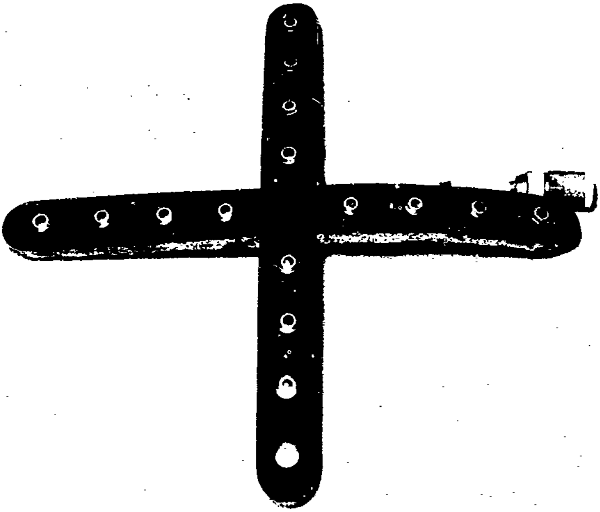

Figure 2-4 Electrotactor Display

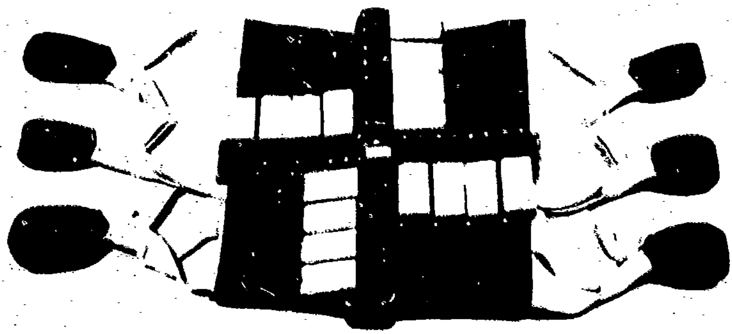

Figure 2-5 Vibrotactor Display.

2.2.2 Display Coding. The tactile display consists of two, parallel channels each capable of presenting polarity sensitive control error data. The channels are operated independently to the extent that each can utilize a separate display code. For these experiments, the same code (No. 3) was used for each channel.

There are two controlling analog input signals for each axis:

- XT is the analog signal that is quantized to 3 levels (A, and C), presently corresponding to 5, 30, and 70 rcent of full scale.

- T is the analog signal that directly controls the tactor excitation ripple rate from 4 to 30 Hz.

The input data directly controls the tactile display such that any control error variation will be transposed to cutaneous communication signals. During an excitation sequence of one axis, 2, 3, or 4 tactor stimulus periods can be generated as determined by which quantization level was maintained during the display period. The freedom within which the display can be coded is set by the following bounds. These are:

- four tactors
- two sequenced clock periods generated for a XT level A
- three sequenced clock periods generated for a XT level B
- four sequenced clock periods generated for a XT level C

Code 3 was used in these experiments. When the error exceeds minimum threshold (level A), the two outer tactors (i.e. X_1 & X_3 for "-" X error) are sequentially energized at a rate determined by the T input level. If the error grows larger, tactor X_2 (level B), then X_1 (level C) will be added to the ripple sequence as their related quantization levels are exceeded. (level C sequence X_4 X_3 X_1 - X_4 X_3 X_2 X_1, ...)

2.2.3 Tactor Excitation. The tactile displays are fabricated using two different tactor types, bimorph (piezoelectric) vibrotactors and electrotactors. The bimorph excitation signal is a six cycle burst of 170 Hz, 140 Vrms; and the electrotactors are excited with seven cycles of biphasic constant current pulses. Representative sketches of these signals are illustrated in Figure 2-6(a). The resulting stimulus period for either of these signals is 30 milliseconds or about as long as the 30 Hz period occurring at the maximum ripple rate. In Figure 2-6(b), the X-axis tactor (1, 2, 3) stimulus periods are shown for Code 1, level B presentation with the ripple rate less than 30 Hz.

2.2.4 Block diagram. The tactile display system block diagram is presented in Figure 2-7. As stated, each axis is independently controlled, thus the system basically consists of two parallel data channels, the X-axis and the Y-axis. They are synchronized only when the alternate-axis display mode is selected. The system description is presented in four parts: analog signal processor, tactor control, electrotactor display and the vibrotactor display.

2.2.5 Analog Signal Processor. The analog signal processor derives its inputs from either the manual controls on the front panel of the Tactile Control Unit (TCU) or from an external control system such as the F4 simulator. For each tactile display axis, two analog signals are required, V_{NT} and $V_{\dot{T}}$.

The F4 simulator computation voltages are ± 100 Vdc full scale; they are rescaled to the ± 8 Vdc full scale voltage used in the tactile display. The MAN-SIM switch on the TCU front panel selects either the analog signals from the SIM receptacle or from the four controls located on the front panel.

The V_{NT} signal for each channel (X, Y) is the input to the three level quantizer and the polarity control. The three levels (A, B, C) for both axes are set by the same voltage divider network. The initial

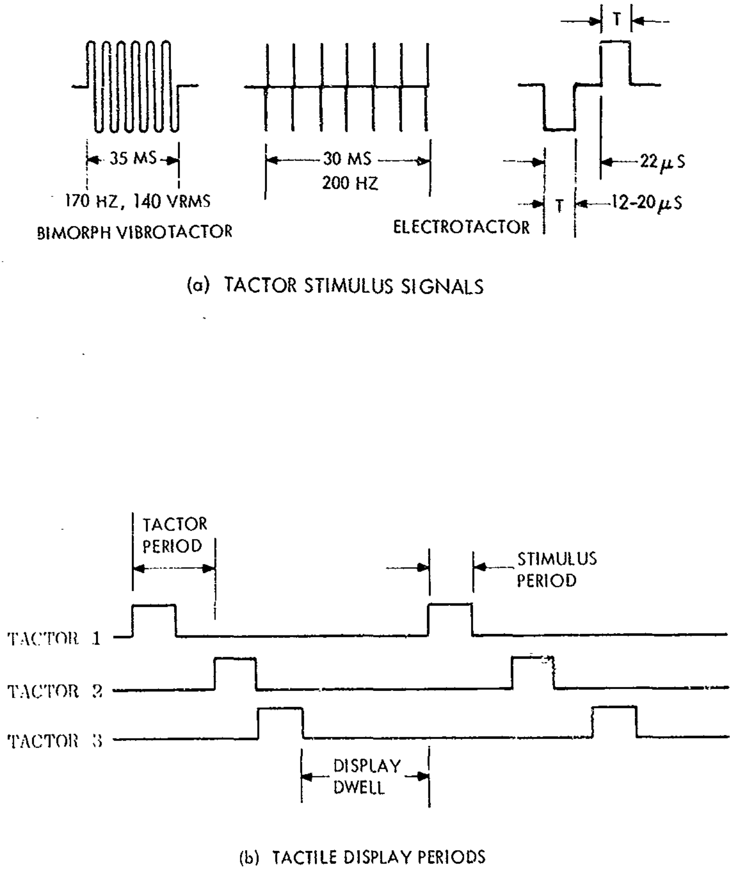

Figure 2-6 Tactor Stimulus Signals and Display Periods.

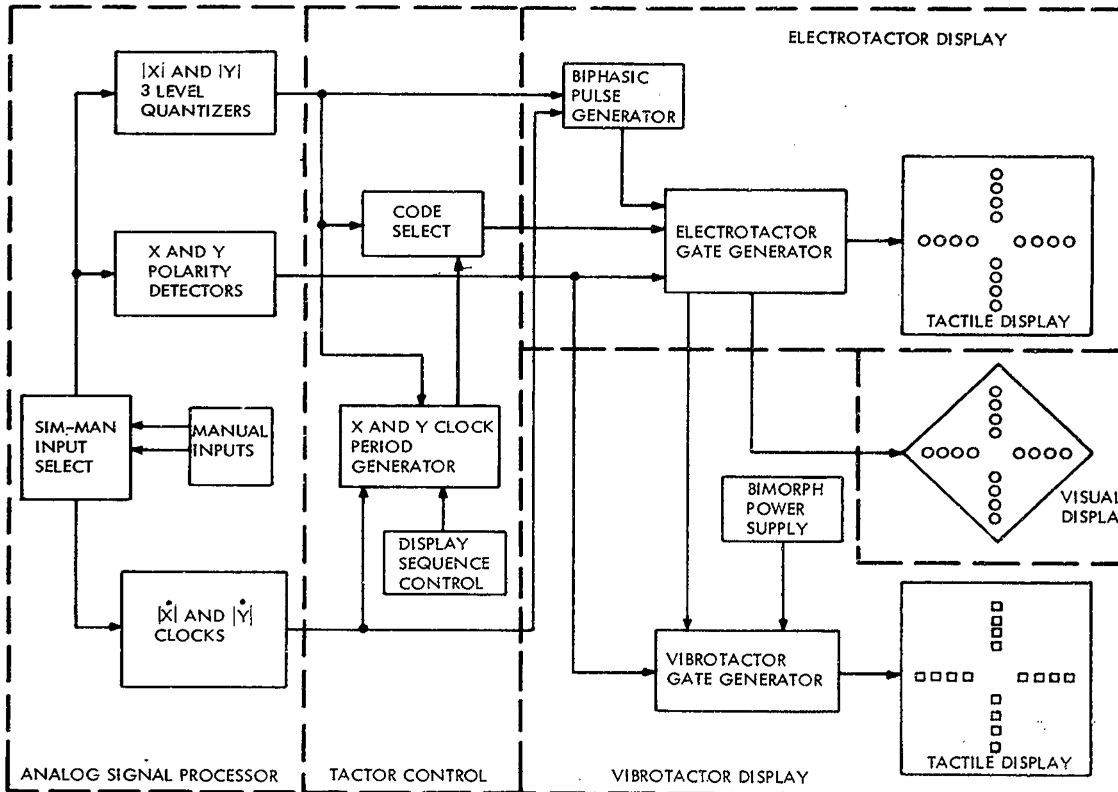

Figure 2-7 Tactile Display Block Diagram.

quantization level reference voltages are A $\geq$ 0.4V, B $\geq$ 2.4V, and C $\geq$ 5.6V, which correspond to 5, 30 and 70 percent of full scale. This resistor network is mounted on a plug board to facilitate changing the reference values when desired. To minimize the number of comparators, the absolute value of the analog signal is used. The quantization levels (A, B, C) control the number of generated clock periods (2, 3, or 4) and are used as variables in the tactor period logic for the selection of various tactor excitation codes. The levels are also inputs to the automatic electrotactor intensity control. The polarity signal (P_X or P_Y) is used in its respective tactor gate generator to determine which of the two, four tactor sets of one axis is to be used to display the error data, i.e., is the data polarity positive or negative.

The absolute values of the $\dot{T}$ data signals ($|\dot{X}|$) and ($|\dot{Y}|$) are used to control the clock rates at which the tactor stimulus periods are generated. The minimum clock pulse rate is set at 4 Hz in order to eliminate excessive display time delays that would occur at lower rates. The maximum clock rate is 30 Hz. The $|\dot{X}|$ and $|\dot{Y}|$ signals are also used in the auto-intensity control for the electrotactors.

2.2.6 <u>Tactor Control</u>. The tactor control section generates the number of clock periods determined by the quantization level (A, B, C) at the rate decreed by the $\dot{T}$ input. This is done by counting the clock pulses and generating gates equal to the interval periods between sequential clock pulses.

The four possible clock periods (T_1, T_2, T_3 and T_4) are combined to form six multiple period combinations (i.e., T_2T_3, $T_1T_2T_3$, etc.). The four clock periods and their combinations serve as inputs to the code selector where they are programmed by the selected code plugboards, and combined with the quantization levels to produce the desired tactor gate sequence. There are four outputs for each axis, T_{15}, T_{26}, T_{37} and T_{48}. Each output controls one of two tactors pending the polarity of the NT signal, for instance T_{15} will control tactor No. 1 if the axis V_{NT} signal is negative and will control tactor No. 5 if the polarity is positive.

2.2.7 Electrotactor Display. The electrotactor gate generator accepts the clock gates from the code selector, the polarity signals, and the biphasic pulse pairs. It then generates the tactor stimulus periods from the clock gate, then, with the polarity signal, routes the biphasic pulses to the proper tactor drivers.

The clock gate onset is coincident with the leading edge of the clock pulse. A post clock pulse is generated coincident to the trailing edge of the clock pulse. The post clock pulse is ANDed with the clock gates to produce the SOS (stimulus onset signal) for the tactor pair (such as T_{15}) having its related clock gate at a "1" level. The SOS resets the stimulus pulse counter which then begins to count the pulse pairs, and gates the pulse pairs, in conjunction with the polarity signal, to the proper tactor drive circuit. When seven pulse pairs have been delivered, the counter is turned off, awaiting its next SOS. The tactor driver converts the low level logic signals to the required high level constant current pulses required to exceed touch threshold.

The biphasic signal described in reference (2) is used as the tactile stimulus. The signal consists of a short burst of seven negative and positive, square, constant-current pulse pairs at a 200 Hz rate, as illustrated in Figure 2-6(a).

The maximum pulse widths are 20 μs and there is a fixed period of 22 μs between the beginning of the negative and the positive pulse. The constant-current magnitude of the pulses is controllable from the front panel which is accessible to the subject. An operating peak current range of 3 to 20 milliamperes is provided.

There are 3 current level controls, one for the X-axis and two for the Y-axis. The X axis is applied laterally on the abdomen and when centrally located, the average touch threshold at each tactor site of the two, 4-tactor sets is equal and a single control is adequate. For the Y-axis, which is oriented longitudinally, the touch threshold varies, requiring separate intensity controls for the upper and lower 4 tactor sets of the array. It is probable that in a future operational system, the individual tactor drivers could be trimmed to the relative mean touch threshold of its location; then with one intensity control, all tactors could be optimally controlled.

Prior data has indicated that the electrocutaneous sensation intensity increases proportionately to the number of tactors being excited and the rate of excitation; or, in other words, proportional to the power dissipated in the skin(12). With the range of excitation codes and ripple rate, it would be impossible to maintain a single, constant level of cutaneous sensation, thus a feed-forward intensity control is used to control the excitation pulse width. If the pulse widths are reduced to about 5 μs, the touch sensation is extremely low even when peak currents of 20 to 25 milliamperes are used, hence controlling the pulse width between 20 and 5 μs provides a very affective intensity control. The pulse width control has been quantized such that 20, 17, 14, or 12 μs pulses will be generated. The decision logic used to select the pulse width is based on the quantization level, ripple rate, and inter-axis intensity magnitudes.

2.2.8 Vibrotactor Display. The vibrotactor display accepts the SOS from the electrotactor gate generator, the polarity signals, and the bimorph power (170 Hz, 140 Vrms). As for the electrotactor channel, the SOS resets a counter which in turn opens the related vibrotactor gate. The gate is ANDed with the polarity signal to turn-on the desired tactor via its driver. The tactor driver converts the logic level vibrotactor gate to the power level necessary to turn on the triac used to switch the 140 Vrms to the selected tactor. With the gate open, the bimorph excitation begins with the next 170 Hz zero-cross-over point. When the counter reaches its full count of six cycles, the vibrotactor gate is closed by the next 170 Hz zero-cross-over, thus terminating the stimulus period.

2.2.9 Visual Display. The front panel LED (light emitting diode) display has three main functions: as a monitor to establish proper system operation, as an aid in training subjects, and as an operational display to establish a performance reference for the selected display format and code. The LED visual display has the same format as the tactile displays but with the lights closer together. The display is fabricated such that it can be used with an extension cable for remote viewing. The drive signals for the LED's are derived directly from the electrotactor gate generators.

2.3 FLIGHT SIMULATOR

The simulation configuration was assembled to allow monitoring and control of all information available to the pilot, his reactions, and simulator status. The integration of the flight simulation with the control and monitoring components is illustrated in Figure 2-8. The major components of the system are as follows:

a) F4 Flight Simulator
b) Dynamic Motion Platform
c) Data Acquisition System

2.3.1 F4 Aircraft Flight Simulation. The F4 flight simulation utilized two flight programs for a general purpose, Beckman 1100 analog computer. A complete description of the simulation appears in an in an informal NMC report (10).

The first program is a Mach 2 Cruise model covering all velocities from Mach 0.4 to 2.0, all altitudes from sea level to 65,000 feet, and all maneuvers such that normal acceleration of the aircraft does not exceed 7g's. This model was programmed for general Mach 2 flight studies and the F4 parameters were chosen largely for convenience, however, the following check was made to assure correspondence between

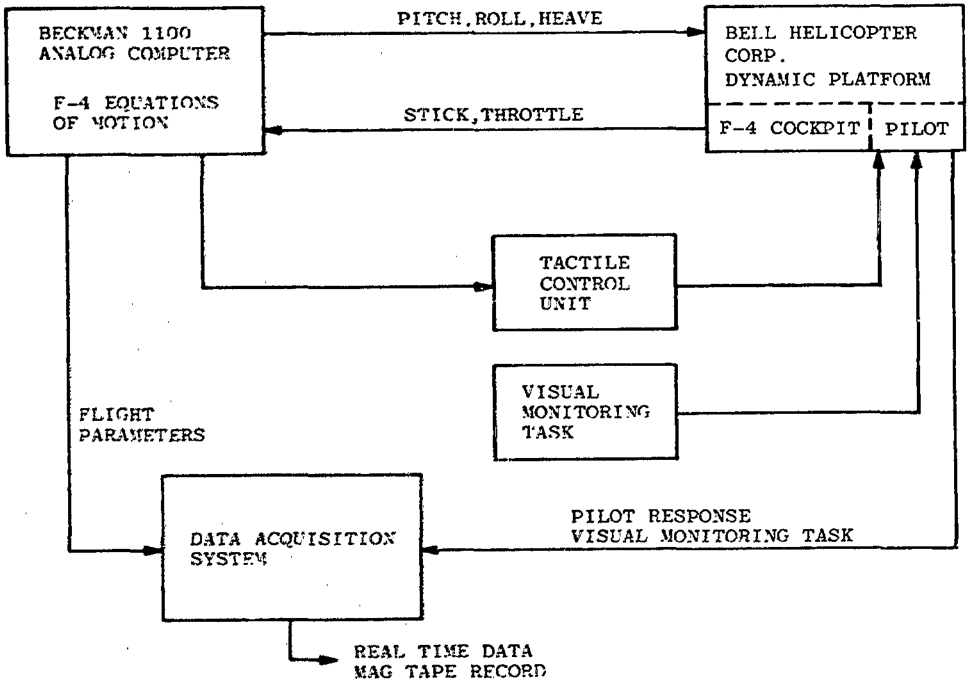

Figure 2-8. Flight Simulation Configuration.

the model and the actual aircraft. The model was trimmed for 1 g level flight at an altitude of 10,000 feet and a velocity of Mach 0.93. For this initial condition, a step aileron deflection of maximum magnitude was applied and the time to bank to 100°, the bank angle at one second, and the steady state roll velocity was measured. The results as compared to F4 flight test data are give in Table 2-1.

TABLE 2-1 Comparison of Simulation with F4 Flight Test Data

Characteristics	Flight Test Data	Simulation Data
Time to bank 100°	0.9 - 1.2 sec	0.8 sec
Roll angle at 1 second	120° - 128°	129°
Steady State Roll Velocity	190° - 255°/sec	240°/sec

The Landing Model is valid for velocities from Mach 0.1 to 0.4 and altitudes from sea level to 4000 feet. This model was constructed primarily for carrier landing studies. Because the flight regime for this model is very restricted, the aerodynamic coefficients and air density ratio were assumed constant. Errors in this decision amounted to less than 2% along the approach glideslope. The model does include a Approach Power Compensator (APC) system, which when activated senses angle of attack and normal acceleration and varies engine thrust to maintain the proper approach glideslope. All experimental trials were made with the APC system inoperative leaving the pilot in complete control of the aircraft.

2.3.2 Dynamic Motion Simulator. The dynamic motion simulator was designed and fabricated with 6 degrees of freedom for helicopter studies. Only 3 degrees of motion, roll, pitch and heave were used for the present tactile control evaluation. An external view of the platform is presented in Figure 2-9 and a view of the instrument panel in Figure 2-10. The entire windshield area of the cockpit was covered to force the pilot to fly on instruments.

Figure 2-9 Helicopter Motion Simulator.

Figure 2-10 Instrument Panel of Simulator Cockpit.

2.3.3 Data Acquisition System. The data acquisition system receives analog data representing flight parameters, pilot control response, and digital data representing test status and visual monitoring task information. The digital information was displayed on a panel for easy identification of test status and proper operation of the visual monitoring task generator and as well as pilot response to the visual monitoring task.

Real time print-out of the flight parameters was available on request at any rate desired from every sample taken to one sample each 16,000 samples. The data sample rate, originally specified to be 20 samples/second, was eventually reduced to about 3 samples/second due to the slowly varying nature of the parameters being monitored. Typical data summary print-outs are shown in Figure 2-11. All data was printed to a three decimal resolution.

The cruise model data periods were under operator control. The experimenter was provided with a "score" switch which initiated and controlled the data collection period. For the landing model, the data collection period was automatically defined between the altitudes of 600 feet and 10 feet. The landing flights originated at an altitude of 1400 feet and were on a stabilized decent path by 600 feet altitude. Thus the approach can be treated as a steady state control problem with a single set of performance statistics collected for the entire approach.

2.4. TACTILE EQUIPMENT

The tactile control unit (TCU) and its companion power supply were mounted in the cockpit on the right side of the pilot's seat. The Tactile Display (either vibrotactor or electrotactor) worn by the pilot was then simply plugged into the TCU after he positioned himself in the seat and unplugged the display prior to his exiting from the cockpit.

```
                    SUMMARY STATISTICS FOR TEST RUN  JW I 30 -9
NUMBER OF SAMPLES =            152
SUMMARY OF SIGNAL DETECTION TASK:
NINT =         7[illegible]
NTARGET        17
NDETECT        1
NFA =          4
P(D/T)=   .0587
P(D/N)=   .3076
SUMMARY OF STATISTICS:
                         MEAN VALUES
PITCH     ROLL    THROTTLE ALTITUDE MACH     MACH E HEADING  ELEVATOR AILERON  CLIMB
 DEG       DEG       %      X100 FT  X.001   X.0000    DEG      DEG      DEG    X100FT
-   46         1       6?       64    .918        67      46  -    1  -    1  -  40?
-    1  -      1  -

                         STANDARD DEVIATIONS:
PITCH     ROLL    THROTTLE ALTITUDE MACH     MACH E HEADING  ELEVATOR AILERON  CLIMB
 DEG       DEG       %      X100 FT  X.001   X.0000    DEG      DEG      DEG    X100FT
     2         1       14       44    76       369       2        0        0      15
     0         5

                                    RMS
PITCH     ROLL    THROTTLE ALTITUDE MACH     MACH E HEADING  ELEVATOR AILERON  CLIMB
 DEG       DEG       %      X100 FT  X.001   X.0000    DEG      DEG      DEG    X100FT
    46         1       70       77    .921      372      46        0        0     400
     0         5
```

(a) Cruise Model Data.

```
                    SUMMARY STATISTICS FOR TEST RUN  JW II 4515
NUMBER OF SAMPLES =            196
SUMMARY OF SIGNAL DETECTION TASK:
NINT =         [illegible]
NTARGET        [illegible]
NDETECT        [illegible]
NFA =          [illegible]
P(D/T)=   .7332
P(D/N)=   .1738
SUMMARY OF STATISTICS
                         MEAN VALUES
PITCH     ROLL    THROTTLE ALTITUDE GLIDE E LOCAL E HEADING ELEVATOR AILERON ATTACK
 DEG       DEG       %       FEET    X10 FT  X10 FT    DEG      DEG      DEG   < X10
  [illegible]      1      100      37[illegible] -  512  -   34  -     2       14  -     1     11[illegible]
  [illegible]      7  -     4        0  -  426       0

                         STANDARD DEVIATIONS
PITCH     ROLL    THROTTLE ALTITUDE GLIDE E LOCAL E HEADING ELEVATOR AILERON ATTACK
 DEG       DEG       %       FEET    X10 FT  X10 FT    DEG      DEG      DEG   < X10
             [illegible]   [illegible]   [illegible]   [illegible]   [illegible]      14        0        1     [illegible]
             [illegible]   [illegible]     0   [illegible]   [illegible]

                                    RMS
PITCH     ROLL    THROTTLE ALTITUDE GLIDE E LOCAL E HEADING ELEVATOR AILERON ATTACK
 DEG       DEG       %       FEET    X10 FT  X10 FT    DEG      DEG      DEG   < X10
             [illegible]            [illegible]   [illegible]      14       14        1     [illegible]
                            [illegible]   [illegible]
```

(b) Landing Model Data.

Figure 2.11 Typical Data Summary Printout.

The Tactile Display equipment was checked regularly for proper operation and proved to be reliable and easy to maintain. For the cruise model, the mach number error from a set value of 0.9 was displayed using the tactile display. The scaling was such that a ±0.1 mach error provided a full scale tactile display. With the landing model, the localizer error and glideslope error were both simultaneously displayed using the vibrotactor array. For this experiment the ull scale error indication represented an error of ±80 feet for glideslope and ±80 feet error for localizer.

2.5 Visual Monitoring Task. The visual monitoring task (VMT) was added to direct a portion of the pilot's visual attention away from the instrument panel. A folding mirror was located ahead of the instrument panel such that the pilot could monitor the CRT of a vertically mounted oscilloscope. The task required the pilot to indicate the presence of a 1 KHz sinusoid masked in white noise. A simulation of this display is illustrated as part of Figure 2-10. A more detailed description of the VMT is presented in paragraph 4.2.2.

SECTION 3
DISPLAY EVALUATION - LABORATORY

3.1 GENERAL

The laboratory display evaluation consisted of optimizing the tactile display, comparing the operational characteristics of the electrotractors and vibrotactors, and evaluating the optimized display to obtain both performance data and model analysis data. The display optimizing and tactor type comparisons have been reported (9) and are not repeated at this time. Code 3 (paragraph 2.2.2) and independent axis control provided the best performance and the vibratactors had a slight edge in the tactor comparison. For the display evaluation, four instrument rated pilots served as the test subjects. Their instrument flight time ranged from 150-1000 hours. The training data is well documented (9) as well as the performance measurements, however, since the model analysis has been derived from the performance measurements and is being presented, the performance measurement data is reprinted in order that all the formal experimental data is contained in this final report.

3.2 TRACKING TASK

The laboratory tracking tasks were designed to explore the limits of performance with the various tactile display configurations.* Accordingly, the subjects performed a simulated, wide-band, attitude tracking task of the type used in the previous study[2]. The simplified vehicle dynamics were intended to represent the response of a high-speed fighter aircraft having good handling qualities (3, 4). It was hoped that this experimental situation would encourage the

*We assume that the displays which provide the best performance in a somewhat stressful tracking task will also be the ones that provide the best performance in less severe tasks of the type contemplated for ultimate application.

subjects to work hard at the tracking task, and allow measurements of pilot performance over a reasonably wide frequency range using both electrotactor and vibrotactor displays.

Specifically, the pitch dynamics were of the form:

$$\frac{\theta}{\delta_e}(s) = \frac{K_\theta(s + 1/T_\theta)}{s(s^2 + 2\xi\omega_o s + \omega_o^2)} \quad . \qquad (3.1)$$

and the roll dynamics were:

$$\frac{\phi}{\delta_a}(s) = \frac{K_\phi}{s(s + 1/T_r)} \qquad (3.2)$$

Values for the dynamic parameters were:

$T_\theta = 0.50$ sec*

$\omega_o = 6.0$ rad/sec

$\xi = 0.85$

$T_r = 0.3$ sec ,

and the control gains were:

$K_\theta = 50$

$K_\phi = 10$.

*A T_θ on the order of 1.0 second is more commonly associated with high-speed pitch dynamics. But because the hand control used in these experiments allowed a very rapid control response, it was necessary to lower the value of T_θ to provide reasonable response dynamics.

The pitch and roll axes were perturbed by independent random-appearing inputs which were applied as vehicle disturbances. The transfer function relating pitch response to pitch-axis disturbance had the same form as the pitch/control relationship shown in Equation (3.1) except that the numerator contained no root. The roll-axis disturbance was applied in parallel with the pilot's control input.

Both disturance inputs were constructed by summing together 12 sinusoids of random phase relationships to simulate first-order Gaussian noise processes having break frequencies of 2.0 rad/sec. Input amplitudes were adjusted during training to yield nearly equal pitch and roll mean-squared error scores for the visual display condition.

A two-axis hand control provided independent control inputs to the pitch and roll axes. The control was primarily a force-sensitive device (0.12 cm of stick motion per newton of force) and could be manipulated with wrist and finger motions.

3.3 PERFORMANCE MEASUREMENT

The primary objective of the formal experiment was to quantify the interaction between the pilot and tactile display in terms of pilot-related model parameters. A secondary objective was to provide a comparison of tactile tracking performance to performance with a continuous visual display.

3.3.1 Experimental Conditions. The simulated attitude regulation task was performed alternately with the tactile and continuous visual displays. Performance measures were obtained for each axis tracked separately, as well as for the combined pitch-roll task.

Two levels of input amplitude were employed for tactile tracking so that display-related threshold effects could be quantified.

Because of the high performance scores obtained with the tactile display, input amplitudes used with this display were lower than the level used with the visual display.

The various conditions explored in this experiment are listed in Table 3-1. Input amplitudes are shown relative to the amplitude used with the visual display. To the extent possible, the various tasks were presented in a balanced order.

TABLE 3-1

EXPERIMENTAL CONDITIONS

Display	Tasks (P=Pitch; R=Roll)	Rel. Input Amplitude	No. Replications Per Condition Per Subject
Visual	P, R, P+R	1.00	2
Tactile	P, R, P+R	0.50	3
Tactile	P, R, P+R	0.25	3

3.3.2 Tracking Performance. Average standard deviation (SD) scores* for error are shown in Figure 3-1. Pitch- and roll-axis scores are given separately; they have not been combined into a single, total-performance measure.

*The standard deviation score was computed as:

$$SD = \left[\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2\right]^{1/2}$$

where x_i is the ith time sample of the variable "x", N is the number of samples obtained during the scoring interval, and $\bar{x}$ is the mean value of x_i computed from the N samples. This measure is equivalent to the "root-mean-squared" measure with the contribution of mean error removed. Note that each SD score represents a single, integrated measure of performance - it does not reflect a trial-to-trial or pilot-to-pilot variability in performance.

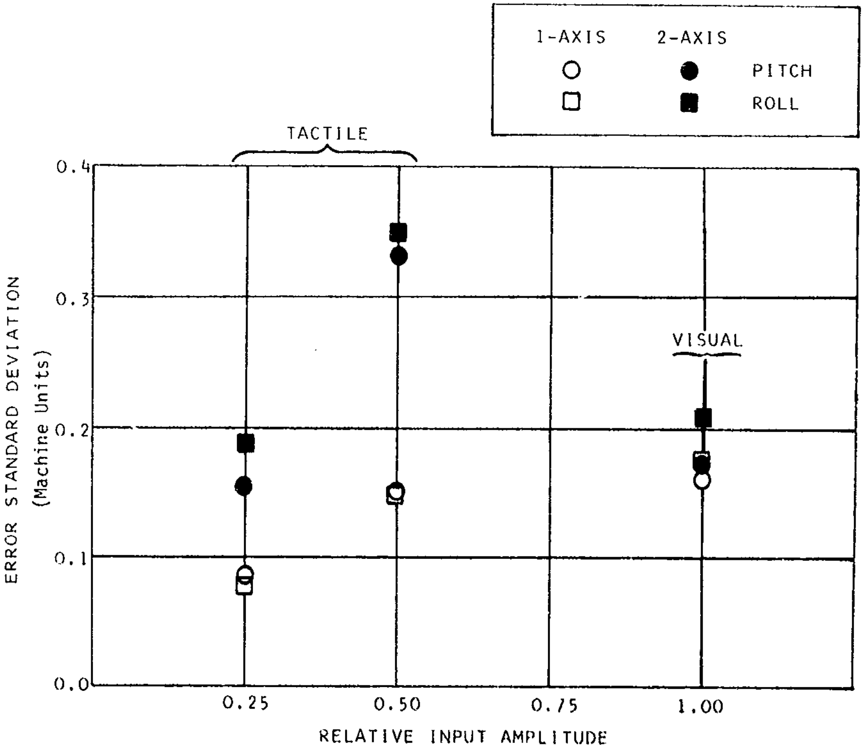

Figure 3-1 Effect of Input Amplitude on Error SD Scores (Average of Four Subjects)

The performance scores shown in this figure and throughout the report are given in terms of analog machine units. One machine unit of error corresponds to 2 cm vertical deflection of the visual error presentation for pitch, and about 50 degrees rotation for roll. One unit of control effort represents approximately 7.7 newtons of force.

The tactile tracking performance was poorer than performance with the visual display. When corrected for differences in input amplitude, the single-axis tactile scores were found to be about 1.9 times as large as the visual scores; this is a considerable improvement over the corresponding figure from last year of 3.5. The two-axis scores, however, were found to be about 3.6 times as large as the visual scores; only a small improvement over the figure of 4.8 from last year.

The scores associated with the tactile display were considerably closer to varying proportionately with input amplitude, than last year's scores. Extrapolation to zero input yields a smaller (positive) non-zero score, suggesting that the thresholdlike effects are reduced.

Significant inter-axis interference effects were found with both the visual and tactile displays, although the size of the effect was much larger with the tactile display than with the visual display. With the visual display, the 2-axis pitch and roll scores were about 7 percent greater and 20 percent greater, respectively, than the corresponding 1-axis scores; while with the tactile display (averaging over the two values of input amplitude), the 2-axis pitch and roll scores were about 100 percent greater and 140 percent greater, respectively, than the corresponding 1-axis scores. The large increase in relative difference from last year (when the 2-axis tactile scores were about 35 percent greater than the 1-axis scores) is due to the substantial decline seen this year in the 1-axis tactile error scores, while the 2-axis scores diminished only slightly.

As was the case last year, use of the tactile display often resulted in pulse-like control inputs, whereas the visual display allowed continuous-looking control activity. However, the tendency towards pulsed control was somewhat reduced from last year, at least in the single-axis runs, despite the fact that the subjects were again instructed to use whatever strategy they felt gave the best performance.

We made a limited examination of this aspect of the data and noted what appeared to be generally three types of control activity: pulsed, oscillatory, and continuous. Data collected during the final testing period which illustrate these different control techniques are shown in Figures 3-2 - 3-6. Figures 3-2 - 3-4 are sample time histories of error and control signals in tactile tracking, while Figures 3-5 and 3-6 contain amplitude densities of control input.

Figure 3-2 represents a two-axis tactile tracking run in which pulsed control behavior is evident. Control pulses were typically applied in a sequence of single pulses to alternate axes, with occasional bursts of pulses on a single axis. Pulses within a sequence were separated by about 0.8 second. The amplitude density of the pitch control signal corresponding to this run is included in Figure 3.5B as subject RF (triangles). As expected, the pulsed control behavior produced a highly non-Gaussian amplitude density having a large peak associated with zero control activity.

Figure 3-3 represents a single-axis tactile pitch tracking run in which large portions of the control signal appear oscillatory. Although the boundaries of the individual oscillatory segments are sometimes ill-defined, we would judge that intervals between oscillatory segments ranged up to about 10 seconds, and the duration of individual segments ranged up to about 15 seconds. The period of the oscillations is on the order of 1 - 1.2 second, a frequency in the neighborhood of 5.7 rad/sec. The amplitude density of the control signal

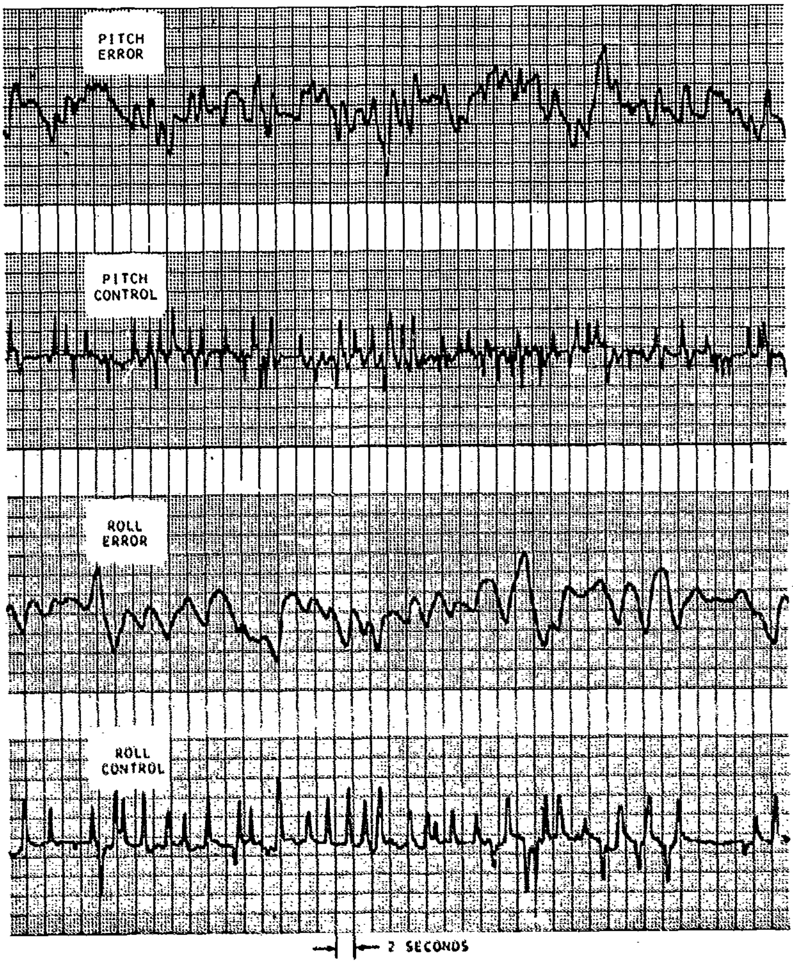

Figure 3-2 Time Histories of Error and Control Signals.
Subject RF; Task = Pitch+Roll
Relative Input Amplitude = 0.25

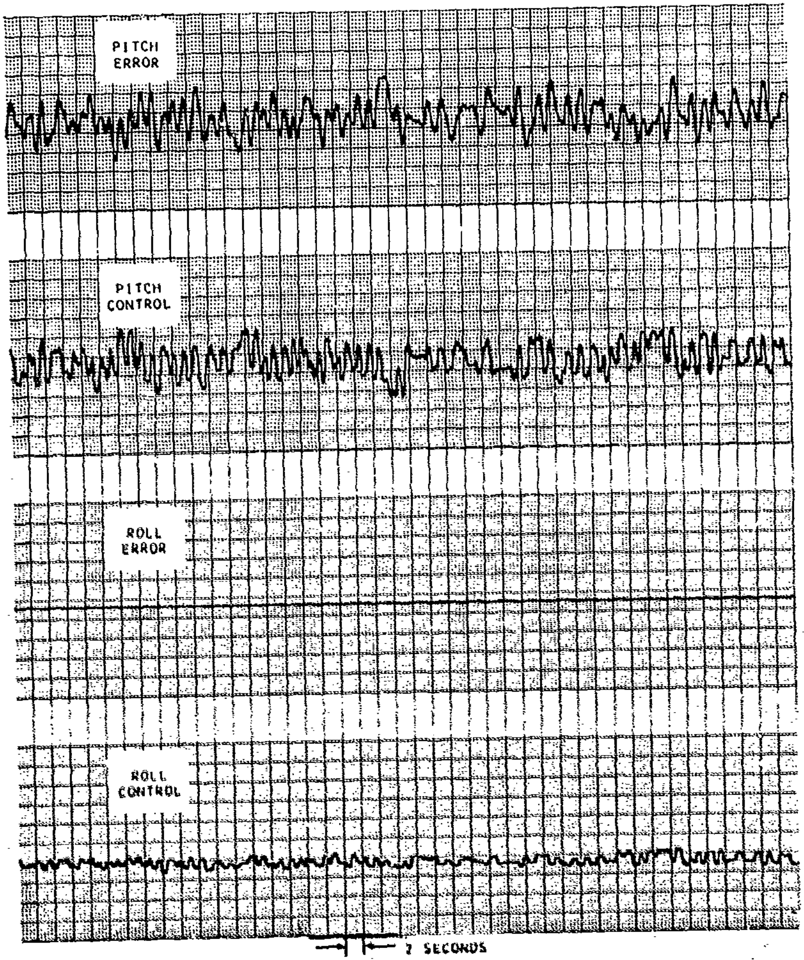

Figure 3-3 Time Histories of Error and Control Signals.
Subject JK; Task = Pitch
Relative Input Amplitude = 0.50

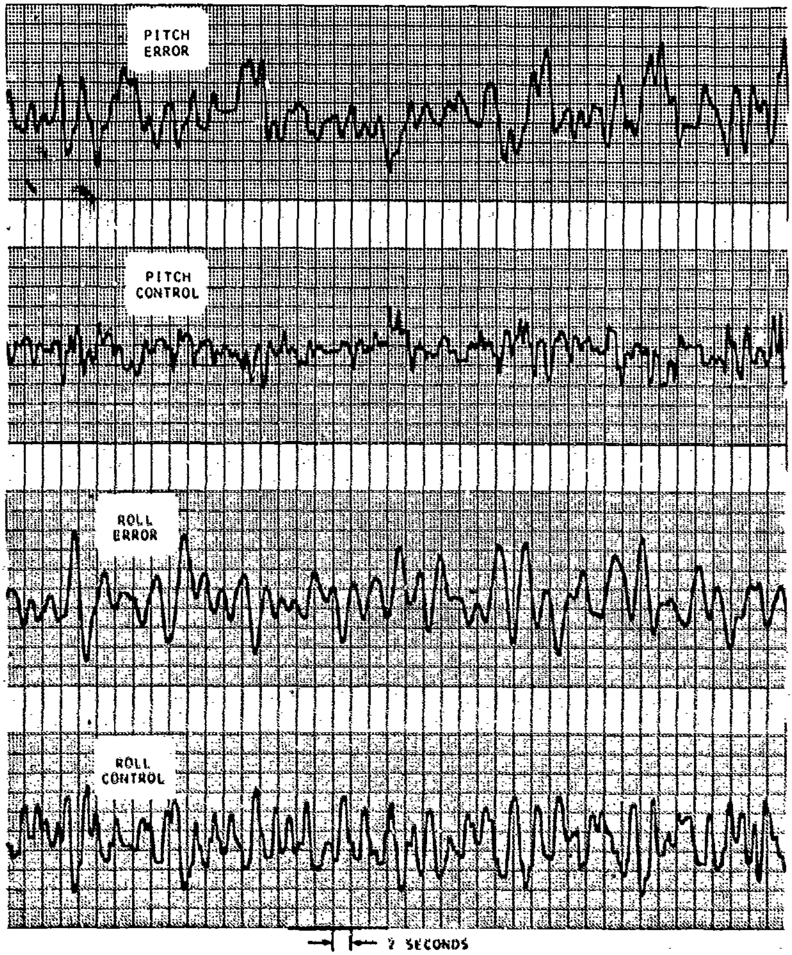

Figure 3-4 Time Histories of Error and Control Signals
Subject JK; Task = Pitch+Roll
Relative Input Amplitude = 0.50

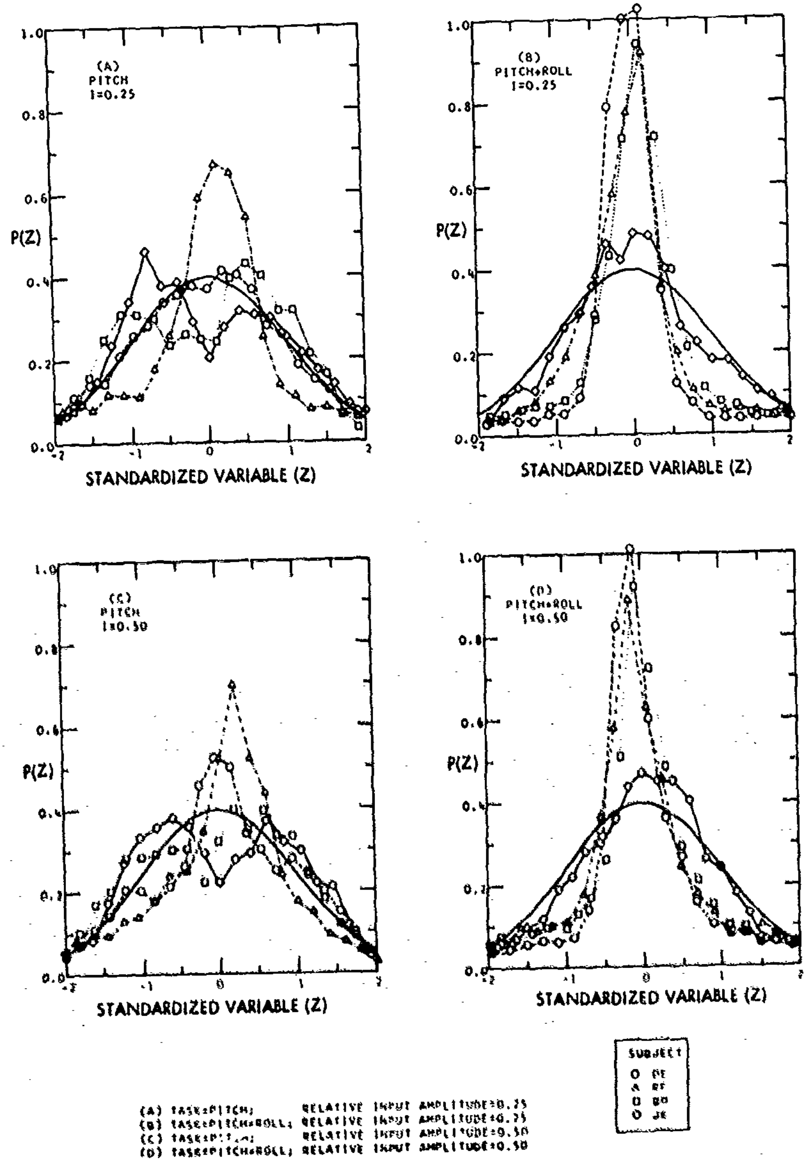

Figure 3-5 Pitch Axis Control Amplitude-Density Distributions in Tactile Tracking.

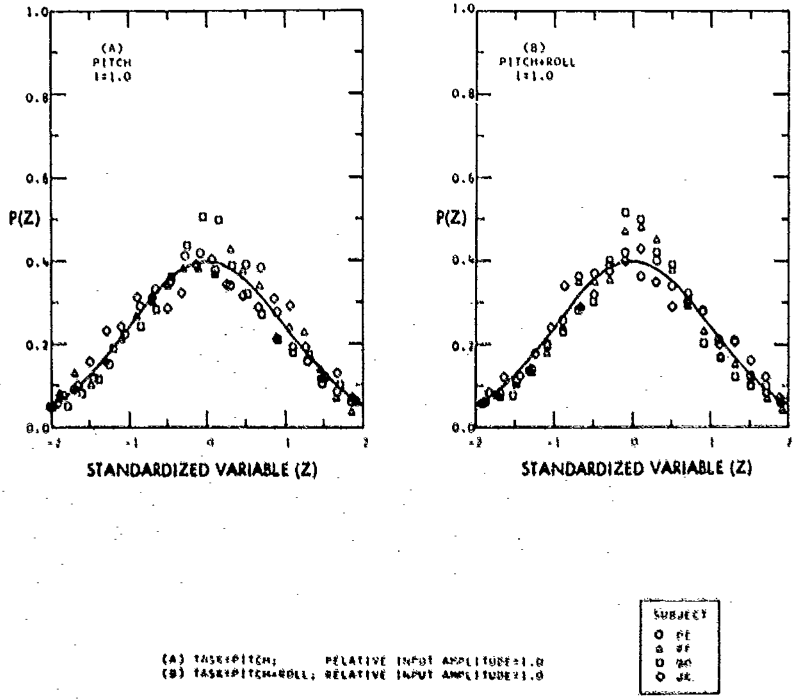

Figure 3-6 Pitch Axis Control Amplitude-Density Distributions in Visual Tracking

corresponding to this run is included in Figure 3-5C as subject JK (diamonds). The oscillatory control behavior produced a highly non-Gaussian bimodal density, with the two peaks associated with the limits of the oscillatory control motions.

Figure 3-4 represents a two-axis tracking run in which the pitch control activity appears continuous, although the roll control appears oscillatory. The amplitude density of the pitch control signal corresponding to this run is included in Figure 3-5D as subject JK (diamonds). As expected, the continuous control behavior produced an approximately Gaussian amplitude density.

Although not shown in these figures, different segments of some individual runs contain different types of control behavior. For example, in one run the subject began by pulsing, switched to oscillations, and then returned to pulsing. As a result, the control amplitude density from that run was roughly Gaussian, although the control activity was definitely not continuous.

Keeping in mind that Figures 3-5 and 3-6 consist of data from only one eighth of the runs performed during the final testing period, and that combinations of the different control strategies may exist within an individual run, we make some general observations regarding control behavior. Both one- and two-axis tracking with the visual display produced continuous control activity with Gaussian amplitude densities. (See Figure 3-6.) Tracking with the tactile display produced various types of control activities. (See Figure 3-5.) Two-axis tactile tracking produced mostly pulsed control behavior with peaked amplitude densities. Single-axis tactile tracking produced a mix of pulsed, oscillatory and continuous control behavior. The amplitude of the input disturbances had little effect on control behavior in tactile tracking.

The reasons for the different types of control behavior are not altogether clear, although it is possible to make some judgments about them. In the two-axis control situation the pulsing seemed to be a means of dividing control activity between the axes. Apparently, subjects who used a pulsed control switched their attention and their control efforts back and forth between the two axes, while the subject who responded continuously, without pulsing had learned to monitor and control both axes simultaneously.

It appeared that the oscillatory control inputs and the corresponding bimodal control amplitude densities may have resulted from a resonance in the closed-loop man-machine system. For example, consider the run plotted in Figure 3-3. A comparison of the pilot describing function relating pitch error to pitch control with the vehicle dynamics transfer function, shows that at a frequency of about 5.6 rad/sec, where the phase shift around the loop is about 360°, the loop gain is about -1.8 dB, a gain margin of less than 2 dB. Consequently, there is a resonance in the closed-loop system at about a frequency of 5.6 rad/sec. This is in agreement with the periodicity seen in the control waveform of Figure 3-3. Furthermore, the driving noise was, in fact, not Gaussian white noise, but rather a sum of 12 sinusoids, one of which had a frequency of about 5.6 rad/sec. Consequently, this component of the input disturbance may have excited the corresponding resonance in the closed-loop system, thereby dominating the control input waveform, and producing the bimodal control input amplitude density.

3.4 MODEL ANALYSIS

Model analysis was undertaken with the following two objectives: (1) determine how the improvements in the tactile display from last year were reflected in changes in display-related model parameters, and (2) demonstrate the utility of the pilot/vehicle model in predicting system performance with the tactile display. Because of the non-Gaussian pilot control activity, the pilot/vehicle model must again be applied with caution. Although we do not expect accurate prediction of detailed <u>control</u> behavior, it is possible that reliable predictions of tracking <u>error</u> can be obtained.

As last year, except for an initial calibration of display-related parameters, emphasis was on predicting, rather than matching, experimental results. We again adopted the following strategy for model analysis:

a. Match the experimental measurements obtained for the single-axis pitch task with the visual display in order to determine pilot time delay, motor time constant, and observation noise/signal ratio.

b. Match the data from the single-axis, large-input pitch task with the tactile display.

c. Use the parameter values determined above to predict the effects of input amplitude, multiple-tasks, and system dynamics on system performance.

Data fitting was again performed by an informal search of the model-parameter space and was terminated when visual inspection revealted a "good" match between model outputs and experimental measurements. In general, error and control scores were matched to within 10 percent, and pilot describing functions and control spectra were matched to within 2 or 3 db. All data used for comparison with model results represents average performance of the four test subjects.

3.4.1 <u>Visual 1-Axis Pitch</u>. An acceptable match to single-axis pitch performance with the visual display was obtained with a time delay of 0.2 second, a motor time constant of 0.11 second, an observation noise/signal ratio of approximately -20 db, and a motor noise/signal ratio of about -25 db. The parameter values are nearly identical with the values from last year, and are consistent with previous analyses of single-variable laboratory tracking tasks (5, 6).

Comparison of experimental frequency-domain measures with model results is provided in Figure 3-7. Note at this time, the comparison is shown for the ratio of remnant-related to input correlated components of the control spectrum.

3.4.2 <u>Tactile Tracking: Single-Axis, Large-Input Pitch</u>. Having quantified the pilot-related parameters on the basis of visual tracking, we then attempted to predict differences between visual and tactile tracking performance from an analysis of the tactile display properties alone. Perceptual time delay was incremented to account for the delay imposed by the tactile coding scheme. The size of the increment had to be recomputed for each experimental condition because of the dependent relationship between tracking error and display-related time delay. The display period associated with the error SD score was used to make a rough estimate of the time-delay increment. The tactor circuitry was redesigned this year so that the tactor ripple rate was updated more rapidly. Consequently, the delay increment was not a whole period, but just the time to the next pulse. An incremental time delay of approximately 0.18 second was derived for the single-axis, large-input pitch task. This increment was added to the 0.2 second delay determined from the visual tracking data to yield a combined pilot-display time delay of 0.38 second.

Since a minimum tracking error of 0.05 unit was required to generate a tractor sequence, an effective threshold y_o of 0.05 units was assumed for perception of error displacement.

Although we first tried an essentially infinite threshold for error rate based on the discrete nature of the display, this led to a poor match with the measured pilot describing function (the predicted gain was generally too low especially for frequencies above about

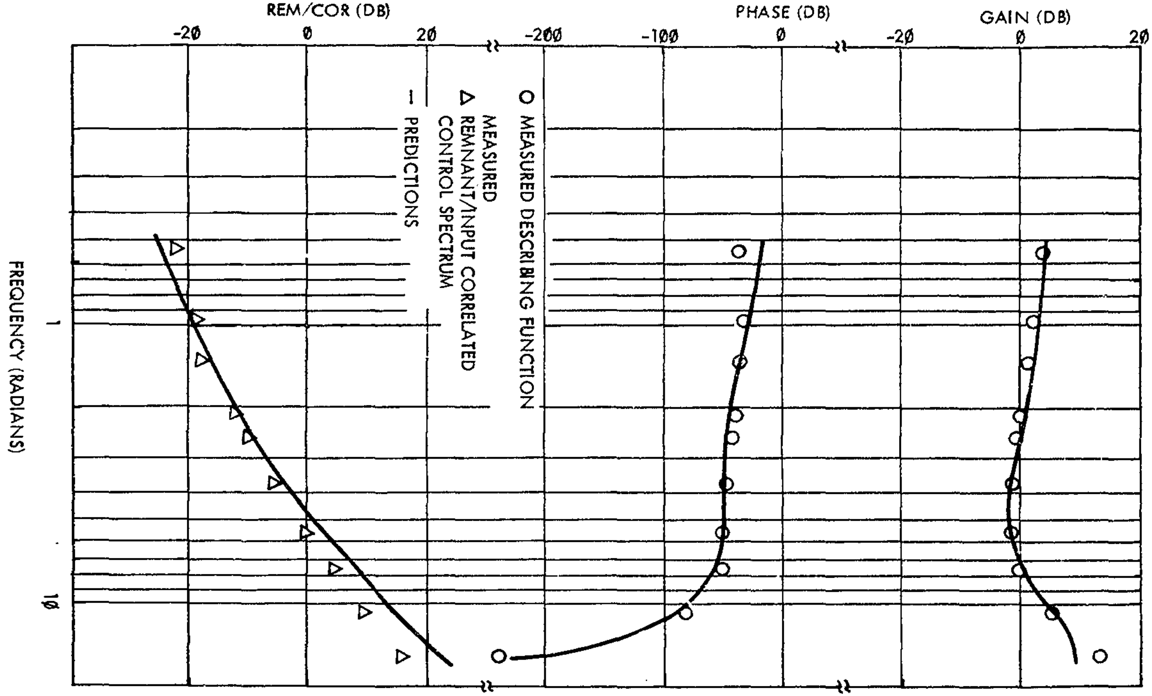

FIGURE 3-7. FREQUENCY-DOMAIN MEASURES FOR VISUAL TRACKING, 1-AXIS PITCH (AVERAGE OF 4 SUBJECTS).

8 radians/sec), as well as with the measured remnant spectrum (the predicted remnant was somewhat too low below about 1 rad/sec, and much too high above about 8 rad/sec). A much better fit was obtained when this threshold was lowered. Apparently, the subjects were able to obtain error rate information directly from the more frequently updated tactor ripple rate. Although there was no explicit threshold on error rate, because of the threshold on error, the error rate information was not available during a certain fraction of the experimental run, i.e., whenever the error was below the error threshold. Consequently, as an approximation, we picked the error rate threshold, $\dot{y}_o$, to be the same fraction of the measured rms error rate, rms($\dot{e}$), as the error threshold, y_o, was of the measured rms error, rms(e):

$$\dot{y}_o = \mathrm{rms}(\dot{e})\left[\frac{y_o}{\mathrm{rms}(e)}\right] \quad .$$

This led to an error rate threshold of 0.15 units for the single-axis large-input pitch task.

Values for motor time-constant and observation noise/signal ratios were assigned the values determined from the visual tracking experiments. Like last year, the motor noise to signal ratio had to be increased from the -25 db value from visual tracking. However, it only had to be raised by 5 db to -20 db, whereas last year it had to be raised by 10.5 db to -14.5 db. The hypothesis suggested last year that this increased motor noise was needed to account for the pulsed control behavior is consistent with this year's finding that somewhat less pulsing was observed and less motor noise was needed. This year the error SD score was matched to within 2%, although the control SD score was only matched to within about 18%. As may be seen from Figure 3-8 a fairly good match to the frequency-domain measures was obtained.

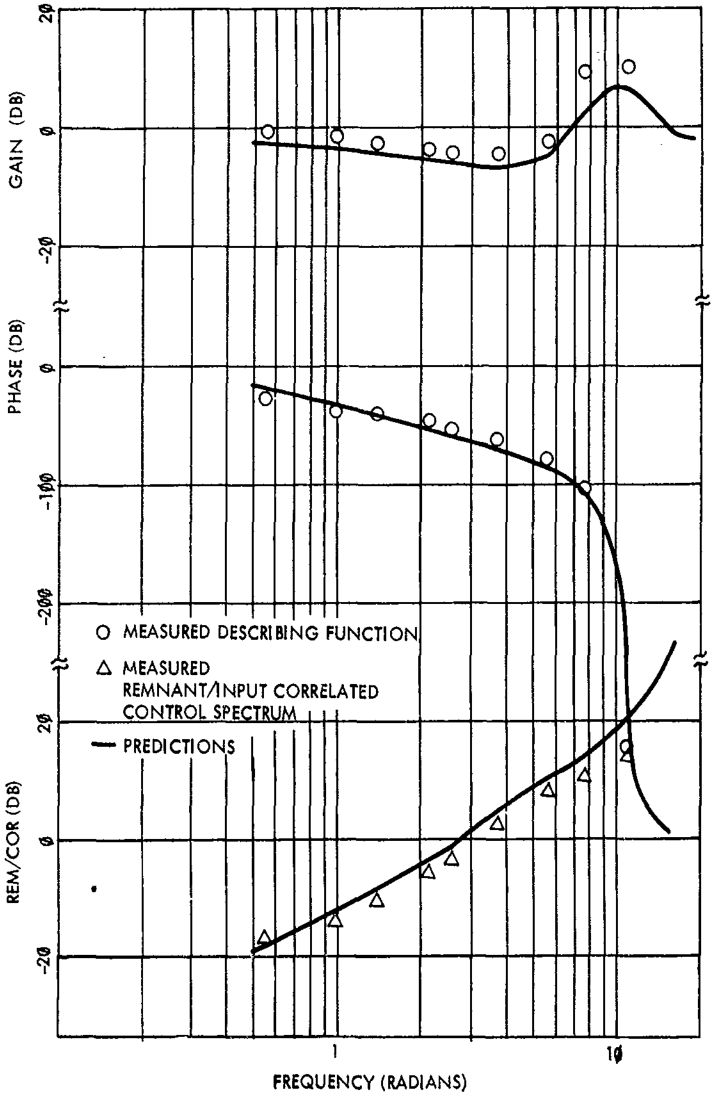

FIGURE 3-8. FREQUENCY-DOMAIN MEASURES FOR TACTILE TRACKING, 1-AXIS PITCH WITH LARGER INPUT (AVERAGE OF 4 SUBJECTS).

3.4.3 Tactile Tracking: Effects of Input Amplitude, Additional Axis and Vehicle Dynamics. Except as noted below, model parameter values determined in the preceding calibration effort were used to predict the effects on system performance of (a) a change in input amplitude, (b) the addition of a second axis of tracking, and (c) the effects of changing the vehicle dynamics from pitch to roll. The time delay and error rate threshold were recomputed in each case (as described above), and the effects of central attention-sharing in the two-axis task were represented by a doubling of the observation noise/signal ratio (see References 7, 8). Parameter values used in obtaining these predictions, as well as those used in the preceding calibration efforts, are shown in Table 3.2.

TABLE 3.2

VALUES FOR PILOT-RELATED MODEL PARAMETERS

Experimental Condition	Parameter Values					
	τ	T_n	y_o	$\dot{y}_o$	P_y	P_m
1-axis pitch, visual disp.	.20	.11	0.0	0.0	-20	-25
1-axis pitch, tactual disp., larger input	.38	.11	0.05	0.15	-20	-20
1-axis pitch, tactual disp., smaller input	.49	.11	0.05	0.13	-20	-20
2-axis pitch, tactual disp., larger input	.29	.11	0.05	0.13	-17	-20
1-axis roll, tactual disp., larger input	.39	.11	0.05	0.13	-20	-20

τ = effective perceptual time delay, seconds

T_n = motor time constant, seconds

y_o = displacement threshold, machine units

$\dot{y}_o$ = rate threshold, machine units

P_y = observation noise/signal ratio, db

P_m = motor noise/signal ratio, db

A comparison of predicted and measured error and SD scores is provided in Figure 3-9. Except for the visual tracking scores and the 1-axis, larger-input pitch scores, all model results are true predictions; parameter values have not been adjusted to provide the best match in each case.

3.4.3.1 1-Axis Pitch, Small-Input. The single-axis, small-input pitch error SD score was predicted to within about 12% (and within one standard deviation) of its measured value, while the control SD score was only predicted to within 21% (about 1-1/2 standard deviations). From Figure 3-10 it may be seen that the predicted describing function gain is generally about 4 db too low, while the predicted remnant is generally about 3 db too high.

3.4.3.2 1-Axis Roll. The single-axis roll error SD score has predicted to within about 6% (and just within one standard deviation) of its measured value, while the difference between the predicted and measured control SD scores was negligible. From Figure 3-11 it may be seen that while a good match was obtained to the pilot describing function, the measured pilot remnant was somewhat lower than predicted at low frequencies.

3.4.3.3 2-Axis Pitch and Roll. The poorest predictions occurred when the roll task was added to the larger-input pitch task. The predicted error and control SD scores were, respectively, 53% and 36% too small; in both cases they were more than 2 standard deviations from the mean SD scores. From Figure 3-12 it may be seen that in the limited region where we were able to measure it, the predicted describing function gain is from 1 to 7 db too high, and the predicted remnant is from 4 to 9 db too low.

We feel that this poor match in the two-axis case was due to the inability of the subjects to control both axes simultaneously. Our basis for this judgement is the observed practice of the subjects to

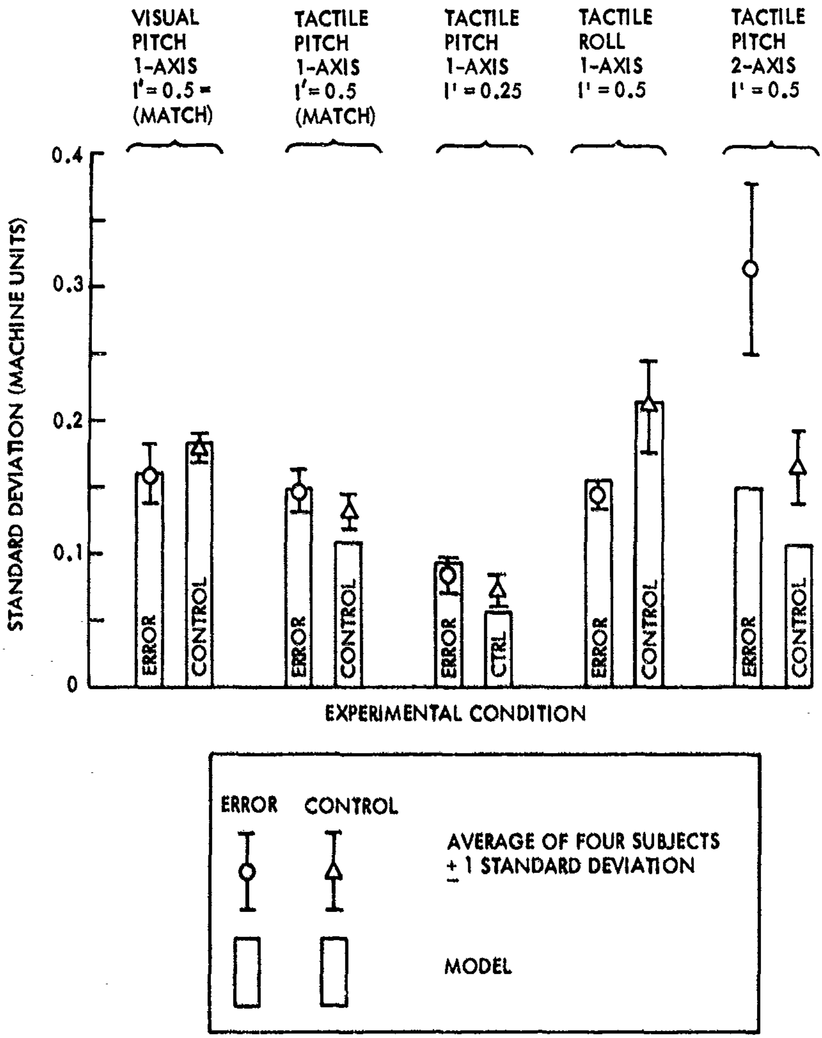

FIGURE 3-9. MEASURED AND PREDICTED SD SCORES.

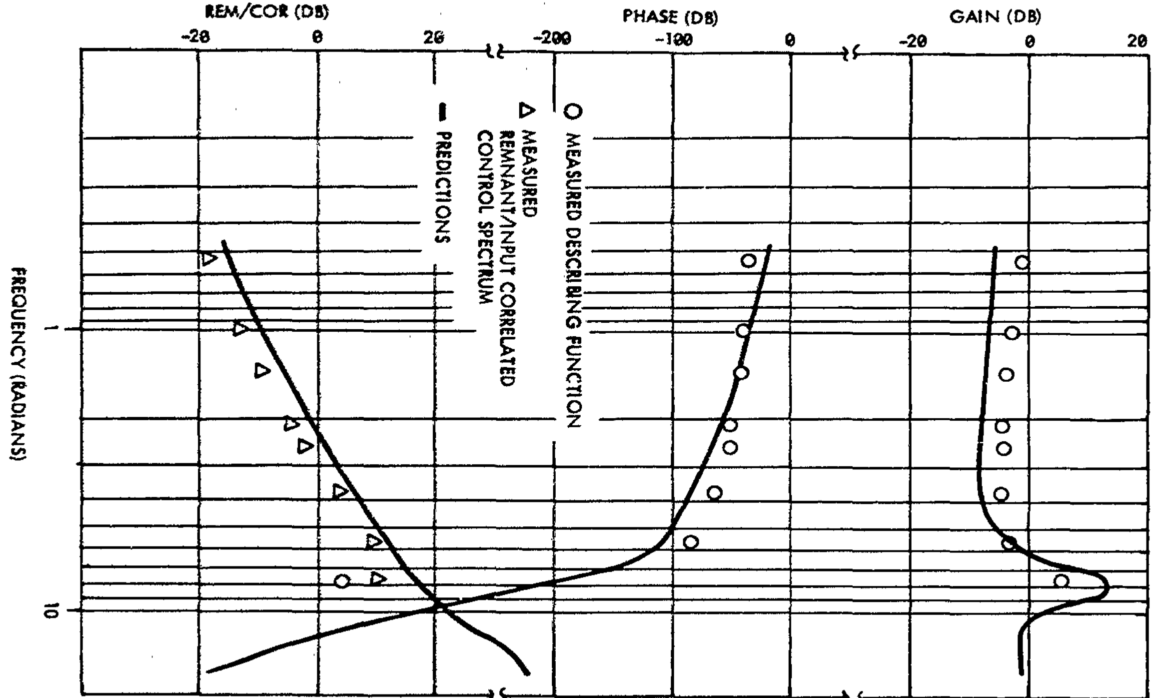

FIGURE 3-10. FREQUENCY-DOMAIN MEASURES FOR TACTILE TRACKING, 1-AXIS PITCH WITH SMALLER INPUT (AVERAGE OF 4 SUBJECTS).

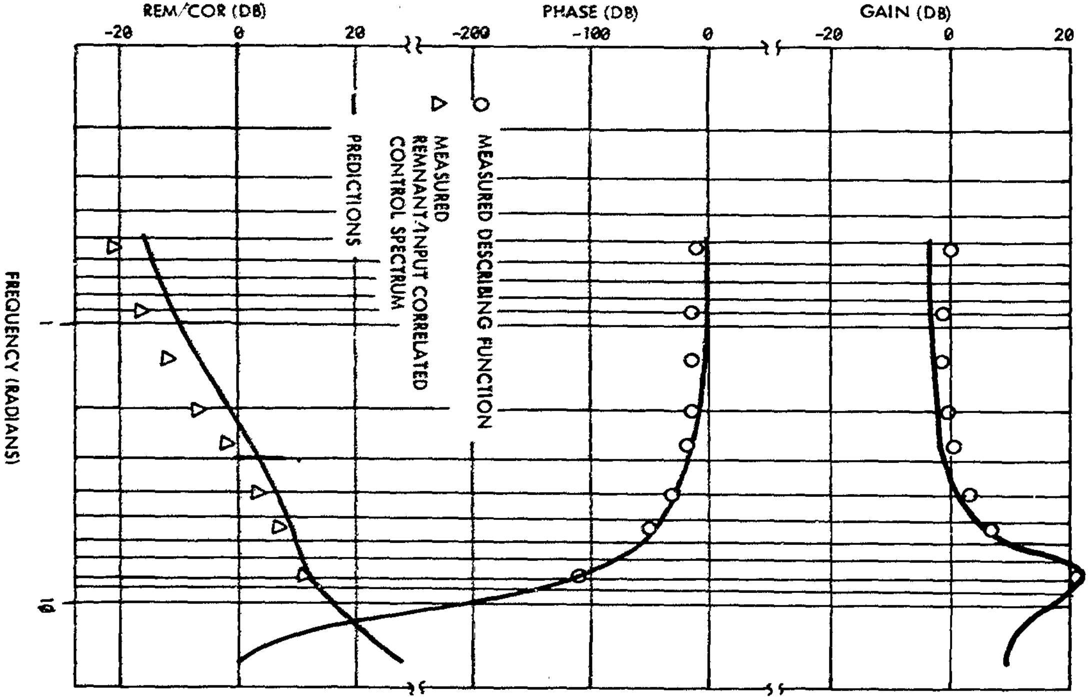

FIGURE 3-11. FREQUENCY-DOMAIN MEASURES FOR TACTILE TRACKING, 1-AXIS ROLL WITH LARGER INPUT (AVERAGE OF 4 SUBJECTS).

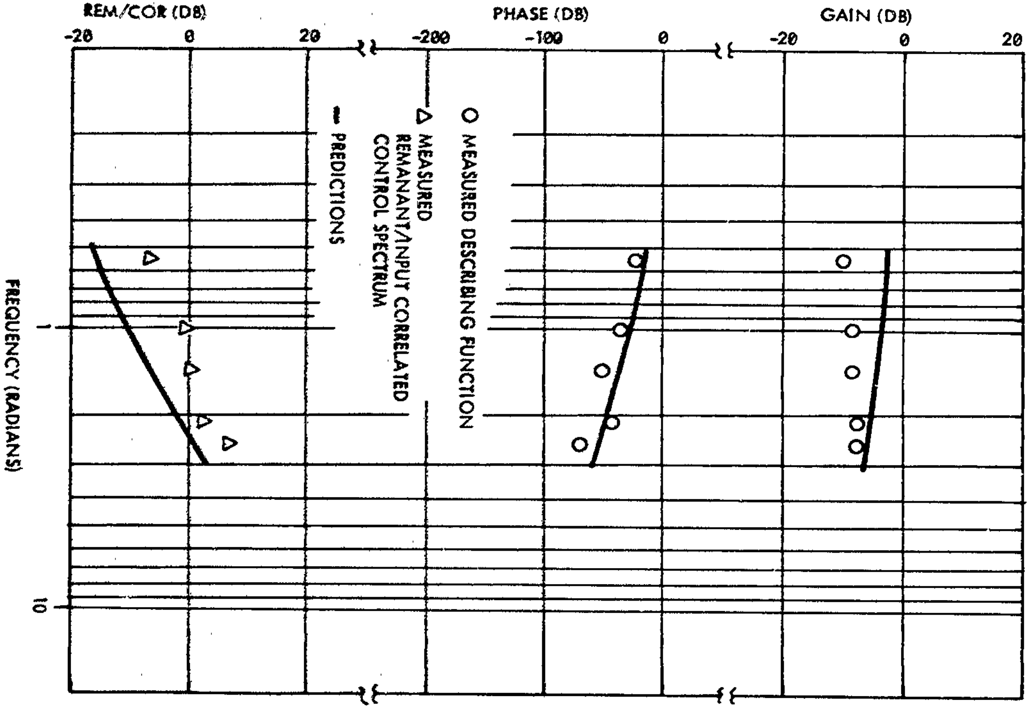

FIGURE 3-12. FREQUENCY-DOMAIN MEASURES FOR TACTILE TRACKING, 2-AXIS PITCH WITH LARGER INPUT (AVERAGE OF 4 SUBJECTS).

divide their control activity by alternately pulsing the two axes. As noted in Section 3.3.2 the pulses were separated by about 0.8 seconds, so that successive pulses to the same axis were separated by about 1.6 seconds. The large time delays introduced by such a switching strategy may well have been responsible for the high error scores obtained for this task, although no attempt has been made to match the data by assuming a larger time delay. Incidentally, the lowest error SD score was obtained by subject JK who exhibited the least pulsing activity; the predicted error score was 32% smaller than his score.

3.4.4 Relation to Last Year. Although we did not analyze all these factors separately, the reduction in error scores in tactile tracking from last year was due to the reduced threshold for error display, the shorter time-delay imposed by the coding scheme, and the availability of error rate during one-axis tactile tracking. The changes in threshold and time delay were intentionally designed into the tactor circuitry this year and were predictable improvements in the display. It was not expected, however, that the error rate would be directly available; this was only determined via the model analysis. This analysis showed that it was responsible for a reduction in error SD scores of roughly 20%.

SECTION 4

DISPLAY EVALUATION - SIMULATION STUDY

4.1 OVERVIEW

The objective of this phase of the evaluation study was to determine the utility of the tactile display as an instrument for providing flight- control information in a moving base simulator having realistic aircraft dynamics. Display effectiveness was based mainly on objective measures of aircraft control and pilot monitoring performance.

The simulation study was performed at the Naval Missile Center (NMC), Pt. Mugu., California in a cooperative effort involving both BBN and NMC personnel. The NMC analog simulator was programmed to simulate aircraft dynamics comparable to that of the F4 aircraft in two configurations: high-speed cruise and approach-to-landing. Cockpit motion in pitch, roll, and heave was provided by the Bell helicopter simulator.

Two sets of experiments were performed: (1) high-speed flight, consisting of a series of linked steady-state maneuvers, with the tactile display providing an indication of mach number error; and (2) approach-to-landing, with the tactile display providing either angle-of-attack (AOA) error or glideslope and localizer errors. All conditions were explored with and without a secondary monitoring task to investigate the capability of the tactile display in relieving visual workload of the flight-control task.

All flight-control information presented to the pilot through the visual sense was provided by panel instruments; no presentation of "real-world" visual cues was attempted (other than visual cues that might be obtained due to cockpit motion). All reference to "visual" presentation of flight-control information in this section refers to information obtained from the panel instruments.

A description of the apparatus and procedures common to the two sets of experiments is given below, followed by discussion of the individual experimental tasks and results.

4.2 APPARATUS AND PROCEDURES

Apparatus and procedures specific to this experimental program are discussed here.

4.2.1 Displays. The simulated cockpit panel included most aircraft instruments needed for flight control, plus some instruments related to fuel management. All instruments were electro-mechanical; no electronic informational display of flight information was provided. Table 4.1 shows the most relevant information quantities provided by the cockpit instruments for the high-speed and approach experiments. (Heading information could not be provided due to a persistent malfunction of the compass.)

The tactile display provided one-dimensional information (mach number error, AOA error) as well as two-dimensional information (Pitch and roll errors, glideslope and localizer errors) on separate experimental trials. With one exception, the coding scheme determined "best" from the laboratory study was used throughout the simulation study. Coding format #3 (defined in paragraph 2.2.2) was used: "error" magnitude information controlled both the number of tactors excited (from 2 to 4) and the rate of stimulation of successive tactors (using an outside-to-center ripple sequence). Full-scale error initiated a ripple of 30 Hz on all four tactors. Independent presentation of error information on the X- and Y-axis arms of the tactile display was adopted for all 2-dimensional error displays.

Tactile display of localizer error differed from this format only in that maximum error produced a ripple rate of 15 Hz. The subjects requested the lower display sensitivity for this variable in order to improve their ability to distinguish between glideslope and localizer errors.

TABLE 4-1

COCKPIT INSTRUMENTATION

a. Most Relevant Flight-Control Information

Flight Variable	Relevant to Cruise Experiment	Relevant to Approach Experiment
Pitch and Roll	x	x
Turn-Bank	x	x
Rate of Climb	x	x
Altitude	x	
Localizer and Glideslope Errors		x
Angle of Attack		x
Mach Number	x	

b. Other Instrumentation

Airspeed

Percent Throttle

The bulk of the simulation trials with tactile displays were performed with vibrotactors. A few trials were performed with electrotactors to provide some comparison between the two tactor types in the simulation study. (The reader is referred to Reference 9 for a formal laboratory comparison of vibro- and electrotactors.) The unwillingness of the NMC pilots to use the electrotactors for more than one or two experimental trials precluded a comprehensive evaluation of this form of tactile stimulation in this phase of the study.

4.2.2 Visual Monitoring Task. When this study program was conceived, it was anticipated that the primary benefit of tactile display of flight-control information would be to relieve the instrument scanning workload, thereby allowing more time for the pilot to attend visually to events outside the cockpit. Accordingly, a visual monitoring task (VMT) was implemented to provide the pilot with a visual task, unrelated to the primary task of flight control, that would direct a portion of the pilot's visual attention away from the instrument panel.

The monitoring task consisted of shape detection in which the pilot was to detect the presence of an intermittently-presented sinusoidal "target" waveform inbedded in a continuously-displayed "noise". The pilot indicated signal detection by depressing a finger-operated switch mounted on the control stick.

The test signal was presented on a CRT located at a viewing distance of about 2 m. The pilot was required to "look through the windescreen" in order to observe this signal. The active area of the display was about 6 cm horizontally. (See Figure 2.10.)

The target consisted of a 1 kHz sinusoid, displayed at a sweep rate sufficient to display 10 cycles of the target in the display area. The amplitude of the target was adjusted according to the desired signal/noise ratio. The noise signal consisted of wide-band Guassian noise having an rms level of about 2 cm.

The time history of a response trial is shown in Figure 4-1. When present for a given trial, the target occurred within the "observation interval" of 0.5 sec. The pilot was afforded the entire "response interval" of 2.5 sec. (i.e., the duration of the VMT trial) to respond to the presence or absence of the target. A response initiated anywhere in this interval was considered as a response to the observation interval of the same VMT trial. Such a response was scored as a correct detection or false alarm, depending on whether or not a target was present during the observation interval. Similarly, the absence of a response was scored as a missed target or a correct null response. If a response overlapped two response

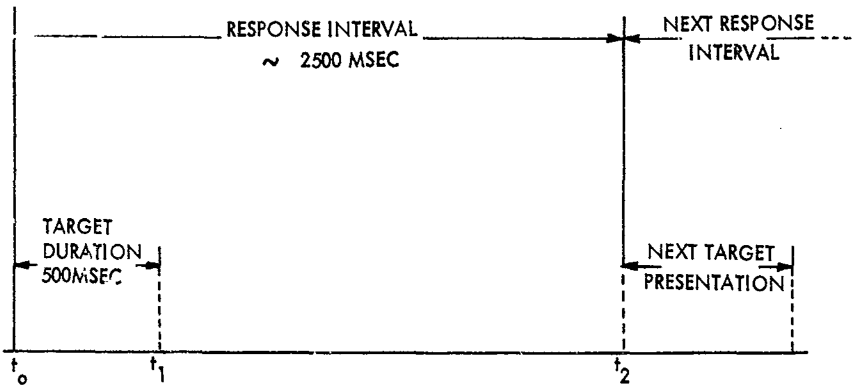

Figure 4-1. Visual Monitoring Task Response Interval

intervals, it was associated with the interval in which the response was initiated. If more than one response was initiated during a response interval, only the first such response was counted. The following VMT performance scores were computed:

P(D/T): probability of a detection given the occurrence of a target (correct detection)

P(D/N): probability of a detection given noise only (false alarm)

The probability of a target occurring during a given response interval was 0.5; successive VMT trials were statistically independent. Task difficulty was adjusted through variation in the signal/noise (S/N) ratio (defined as the ratio of the rms amplitude of the target to the rms amplitude of the noise). Because of the differing capabilities of the test subjects, the S/N ratio was adjusted for each subject in an attempt to maintain an approximate average detection performance of 70% correct detection. The S/N ratio was kept fixed for a given subject during data collection so that the interactions between the detection task, the flight-control task, and the display configuration could be explored. The average S/N ratio was -10 dB for the simulated high-speed maneuver and -5 dB for the more difficult approach task.

4.2.3 Task Requirements and Performance Measurement. The pilot's primary task was to minimize deviations of relevant flight variables from their desired trim values. Simulated wind-gust disturbances were included in the analog simulation to provide a reasonable task workload.

As described more fully later in this section, the flight tasks were structured as a series of steady-state maneuvers (e.g., straight-and-level flight, constant climb, approach). Performance scores were computed during steady-state flight for all relevant display variables (shown in Table 4-1) and for control quantities as well (elevator, aileron, and throttle deviations). The primary measure of performance was the "standard deviation" (or "SD") score, defined as in Section 3.3.2. Performance scores were computed digitally from samples of data obtained every 300 milliseconds (i.e., each flight variable was sampled about 3 times/second). The subjects were informed of their performance scores during the training phase.

4.2.4 Subjects. Experimental test subjects were recruited from flight-qualified NMC personnel. The flight experience of these subjects was varied, as it was not feasible to restrict the study to a subject population having a homogeneous background. Subjects for whom data are reported ranged in age from 27 to 38 years. Six subjects participated in the first experiment (high-speed flight) and six in the second (approach). Four subjects were common to the two groups.

4.3 EXPERIMENT 1: HIGH-SPEED FLIGHT

4.3.1 Task Requirements. Each training and data-collection trial consisted of a series of 12 steady-state maneuvers ("phases") performed in the sequence shown in Table 4-2. Each simulated, 12 phase "flight" lasted approximately 30 minutes, including the transition time between phases. During each phase, the pilot was required to maintain flight variables as close as possible to the following trim conditions:

Mach Number: 0.9 units for all phases.

Altitude: constant except for climb and dive.

Attitude: pitch trimmed appropriately for the task; wings level except for steady bank.

Speed brakes were deployed for the 45-degree dive (phase 9); for all other flight phases, the aircraft was in a clean configuration.

TABLE 4-2

HIGH-SPEED FLIGHT PROFILE

Phase	Task Description	Duration (Min.)
1	Straight and level, 10,000 ft.	4.0
2	Climb at 12,000 ft/min to 35,000 ft.	2.5
3	Bank left 45° at 35,000 ft.	1.0
4	Right bank 45° at 35,000 ft.	1.0
5	Descend at 4,500 ft/min to 24,000 ft.	4.0
6	Straight and level, 24,000 ft.	3.0
7	Right bank 60° at 24,000 ft.	1.0
8	Left bank 60° at 24,000 ft.	1.0
9	Dive at 45° to 10,000 ft.*	0.5
.10	Straight and level, 10,000 ft.	3.0
11	Climb at 6,000 ft/min to 30,000 ft.	3.5
12	Straight and level, 30,000 ft.	1.0

*Speed brakes fully deployed.

4.3.2 Experimental Conditions. The tactile display was employed to provide an indication of mach number error during the course of this experiment. A deviation of 0.1 unit was defined as full-scale error display (threshold of ±0.005 unit); that is, zero error corresponded to 0.9 mach unit, with full-scale negative and positive errors corresponding to 0.8 and 1.0 units, respectively. Polarity of the presentation was such that a positive error (too fast) stimulated tactors in the upper arm of the display.

A two-factor experiment was performed: (1) presence or absence of the VMT, (2) display configuration. Half the data trials were performed with the addition of the visual monitoring task described above; half were performed without this secondary task (i.e., flight-control only).

The following three flight display configurations were explored in this experiment: (a) visual only; (b) visual instruments plus tactile display of mach number error; (c) same as condition (b) but with the visual display of mach number obscured. The last condition was included in the study to help us determine which sensory mode was primarily relied upon for speed-error information when both tactile and visual information was available. In addition, we expected that the pilots would learn more rapidly to interpret tactile display of mach number error if, in fact, there were no alternative source of similar information.

4.3.3 Training and Data Collection. The experimental plan followed for the high-speed flight simulation is shown in Table 4-3. The test pilots were first provided "free" time in the simulator to familiarize themselves with the response of the simulated aircraft. They then practiced the flight profile (Table 4-2) with and without the VMT, using visual instruments only.

To facilitate interpretation of the information provided by the tactile display, the subjects were first allowed to provide their own inputs to the display through the manual controls on the tactile control unit (see Figure 2-2). Next, the tactile unit was driven by a simulated mach number "error". The cockpit mach number instrument was driven by the same error signal; in all other respects, the flight simulator was in the reset mode. In this way, the pilots learned to relate tactile sensations to mach number deviations. The subjects were given one practice "flight" on each of the four display configurations involving tactile presentation of mach number error (i.e., with and without the VMT; with and without use of the visual display of mach number). Each subject then flew one data-collection trial of each of the six experimental conditions.

TABLE 4-3

EXPERIMENTAL PLAN FOR HIGH-SPEED FLIGHT

Program Phase	Display Conditions Visual Monitoring Task	 Visual Mach Number	 Tactile Mach No. Error
Initial Familiarization,	-	x	-
Cockpit Instruments	x	x	-
Initial Familiarization,	-	x	x
Tactile Display			
Training With	-	-	x
Tactile Display	x	-	x
	-	x	x
	x	x	x
	x	x	-
	-	x	-
Data Collection	x	x	x
	-	x	x
	x	-	x
	-	-	x

Order of experimental conditions counterbalanced across subject for data collection.

Training trials were presented in the order shown in Table 4-3 for all test pilots. During data collection, however, ordering of the conditions was counterbalanced among the subjects to the extent possible to avoid biasing the results due to learning effects and/or fatigue.

Coordination was maintained as follows between the experimenter and the pilot to assure that performance scores would be computed only for the steady-state phases of the flight profile:

a. The experimenter announced the desired maneuver to the pilot over the intercom.

b. The pilot transitioned the aircraft to the desired state and informed the experimenter that he had achieved the required steady-state condition.

c. The experimenter initiated digital computation of performance scores by starting a timer set to the desired scoring interval (Table 4-2).

d. Performance computations were automatically terminated at the end of the scoring interval, and the experimenter informed the pilot of the next maneuver.

4.3.4 Experimental Results. Preliminary analysis of variance (A of V) was performed on the root variance scores for mach number error as well as on the probability of detecting a VMT target in order to determine whether or not (1) performance with the tactile display depended on the presence or absence of the visual mach number instrument, and (2) the four phases of straight-and-level flight in the flight profile could be considered as replications of the same task. The A of V tests failed to reveal statistical significance in either case. Therefore, all data obtained with the tactile display operative were pooled (in this experiment only) for comparison with the visual-only display, and the four straight-and-level phases were treated as replications in further A of V testing. All results presented for this experiment are the average of 6 subjects.

Standard deviation (SD) scores for the important flight variables are shown for straight-and-level flight in Figure 4-2; also shown is the probability of detecting a target presented by the VMT.*

*Only the P(D/T) score has been analyzed. Occurrences of false alarms were so infrequent (there were many trials with no false alarms) that meaningful analysis of the P(D/N) score was precluded.

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The addition of the VMT resulted in larger SD scores for most flight variables; that is, the secondary visual task detracted from the performance of the primary flight-control task, as one might expect. Of greater relevance to this study, however, is the effect of the tactile mach number error display on performance.

Figure 4-2 shows a beneficial effect of the tactile display on both detection performance and regulation of mach number. Use of the tactile display resulted in a 20% reduction in SD mach number error in the absence of the VMT task and a 25% reduction when the monitoring task was required. In addition, the probability of missing a target (computed as 1-P(D/T)) was approximately halved through use of the tactile display. A of V revealed that improvements in detection performance and regulation of mach number were both statistically significant at the 0.001 confidence level. Use of the tactile display did not consistently affect performance along other dimensions, and whatever differences were observed were, for the most part, not statistically significant.* Thus, for straight-and-level flight, the tactile display improved flight performance and reduced the scanning workload of the flight-control task.

The subjects apparently relied primarily on the tactile display of mach number error when both tactile and visual information was presented. Since both speed control and signal detection improved when the tactile display replaced the corresponding visual display, the subjects were clearly able to rely solely (and beneficially) upon the tactile display for speed information. The lack of a significant difference in performance when the visual display complemented the tactile display implies that the pilots continued to rely upon the tactile display for speed information even when the visual instrument was available.

*A confidence level of 0.05 is our criterion for judging statistical significance.

	Visual		Tactual	
Variable	VMT	No VMT	VMT	No VMT
Mach No. Error (units)	.0105	.0083	.0079	.0067
Pitch (degrees)	1.02	1.10	1.10	.82
Roll (degrees)	3.32	2.63	3.43	2.45
Throttle (percent)	3.69	4.75	5.76	4.52
Altitude (100 feet)	2.10	1.64	2.19	1.50
Elevator (degrees)	.297	.345	.302	.259
Aileron (degrees)	.364	.317	.338	.259
VMT Score P(D/T)	.778		.878	

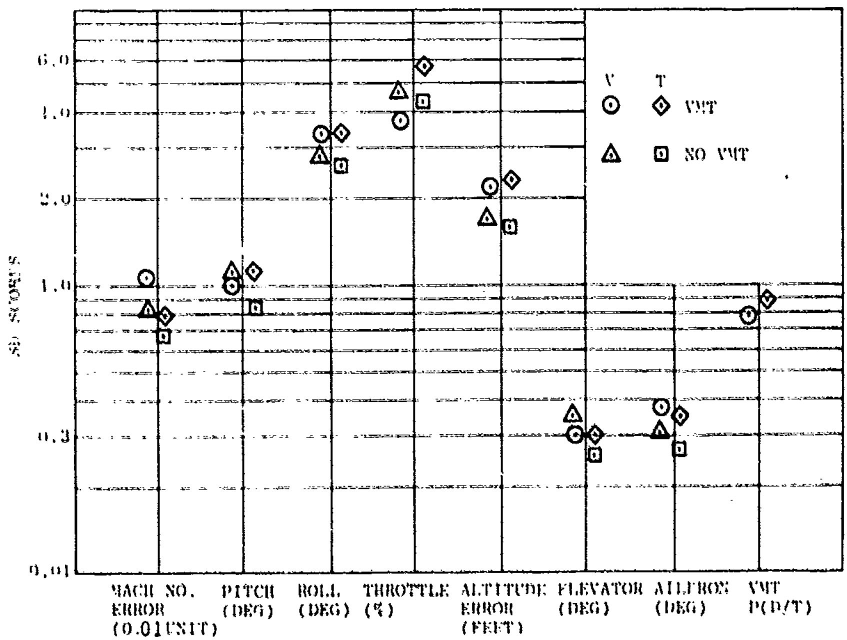

Figure 4-2. Performance Scores for Straight and Level Flight. (Average of six subjects).

Because of the clear difference in task difficulty, results of the 45-degree-bank task (phases 3 and 4) and the 60-degree-bank task (phases 7 and 8) were analyzed separately. Average performance scores for these two tasks (averaged over left and right bank) are shown respectively in Figures 4-3 and 4-4. With the tactile display, detection performance improved in both cases (significant at the 0.001 level for both tasks). Although mach number error was more tightly controlled in both tasks, the percentage improvement was appreciably greater for the 45-degree bank. Differences in mach number error were significant only for the 45-degree bank (0.05 level).

The effects of the tactile display on other flight variables were not statistically significant except for pitch and roll scores in the 45-degree, no-detection task (0.05 level), and in both cases, SD scores were lower with the tactile display. Thus, as with straight-and-level, the tactile display afforded improvements in both the flight-control and detection tasks.

The two climb and descend flight phases were analyzed separately. Figure 4-5 shows that, except for the 45-degree dive, that tactile display consistently resulted in a reduced SD speed error score. In some cases, deviations in mach number were reduced by about 50%. All four tasks showed a slight improvement in monitoring performance when the tactile display was used.

The insensitivity of speed control to display configuration in the 45-degree dive was most likely due to the fact that speed was limited (in this task only) by the aerodynamic action of the speed brakes, rather than by throttle control. Since the brakes were not continuously controlled during this phase (they were fully deployed), control of mach number was not dependent on the nature of the informational inputs to the pilot.

Variable	Visual		Tactual	
	VMT	No VMT	VMT	No VMT
Mach No. Error (units)	.0234	.0147	.0152	.0088
Pitch (degrees)	1.20	1.09	.96	.739
Roll (degrees)	3.31	2.90	3.56	2.42
Throttle (percent)	9.75	9.39	12.4	9.88
Altitude (100 feet)	2.12	1.73	1.86	1.56
Elevator (degrees)	.76	.643	.695	.526
Aileron (degrees)	.847	.656	.657	.601
Turn Rate (deg/sec)	.826	.651	.645	.634
VMT Score P(D/T)	.639		.819	

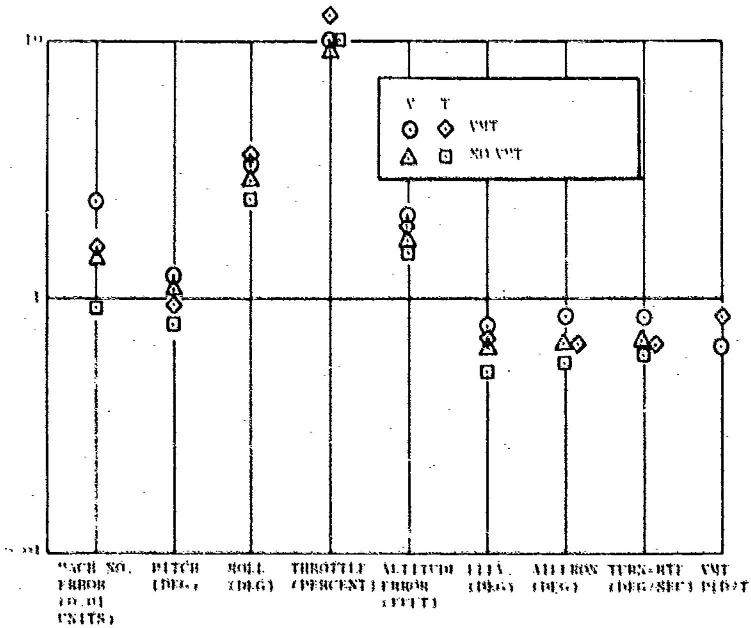

Figure 4-3. Performance Scores for 45° Bank. Average of six subjects.

Variable	Visual VMT	Visual No VMT	Tactual VMT	Tactual No VMT
Mach No. Error (units)	.0219	.0198	.0208	.0167
Pitch (degrees)	1.23	1.22	1.30	.99
Roll (degrees)	4.24	3.10	4.76	3.09
Throttle (percent)	8.65	11.2	11.8	11.5
Altitude (100 feet)	2.12	1.92	2.44	1.98
Elevator (degrees)	.77	.828	.866	.795
Aileron (degrees)	.954	.682	.902	.702
Turn Rate (deg/sec)	1.10	.940	1.06	.890
VMT Score P(D/T)	.696		.808	

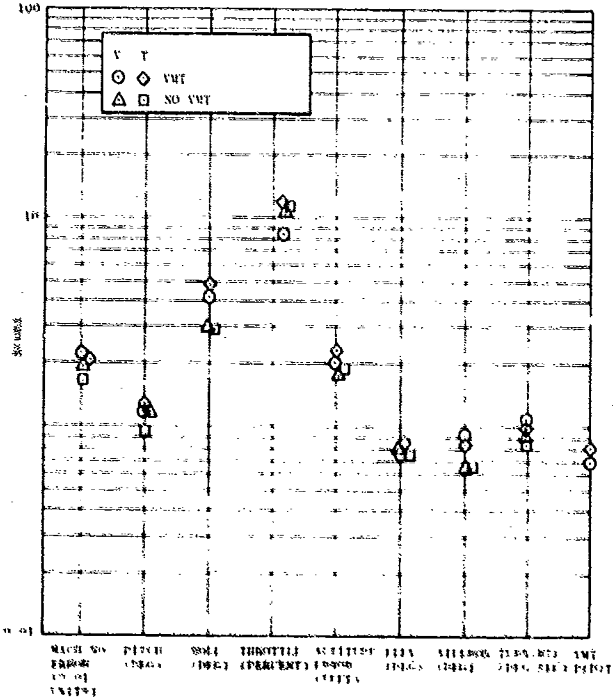

Figure 4-4. Performance Scores for 60° Bank. Average of 6 Subjects

	Visual		Tactual	
	VMT	No VMT	VMT	No VMT
Mach No. Error (units)				
Climb at 12,000 ft/min	.0140	.0146	.0101	.0073
Climb at 6,000 ft/min	.0121	.0106	.0069	.0060
45° Dive	.0269	.0308	.0292	.0293
Descend at 4,500 ft/min	.0132	.0112	.0085	.0062
P(D/T)				
Climb at 12,000 ft/min	.7010		.8313	
Climb at 6,000 ft/min	.7679		.8289	
45° Dive	.7936		.8743	
Descend at 4,500 ft/min	.7527		.8658	

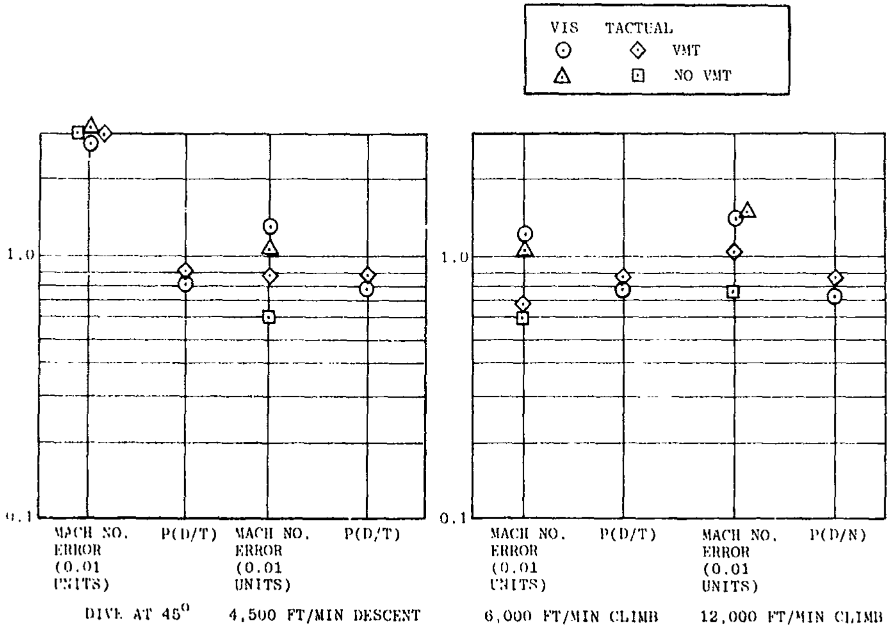

Figure 4-5. Performance Scores of Steady Climb and Descent. Average of 6 subjects.

Because of the subject-to-subject variability, analysis of variance failed to reveal statistical significance for most of the performance differences shown in Figure 4-5. Nevertheless, because performance improvement was found for both speed control and monitoring in all four subtasks (with the single exception noted above), we consider the tactile display to have demonstrated a true beneficial effect in the climb and dive phases of the flight profile.

Each subject was familiarized with the electrotactors upon completion of the experimental plan shown in Table 4-3, and one simulated flight was performed by each subject with the electrotactors (visual mach number instrument covered, VMT task required). Figure 4-6 compares average mach number error SD score and detection performance for the two tactor types (straight and level flight). Detection scores were virtually identical for the two tactor types. The mach number error SD score was about 15% greater with electrotactors; this difference, however, was not found to be statistically significant. As discussed below, there was a considerable subjective difference between the tactor types, with the vibrotactors strongly preferred.

4.3.5 Subjective Evaluation. A written multiple-choice type questionnaire was given to the test pilots to explore subjective differences between tactor types and to determine the pilot's evaluation of the tactile display as a potential operational device. Since pilot acceptance will be mandatory if this type of display is to become operational, a brief review of the results of this questionnaire is in order.

Variable	Vibrotactor	Electrotactor
Mach No. Error (units)	.00815	.0094
P(D/T)	.879	.880

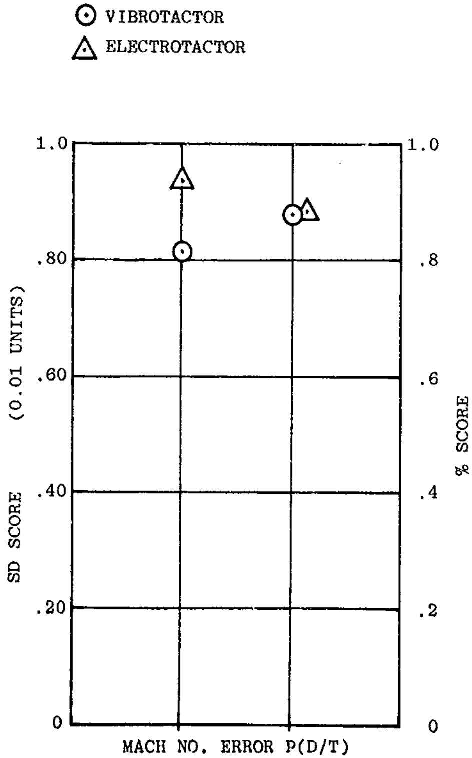

Figure 4-6. Comparison of Vibrotactors and Electrotactors Straight and Level, Average of 6 Subjects.

All six pilots felt that the simulated aircraft was controlled better with the vibrotactors than with the electrotactors. All pilots felt the vibrotactors were comfortable to use after they had received some training, ranging in their opinions from "slightly comfortable" to "very comfortable". Five of the pilots, on the other hand, considered electrotactors "not at all comfortable" to use, while the remaining pilot thought them "slightly comfortable". When asked which tactor type was preferred overall, four of the pilots expressed a strong preference for the vibrotactors, whereas two expressed no preference. All six pilots expressed a willingness to use the vibrotactile display as a supplement to the visual display of mach number in actual flight, whereas only one of the subjects was willing to use the electrotactors in actual flight (and then only with certain modifications to the display).

4.4 EXPERIMENT 2: APPROACH

4.4.1 Description of the Task. The pilots were required to "fly" simulated approach-to-landing trials during the second experiment. The task was designed as a steady-state tracking task: the parameters of the gust disturbances remained stationary during the course of the flight, and the glideslope and localizer instruments were programmed to indicate consistent full-scale errors of 50 feet.* The pilot's task at all times was to minimize deviation of aircraft parameters from the trim condition appropriate to approach.

The aircraft was initialized on the approach with zero trim error at a simulated altitude of 1400 feet. Airspeed and rate-of-descent, respectively, were 132 knots and 10 ft/sec. Simulated approach continued down to (but not including) touchdown, for a trial time of about 140 seconds. SD and monitoring performance scores were computed for the last 60 seconds of each trial.

*It is not uncommon in actual flight to program these indicators to display deviation in angular parameters, in which case the effective display scaling increases as touchdown is approached.

The major relevant flight instruments used in this task were as shown in Table 4-1.

4.4.2 Experimental Conditions. As in the preceding experiment there were two experimental factors: (1) presence or absence of the VMT, and (2) display configuration.

Two different uses of the tactile display were explored in separate trials: (1) angle-of-attack error, and (2) glideslope and localizer errors. Each of these conditions was explored with and without the capability to observe the corresponding (visual) cockpit instrument. In addition, the all-visual display was explored as a baseline, making a total of seven display configurations.

Display scaling and directional conventions were as follows:

a. Angle-of-Attack Error. AOA above the 12-degree trim setting stimulated the upper arm of the display. Full-scale error corresponded to about 4-1/2 degrees deviation from trim (display threshold of 0.23 degree).

b. Glideslope and Localizer. Compatibility was maintained with the ILS cockpit instrument. Aircraft too high on glideslope stimulated the lower display arm, and aircraft to the right of center stimulated the left arm. Full-scale error to the tactile display represented approximately an 80-foot error for both glideslope or localizer (display threshold of 4 feet, or 30% of altitude during last part of scoring period).

4.4.3 Experimental Plan. The experimental plan for the approach experiment is shown in Table 4-4. As in the first experiment, the pilot was allowed to familiarize himself with the use of tactile information in a nonflight setting prior to each new use of the tactile display. Training flights were flown by each subject in the

TABLE 4-4
EXPERIMENTAL PLAN FOR APPROACH-TO-LANDING

Program Phase	Use of Tactile Display	Display Conditions: Corresponding Visual Display	Display Conditions: Visual Monitoring Task
Initial Familiarization	None		-
			x
Training	AOA Error	-	-
		-	x
		x	-
		x	x
Training	ILS Error	-	-
		-	x
		x	-
		x	x
Data Collection	All of the above conditions performed in a counterbalanced order.		

order shown, whereas ordering of conditions was counterbalanced for data collection.

Each subject received about 6 runs for the two initial familiarization conditions and 4 or 5 training trials for each of the conditions involving tactile display of AOA and path error. Four or five flights per condition were flown for data collection.

4.4.4 Experimental Results. Although 6 subjects participated in this experiment, part of the data base for two subjects was lost during the recording process. Accordingly, the results presented for the approach study represent average performance for four pilots.

The effects of display conditions and the VMT on glideslope and localizer errors are shown in Figure 4-7; effects on AOA error score and monitoring performance are shown in Figure 4-8. Unlike the high-speed flights, these results revealed no statistically significant improvements in either flight-control or detection performance.

Control of lateral path deviation (as indicated by the localizer error score) was most affected by the display configuration. Error scores were greatest when ILS information was provided solely by the tactile display. In a number of trials, this display configuration caused the entire flight (at least the portion for which scores were computed) to be flown with the localizer showing full-scale* error of 50 ft. It should be noted, however, that the difficulty of the lateral path regulation task was increased by the absence of an operating heading indicator. Thus, the pilots may have been required in this simulation study to obtain more precise information (especially rate information) from the ILS indicator than is usually the case.

* The range of the ILS indications of glideslope and localizer error was ± 50 feet, as opposed to the larger range allowed with the tactile display.

Glide Slope Error (feet)

	W/Visual		W/O Visual	
	VMT	No VMT	VMT	No VMT
Standard	23.3	14.7		
Tactile - AOA	22.4	18.7	21.2	17.5
Tactile - ILS	21.4	16.0	25.9	19.2

Localizer Error (feet)

	W/Visual		W/O Visual	
	VMT	No VMT	VMT	No VMT
Standard	5.5	4.3		
Tactile - AOA	8.9	7.1	7.1	7.4
Tactile - ILS	7.4	5.0	21.8	11.6

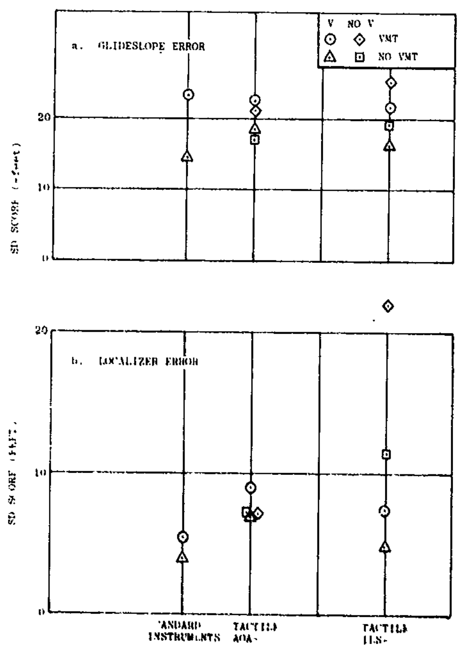

Figure 4 7. Effects of Display and VMT on Path Performance, Average of 4 subjects.

Angle of Attack Error (degrees)

	W/Visual		W/O Visual	
	VMT	No VMT	VMT	No VMT
Standard	.48	.386		
Tactile AOA	.427	.417	.495	.482
Tactile ILS	.368	.417	.554	.500

VMT Score P(D/T)

	W/Visual		W/O Visual	
	VMT	No VMT	VMT	No VMT
Standard	.3845			
Tactile AOA	.4814		.5114	
Tactile ILS	.4953		.5836	

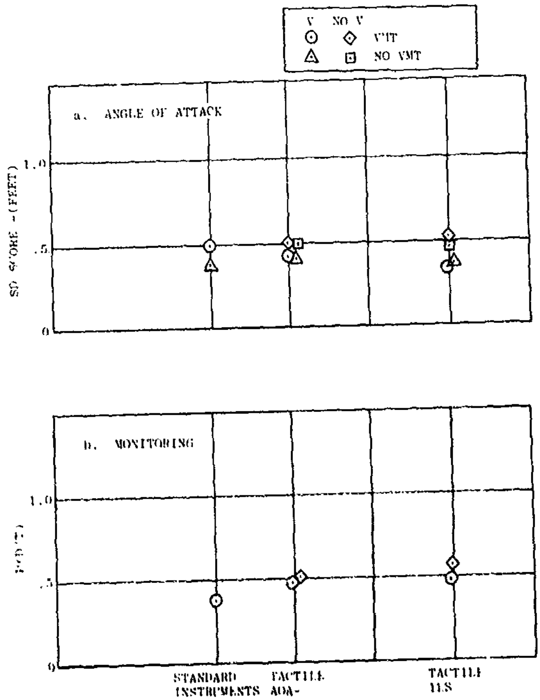

Figure 4-8. AOA Error and Monitoring Performance Average of 4 subjects.

Angle of Attack Error (degrees)

	W/Visual		W/O Visual	
	VMT	No VMT	VMT	No VMT
Standard	.48	.386		
Tactile AOA	.427	.417	.495	.482
Tactile ILS	.368	.417	.554	.500

VMT Score P(D/T)

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	VMT	No VMT	VMT	No VMT
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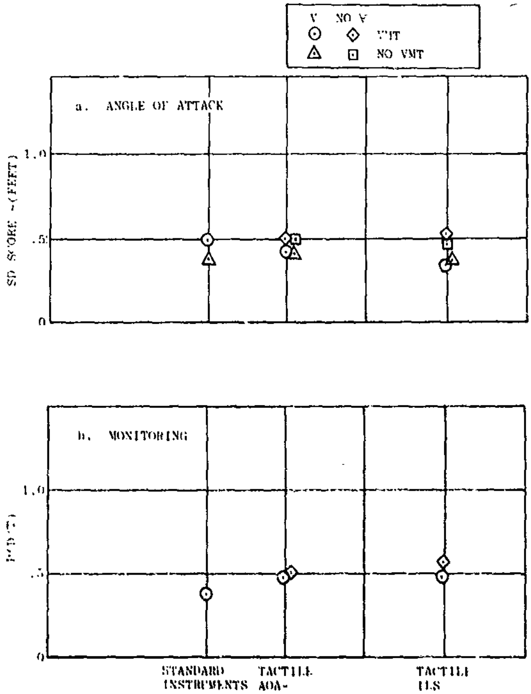

Figure 4-8. AOA Error and Monitoring Performance Average of 4 subjects.

Glideslope regulation was much less affected by display configuration. Neither the glideslope SD score nor the AOA error score were consistently effected by the presence or absence of tactile information. Detection performance did appear to improve somewhat with the addition of tactile information, although this difference was not statistically significant.

The results of this experiment, as well as of the laboratory evaluation phase, suggest that the tactile display is not well-suited for providing 2-axis information for continuous flight control. There appeared to be occasional difficulty in discriminating between X- and Y-axis errors. During the approach experiment, one subject commented on the "masking" effect whereby a large error on one axis obscures a relatively small error on the other. As mentioned above, path-rate information was required for effective control of path position (especially localizer). Information of this type is apparently not well perceived from the tactile presentation when two axes are displayed concurrently. (Also recall that no error rate data was used to control the tactile display.)

The failure of the tactile AOA display to significantly improve flight-control and/or monitoring performance seems contradictory to the results of the preceding experiment in which there was a significant improvement. We suspect, however, that the flight task in the approach experiment was dominated by the task of controlling localizer error - made more difficult by the absence of a reliable heading indicator. The relatively low AOA error scores (typically less than 0.5 degrees) suggests that controlling AOA was not particularly demanding (compared with control of path errors); thus, little advantage was to be gained by relieving the pilot of the burden of scanning the AOA display.

SECTION 5
CONCLUSIONS

5.1 DISPLAY OPTIMIZATION

The following conclusions were reached during the display optimization phase of the project:

The most suitable tactor excitation code tested to date has been one in which the outermost tactor is always exicted first, thus providing maximum spatial separation for even small error displays. The code was best for both one-axis and two-axis tracking tasks.

Although the equipment was designed for a maximum tactile ripple rate of 60 Hz, it was found that a maximum rate of 15 Hz was good for training and 30 Hz adequate for the formal tests. An underlying reason for this may well be the overlapping of tactor-ON periods which begins to occur at 30 Hz, and at 60 Hz, two adjacent tactors are excited simultaneously during one-half of their ON periods.

The simultaneous or independent operation of the two data channels proved to be superior to the sequential operation but not to the expected degree. What may be a more important conclusion is the fact that the subjects did not exclusively use control pulsing for error correction as they had last year when only the sequential display mode was used.

The tactile transducer, or tactor has been valiantly pursued by many, but as yet an operational tactor has not yet been developed. The electrotactor has the best physical size but its data presentation is the most variable and least tolerated; perhaps the optimum configuration and excitation signal is yet to be found. The bimorph vibrotactors which were used during this program appear to be quite acceptable for laboratory studies, but they are too large for consideration in an operational display. Small electromagnetic vibratoctors have been explored and possibly with the new magnetic materials being developed, a small, reliable and efficient tactor may someday be available.

In the design of the tactile array, we ignored the possible effects of one axis masking the other during 2-axis tracking. Our objective was an operational array that would be convenient to apply. However, masking is a serious problem, and even extreme spatial separation of the tactor sets may not solve the problem as shown by Gilson(11).

The auto-intensity control for the electrotactor display proved very beneficial in maintaining the electrocutaneous sensations within the comfort range. The variation of comfort level with body location was resolved to some degree by providing one intensity control for the X or roll axis and individual controls for the upper and lower halves of the Y or pitch axis. With sufficient data, it may be possible to adjust the gain of the elemental tactor drivers such that a single intensity control could provide uniform excitation levels for all the tactors in a specified array.

Since the additional intensity controls were not added until after the formal tests were run, a final performance comparison between electrotactor and vibrotactors could not be made, but the comparison is expected to be close. The problem encountered with the skin contact variation may be eliminated by employing a different shape for the electrode pairs. Since the coaxial configuration does not localize skin current, a flat surface tactor may not be necessary.

5.2 LABORATORY EVALUATION

The laboratory evaluation of the tactile display system has shown that the tracking scores of the subjects have been substantially improved over those recorded for the system tested during the previous year. The best improvement was observed with the tests involving only a single-axis tracking task, while the two-axis tracking performance improved by only half as much.

The improvement in single-axis tracking was directly due to the reduced threshold and shorter time delay of the tactile display system, features which were explicitly designed into the tactor circuitry this year. In addition, it was found that the scores were further improved because the revised display allowed the subjects to directly perceive error rate.

The failure of the two-axis tracking scores to show as much improvement was apparently due to the subjects' inability to track both axes simultaneously.

Despite the marked improvement in tactile tracking performance over the previous year, it remains that the continuous analog visual display produces much better performance by a factor of about 2 to 1 in rms error for single-axis tracking, and about 3 1/2 to 1 for two-axis tracking. It appears from our model analysis that the remaining threshold and time-delay of the tactile display would account for the bulk of the difference in the single-axis case, thus reducing the 5% FS display threshold may provide some improvement.

5.3 SIMULATION EVALUATION

When the tactile display was used to provide an indication of mach number error, flight control was improved and scanning workload was alleviated. Mach number was more tightly controlled, and performance on the independent, visual monitoring task was enhanced. Variability scores associated with other flight parameters were generally unchanged, indicating an overall beneficial effect of the tactile presentation. When both tactile and visual sources of mach information were available simultaneously, the test pilots appeared to rely primarily on the tactile presentation.

No statistically significant changes in either control or monitoring performance were found when the tactile display was used for angle-of-attack or path error information in an approach-to-landing task. The lack of positive results in this situation may have stemmed largely from the nature of the path regulation task (primarily in the lateral axis), which may have required the use of derivative information for effective control.

5.4 RECOMMENDATIONS

A tactile display system has many variables, all of which affect its performance as a tracking-error instrument. The evaluation phases of the program were limited; consequently little time was spent on optimizing parameters or their permutations. Except for reducing the maximum ripple rate to 30 Hz (from 60 Hz), the display parameters remained fixed throughout the evaluation phase. It is recommended that further experimentation be conducted with parameters such as quantization levels, excitation frequency, and controlling tactor ripple rate with data error rate.

As an example of the possible performance improvement, consider the display quantization levels (5%, 30% and 70% of FULL SCALE were used), no data can be displayed until the tracking error is equal to or greater than 5%, hence, performance can never be better than 5% of full-scale error. Reducing this threshold may improve the display performance. The results of the mach number tracking tests support this contention because, by setting the full-scale tracking error to performance on the independent, visual monitoring task was enhanced. Variability scores associated with other flight parameters were generally unchanged, indicating an overall beneficial effect of the tactile presentation. When both tactile and visual sources of mach information were available simultaneously, the test pilots appeared to rely primarily on the tactile presentation.

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It is recommended that an effort be made to develop a small, efficient readily acceptable tactor for use as a tool for all researchers pursuing tactile displays as well as an element of an oprational display. The physical size of the electrotactor is ideal but its acceptance is not quite universal. One of our dilemmas was the excitation frequency, from prior experimentation we found that excitation frequencies of less than 100 hertz appeared more comfortable as the stimulus was perceived more like a vibration, however, due to the required data rates, 200 hertz frequency was selected. Use of the lower frequencies should be pursued.

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