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JUL 79 J A SEEVERS, R L MAKINNEY

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# AIR FORCE



SIMULATOR FOR AIR-TO-AIR  
COMBAT MOTION SYSTEM INVESTIGATION

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July 1979

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platform's motion is about a multiple set of axes rather than a single axis as the command would direct. Also, because of physical constraints on the size of the system, the magnitude and deviation of the motion are limited. A fourth major problem is that when the excursion is near the maximum allowable, the motion is stopped too abruptly, and this stopping is readily perceived by the pilot (the washout problem). ↙

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## SUMMARY

### Objective

The objective of this study was to investigate the fidelity of the Simulator for Air-to-Air Combat (SAAC) motion system responses to inputs simulating control stick movements by the pilot in the simulator.

### Approach

Platform motion accelerations, velocities, and positions resulting from controlled electrical signal inputs were measured and computed to investigate system response.

### Background

This study follows a number of similar efforts conducted on other simulators, in particular, the Advanced Simulator for Pilot Training (ASPT), evaluating both the effectiveness and fidelity of motion systems in visual flight simulators.

### Specifics

Controlled electrical signals were input through system electronics at the analog-to-digital converter (ADC) to simulate control stick movements. Resulting motion platform accelerations were then recorded by linear and angular accelerometers strategically mounted along the body axis of the simulator and at its centroid. Lags in response time between command signals and platform movement were recorded, and final platform position was measured as a function of leg length extensions. Velocities to achieve final position were computed. A comparative evaluation of responses of each leg disclosed discrepancies, including excessive lag times and cross-coupling between movements, that indicate errors exist in movement of the platform. This would suggest that erroneous onset cues are provided the pilot, tending to compound further the dilemma of the utility of motion systems employed on visual system simulators.

### Conclusion

The conclusion drawn from this investigation was that the fidelity of the SAAC motion system is suspect, and before use of the platform motion is continued for whatever purpose, training or research, a major updating of the system should be performed. Regardless of its degree of fidelity, however, there remains a reasonable doubt as to how well, if at all, the motion system onset cueing scheme contributes to simulator effectiveness.

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## PREFACE

The technical effort included in this report was conducted by Dr. John A. Seevers as a part of the 1977 USAF/ASEE Summer Faculty Research Program, approved by the Air Force Office of Scientific Research. The intent of pursuing this investigation was to evaluate the responses of the motion system for the Simulator for Air-to-Air Combat (SAAC) to controlled signal inputs, and characterize those responses to define the frequency domain in which the system is capable of functioning. Should operation of the motion system be required for some future operational task or investigation, the recommendations of this report include action to be considered to enhance the reliability and fidelity of the system's response.

This is to acknowledge the efforts of Dr. Seevers in conducting essentially all of the work in this investigation. His technical approach and findings have not been altered. Only the statements used in the text of Dr. Seever's report alluding to the utility of motion systems, per se, was edited. Recent studies on the motion/no motion issue tend to deny any positive contribution of the platform motion system, relative to highly maneuverable fighter and trainer-type aircraft. That a platform motion system, when performing properly, i.e., according to design, will enhance the utility of the simulator by providing onset motion cues that will be beneficial to the pilot is still an unsolved or unanswered issue.

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## SIMULATOR FOR AIR-TO-AIR COMBAT MOTION SYSTEM INVESTIGATION

### I. INTRODUCTION

The Simulator for Air-to-Air Combat (SAAC) was designed to provide pilots with a realistic experience in training for air combat engagements. In addition to the visual images displayed, the system has motion capabilities that allow onset motion cues to be presented. These cues are short duration velocities and accelerations of the motion platform and were designed to present the illusion of the initial phases of entry into a maneuver. The motion system was originally intended to provide a more realistic, hence a better, training environment for pilots operating the system.

The SAAC consists of two F-4E cockpits mounted one each on 60-inch stroke, synergistic six degrees-of-freedom motion systems. Cockpit movement is based upon the computed six degrees of aircraft motion freedom and is correlated with the motion of the simulated aircraft. All aircraft stability derivatives are accounted for in such a manner that aircraft movement in any degree of freedom will influence movement along or about the axes of the motion system. The sensations of motion are intended to be representative, as nearly as possible, of sensations experienced in the operational aircraft.

In addition to being used as a research tool, the SAAC is being used as a training device for F-4E pilots as part of their normal training sequence. Presently, the motion system has been found to differ significantly from sensations experienced in the actual aircraft. In fact, instructor pilots actually feel that better training is accomplished with the platform motion system turned off. Hence, the motion system is not presently used in pilot training.

As a first step toward characterizing the existing system, it was necessary to develop a program to accurately describe the dynamics of the system. This characterization assumes added importance in light of tests, conducted for the Scientific Advisory Board, that seem to indicate exceptionally long system lags between an input and the resulting motion. These tests conducted on the SAAC also suggest somewhat irregular behavior of the motion platform (Note 1).

### II. OBJECTIVES

The primary objective of this investigation is to document the motion of the existing system in a state of adjustment that is consistent with that normally seen by student pilots and to compare this performance with established criteria. Additional objectives are to establish important parameters that adequately describe the system, establish the equipment necessary to monitor the system, recommend a test procedure to check the motion platform for faithfulness, and identify weak areas where the system needs to be improved.

### III. BACKGROUND AND MOTION PLATFORM DESCRIPTION

#### Block Diagram Representation

A block diagram of the basic components that comprise the motion system is shown in Figure 1. Cockpit control movements are transformed to electrical analog signals and then digitized by an analog-to-digital converter (ADC) at a frequency of 20 iterations per second. The digitized control inputs are fed into the flight equations which are updated 20 times per second. The output of this block is a series of digital signals that represent aircraft position and velocity and acceleration, both linear and angular. These signals are then fed into a program that computes platform leg lengths (at 10 times per second) and are converted to analog signals by the digital-to-analog converter (DAC) at 20 times per second. These

analog signals for the legs then are processed as analog signals by the motion electronics cabinet which produces a reference signal that is nulled out when the platform achieves the desired attitude. As a result, the platform accelerates, and a position change can be noted.

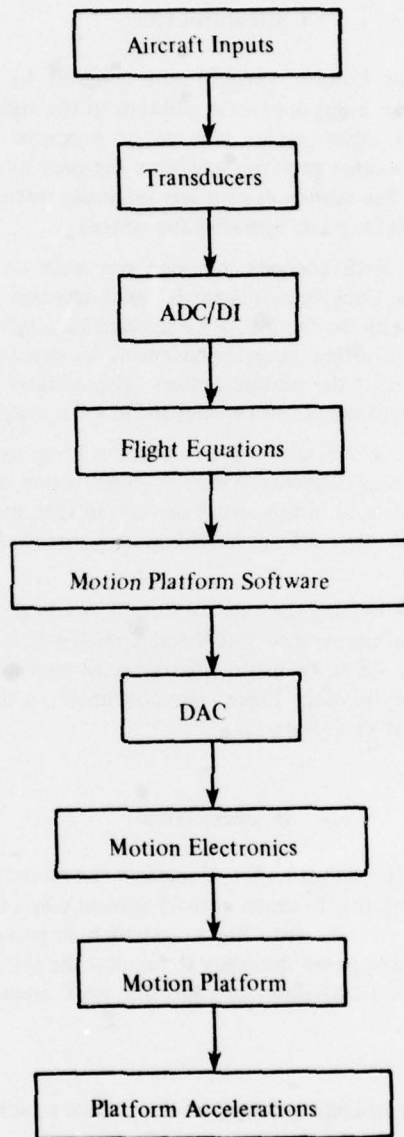


Figure 1. SAAC motion system block diagram.

In light of the block diagram in Figure 1, the primary intent of the present investigation can be restated: describe the system dynamics of the pertinent blocks individually and of the overall system. All blocks taken together would be the through-system dynamics from the stick input to the platform motion as the output. In the limited investigation undertaken here, it was felt that greatest emphasis should be placed on instrumenting and documenting the right-hand half of the block diagram, i.e., from the motion platform driving software package through the resulting platform motion.

### Platform Acceleration Equations

Before instrumenting the platform, the acceleration equations for any point on the platform need to be established. Also, the angular acceleration of the platform needs to be expressed in terms of linear accelerations of points on the platform. From Meriam (1971), the absolute acceleration of any point P on a translating and rotating body expressed as a vector

$$\underline{a}_p = \underline{a}_0 + \underline{\dot{\omega}} \times \underline{r}_{p/0} + \underline{\omega} \times (\underline{\omega} \times \underline{r}_{p/0}) \quad (1)$$

where 0 is any other point on the same rigid body,  $\underline{\omega}$  and  $\underline{\dot{\omega}}$  are the absolute angular velocity and acceleration of the rotating body and  $\underline{r}_{p/0}$  is the vector representing the distance from the point 0 to point P. Using aircraft axes with X out the nose, Y out the right wing, and Z down, equation 1 can be expanded into

$$a_{p_x} = a_{0_x} + Z(\dot{q} + pr) + Y(pq - \dot{r}) - X(q^2 + r^2) \quad (2)$$

$$a_{p_y} = a_{0_y} + Z(qr - \dot{p}) - Y(p^2 + r^2) + X(\dot{r} + pq) \quad (3)$$

$$a_{p_z} = a_{0_z} - Z(p^2 + q^2) + Y(\dot{p} + qr) + X(pr - \dot{q}) \quad (4)$$

where p, q, and r are the aircraft angular velocities while X, Y, and Z are the coordinate distances from point 0 to point p. Physically, let point 0 be the geometric centroid of the platform and point p<sub>1</sub> be the location of the first linear accelerometer and p<sub>2</sub> be the location of the second linear accelerometer. Assume that all points p and 0 are in the same X-Y plane. Find the angular acceleration p using linear accelerometers. Apply equation 4 twice with X<sub>1</sub> = 0 = X<sub>2</sub> (accelerometers mounted on the y-axis), subtract and rearrange. The result is as follows:

$$\dot{p} = \frac{1}{(y_1 - y_2)} (a_{p_{z1}} - a_{p_{z2}}) - qr \quad (5)$$

In a similar manner

$$\dot{q} = \frac{1}{(x_1 - x_2)} (a_{p_{z2}} - a_{p_{z1}}) + pr \quad (6)$$

$$\dot{r} = \frac{1}{(y_1 - y_2)} (a_{p_{x2}} - a_{p_{x1}}) + pq \quad (7)$$

$$\text{or } \dot{r} = \frac{1}{(x_1 - x_2)} (a_{p_{y1}} - a_{p_{y2}}) - pq \quad (8)$$

In the above equations, the quantity (x<sub>1</sub> - x<sub>2</sub>) or (y<sub>1</sub> - y<sub>2</sub>) is the distance between the mountings for accelerometers 1 and 2. According to Singer's specifications on the SAAC (The Singer Company, 1972), the maximum angular velocities are 15 degrees/second. Consequently, the product of angular velocities is less than 0.068 rad/sec<sup>2</sup>. Furthermore, if motion is driven about one axis at a time, only extraneous angular velocity terms would appear at all. The result is that the product of angular velocity terms can be dropped from the angular acceleration equations, leaving

$$\dot{p} = \frac{1}{(y_1 - y_2)} (a_{p_{z1}} - a_{p_{z2}}) \quad (9)$$

$$\dot{q} = \frac{1}{(x_1 - x_2)} (a_{p_{z2}} - a_{p_{z1}}) \quad (10)$$



the reference signal on an oscilloscope and/or the brush recorder, and (c) record the system's or subsystem's responses (displacements or accelerations) on the brush recorder or the FM recorder.

During testing, it was found that if accelerations were to be recorded, the air conditioner for the platform's visual system had to be turned off. It generated vibrations that were transmitted to the platform structure. These vibrations created extreme noise interference in all accelerometer measurements.

## VI. RESULTS

Numerous tests were conducted to investigate various aspects of the total system. Each phase of the investigation will be discussed separately.

### Positions

Five separate articles of information were gathered in this series of tests. First, a common analog step input signal was applied at the motion electronics cabinet by passing all digital computer hardware. Since all legs were driven with the same signal, it was expected that the responses would be identical. The results for a step input of -5 volts to +5 volts are in Table 1. The accuracy of the length measurement is  $\pm 1/32$  inch for all legs. Considering the maximum allowable errors, there is still a discrepancy of  $7/16$  inch in the extension of the legs for an identical signal. Extending this test to examine velocity for a step input of 6 volts (approximately 16 inches), the output displacement calibrations, maximum velocity of each leg and difference in leg extensions at a nominal point halfway into the step are shown in Table 2. There is indeed a considerable difference in legs. In fact, the maximum velocities of the legs differ by 13 percent.

Table 1. Leg Scale Factors

| Leg | Leg Travel (inch) | Leg Scale Factor (in/volt-inch) |
|-----|-------------------|---------------------------------|
| 1   | 25 15/16          | 2.594                           |
| 2   | 25 27/32          | 2.584                           |
| 3   | 26 9/32           | 2.628                           |
| 4   | 26 11/32          | 2.634                           |
| 5   | 25 27/32          | 2.584                           |
| 6   | 26 1/16           | 2.606                           |

Table 2. Leg Maximum Velocities

| Leg | Displacement/Output (in/out) | Max (in/sec) | t = 1/2 Ht. Diff. (inch) |
|-----|------------------------------|--------------|--------------------------|
| 1   | 1.339                        | 14.04        | 0                        |
| 2   | 1.319                        | 14.52        | 0                        |
| 3   | --                           | --           | --                       |
| 4   | 1.345                        | 15.83        | +0.3                     |
| 5   | 1.319                        | 14.10        | +0.2                     |
| 6   | 1.331                        | 15.19        | +0.9                     |

From the data in Table 2, the different slopes can be seen, as well as different values of the legs, at the same point in time. The data also show that the motion can be grouped into three categories: (a) acceleration from 40 milliseconds (ms) to 104 ms after the start of the input, (b) a time of almost constant velocity (104 ms to 696 ms) and (c) a time of deceleration (from 696 ms to 1.120 sec). The motion has essentially ceased after 1.120 seconds.

An additional discrepancy in leg velocities was noted on a test when the motion platform software was driven with a vertical command, and the inputs to the motion electronics showed the maximum

velocities of legs 1, 2, 4, 5, and 6 to be about 140 in/sec, while leg 3 was about 110 in/sec. This is disturbing and indicates a definite problem in the software or the DAC. In other modes of motion, this could produce extraneous accelerations of the platform.

Another positional finding was that in yaw the angular displacement is almost linear with input. The following yaw scale factor was observed for inputs of  $-0.1$ ,  $-0.2$ ,  $-0.3$ , and  $-0.4$  volt, respectively: 55.4, 55.3, 56.4 and 56.8 degrees/volt.

After the motion of the platform was observed, it was felt that it would be beneficial to determine the location of the axis about which an angular acceleration was occurring. Consider a profile view, (Figure 3) showing two linear accelerometers with an angular acceleration such as to produce linear accelerations along the sensitive axis of the accelerometers. Let  $d_1$  be the distance from accelerometer 1 to the point of rotation (may be positive or negative) and  $D$  be the distance between accelerometers. Note:  $d_2 = D + d_1$ .

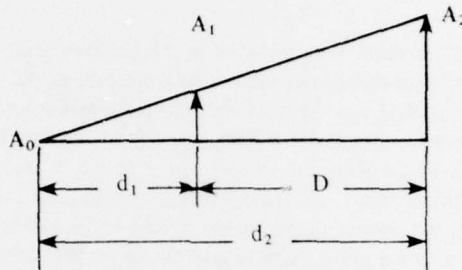


Figure 3. Location of axis for acceleration.

Let  $A_1$  and  $A_2$  be the linear acceleration of the accelerometers in addition to that of point 0.

Then  $A_{1 \text{ total}} = A_0 + A_1$

and  $A_1 = -d_1 \alpha$

$A_2 = -d_2 \alpha$

subtracting  $A_2 - A_1 = -(d_2 - d_1) \alpha = -D \alpha$

substituting and solving for  $d_1$  we have

$$d_1 = \frac{-A_1}{\alpha} = \frac{A_1 \times D}{A_2 - A_1}$$

The distance  $D$  for roll, pitch, and yaw, respectively, is 12.17, 16.47, and 16.04 feet, and the accelerometers are symmetrically mounted about the platform geometric centroid (see Figure 2).

There are two important points to be made by these data. First, the platform is pitching about a point considerably in front of the geometric centroid, and second, the point about which rotation occurs is *not constant*, i.e., it moves around to a significant extent (see Table 3). The first point is consistent with the fact that the platform is heavier, and the center of gravity is farther forward than originally believed. The center of gravity being further forward and higher than originally calculated might also help explain the variation of rotation point. (The manufacturer reported that the center of gravity was 6.22 feet aft of the forward pivot and 4.43 feet above the plane of pivots.)

Table 3. Platform Rotation Points

| Axis           | Reference Accelerometer | Positive Jerk | d <sub>i</sub> (feet) | Negative Jerk |
|----------------|-------------------------|---------------|-----------------------|---------------|
| Positive Roll  | +Y                      | -6.69         | -6.66                 | -6.59         |
| Negative Roll  | +Y                      | -7.66         | -5.66                 | -3.65         |
| Positive Pitch | +X                      | -8.24         | -5.49                 | -4.94         |
| Negative Pitch | +X                      | -5.44         | -6.54                 | -7.53         |
| Positive Yaw   | +X                      | -8.02         | -7.11                 | -8.60         |
| Negative Yaw   | +X                      | -8.5          | -7.57                 | -8.02         |

### Dead Time

Dead time refers to the time between which an event should occur without any system delays and the time the event actually does occur. In the present context, it refers to the time between an applied step input and the time when resulting motion occurs. First it should be mentioned that on one test an 8 ms difference in dead time was observed between the six legs when a step was applied to the motion software program and the leg command signals were monitored. A discrepancy this large was observed only once in about 15 tests, but even at this low rate, could prove troublesome.

The data clearly show the difference in observed dead time of position and acceleration for the same step input. This step input to heave was applied at the motion electronics cabinet. The difference between the 40 ms position is a double integration of acceleration and that acceleration would have to occur over some period of time before position displacement could be seen. Expressed another way, if the time rate of change of acceleration (jerk) is about 5g/sec, then if it is assumed that 0.005 inch or more of platform movement can be seen, it would take about 25 ms of platform acceleration before any platform motion at all could be seen. This would be an additional 25 ms dead time in the position observation over acceleration. Consequently, using position outputs for any type of absolute dead time investigation is extremely dangerous at best.

Over a series of 25 step inputs to the Y, Z, roll, pitch, and yaw axes, the observed acceleration dead times range from 0.080 to 0.168 second with an uncertainty for each reading of about 0.008 second. Even taking into account this uncertainty, there is about an 80 ms difference in dead time for observed acceleration. This is not surprising as this input was processed by the software program at the rate of 10 times per second, or 0.100 second between samples.

### Acceleration Step Responses

At this point, some mention should be made of what values are appropriate to acceleration levels in order to present a proper cue to a pilot. Gundry (1976) established the fact that subliminal levels change depending on the difficulty of the tasks being performed by the pilot. As air-to-air combat is very demanding, accepted literary values may not be applicable. However, due to the lack of better data, the generally accepted perception values of 0.08g for translational and 0.01 rad/sec<sup>2</sup> for angular accelerations will be used. A typical value for subliminal translational jerk value is 0.08g/sec.

A series of acceleration tests were conducted where the motion electronics cabinet was driven with a step input to determine the absolute capability of the physical platform. During this test, two linear accelerometers were mounted on the platform, one 8 feet forward and one 8 feet aft of the geometric centroid. For a commanded platform step of 7.2 inches up, the front accelerometer showed a maximum acceleration of 0.38g and a maximum jerk of 6.8g/sec while the back accelerometer showed 0.48g and 11.2g/sec. For a platform down command, the front showed 0.32g and 7.1g/sec while the back indicated 0.40g and 12.5g/sec, respectively. The duration of positive acceleration was about 0.470 sec. The difference

between the front and rear accelerometer indicates a pitch acceleration coupling of  $0.235 \text{ rad/sec}^2$ . This is 23 times larger than threshold values. The excessive weight and forward center of gravity would contribute to this problem. Apparently, Military Standard 1558 establishes the requirement that the longitudinal and lateral accelerations should be at least  $\pm 0.6g$ , with the vertical being at least  $\pm 0.8g$ . Clearly the SAAC does not have the capability to even come close to this level.

Next, the motion software program was driven with a long period square wave to generate step responses about a neutral platform position. The results are summarized in Table 4. It should be pointed out that platform up is +Z motion (as opposed to down for aircraft axes).

In Table 4, jerk was determined by graphically taking the slope of the acceleration curve at its steepest point. This rapid change in acceleration would manifest itself as a change in seat pressure on the pilot and should be quite noticeable. Washout values may be found in the table for a positive motion by looking at the maximum negative value for the acceleration of that variable.

Table 4. Platform Step Responses

| Motion        | p    |      | q    |      | r    |      | y    |     | z    |     | jerk |       |
|---------------|------|------|------|------|------|------|------|-----|------|-----|------|-------|
|               | -    | +    | -    | +    | -    | +    | -    | +   | -    | +   | -    | +     |
| +5"Y          | .20  | .20  | .08  | .08  | .50  | .68  | .04  | .12 | .01  | .01 | -.8  | 1.9   |
| -5"Y          | .25  | .20  | .06  | .06  | .20  | .15  | .12  | .05 | .01  | .01 | 2.0  | .5    |
| +10"Y         | .30  | .33  | .12  | .12  | .15  | .45  | .10  | .19 | .02  | .02 | .9   | 2.4   |
| -10"Y         | .35  | .33  | .06  | .06  | .15  | .20  | .19  | .11 | .01  | .01 | 2.8  | .9    |
| "Noise Level" | .08  |      | .03  |      | .04  |      | .006 |     | .006 |     |      |       |
| +5"Z          | .19  | .19  | .08  | .12  | .18  | .18  | .01  | .02 | .04  | .14 | .8   | 4.4   |
| -5"Z          | .15  | .10  | .16  | .08  | .20  | .35  | .02  | .02 | .16  | .04 | 2.7  | 1.1   |
| +10"Z         | .35  | .25  | .16  | .12  | .30  | .28  | .01  | .03 | .05  | .26 | 1.5  | 8.5   |
| -10"Z         | .38  | .25  | .16  | .12  | .35  | .63  | .04  | .03 | .27  | .07 | 5.4  | 1.6   |
| +2φ           | .70  | 1.30 | .12  | .16  | 1.10 | .55  | .10  | .22 | .04  | .02 | 6.0  | 27.2  |
| -2φ           | 1.55 | .65  | .16  | .12  | .80  | .55  | .17  | .10 | .04  | .04 | 23.6 | 6.3   |
| +2θ           | .25  | .30  | .47  | 1.33 | .9   | .95  | .06  | .05 | .12  | .05 | 5.6  | 24.1  |
| -2θ           | .20  | .10  | 1.41 | .55  | 1.15 | .70  | .04  | .06 | .02  | .08 | 32.6 | 7.0   |
| +4θ           | .30  | .20  | .86  | 2.11 | 1.00 | 1.00 | .10  | .07 | .17  | .14 | 15.2 | 39.1  |
| -4θ           | .20  | .20  | 2.35 | .78  | 1.25 | .75  | .09  | .11 | .07  | .14 | 34.3 | 11.9  |
| +2ψ           | .10  | .10  | 0.0  | .12  | .45  | 2.25 | .02  | .02 | .05  | .02 | 52.1 | 104.2 |
| -2ψ           | .30  | .25  | .16  | .16  | 1.65 | .55  | .03  | .02 | .04  | .06 | 28.4 | 11.8  |
| +4ψ           | .25  | .37  | .25  | .43  | 1.30 | 2.81 | .12  | .14 | .05  | .07 | 41.1 | 130.2 |
| -4ψ           | .30  | .18  | .24  | .59  | 2.75 | 1.75 | .05  | .07 | .07  | .11 | 50.4 | 22.0  |

Notes. — 1. Maximum values are indicated  
2. Units:  $\text{rad/sec}^2$ ,  $\text{rad/sec}^3$ , g, g/sec

The linear motions of Y and Z are not too bad as far as inducing extraneous linear accelerations. However, by almost any comparison that can be drawn, the angular accelerations are not consistent with desired values. Washout values are excessive and cross-couplings between desired platform motions and other axes are alarming. Cross-coupling should be restricted to that induced by the software package logic where desired representations for platform position of the SAAC are as follows:

$$X_p = 4(2.25A_{X_A} - \sin \theta)$$

$$Y_p = 2(2r_A - A_{Y_A}) - 36\phi_p$$

$$Z_p = -2(1 + A_{Z_A})$$

$$\theta_p = 0.625 \sin \theta + 0.3125 q_A$$

$$\phi_p = 0.125 p_A$$

$$\psi_p = (1/16) (r_A + (1/16)\beta)$$

where  $p_A$ ,  $q_A$ , and  $r_A$  are in rad/sec.

$A_{X_A}$ ,  $A_{Y_A}$ , and  $A_{Z_A}$  are in units of g.

$\beta$  is in degrees.

$X_p$ ,  $Y_p$ , and  $Z_p$  are in inches. (Note: For the platform equations,  $Z_p$  is positive upwards.)

$\theta$ ,  $\phi_p$  and  $\psi_p$  are in radians.

Clearly, the lateral and longitudinal modes of motion should not be coupled. Table 4 shows coupling, especially pitch inducing yaw which indicates the motion system is not behaving properly. Much of this coupling was visually evident during the acquisition of the data.

Strip chart recordings clearly demonstrate the washout problem. The washout phase of the motion which is supposed to be below a subliminal level is almost 50 percent of the cue signal. This washout is governed by a linear washout scheme, and the problem could be greatly reduced if a nonlinear washout scheme similar to Parrish's was employed (Parrish & Martin, 1975). The effect vertical motion has on yaw and roll was illustrated. This is undesirable and no yaw or roll acceleration should be observed for vertical motions. Also, the slope of the acceleration curve changes abruptly several times during the course of the cues. The cause of this behavior has not been determined.

#### Frequency Response

Linear systems theory states that for a sinusoidal input to stable linear dynamic systems the steady state output will be a sine wave of the same frequency. As a result, linear dynamic systems may be completely characterized by the amplitude ratio and the phase angle of the output as a function of the frequency of the input signal. One graphical representation of these data is the Bode plot where the amplitude is expressed as log-magnitude,  $L_m$ , which is defined as:

$$L_m(G) = 20 \log_{10} |G(i\omega)|$$

where  $G(i\omega)$  is the transfer function of the process relating the output to the input.

Sinusoidal position responses were recorded for each of the six legs. In addition, frequency responses were recorded for the platform acceleration in both heave and pitch for small amplitude motion. Bode plots of the results were drawn.

The data used to generate these Bode plots showed several interesting features that cannot be included on the plots themselves. First, at frequencies above 2 Hz, there was a noticeable lack of symmetry in the platform's motion, i.e., the amplitude and velocity of the up motion was less than the down motion. Also, above 2 Hz, large variations developed in the peak amplitudes at a constant frequency and higher harmonics appeared in the output. Some degradation of the motion occurred at input frequencies under 1 Hz.

Based on the Bode plots and the time histories for sinusoidal inputs, it is the author's opinion that platform motion has deteriorated to the point where it must be considered non-linear for input signals above 3 Hz. In some cases, the non-linear aspect of the motion may significantly affect results at frequencies as low as 0.5 Hz.

From the Bode plots for low frequencies the platform's response pretty well behaves like an overdamped second order linear dynamic system with a slight difference in each individual leg. If the natural frequency is taken as the frequency when the phase angle is 90 degrees, then the natural frequencies of the six legs are 0.52, 0.62, 0.56, 0.51, 0.61, and 0.56, respectively. The Bode plots for accelerations also suggest an overdamped second-order system with a natural frequency of about 1/2 Hz.

Due to time limitations, no attempt was made to formulate a mathematical model for the system from the Bode plots.

#### VII. CONCLUSIONS AND RECOMMENDATIONS

The conclusions to be drawn from this effort must first be prefaced by a statement regarding the utility of motion systems in simulation of highly maneuverable fighter or trainer-type aircraft. Recent studies in this area have produced evidence that seriously questions the contribution made by the platform motion system toward enhancement of the training effectiveness of simulators of this type. One might conclude that the physical constraints induced by being bolted to floor and restrictions to leg length extensions preclude imparting cues of sufficient magnitude and duration to be discernible to the sensory system of the human body. Since in the case of the SAAC, the movement of the motion platform is distracting and, in the opinion of the Instructor Pilots utilizing the device, does not accurately replicate the "feel" of the aircraft, it is no longer being used in the training program.

From this investigation it has been determined the SAAC motion system is not performing at a level sufficient for training purposes. Before future employment of the system, should the requirement arise, there are four areas where deficiencies should be assessed for possible corrective action. First, the present motion hardware is not mechanically functioning properly and should be "tuned up" to specifications. Specific problems that should be remedied are the cross-couplings of motions and the abruptness of certain modes of motion. Secondly, there is a question of whether the hardware has the basic capability of meeting Military Standard 1558 which governs motion platform systems. The third area is in the software package associated with the SAAC; as an example, the present logic calls for the acceleration of the platform centroid, rather than a point corresponding to the pilot. The fourth area that needs improvement is in the basic simulator logic and concerns the best method to present cues to the pilot; for example, a non-linear washout scheme should greatly improve the illusion of aircraft motion.

#### REFERENCES

- Gundry, A.J.** *Thresholds to roll motion in flight simulator*. Visual and Motion Simulation Conference, Dayton, Ohio, April 26-28, 1976.
- Liebman, R.** *Strong motion seismic systems*. Technical Note De-TN-76-016. Kirtland AFB, NM: Air Force Weapons Laboratory, July 1976.
- Meriam, J.L.** *Dynamics* (2nd ed.). New York: John Wiley and Sons, 1971.
- Parrish, R.V., & Martin, D.J., Jr.** *Empirical comparison of a linear and a nonlinear washout for motion simulations*. Paper 75-106. AIAA 13th Aerospace Sciences Meeting, January 1976.
- Technical specification for a 60-inch stroke six-degree-of-freedom motion system*. Singer Products Division, The Singer Company, Binghamton, New York, May 6, 1972.

#### REFERENCE NOTE

1. Unpublished data gathered for the Scientific Advisory Board's June meeting at Williams Air Force Base, Chandler, Arizona, June 1977.

#### BIBLIOGRAPHY

- Brewer, J.W.** *Control systems: Analysis, design and simulation*. Englewood Cliffs, NJ: Prentice-Hall, 1974.
- Harrison, H.L., & Bollinger, J.G.** *Introduction to automatic controls* (2nd ed.). New York: International Textbook Company, 1959.

APPENDIX A: DESCRIPTION OF TEST EQUIPMENT USED IN THIS STUDY

1. 50 rad/sec<sup>2</sup> angular accelerometers, Schaevitz Engineering Model ASBC39-50:
  - a. Yaw axis – Serial No. 3372G.
  - b. Roll axis – Serial No. 3373G.
2. 2-g linear accelerometers, Schaevitz Model LSBC-2:
  - a. Y axis – Serial No. 3672.
  - b. Front mount for pitch axis – Serial No. 3681.
  - c. Rear mount for pitch axis – Serial No. 3679.
3. Cannister No. 5 with 3 orthogonally mounted 5g linear accelerometers supplied by Air Force Weapons Laboratory, Kirtland AFB, as described in Technical Note No. DE-TN-76-016. Accelerometers were manufactured by Enderco.
4. Gould six channel brush recorder Model 260.
5. Two Lambda power supplies, Models LP-522-FM (0-40 volts) and LP-521-FM (0-20 volts).
6. Function Generator, Hewlett-Packard Model 3310B.
7. Time Code Generator, Model HI-188-632.
8. 14 channel FM tape recorder, SANGAMO Sabre VI Model 632, Tape Transport Serial No. 6221, recorder Serial No. 772.
9. Amplifier – Filters built around 747 amplifiers. All signals have a 30 Hz, one-half power frequency. The angular accelerometers have a gain of 20, the linear 2g has a gain of 4, the difference circuit (used for pitch accelerations) has a unity gain, and the cannister accelerometers have a gain of 10.

Note: Linear accelerometers were cross-checked against each other while the angulars were checked with the difference circuit. The scale factors for the accelerometers are as follows:

$$\text{Cannister } A_x = 8.25 \text{ volts/g}$$

$$A_y = 8.25 \text{ volts/g}$$

$$A_z = 8.35 \text{ volts/g}$$

$$\text{Linear 2g } A = 10.00 \text{ volts/g}$$

$$\text{Angulars } \alpha_s = 2.00 \text{ volts/rad/sec}^2$$

$$\text{Difference } \alpha = 1.28 \text{ volts/rad/sec}^2$$

(pitch)

