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A STUDY OF TECHNIQUES FOR
CALCULATING MOTION DRIVE SIGNALS FOR
FLIGHT SIMULATORS

by Bjorn Conrad and Stanley F. Schmidt

July 1971

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ANALYTICAL MECHANICS ASSOCIATES, INC.
Mountain View, California

for

NASA AMES RESEARCH CENTER
MOFFETT FIELD, CALIFORNIA



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Stanley F. Schmidt
Bjorn Conrad

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SECTION 1

INTRODUCTION

One of the challenging and unsolved problems in applications of piloted-flight simulators is how the very restricted motion freedom of the translational and rotational drive systems can "best" be used to simulate realistic flying sensations. The problem is difficult to solve because the constraints of the motion drive systems (position limits, velocity limits, and acceleration limits) preclude duplication of the body rates and forces on the pilot of the real aircraft except in a few tasks like hovering, refueling, and formation flying. As a result, the "best" motion is a compromise which attempts to provide the simulator test pilot with those flight sensations and motion "cues" that he needs while staying within the constraint barriers of the motion drive systems. The lack of knowledge on pilot needs, and the lack of a fundamental understanding of how such compromises in motion fidelity degrade the usefulness of the simulation test results, make the problem even more difficult.

In a previous study effort (Ref. 1), a number of empirical "rule-of-thumb" solutions to the problem were reviewed and documented. Also, a "heuristic" mathematical approach was given which tended to "explain" the empirical solutions. This approach was used to develop two promising washout* circuits for the Ames All-Axis Motion Simulator. In order to evaluate these circuits, a "formation-type" flying task was conceived. In this task, the motion quality could be varied from near-perfect reproduction of real flight to a fixed-base (no motion) solution. The previous study effort terminated with the completion of an experimental program in which several pilots flew the formation-flying task for three different aircraft lateral handling characteristics with one-to-one motion and fixed-base (no motion). The results of that program showed that the task and simulated

* The name "washout circuits" is traditionally given to solutions of the motion drive problem.

aircraft were such that one-to-one motion was very important to the simulator test pilots. The effect of motion was readily measured by rms calculations based on the pilot's ability to hold a tight formation. Hence, it was believed that the effects of washout circuit parameter variations (which affect the quality of motion) could be measured and the parameters optimized in an experimental investigation which used the formation-flying task.

The objectives of the study effort described in this report were as follows:

1. Develop an experimental test plan using the formation-flying task for the validation and refinement of the washout circuits described in Reference 1. The details of this plan are given in Section 2.
2. Execute the test plan in conjunction with NASA scientists and test pilots on the Ames simulation facilities. Some of the experimental results obtained in these tests are given in Section 3.
3. Analyze the experimental data in conjunction with NASA scientists, using pilot model identification methods. Difficulties encountered with these procedures are given in Section 4, along with a few preliminary results.
4. Develop FORTRAN IV washout programs for applications on the Ames All-Axis Simulator. Two such programs are described in the Appendix. Section 5 describes the use of these circuits.
5. Develop a questionnaire-type log to assist NASA personnel in documenting the experience obtained with the application of washout circuits to operational simulations. This log is presented in Section 6.

Section 7 reviews the overall study effort and gives recommendations for future investigations.

SECTION 2

EXPERIMENTAL TEST PLAN

2.1 Testing Objective

The motivation for performing moving-base simulation tests came from the research and development effort summarized in Reference 1. That reference suggested two types of six-degree-of-freedom washout circuits: an uncoordinated version based on extensions and modifications of two-degree-of-freedom ideas, and a coordinated circuit designed with emphasis on producing good specific force cues. The primary objectives of testing were to validate these circuits, compare them, and draw any conclusions possible about the relationship of motion cues and pilot performance when flying a formation-flying task. There were also important secondary objectives such as determining whether circuit parameters, chosen on the basis of the formation-flying task, might serve as initial trial points for other tasks.

2.2 Test Outline

In order to achieve the general objectives cited above, the following sets of tests were proposed, each to take approximately one week of testing:

1. Body-fixed angular rate and force scaling tests, utilizing the formation-flying task
2. Parameter search and validation tests, with emphasis on the coordinated circuit using the formation-flying task
3. Parameter adjustment on the uncoordinated circuit with the formation-flying task
4. Refinement and comparison of the coordinated and uncoordinated circuits, using the formation-flying task

5. Approach and landing tasks, with various levels of pilot experience and aircraft stability.

The objectives of each set of tests will now be summarized.

The scaling tests had two major objectives. First, since both the uncoordinated and coordinated circuits contain logic for scaling specific force and angular-rate cues coordinated in a body-fixed frame, it was desirable to have information on the effect of motion attenuation based purely on scaling, rather than on a mixture of scaling and more complicated dynamic washout schemes. Second, by independently scaling the two types of motion cues available to a pilot, insight would be gained on the relative importance of these cues in the formation-flying task. It should be noted that motion scaling has been investigated by others (e. g. , Ref. 2).

The parameter search and validation tests on the coordinated circuit were particularly important because this logic had not been exercised in flight-simulation facilities. Hence these tests were necessary for the purpose of finding reasonable operating ranges for the coordinated circuit parameters and demonstrating the feasibility of this washout configuration.

Tests on the uncoordinated circuit were planned to permit optimization of its parameters for the formation-flying task. This circuit had been used for the Ames All-Axis Motion Generator in piloted-flight simulation studies of the German Do-31 VTOL aircraft (see Ref. 1) and hence required less testing.

The next set of tests was planned in order to allow direct comparisons of the two washout circuit configurations in formation-flying. It was expected that refinements of the circuits would be carried out during these tests to determine if differences were due simply to particular parameter settings or to other causes related to the difference in motion fidelity between the two circuits.

The final set of tests was planned in order to determine the degree of applicability of formation-flying task results to other tasks. It was not necessarily expected that the washout settings for a particular task, such as formation-flying, with a given aircraft would be best for all other tasks. It was hoped, however, that a set of parameters could be defined which could be varied in an orderly manner to accommodate any particular problem. To test this philosophy, approaches and landings were to be conducted using the washout circuit parameters derived from the formation-flying task as a "first cut." Then the circuit parameters were to be varied to determine settings appropriate for the approach and landing tasks. The resulting uncoordinated and coordinated circuits were then to be given a final comparison.

Table 2.1 represents the formalized schedule prepared prior to the scaling tests. It is typical of the procedures intended for each of the tests, calling for the use of a large sample of pilots and task configurations. Figure 2.1 shows the scaling combinations planned for these tests. The circled points represent optional values.

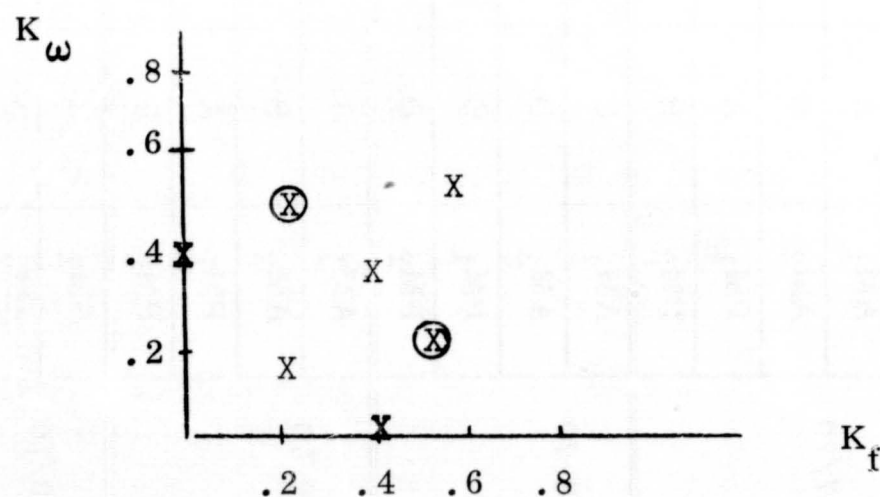


Figure 2.1 - Combinations of Rate Scalings, K_ω , and Force Scalings, K_f , to be Tested

TABLE 2.1

TEST PLAN FOR SCALING TESTS

DATE	TIME	PILOT	WIND	AIRCRAFT	WASHOUT
7/27/70	AM ₁	A	LOW	DC-8 - MED STAB	6 SCALED RUNS
	AM ₂	B	LOW	DC-8 - MED STAB	6 SCALED RUNS
	PM ₁	A	HIGH	DC-8 - MED STAB	6 SCALED RUNS
	PM ₂	B	HIGH	DC-8 - MED STAB	6 SCALED RUNS
7/28/70	AM ₁	C	LOW	DC-8 - MED STAB	6 SCALED RUNS
	AM ₂	D	LOW	DC-8 - MED STAB	6 SCALED RUNS
	PM ₁	C	HIGH	DC-8 - MED STAB	6 SCALED RUNS
	PM ₂	D	HIGH	DC-8 - MED STAB	6 SCALED RUNS
7/29/70	AM ₁	A	LOW	DC-8 - LOW STAB	6 SCALED RUNS
	AM ₂	B	LOW	DC-8 - LOW STAB	6 SCALED RUNS
	PM ₁	A	HIGH	DC-8 - LOW STAB	6 SCALED RUNS
	PM ₂	B	HIGH	DC-8 - LOW STAB	6 SCALED RUNS
7/30/70	AM ₁	C	LOW	DC-8 - LOW STAB	6 SCALED RUNS
	AM ₂	D	LOW	DC-8 - LOW STAB	6 SCALED RUNS
	PM ₁	C	HIGH	DC-8 - LOW STAB	6 SCALED RUNS
	PM ₂	D	HIGH	DC-8 - LOW STAB	6 SCALED RUNS
7/31/70	PRELIMINARY TEST COMPARISON OF A CLASSICAL AND A COORDINATED WASHOUT CIRCUIT - WILL SLIP IN THE FIRST FOUR DAYS IF DATA AVAILABLE.				

2.3 Experimental Data

The experimental test plan called for the collection of three types of data:

- subjective pilot opinions via a questionnaire
- formation-flying task performance information based on rms tracking errors from a mean tracking position
- digital outputs of time histories of various simulation variables suitable for later processing on the Ames IBM 360/67 computer facility.

A brief discussion of each of these follows.

Figure 2.2 presents the pilot questionnaire which was developed after considerable consultation with Ames personnel (including pilots and engineers) experienced in their construction and usage. The purpose of this questionnaire was to determine subjectively sensed characteristics of alternative washout circuits and/or parameter settings presented to pilots. The first five questions are fairly general, relating to the overall performance of a washout circuit, whereas the last four try to isolate specific aspects of the circuits. The questionnaire is relatively short since it was designed to be used after each alteration of a washout configuration.

On-line rms performance computations were planned as one quantitative measure which could be used to show the effect of various types of motion logic on a pilot. The rms calculations were made for x, y, and z displacement errors (from a mean position), and the pilot control movements of the throttle, aileron, elevator, and rudder. Reference 1 demonstrates how such errors change when comparing fixed- and moving-base simulations. Reference 2 demonstrates how the rms errors can change for simple tracking problems with one- and two-degrees-of-freedom and various scalings of angular rate motion drives.

Digital output capability was chosen for data recording purposes, since large amounts of data could be stored for later analysis. Original planning called for up to 49 variables to be saved on magnetic tape at specified integer multiples of the basic

1. How realistic was the motion fidelity with respect to the visual display?
2. The effect of the motion on your performance of the task is judged to be
3. How good was your sense of orientation through the run?
4. How good was the sense of translation movement?
5. How good was the sense of rotational movement?
6. How good was the sense of motion corresponding to the application of aileron?
7. How good was the sense of motion corresponding to rudder input?
8. How good was the sense of motion corresponding to elevator input?
9. How good was the sense of motion corresponding to throttle input?

	Excellent	Good	Fair	Poor	Unacceptable

Figure 2.2 - Pilot Questionnaire for Washout Tests

TABLE 2.2

DIGITALLY-RECORDED SIMULATION VARIABLES

	<u>Parameter</u>	<u>Units</u>
t	time	seconds
x, y, z	a/c inertial position coordinates	feet
θ, ϕ, ψ	a/c attitude	radians
α	a/c angle of attack	radians
v	a/c velocity	ft/sec
$\ddot{x}, \ddot{y}, \ddot{z}$	a/c linear accelerations in inertial coordinates	ft/sec ²
p, q, r	a/c angular rates in body coordinates	rad/sec
$\dot{p}, \dot{q}, \dot{r}$	a/c angular accelerations	rad/sec ²
f_1, f_2, f_3	pilot station specific forces in a/c coordinates	ft/sec ²
x_{fu}, y_{fu}, z_{fu} $\theta_{fu}, \phi_{fu}, \psi_{fu}$	{ simulator follow-up signals (not sampled)	
$\hat{x}, \hat{y}, \hat{z}$	simulator position	feet
$\hat{\theta}, \hat{\phi}, \hat{\psi}$	simulator attitude	radians
$x_{err}, y_{err}, z_{err}$	a/c position coordinates centered at initial conditions	feet
dummy		
$\delta_e, \delta_a, \delta_r$	elevator, aileron, and rudder input	radians
$T_{\omega x}$	throttle input (constant for some tests)	
$\hat{p}, \hat{q}, \hat{r}$	simulator angular rates in body coordinates	rad/sec
$\hat{f}_1, \hat{f}_2, \hat{f}_3$	simulator pilot specific force cues in body coordinates	ft/sec ²
xrn_1, xrn_2, xrn_3	visual disturbance noises (not used)	feet

computer cycling time. The Ames IBM 360/67 computer facility was to be used to analyze the data. It was intended that various types of processing, such as plotting or cross-plotting of various records, be done between tests. Furthermore, the data was to be stored in a format suitable for such purposes as pilot modeling studies to be conducted by Ames personnel. Table 2.2 presents a list of variables scheduled for recording.

2.4 Aircraft and Cockpit Configuration

Most of the details related to simulation configuration are identical to those discussed in Reference 1. The only major difference was that some of the tests were conducted without the use of throttle control. The throttle management necessary for maintenance of a fixed-lateral displacement behind a lead aircraft in formation flying poses a difficult pilot control problem which is not directly aided by cues from the longitudinal motion. With throttle in, and little or no dynamic washout, pilots could not track a lead aircraft and stay within the limits of the longitudinal drive of the All-Axis Motion Generator. Hence, some tests, such as those involving scaling, were planned with the throttle control effectively replaced by an autopilot so that no pilot control of relative x displacement was necessary. Moving-base tests (listed in Ref. 1) were conducted by disconnecting the x -channel drive of the motion generator while leaving the throttle control in, as this affects the visual displays. The "fair" and "poor" scaled-down DC-8 aircraft described in Ref. 1 were to be used for simulation.

2.5 Planned Simulation Testing Schedule

The test plan called for one-week tests alternating with six- to eight-week periods in which to analyze data. This was done so that the occurrence of new or unexpected results would permit the redirection of tests in future simulations.

SECTION 3

SIMULATION TEST RESULTS

3.1 Simulation Tests: An Overview

The washout tests actually performed on the Ames All-Axis Simulator were continuously tailored to reflect experience gained during simulation as well as the availability of personnel and equipment at Ames Research Center. As a consequence, the tests were not as exhaustive as anticipated in the plan of Section 2. However, the overall testing pattern was retained. This section summarizes those tests and the conclusions drawn from them.

As planned, three washout circuits were mechanized and tested on the Ames EAI digital simulation system: a scaled circuit, an uncoordinated circuit, and a coordinated circuit. These circuits are described in the Appendix, modeled in the form they took as a result of the washout tests. The Appendix also contains a synopsis of soft limiting logic and inertial washout common to all of the circuits.

Four series of tests produced most of the results associated with the washout tests, including the final coordinated and uncoordinated circuit configurations discussed above. These tests consisted of:

1. scaling tests, conducted prior to the testing of the dynamic washout circuits, without throttle control,
2. coordinated circuit validation tests, consisting of searches for nominal operating points and checkout, with and without throttle control,
3. coordinated, uncoordinated, and scaling tests with throttle control, using formation-flying and landing-approach tasks,
4. final circuit refinement and check, using formation-flying and approach tasks.

The first three tests were conducted with two Ames test pilots. The last test used four pilots and an engineer who was experienced in the use of motion simulators.

These tests and results are reviewed in Sections 3.2 through 3.5, respectively. The scaling and final circuit tests were of particular interest. The former produced potentially-valuable information on this generally-useful method of motion attenuation whereas the final tests were used to confirm phenomena regarding questionnaire and rms data observed in the preceding tests.

3.2 Scaling Tests and Results

The following table shows a partial list of the combinations of force and angular-rate scaling which were tested.

TABLE 3.1
SCALING COMBINATIONS TESTED

Angular-rate scaling, K_{ω}	1.0	0.6	0.6	0.0	0.2	0.2	0.2	0.4	0.4	0.2	0.5	0.3
Force scaling, K_f	1.0	0.6	0.0	0.6	0.0	0.6	0.5	0.4	0.0	0.2	0.0	0.0

Unlike the one-to-one motion run discussed in Reference 1, these tests were run without throttle control, so that the relative longitudinal displacement in the visual picture remained constant. Two pilots flew the aircraft labeled "poor" in Ref. 1 and a completely unstable version of the same aircraft, which was obtained by changing the sign of C_{ℓ}^p . Despite a number of difficulties encountered with data recording procedures, these tests were judged to be extremely valuable.

The scaling experiments brought out the following points:

- The relationship between motion cues and the difficulty of a particular simulation task can be strongly affected by workload factors not directly related to motion.

- An angular-rate scaling level of approximately 0.5 appears to be reasonable with 0.4 representing a lower bound for the control of a laterally unstable aircraft.
- Arbitrary values of the force scaling had little effect on the pilot's ability to fly the formation task.
- The primary motion cue needed by pilots for control in this task appears to be roll rate (or rolling acceleration).
- The pilots flying this task found it difficult to consciously determine the difference between angular-rate and force cue inputs, even when they were clearly using the former for control purposes.

The first point was discovered as a result of removing throttle management from the pilots' workload. It was discovered that maintaining a fixed distance behind the lead aircraft required intense concentration. Removing this portion of the task made the problem fairly easy to fly with or without motion. With the throttle control task included, the problem was difficult to fly with motion, and practically unflyable without motion.

Digital data recording procedures did not function well until the last two series of tests. Furthermore, the rms and questionnaire data did not appear to depend on the magnitude of scaling and thus did not indicate significant trends. This may have been due to the small sample sizes available or to the complicated nature of the task. Note that the angular-rate scaling tests discussed in Ref. 2 did show an increase in the rms errors with decreased values of motion. In order to determine whether or not there was some fundamental level of scaling below which performance would be degraded, the simulated airplane was made unstable. The altered aircraft was flyable when angular rates were scaled at or above 0.5 for one pilot, and at or above 0.4 for the other. Level of force scaling had no effect on the flyability of the aircraft. It is interesting to note that these scaling levels correspond to the start of performance degradation, as described in Ref. 2.

The questionnaire was revealing in an indirect fashion. A brief summary of the answers to the questionnaire (see Fig. 2.2) is presented in Table 3.2. Because

the pilots had difficulty with Questions 4 and 5, dealing with force and angular-rate cues, some special tests were run. The pilots were given various combinations of angular-rate and force scalings and asked which quantity was scaled up and which down. They were unable to determine this, even when the scaling changes were sufficient to cause the task to alternate between being controllable and being uncontrollable.

The pilots' inability to differentiate between various cues might be a function of the All-Axis Simulator rather than a phenomenon associated with the sensing of motion cues. For example, structural vibration of the cab gantry might produce anomalous force cues capable of confusing pilots who were attempting to discern whether or not force cues are present. It is also possible that pilots encountering difficult realistic tasks utilize motion cues at such a low level of consciousness that they cannot be recalled.

The concept of scaling force and angular-rate cues in body-fixed frames of reference seemed to work well in these tests. None of the comments made by the pilots, even under unstable (unflyable) conditions, indicated any pilot disorientation associated with scaling. As a result of these tests, a scaling of 0.5 (on both force and angular rate) was chosen as a nominal value for future experiments.

3.3 Coordinated Circuit Validation Tests

These experiments were, for the most part, carried out in a trial-and-error fashion. Information was obtained from running dialogues with the test pilots. The throttle was not used for the first portion of these tests, but was added later. Some of the results of these tests were:

- An initial operating point was found for the parameters K_1 , K_2 , and K_3 . The values were $K_1 = .031$, $K_2 = 1.4$, and $K_3 = 0.25$ (see Fig. A.7 in the Appendix).
- Slight variations of such parameters as the low-pass network damping ratio and natural frequency did not noticeably affect pilot-sensed motion cues.

TABLE 3.2

SUMMARY OF PILOT QUESTIONNAIRE ANSWERS
FROM SCALING TESTS

<u>Question Number</u>	<u>Pilot Responses</u>
1	Both pilots rated all scalings good when flyable
2	Both pilots rated all scalings good when flyable
3	Both pilots rated all scalings good when flyable
4,5	Both pilots found these hard to separate and could not judge
6	All scalings were rated excellent by both pilots for flyable cases
7	Neither pilot used significant rudder input and therefore could not answer
8	Both pilots rated excellent in all flyable cases
9	Throttle was not used in these tests

- Comparison of fixed-base and washed-out moving-base runs, with throttle in, produced results similar to the motion/no motion tests of Ref. 1. The aircraft was flyable with motion, but almost impossible to fly without motion.

On some runs, the pilots intentionally flew excursions from their normal formation position behind the lead aircraft. This was done to excite larger motions than those encountered in tight tracking. Both pilots evidenced general satisfaction with the "washed-out" motion for "loose" tracking and tight tracking.

Following completion of these tests of the coordinated circuit, it became evident that the scope of the planned simulations would have to be reduced. Because the coordinated circuit had shown great promise, tests involving additional parameter variations were scheduled for this circuit. At the same time, it was decided to omit tests involving parameter variations from the uncoordinated logic.

3.4 Uncoordinated, Coordinated, and Scaling Tests

The principal functions carried out in this test period were:

- Variation of the parameters K_1 and K_2 in the coordinated circuit to obtain a measure of the range through which these could comfortably be varied for the All-Axis Simulator.
- Comparisons of the coordinated and uncoordinated circuits during formation-flying and approach-to-landing tests.
- Rerun of scaling (with throttle in) for data recording purposes.

The digital data recording techniques worked well for these experiments so that a large quantity of data was produced for later processing and analysis.

A large number of tests were carried out for parametric variations in the coordinated circuit. Figure 3.1 presents typical simulator position histories commanded by the washout circuit for the formation-flying task. The histories shown in Fig. 3.1 were generated by varying the circuit gains K_1 and K_2 according to the table below.

CASE	PARAMETER	
	K_1	K_2
1	.00195	5.6
2	.0078	2.8
3	.031	1.4
4	.124	.7
5	.5	.35

($K_3 = .25$, force and angular-rate scaling = 0.4)

As the gain K_1 is increased, the simulator translation drives move less but angular rate is progressively distorted. This distortion is evidenced in Fig. 3.2 where the simulated aircraft angular rate and "washed-out" rate (about the x-axis) are plotted. For comparison purposes, Fig. 3.3 presents a typical history for an uncoordinated circuit run with a force and angular-rate scaling of 0.4.

Pilots indicated disorientation with the value of K_1 set at 0.5 and discomfort with the value set at 0.00195. Intermediate values were all felt to be acceptable. At the high value of K_1 , the distortion of the washed-out rate is quite large. It was expected that pilots might prefer the lowest possible value of K_1 , but this was not the case. The reason for this is moot, but it may be related to the dynamic characteristics and audible noise of the cab drive systems. Note that a small K_1 causes more translation, which increases audible noise and vibration.

The linearized coordinated circuit has a complicated closed-loop transfer function between angular-rate input and output. The primary effect of varying K_1 is to change the natural frequency of this loop, while K_2 can be used to maintain a constant damping ratio. Varying the damping ratio in the range 0.3 to 0.9 seemed to have no appreciable effect.

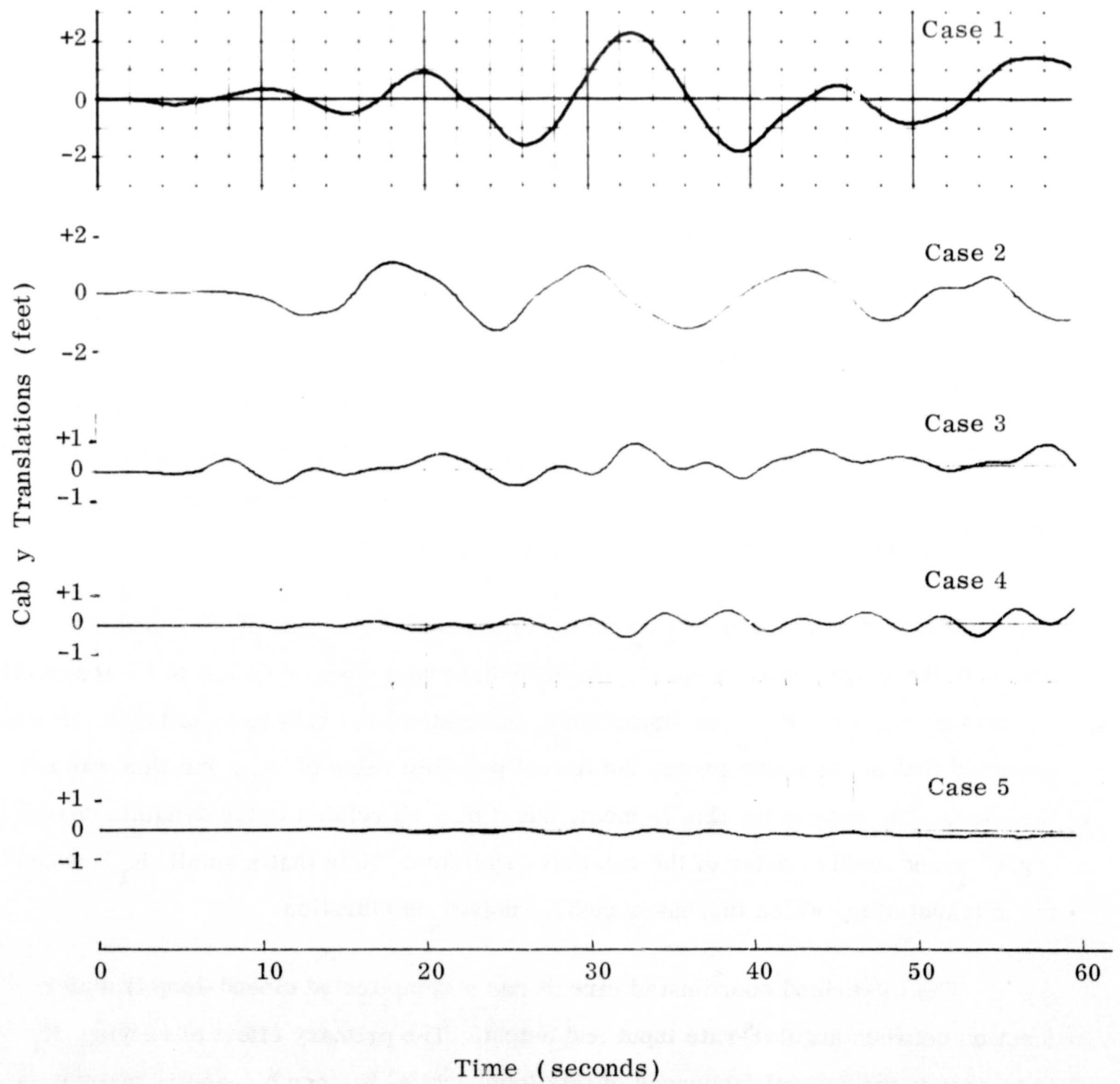


Figure 3.1 - Lateral Cab Translation Histories: Increasing K_1 in Coordinated Circuit

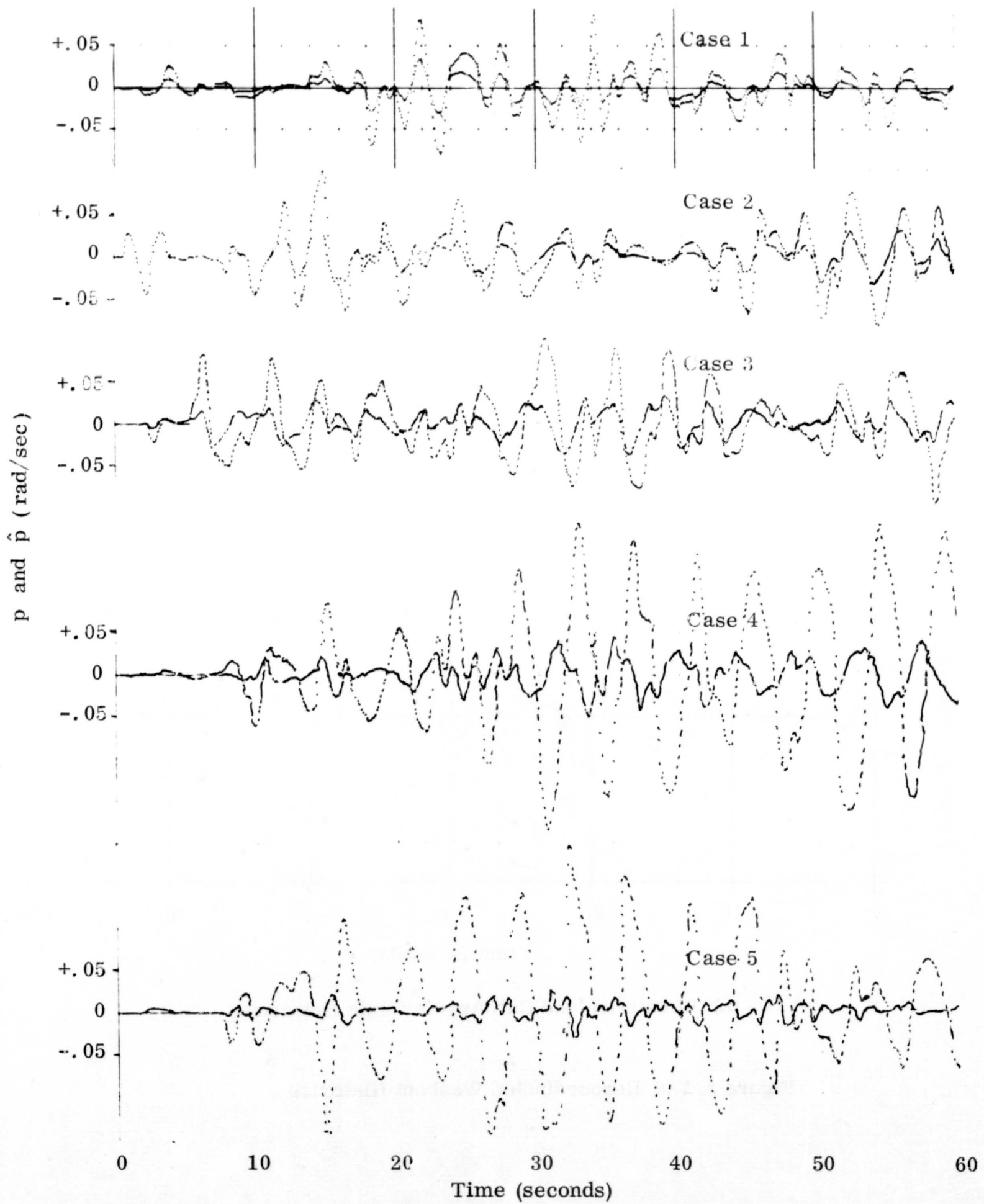
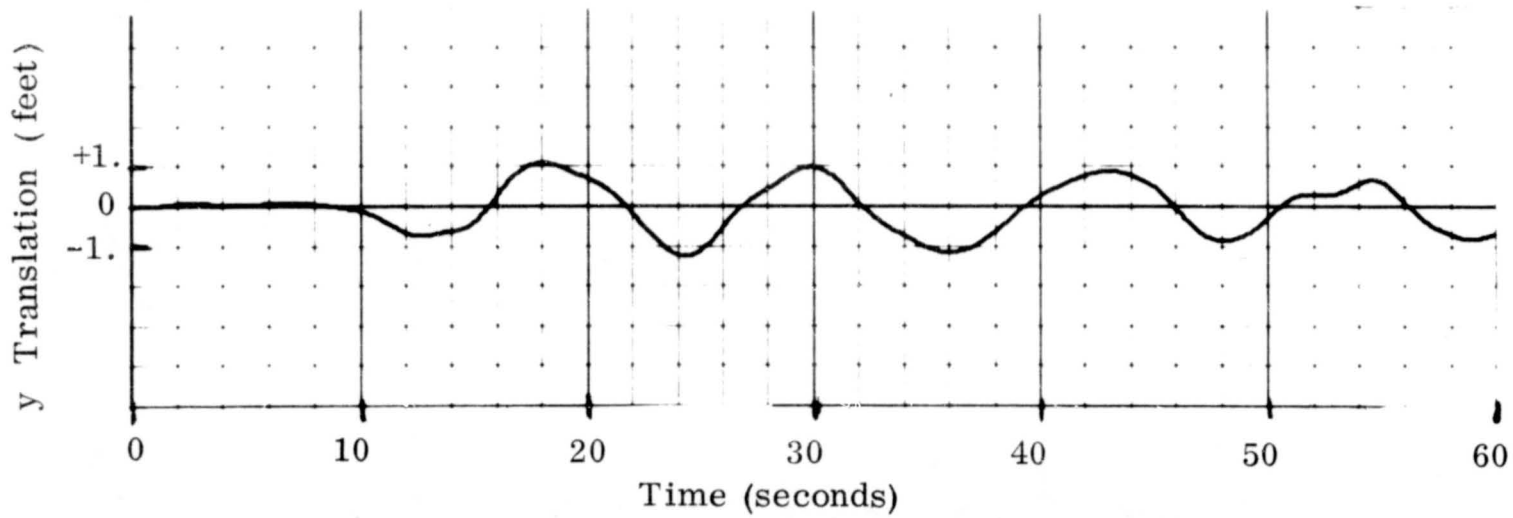
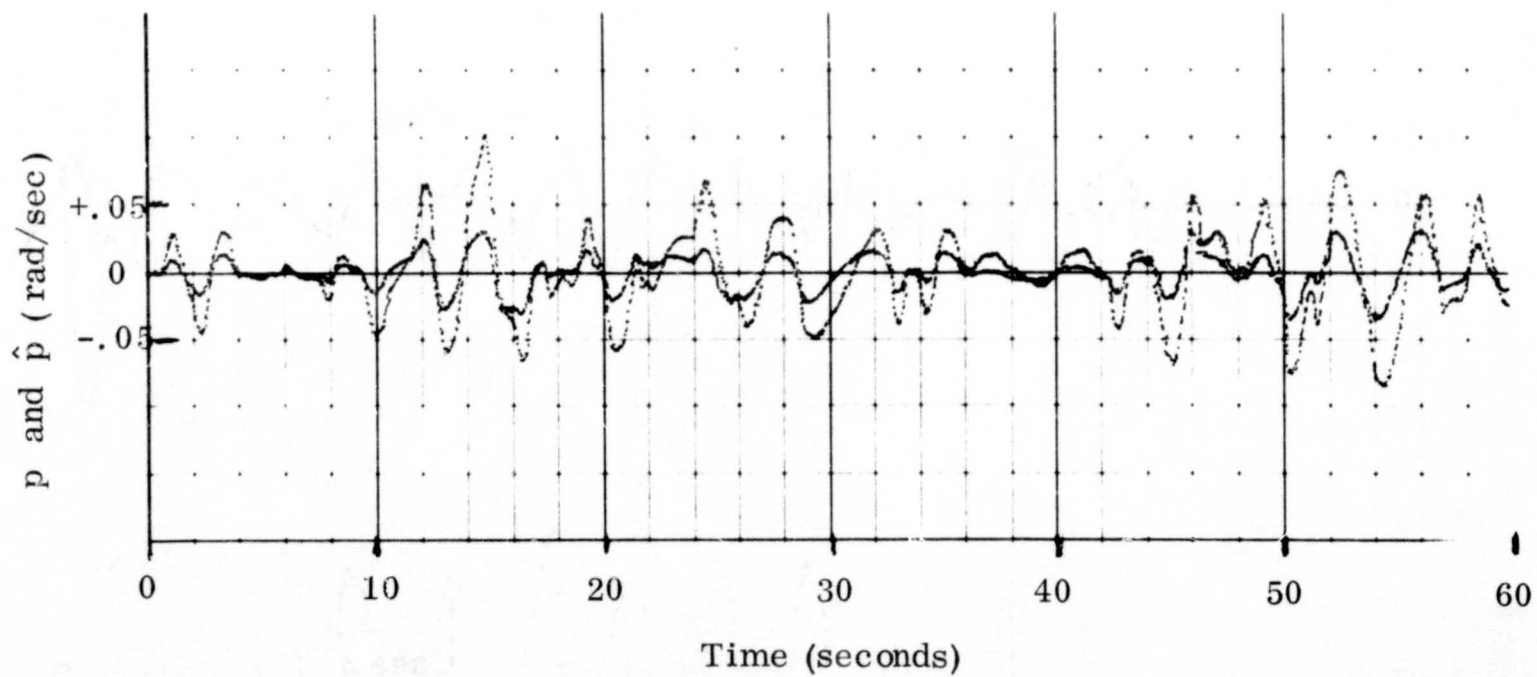


Figure 3.2 - Comparison of Simulated and Washed-Out Angular Rates
 About the x-axis: Increasing K_1 in Coordinated Circuit



(a) Commanded Translation



(b) Simulation and Cab Angular Rate Histories

Figure 3.3 - Uncoordinated Washout Histories

Back-to-back comparisons of the coordinated circuit with the uncoordinated circuit produced a slight preference for the coordinated circuit in formation flying.

Approaches to a landing were performed with both the coordinated and uncoordinated circuits. The simulation was not fully set up for touchdown, so pilots flew to the point of touchdown or to a hundred or so feet above the touchdown point. In the latter case, they would commence such maneuvers as s-turns over the runway to get a feel for the effect of the washed-out motion in situations involving large side maneuvers. Back-to-back comparisons between several coordinated washout configurations and the uncoordinated configurations produced a distinct preference for the coordinated circuit for those situations involving turns. This is believed to be due to unrealistic side forces generated in the uncoordinated circuit during turning maneuvers.

3.5 Circuit Refinement Tests

The concluding set of tests dealt primarily with the coordinated circuit. Two pilots and an engineer were added to the two pilots who performed all the previous tests. The engineer had great familiarity with moving-base simulations and the use of washout logic. Important aspects of these experiments were:

- The questionnaire discussed in Section 2 was replaced by an alternative procedure for obtaining pilot opinion. Opinions were based on direct comparisons between coordinated circuits and their pure scaling counterparts.
- The coordinated circuit was exercised with a precise set of parameter variations. These included two sets of scaling (0.5 and 0.7) and natural frequency variations in the tilt loop from 0.3 to 0.8.
- The parameter K_3 was reduced from .25 to .05 to reduce the rate at which the simulator returns to null after a right or left coordinated turn.
- The addition of new pilots provided some data on subjects less skilled with the formation-flying task.

The scaling comparisons were made as follows. The test pilot was given one or more minutes of formation flying with a scaled-motion circuit, using 0.5 or 0.7 scaling, as appropriate. Following this, he flew the coordinated circuit configuration for one or more minutes. He was then asked if the coordinated circuit was much harder, harder, the same, easier, or much easier to fly than the scaled circuit. Occasionally the pilot asked for a repeat of the scaled motion before making his decision. The results of these tests are presented in Table 3.3. From this table, it appears that pilots find little difference between coordinated washout and scaling. It should be emphasized that pilots, for the most part, interpreted "harder" and "easier" as being "detectably" harder or easier since they felt all differences to be slight.

Table 3.4 lists the coordinated circuit configurations adopted for these experiments. The natural frequencies correspond to the natural frequency of the second-order poles occurring in the linearized transfer functions as a result of the cross-product feedback dynamics. These dynamics are determined by the parameters K_1 , K_2 , and K_3 . The frequency responses corresponding to three cases ($\omega = .3$, $\omega = .5$, $\omega = .7$) are given in Fig. A.8 of the Appendix for the case of 0.5 scaling.

The rms performance calculations were made by summing the rms y and z tracking errors with .02 times the rms x-position tracking error. The performance results summarized in Fig. 3.4 seem to confirm the comparison test results. In addition, they indicate that little or no difference exists between 0.5 and 0.7 scaling. If anything, 0.5 might give slightly better performance than 0.7. The inexperienced pilots possessed higher rms values than the experienced ones, but they evidenced similar trends.

Pilots flying the approach tasks gave verbal indication that they were not very sensitive to changes in scaling or natural frequency. There was, however, indication that a smaller value of K_3 (perhaps .005 to .01) might be used when

TABLE 3.3

COMPARISON OF COORDINATED AND
SCALED WASHOUT

Pilot(scaling)	Natural Frequency					
	.3	.4	.5	.6	.7	.8
1(.5)	E	E	E	H	H	H
1(.7)	H		H		H	
2(.5)	H		H			
2(.7)	H		H		H	
3(.7)	ME	E	E	E		
4(.7)	E	E	H	E	H	H
4(.7)	H	E	E	H	E	H

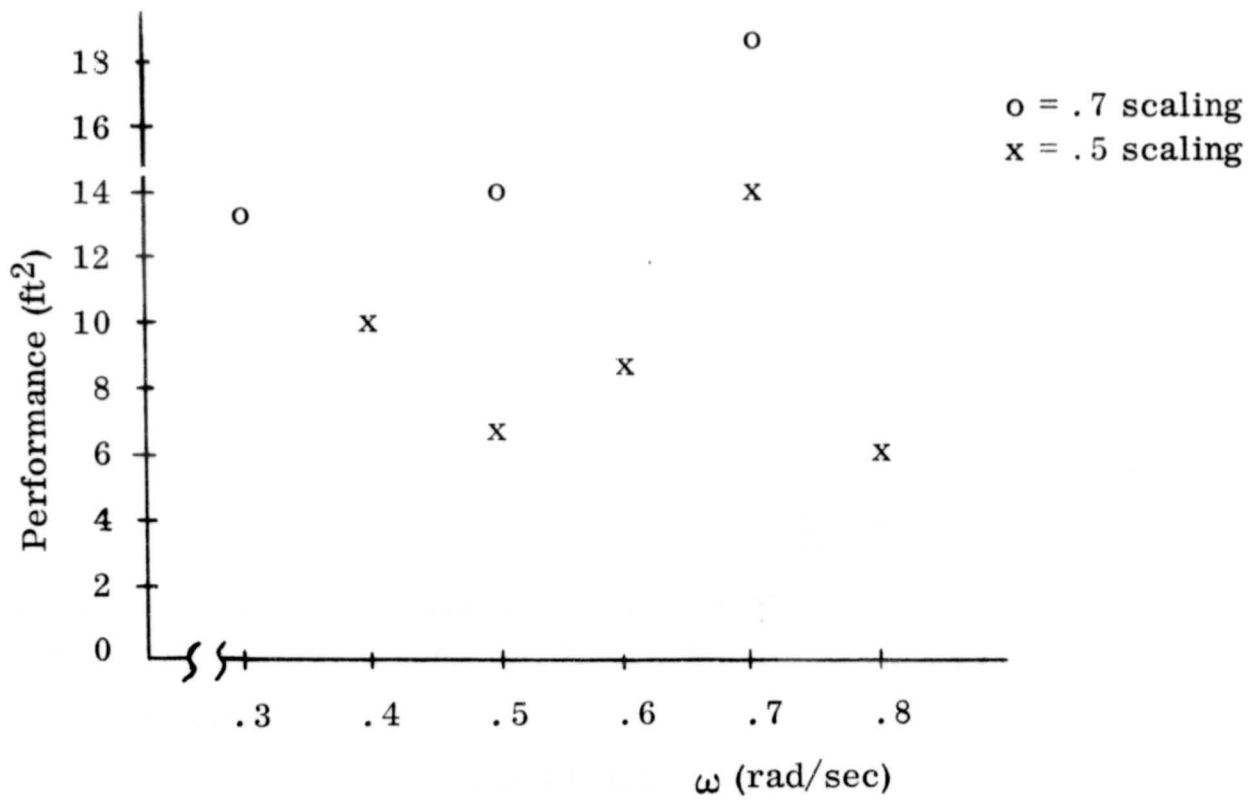
MH = much harder, H = harder*, S = same, E = easier*, ME = much easier

* Generally interpreted by pilots as detectably easier or harder, since they often used the word "slightly" or "maybe" as unsolicited modifiers.

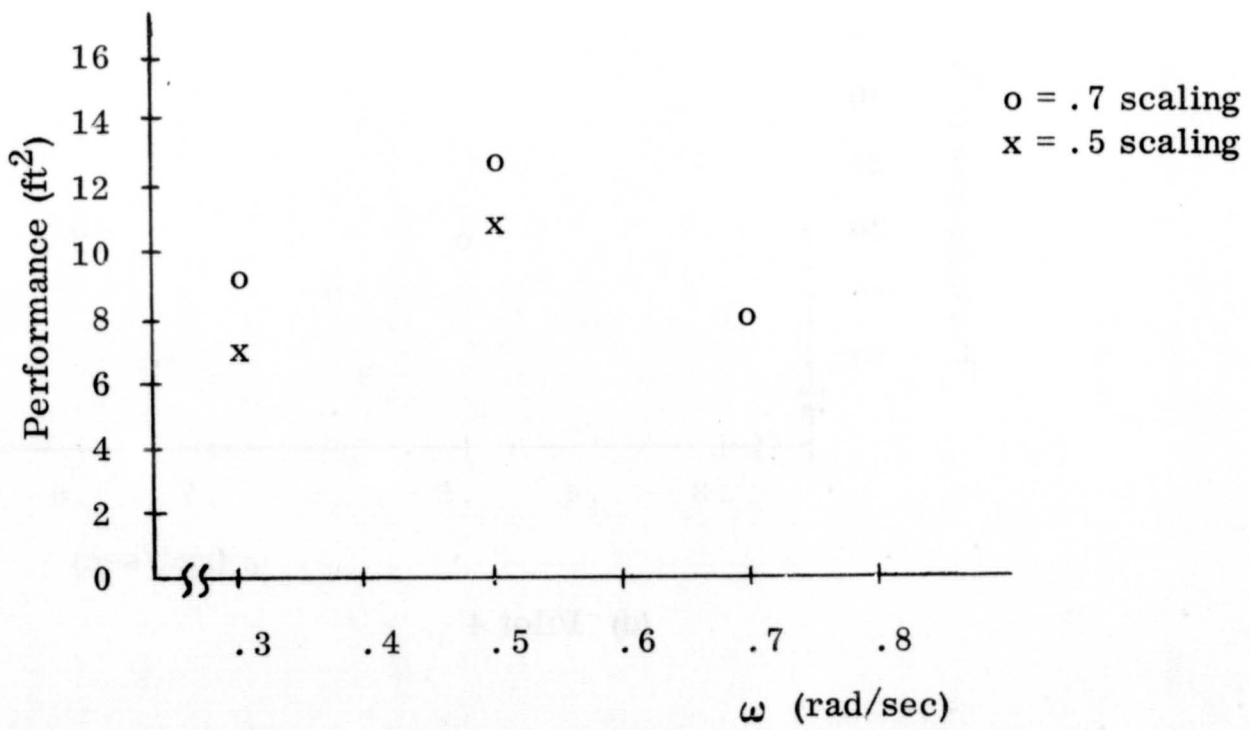
TABLE 3.4
COORDINATED CIRCUIT PARAMETERS USED IN
REFINEMENT TESTS

$$K_3 = .05$$

K_1	K_2	EFFECTIVE NATURAL FREQUENCY
.004	3.8	.3
.006	3.15	.4
.009	2.6	.5
.013	2.05	.6
.017	1.83	.7
.0225	1.6	.8

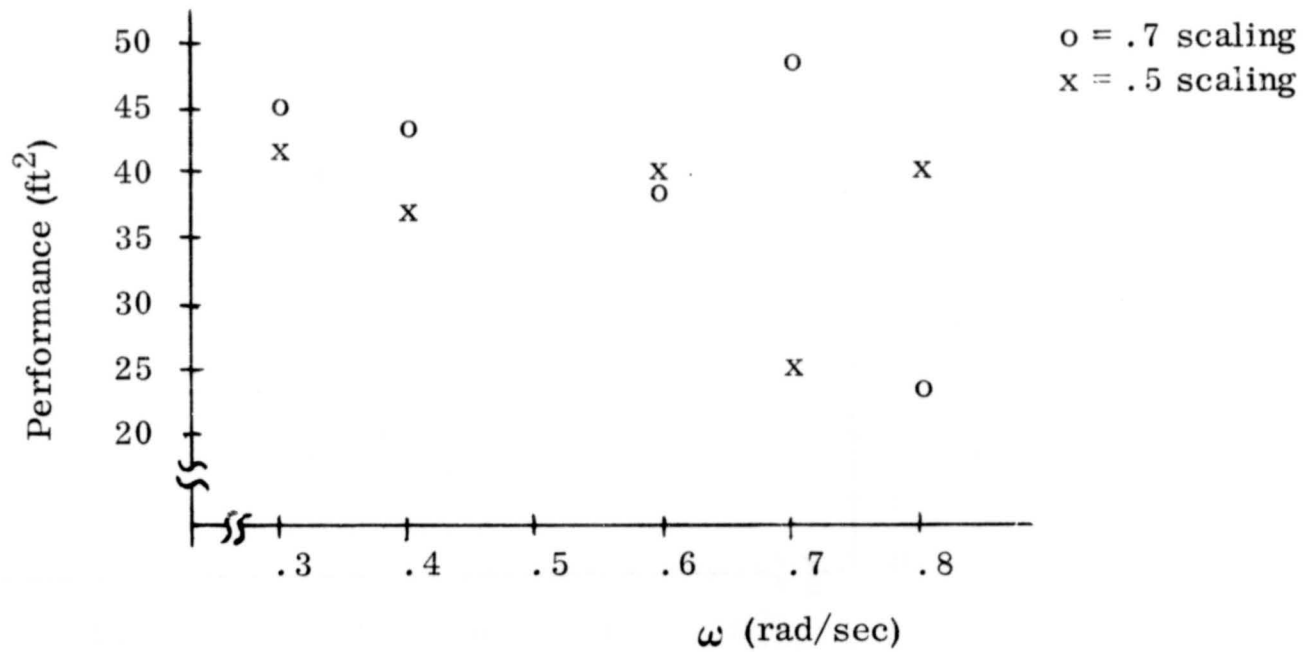


(a) Pilot 1

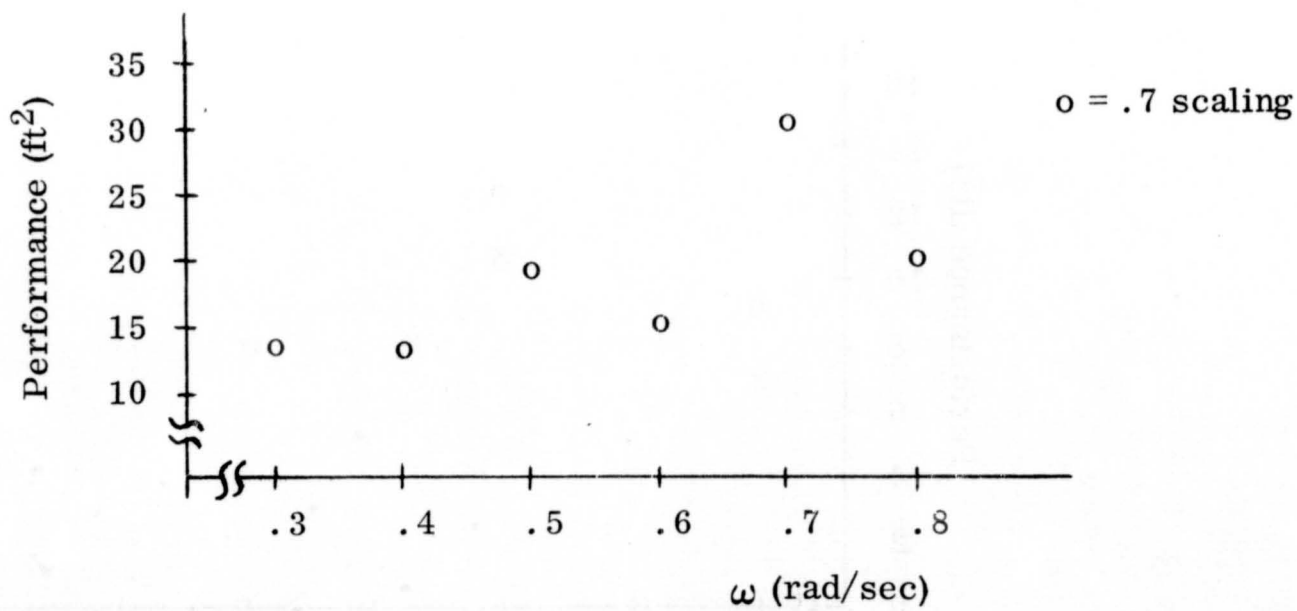


(b) Pilot 2 (based on $\sigma_y^2 + \sigma_z^2$ only)

Figure 3.4 - Pilot Performance for Coordinated Circuit Variations

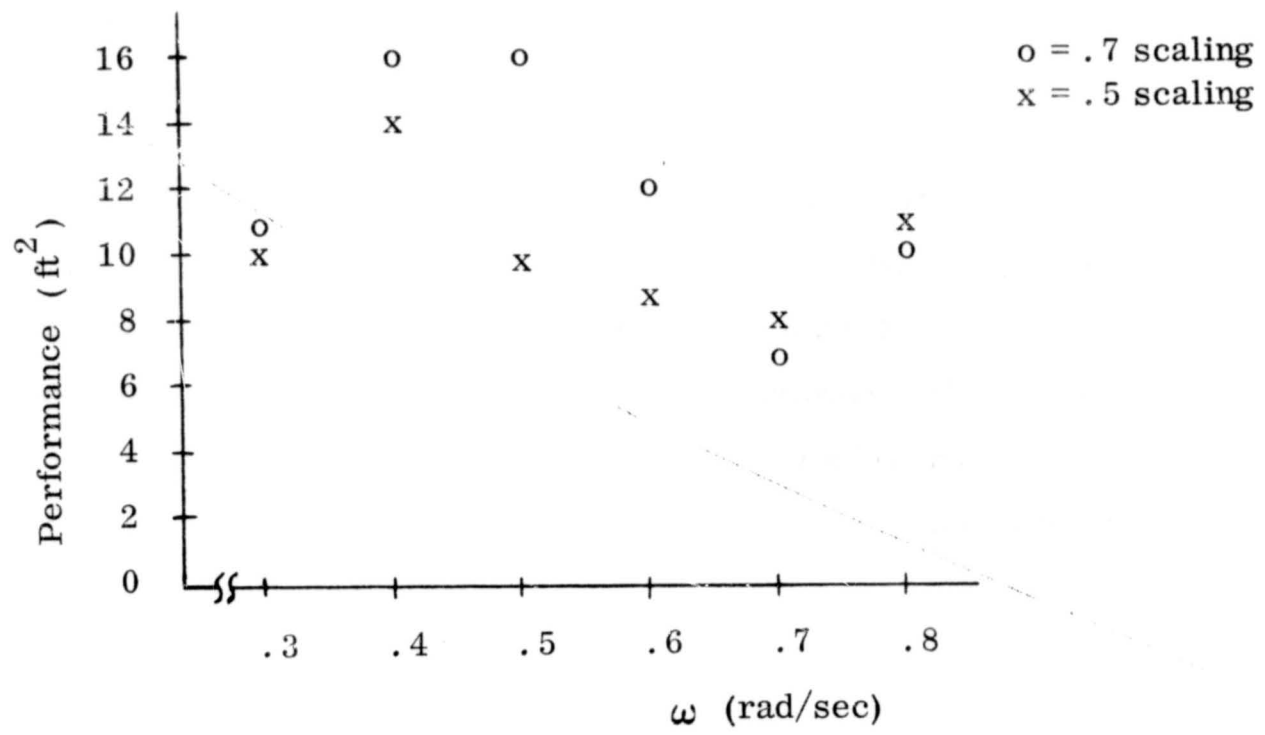


(c) Pilot 3



(d) Pilot 4

Figure 3.4 (continued)



(e) Pilot 5

Figure 3.4 (continued)

s-turn maneuvers are to be flown. This reduces the rate at which the simulator cab returns to zero following a coordinated turn in one direction, so that it will have more travel available for the ensuing turn in the opposite direction.

The large tolerable range of natural frequency in the tilt loop was surprising since classical circuits have typically employed natural frequencies on the order of 0.3 to 0.5 radians per second in their washout logic. Additional simulation experience will be required to determine whether this large range was a function of the simulation tasks involved in these tests or due to the nature of the coordinated washout circuit.

SECTION 4

PILOT MODELING

4.1 Pilot-Modeling Objectives

It was initially proposed that pilot-modeling techniques might be used to measure the effect of washout on pilot performance. Pilot modeling has often been treated as an end in itself (e. g. , Ref. 4). In this case, however, it was to be used to detect changes in a pilot's behavior during complicated simulation tasks: tasks which can involve conflicting pilot inputs due to differences between motion and visual cues. It was hoped that any changes detected could be correlated with pilot questionnaire and rms data to yield an objective source of information on simulation motion requirements. Due to delays encountered with the procedures for recording the data on the EAI system and then converting it to an IBM-compatible format, only a limited amount of modeling could be carried out. At the writing of this report, conversion of data had not been completed for the last series of tests. The data for the third set of tests had been partially processed. The time histories of this report correspond to the third set of tests.

4.2 Preliminary Pilot Modeling

The pilot models used to fit data from the third series of tests consisted of gains and time delays. Gains between lateral errors and aileron control seem to be the easiest to determine. Many other gains were estimated but correlation was not very strong between these parameters and the performance functions used to obtain them. The gains and time constants determined so far show no obvious trends.

Very little data were available from the scaled tests. Hence, only data from washout cases have been processed. It is felt that trends might be recognized if scaled-motion cases could be compared with washed-out motion cases. However, the data processing carried out to date has produced no conclusive method for using pilot modeling to evaluate washout circuits.

SECTION 5

IMPLEMENTATION AND USE OF THE WASHOUT CIRCUITS

5.1 Input and Output Variables

Two subroutines are used to implement each type of washout logic. One subroutine generates translation drive commands while another generates gimbal drive commands. The uncoordinated translation and rotation circuits are contained in WASHTO and WASHRO, respectively. The corresponding coordinated circuit subroutines are called WASHTN and WASHRN. Listings of these subroutines are given in the Appendix. The subroutines communicate with each other by means of labeled common. Inputs and outputs are transmitted through CALL lists which are identical for both pairs of subroutines. Input variables are listed in Table 5.1(a) and outputs are listed in Table 5.1(b).

5.2 Subroutine Calling Sequence

Each subroutine of a washout circuit must be called at least once during initial-condition operation. The rotation routine should be called first and the translation routine second. The calling sequence is not important thereafter.

5.3 Uncoordinated Circuit Parameter Adjustment

The circuit parameters are assigned values in the program by means of DATA statements. The chosen values for these parameters provide a reasonable operating point from which to make adjustments, increasing or decreasing washout to accommodate a given task. A detailed description of the uncoordinated circuit logic, including a block diagram of the continuous circuit, linearized transfer functions, frequency responses, and transient responses, may be found in the Appendix. If major changes are to be made, this description and the corresponding

TABLE 5.1

INPUT AND OUTPUT VARIABLES FOR
COORDINATED AND UNCOORDINATED WASHOUT CIRCUITS

(a) Input Variables

Variable	Description
MODE	Integer variable: negative for initial conditions, 0 for hold, and positive for operate
DT1	Frame time (in seconds) for rotation routine
DT2	Frame time (in seconds) for translation routine
P, Q, R	Aircraft rotation rates (in radians/second) expressed in body-fixed coordinates
FP	Three-dimensional vector of pilot-sensed specific forces at the pilot station (in feet/second ²), expressed in an aircraft-fixed frame which is so oriented that it has only a vertical component in trim

(b) Output Variables

Variable	Description
PHIGC THETGC PSIGC	{ Gimbal drive commands for the All-Axis Simulator (in radians)
XDV YDV ZDV	{ Translation drive commands for the All-Axis Simulator (in feet)

TABLE 5.2

UNCOORDINATED CIRCUIT PARAMETER VARIATIONS FOR
ADJUSTING MOTION WASHOUT LEVELS

Parameter	Function	Effect of an Increase	Suggested Increments
KW	angular-rate cue scaling	increases gimbal motion	0.1
TAUW	time constant of angular-rate high-pass washout	increases gimbal motion	0.5
KR	closed-loop residual tilt channel gain	increases residual tilt rates and washout angular rates faster	0.001
KS1 , KS2	gains on x and y force commands to the residual tilt loop	increases specific-force cues due to residual tilt	0.1
W	natural frequency of high-pass filter on force commands	decreases translational motion	0.1
KA	gain on force cues obtained via translational drives	increases translational motion	0.1

subroutine listing (also to be found in the Appendix) will prove helpful. Table 5.2 lists the parameters which would ordinarily be varied to increase or decrease motion attenuation. Table 5.2 also includes typical increments to use when searching for suitable settings for a particular task. The experimenter should be cautious about making excessively large changes in a single parameter, such as scaling, to achieve desired washout levels. Instead, he should make a series of small changes in each of the parameters affecting the appropriate drive channels, noting the effect of each change on a pilot's opinion of the resulting motion cues. Parameter values can then be chosen to achieve a reasonable compromise between resulting motion cues and available simulator travel.

5.4 Coordinated Circuit Parameter Adjustment

A relatively detailed description of the coordinated circuit is also presented in the Appendix. Table 5.3 contains information for altering the washout characteristics of the coordinated circuit. The form of the dynamic circuit used in the residual tilt loop necessitates the use of figures such as Figs. 5.1 and 5.2 to set the parameters, K_1 and K_2 . In general, the natural frequency, ω , for the residual tilt loop would first be chosen. Then the figures would be used to find appropriate values of K_1 and K_2 to obtain this frequency along with a damping ratio of 0.7.

TABLE 5.3

COORDINATED CIRCUIT PARAMETER VARIATIONS FOR
ADJUSTING MOTION WASHOUT LEVELS

Parameter	Function	Effect of an Increase	Suggested Increments
KW	angular-rate cue scaling	increases gimbal motion	0.1
KF	gains on x and y force commands	increases x and y translational motion	0.1
KA	gain on z force cues	increases z translational motion	0.1
WN	natural frequency of high-pass z force filter	decreases z translational motion	0.1
ω^* (K1, K2)	natural frequency of residual tilt loop	increases gimbal washout and x and y translational motion	0.1

* See Sect. 5.4 and note that K1 and K2 are also referred to as K1SS and K2SS.

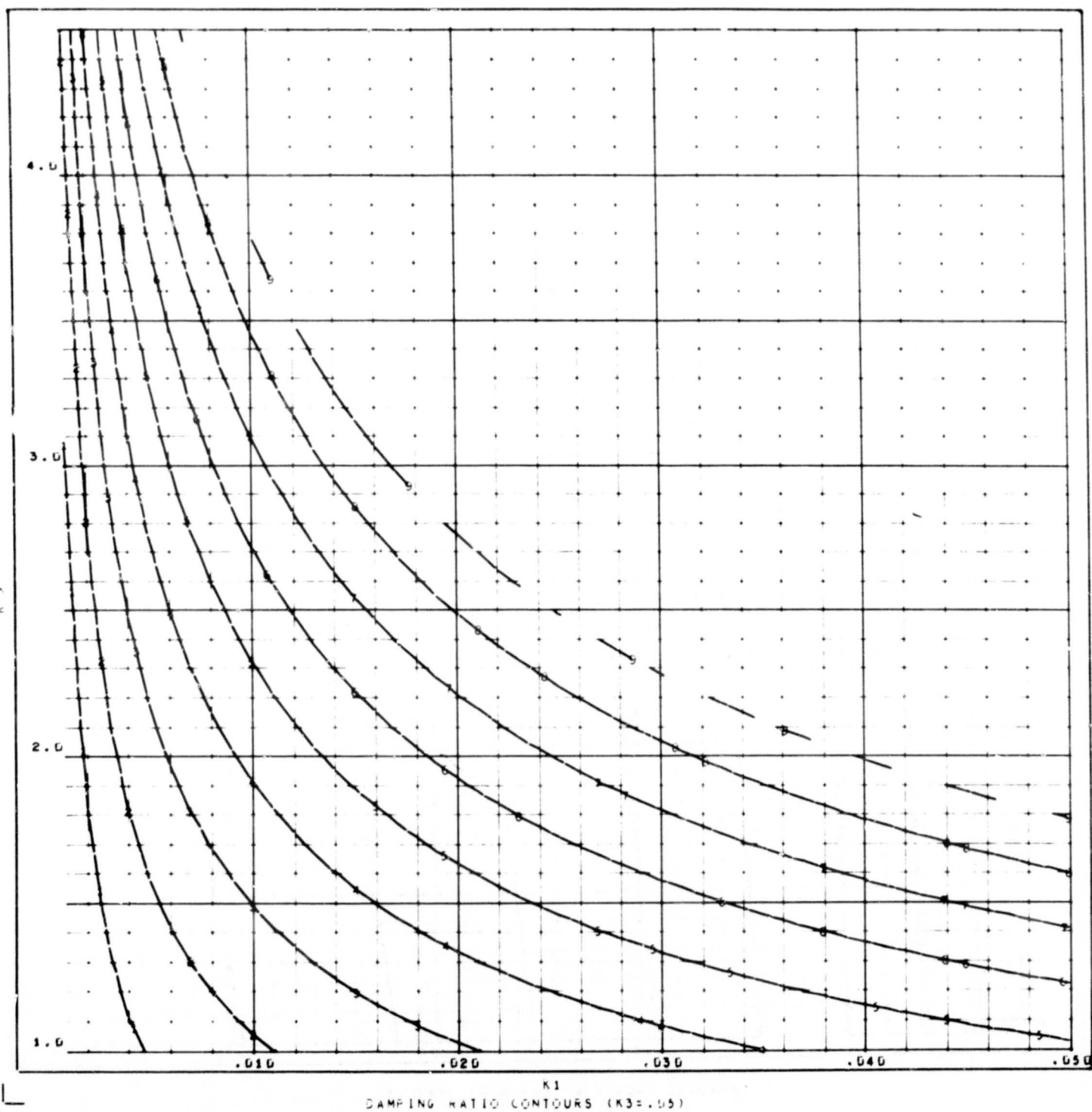


Figure 5.1 - Damping Ratio Contours

Contour No.	Damping Ratio ζ
1	0.13000
2	0.26000
3	0.39000
4	0.52000
5	0.65000
6	0.78000
7	0.91000
8	1.04000
9	1.17000
A	1.30000

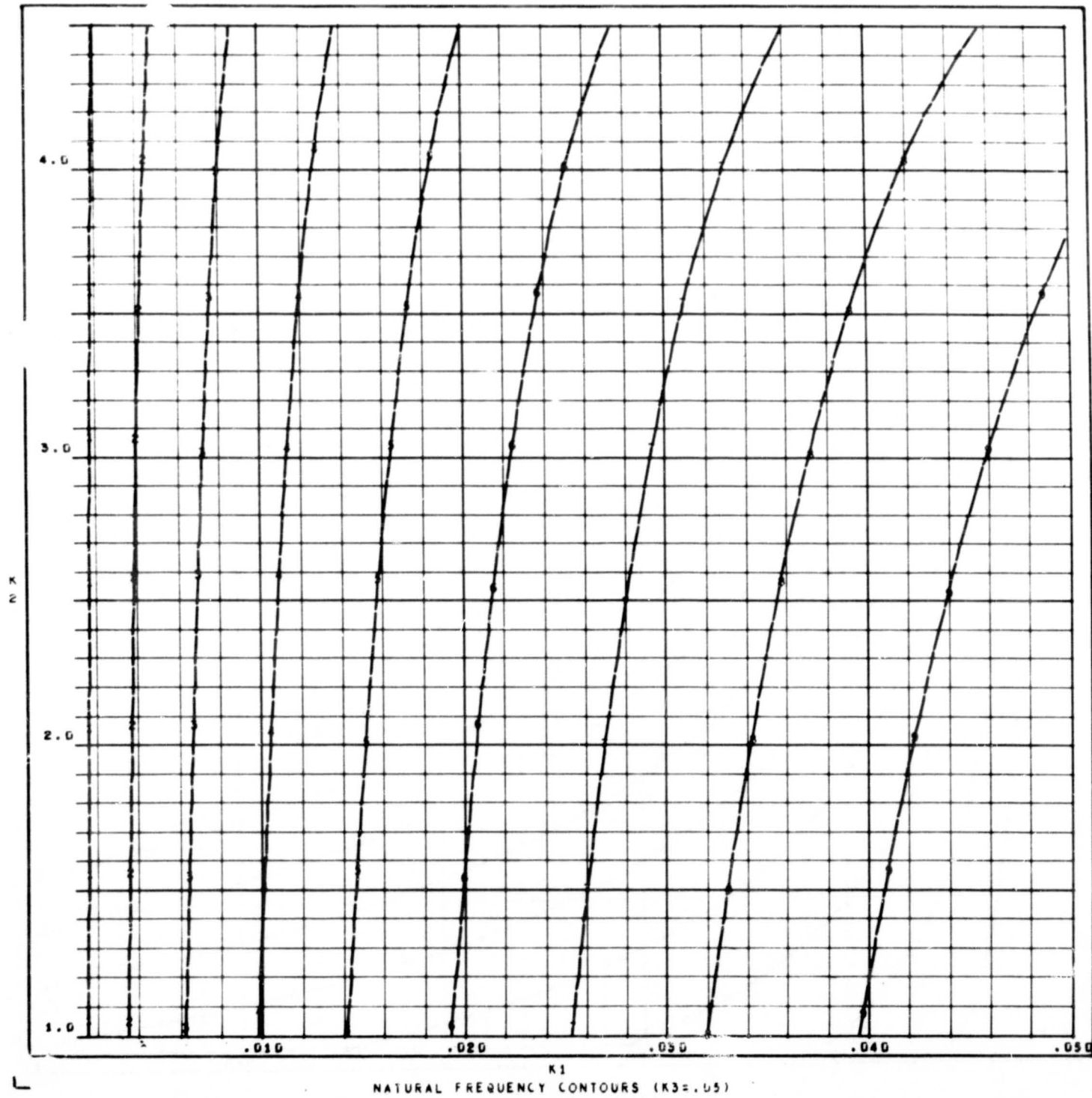


Figure 5.2 - Natural Frequency Contours

Contour No.	Natural Frequency ω
1	0.22000
2	0.33000
3	0.44000
4	0.55000
5	0.66000
6	0.77000
7	0.88000
8	0.99000
9	1.10000
A	1.21000

SECTION 6

QUESTIONNAIRE FOR SIMULATED FLIGHT FACILITIES

This section presents a questionnaire for use in documenting information about the motion and washout circuits used for various flight simulations. It is intended that this questionnaire be kept as a log and completed for each project tested on the motion facilities at NASA Ames. This should include

- the FSAA motion generator
- the All-Axis motion generator
- the Ames S-16 motion generator

The purposes of keeping such a log are twofold. First, the log can be analyzed to gain information on requirements and directions for potential improvements in washout circuit and/or motion-drive system design. Second, the log could be analyzed to determine certain type patterns or consistencies. The patterns may suggest additional tests for gaining information on how pilots use motion in realistic situations. This latter usage could eventually lead to a basis for

- compensating experimental data for the effects of washout circuitry,
- selecting the simulation facility required for a given experiment,
- setting up specifications for new simulation facilities.

The proposed questionnaire is shown in Figure 6.1. It consists of a number of items or questions which require a brief statement for completion. Figure 6.2 shows an example of how the log would have been filled out for one of the tests conducted during the washout study reported here.

FIGURE 6.1

QUESTIONNAIRE FOR USERS OF MOTION GENERATORS

Project: _____
 Project Engineer: _____
 Project Pilot: _____
 Date: _____
 Facility: (e.g., All-Axis, FSAA) _____

1. Type aircraft simulated:
(e.g., VTOL, transport, helicopter) _____
2. Type tasks performed:
(e.g., landing-approach, take-off, hovering, tracking) _____
3. Was the pilot A/C combination ever unstable (uncontrollable) during this investigation? _____
4. What was COOPER rating of A/C handling characteristics? _____
5. Were abrupt motions (pilot-induced or otherwise) used in the study effort? _____

6. Give ranges for the forces and the rates on the cockpit of the simulated aircraft: (force in ft/sec ² , rate in rad/sec)	<u>Force</u>	<u>min</u>	<u>max</u>	<u>Rate</u>	<u>min</u>	<u>max</u>
	side	_____	_____	roll	_____	_____
	long.	_____	_____	pitch	_____	_____
	vert.	_____	_____	yaw	_____	_____

7. Washout circuit used?
Please attach a block diagram or give equations and parameter values if a non-standard design was used. _____
8. Any problems with the washout circuit?
Please explain: _____

Figure 6.1 (cont)

9. Pilot (or pilots) comments on motion fidelity:
(e.g., excellent, good, fair, poor, unacceptable) _____
10. Pilot (or pilots) comments on audible motion drive
noise: (e.g., not noticed, noticed but not dis-
tracting, distracting, very distracting) _____
11. Pilot (or pilots) comments on motion drive
vibrations: (e.g., not noticed, noticed but
not distracting, distracting, very distracting) _____
12. Pilot (or pilots) comments on difficulty of task:
 a) with motion _____
 b) without motion _____
13. Did any of the pilots have a tendency towards
disorientation? _____
- Please explain: _____

FIGURE 6.2

SAMPLE QUESTIONNAIRE

Project: DC 8/2
 Project Engineer: BJORN CONRAD
 Project Pilot: BILL BJORKMAN
 Date: 7/1/71
 Facility: (e.g., All-Axis, FSAA) ALL-AXIS

1. Type aircraft simulated:
(e.g., VTOL, transport, helicopter) TRANSPORT - SCALE DC-3
2. Type tasks performed:
(e.g., landing-approach, take-off, hovering, tracking) FORMATION FLYING AND APPROACHES W/O TOUCHDOWN
3. Was the pilot A/C combination ever unstable (uncontrollable) during this investigation? A/C HAD POOR LATERAL STAB. UNSTABLE FIXED-BASE
4. What was COOPER rating of A/C handling characteristics? NOT USED
5. Were abrupt motions (pilot-induced or otherwise) used in the study effort? NO
6. Give ranges for the forces and the rates on the cockpit of the simulated aircraft: (force in ft/sec², rate in rad/sec)

	<u>Force</u>	<u>min</u>	<u>max</u>	<u>Rate</u>	<u>min</u>	<u>max</u>
side		<u>-3/4</u>	<u>+3/4</u>	roll	<u>-.2</u>	<u>+.2</u>
long.		<u>-2</u>	<u>+2</u>	pitch	<u>-.1</u>	<u>+.1</u>
vert.		<u>-4</u>	<u>+4</u>	yaw	<u>-.3</u>	<u>+.3</u>
7. Washout circuit used?
Please attach a block diagram or give equations and parameter values if a non-standard design was used. "COORDINATED" NOMINAL (SEE FIG. 3.5)
8. Any problems with the washout circuit?
Please explain: HIT SIMULATOR SHUTDOWN STOPS SEVERAL TIMES DUE TO EXCESSIVE ACCELERATIONS IN VERTICAL DIRECTION.

Figure 6.2 (cont)

9. Pilot (or pilots) comments on motion fidelity:
(e.g., excellent, good, fair, poor, unacceptable) GOOD
10. Pilot (or pilots) comments on audible motion drive
noise: (e.g., not noticed, noticed but not dis-
tracting, distracting, very distracting) DISTRACTING
TRANSLATION DRIVE NOISES
11. Pilot (or pilots) comments on motion drive
vibrations: (e.g., not noticed, noticed but
not distracting, distracting, very distracting) NOTICED SOME UNCOMFORTABLE
LATERAL OSCILLATIONS
12. Pilot (or pilots) comments on difficulty of task:
- a) with motion DIFFICULT, BUT NO CONTROL PROBLEM
 - b) without motion ALMOST IMPOSSIBLE
13. Did any of the pilots have a tendency towards
disorientation? NO

Please explain: _____

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

This study had as its principal goal the mechanization and testing of several washout circuits presented in Reference 1. This goal was accomplished. Furthermore, in the course of this work certain general concepts were also tested, such as the feasibility of motion cue scaling in preferred coordinates, and the usefulness of formation flying as an experimental tool for motion testing. Some of the results of this effort should be of immediate value to users of the Ames piloted-flight simulation facilities. These include

- a demonstration of the effectiveness of angular-rate and force scaling as a motion attenuation device in realistic simulations (levels of 0.5 appeared to be very effective),
- the mechanization and validation of two washout circuits for the Ames All-Axis Motion Generator,
- the determination of circuit parameters that can serve as initial trial values for a wide variety of tasks.

Other results should contribute to the general body of knowledge concerning the relationship between motion cues and pilot performance in simulation tasks.

Based on experience gained during this effort, it is recommended that additional work be performed on:

- the fabrication of a single multi-purpose washout circuit capable of operating in a coordinated, uncoordinated, or hybrid mode,
- the adaptation of this single circuit to both the All-Axis and the FSAA Motion Generators,
- the performance of short on-going motion tests in conjunction with the set-up of operational simulation programs on the Ames moving-base simulators.

The fabrication and validation of the single-purpose program could be accomplished using an IBM 360/67 simulation developed for these tests. Such a circuit would include the capability of using different washout parameters in all channels. Only slight modification would be necessary to make an Ames All-Axis version of the circuit compatible with the FSAA version of the circuit.

On-going low-level motion tests would utilize only a few hours of simulation time for each new operational program on the FSAA and the All-Axis Motion Generators. Using a circuit such as the one mentioned above, simple experiments would be conducted to find the circuit parameters most suitable for realistic tasks, and the results documented in the questionnaire of Section 6. It is expected that this procedure will lead to both improved washout logic and a better understanding of the effect of anomalous motion on simulation tasks.

APPENDIX

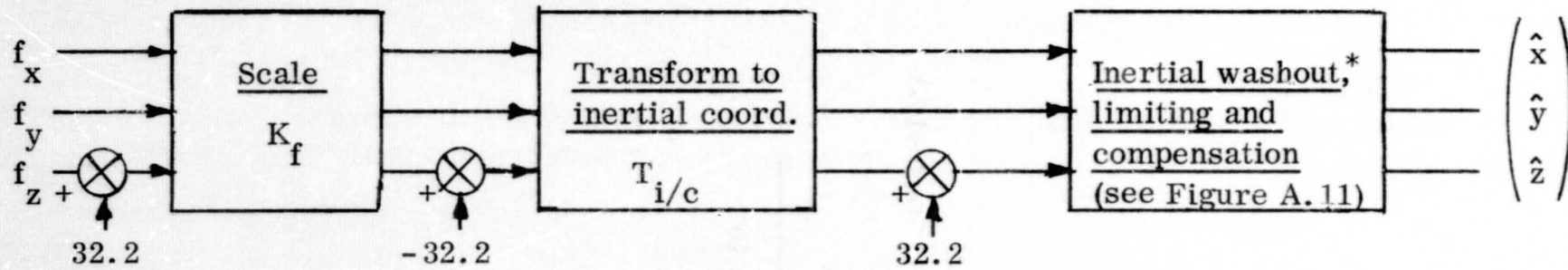
WASHOUT CIRCUIT DESCRIPTIONS

A.1 Scaling Circuit

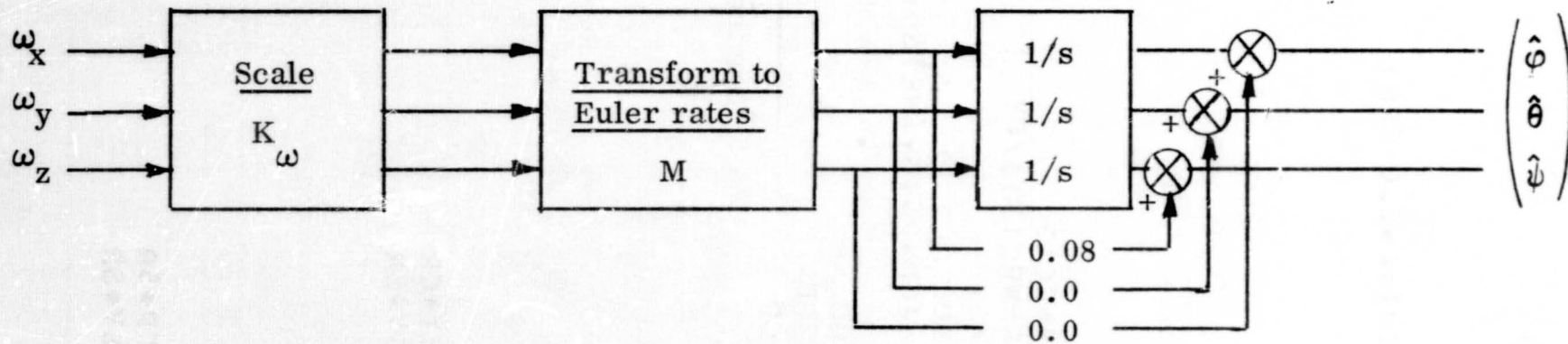
Figure A.1 presents the circuit used for the scaling experiments. The inputs to this circuit are the three components of angular rate and the three components of specific force, all of which are coordinated in an aircraft body-fixed frame of reference centered at the cockpit. These quantities are scaled (except for z-direction force, where the difference from 1g is scaled rather than the whole force) and the result transformed and integrated to give the cab drive signals. Some dynamic washout is used in the translation channels to remove limiting caused by certain effects such as long-term integration drifts. This washout, as well as limiting logic used to keep the simulator off shut-down stops, is discussed in Section A.4. A listing* of the digital mechanization of the program used on the Ames EAI computer is presented in Figure A.2.

The scaling circuit is useful only when used in conjunction with a task such as formation flying, where it can be used to alter various motion cues with a minimum of dynamic washout (such as high-pass filtering). In fact, certain scaling combinations can actually produce more motion than no scaling at all. For example, if forces are scaled to zero and angular rates scaled to unity, large simulator translation excursions can be required to prevent a side force cue from being sensed, if that cue is caused by a sudden roll rate.

* The subroutines GRATON and MGRATE used in the washout circuits are part of the Ames simulation computer library. MGRATE initializes GRATON. GRATON is a general purpose numerical integration routine which is used in a simple rectangular integration mode in the washout routines.



* Double integration is incorporated in the inertial washout



Key

$$\begin{pmatrix} f_x \\ f_y \\ f_z \end{pmatrix} = F_p = \text{Force on pilot in A/C coordinates}$$

$$\begin{pmatrix} \hat{x} \\ \hat{y} \\ \hat{z} \end{pmatrix} = \text{Cab translational drive commands}$$

$$\begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix} = \omega_p = \text{Angular rate on pilot in A/C coordinates}$$

$$\begin{pmatrix} \hat{\phi} \\ \hat{\theta} \\ \hat{\psi} \end{pmatrix} = \text{Cab gimbal drive commands}$$

Figure A.1 - Block Diagram of Washout Circuit for Scaling

```

SUBROUTINE WASHRS (MODE,P,Q,R,PHIGC,THETGC,PSIGC,DT1 )
COMMON/WASHS/TG(3,3)
COMMON/DATL/DAT(200)
DIMENSION WPQR(3),WRC(3),L1WINT(50)
REAL KW
EQUIVALENCE (KW,DAT(101))
DATA CG1,CG2,CG3/.08,0.,0./
RTD=57.3
IF (MODE) 100,6300,220
100 PHIG=0.0
    PSIG =0.
    THETG=0.
    + CALL MGRATE(3,DT1,L1WINT,4,0.0,ERR)
C
220 CONTINUE
    WPQR(1) = P
    WPQR(2) = Q
    WPQR(3) = R
C
    DO 250 IFR=1,3
250 WRC(IFR)=KW*WPQR(IFR)
280 CONTINUE
    PSIGD = CR*WRC(3) +SR*WRC(2)
    THETGD= (CP*WRC(2) -SR*WRC(3))/CY
    PHIGD = WRC(1) -THEGD*SY
    + IF (MODE.NE.1) GO TO 300
    + CALL GRATON (L1WINT,PSIGD,PSIG,THETGD,THETG,PHIGD,PHIG)
300 CONTINUE
    PHIGC = PHIG +CG1*PHIGD
    THETGC= THETG+CG2*THETGD
    PSIGC = PSIG +CG3*PSIGD
C
CR = COS(PHIG)
SR = SIN(PHIG)
CP = COS(THETG)
SP = SIN(THETG)
CY = COS(PSIG)
SY = SIN(PSIG)
C
    DIRECTION COSINES
    TG(1,1) = CP*CY
    TG(1,2) = SP*SR -CP*SY*CR
    TG(1,3) = SP*CR +CP*SY*SR
C
    TG(2,1) = SY
    TG(2,2) = CY*CR
    TG(2,3) = -CY*SR
C
    TG(3,1) = -SP*CY
    TG(3,2) = SP*SY*CR +CP*SR
    TG(3,3) = CP*CR -SP*SY*SR
6300 CONTINUE
RETURN
END

```

⁺ See footnote page 45

(a) Subroutine WASHRS

Figure A.2 -Scaling Circuit Subroutine Listings

```

SUBROUTINE WASHTS (MODE,FP,XDV,YDV,ZDV,DT2)
COMMON/WASHS/TG(3,3)
COMMON/DATL/DAT(200)
EQUIVALENCE (KS1,DAT(104)),(KS2,DAT(105)),(KS3,DAT(106))
DIMENSION TMO(3),TMOD(3),FP(3),L2WINT(50),FSTAR(3),TAB(3),TRLIM(3)
1      ,ACCLIM(3),TMO(3),AB(3),TMO(3)
REAL KS1,KS2,KS3
DATA KS1,KS2,KS3/.5,.5,.5/
DATA TRLIM/8.,8.,8./,ACCLIM/7.,7.,6./
DATA AW1,AW2,AW3,BW1,BW2,BW3/.16,.14,.23,.0375,.0376,0./
DATA CTDD,AL,BL/5.,.14,.01/

IF (MODE) 100,6300,220
100 CONTINUE
DO 105 J=1,3
TMO(J) = 0.
105 TMO(J) = 0.
†CALL MGRATE (6,DT2,L2WINT,J,0,0,ERR)
220 CONTINUE
FSTAR(1)=KS1*FP(1)
FSTAR(2)=KS2*FP(2)
FSTAR(3)=-32.2+KS3*(FP(3)+32.2)
DO 6220 KK1=1,3
ABD=0.
DO 6219 KK2=1,3
6219 ABD=ABD+TG(KK1,KK2)*FSTAR(KK2)
6220 TAB(KK1)=ABD
C
C      PUT IN ONE G IF CAR REFERENCE WASHOUT ON FORCES
TAB(3)=TAB(3)+32.2
C      LIMITING SCHEME
DO 280 IL=1,3
256 TAB(IL) = TAB(IL) -AL*TMOD(IL) -BL*TMO(IL)
TMODD(IL) = TAB(IL)
IF(ABS(TAB(IL)).GT.ACCLIM(IL)) TMODD(IL)=SIGN(ACCLIM(IL),TAB(IL))
258 ABD = ABS(TMO(IL)) -TRLIM(IL)
IF(ABD) 263,259,259
259 TMODL = 0.
GO TO 276
263 IF(TM(OD(IL))) 264,280,272
264 TMODL = -SQRT(14.*(TMO(IL) +TRLIM(IL)))
IF(TM(OD(IL))-TMODL) 276,280,280
270 TMODD(IL) =TMODD(IL) -CTDD*(TM(OD(IL))-TMODL)
GO TO 280
272 TMODL = SQRT(14.*(TRLIM(IL) -TMO(IL)))
IF(TM(OD(IL) -TMODL) 280,280,276
276 TMODD(IL) = TMODD(IL)-CTDD*(TM(OD(IL))-TMODL)

```

†See footnote page 45

(b) Subroutine WASHTS

Figure A.2 (continued)


```

        IF (ABS(TMODD(IL)) .GT. ACCLIM(IL)) TMODD(IL) = SIGN(ACCLIM(IL),
1 TMODD(IL))
280 CONTINUE
C      INTEGRATION OF MOTION (TRANSLATIONAL) SIGNALS
      IF (MODE.NE.1) GO TO 300
      †CALL GRATON (L2WINT,TMOD(1),TMO(1),TMOD(2),TMO(2),TMOD(3),TMO(3),
1 TMODD(1),TMOD(1),TMODD(2),TMOD(2),TMODD(3),TMOD(3))
300 CONTINUE
      XDV = TMO(1) +AW1*TMOD(1) +BW1*TMODD(1)
      YDV = TMO(2) +AW2*TMOD(2) +BW2*TMODD(2)
      ZDV = TMO(3) +AW3*TMOD(3) +BW3*TMODD(3)
      TMODD(3) = TMODD(3) -32.2
C      PILOT ACCELERATIONS FROM LIMITING CCT W/O COMPENSATION (BODY AXES)
      DO 308 IDD=1,3
      TMODUM = 0.
      DO 306 KDD=1,3
306 TMODUM = TMODUM +TG(KDD,IDD)*TMODD(KDD)
308 TMODDB(IDD) = TMODUM*FPSTG
C      COMPENSATION
325 CONTINUE
6300 CONTINUE
      RETURN
      END

```

† See footnote page 45

Figure A.2 (b) (continued)

A.2 Uncoordinated Circuit*

This circuit is depicted in Figure A.3. A version of this logic was actually used in an Ames simulation program, where it appeared to give acceptable performance. This circuit takes as its input three channels representing the components of specific force and three channels representing angular rate (sensed at the pilot station and coordinatized in a standard aircraft-fixed frame). Principal features of this are:

- Most motion attenuation is accomplished by operating on quantities coordinatized in an aircraft-fixed frame to prevent motion cue coupling.
- Angular-rate and force inputs can be arbitrarily scaled.
- Second-order high-pass filters are used to determine the portion of the input force cues provided by the translation drives.
- Low-frequency side forces are produced via residual tilting of the simulator cab accomplished by a nonlinear feedback control law that nulls the cross-product of gravity and a desired force vector (see Ref. 1).
- Angular washout is achieved by the nonlinear residual tilt control law mentioned above as well as by a first-order high-pass filter on input rates.
- A small amount of high-pass filtering is performed on the translation signals (this is referred to as inertial washout) prior to limiting and compensation.

This circuit is basically nonlinear. However, when it is linearized for the purpose of analysis, it looks much like a combination of the circuits used classically for two-dimensional washout. Table A.1 presents the transfer functions associated with the linearized circuit. The x - z plane transfer functions associated with θ and the x motion are not shown since they are similar to those associated with the lateral plane represented by ϕ and y .

* This circuit was referred to as the "classical" circuit in Reference 1.

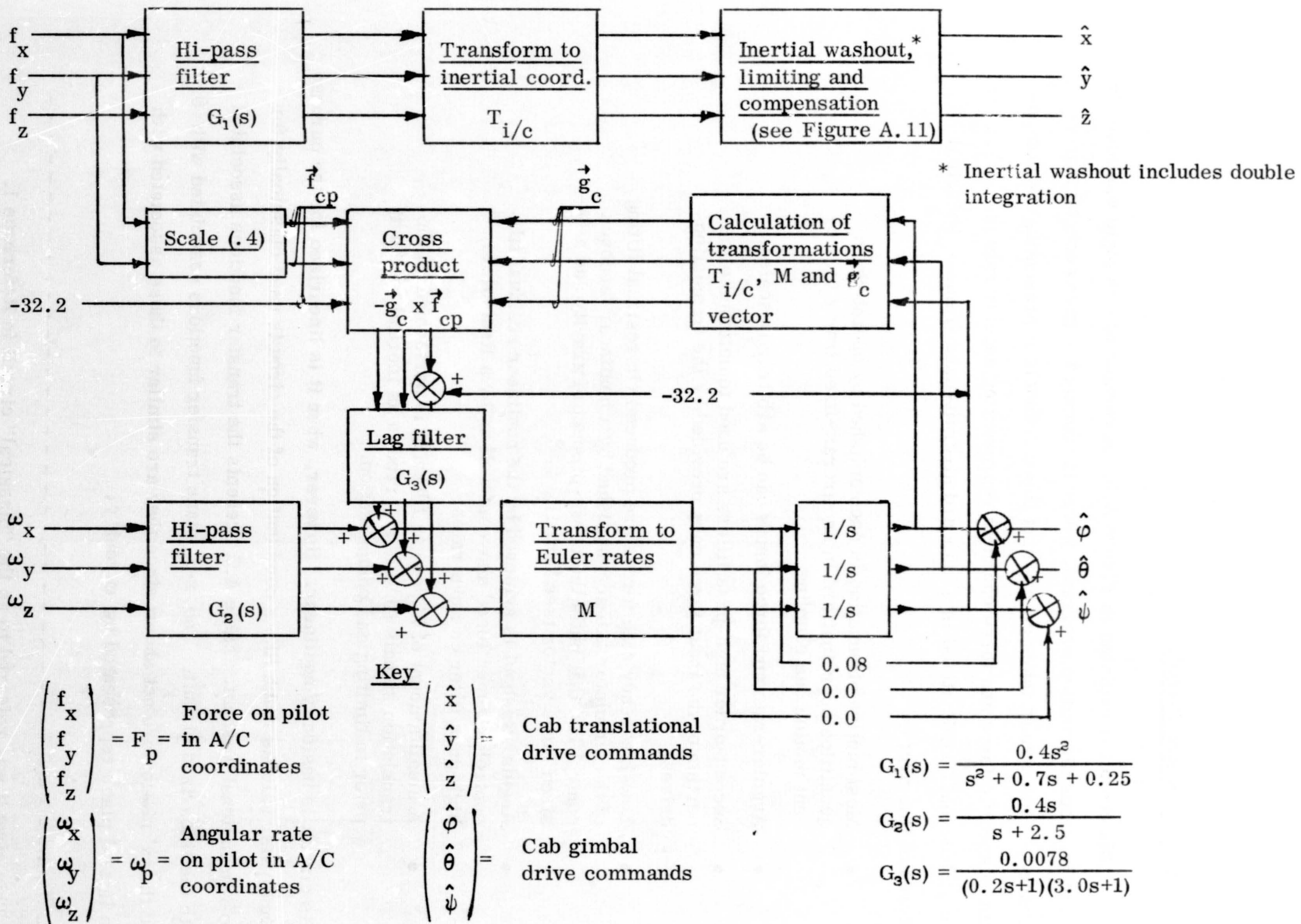


Figure A. 3 - Block Diagram of Uncoordinated ("Classical") Washout Circuit

TABLE A. 1

TRANSFER FUNCTIONS FOR THE LINEARIZED UNCOORDINATED CIRCUIT

INPUT	OUTPUT			
	Position, \hat{y}	Angle, $\hat{\phi}$	Specific Force, \hat{f}_y	Angular rate, $\dot{\hat{\phi}}$
Specific Force f_y	$\frac{0.5s^2}{D_0(s)D_1(s)}$	$\frac{0.5(.0078)}{D(s)}$	$\frac{N(s)}{D_0(s)D_1(s)D(s)}$	$\frac{0.5s(.0078)}{D(s)}$
Angular Rate ω_x	---	$\frac{0.5s(0.2s+1)(3s+1)}{(s+1/2.5)D(s)}$	$\frac{16.1s(.2s+1)(3s+1)}{(s+1/2.5)D(s)}$	$\frac{0.5s^2(0.2s+1)(3s+1)}{(s+1/2.5)D(s)}$
	Position, \hat{z}	Angle, $\hat{\psi}$	Specific Force, \hat{f}_z	Angular rate, $\dot{\hat{\psi}}$
Specific Force f_z	$\frac{0.5s^2}{D_0(s)D_1(s)}$	---	$\frac{0.5s^4}{D_0(s)D_1(s)}$	---
Angular Rate ω_z	---	$\frac{0.5s(0.2s+1)(3s+1)}{(s+1/2.5)D(s)}$	---	$\frac{0.5s^2(0.2s+1)(3s+1)}{(s+1/2.5)D(s)}$

Key

$$D(s) = 0.6s^3 + 3.2s^2 + s + 32.2(.0078)$$

$$D_0(s) = s^2 + 0.7s + 0.25$$

$$D_1(s) = s^2 + 0.14s + 0.01$$

$$N(s) = 0.5 [D(s)s^4 + 0.251D_1(s)D_0(s)]$$

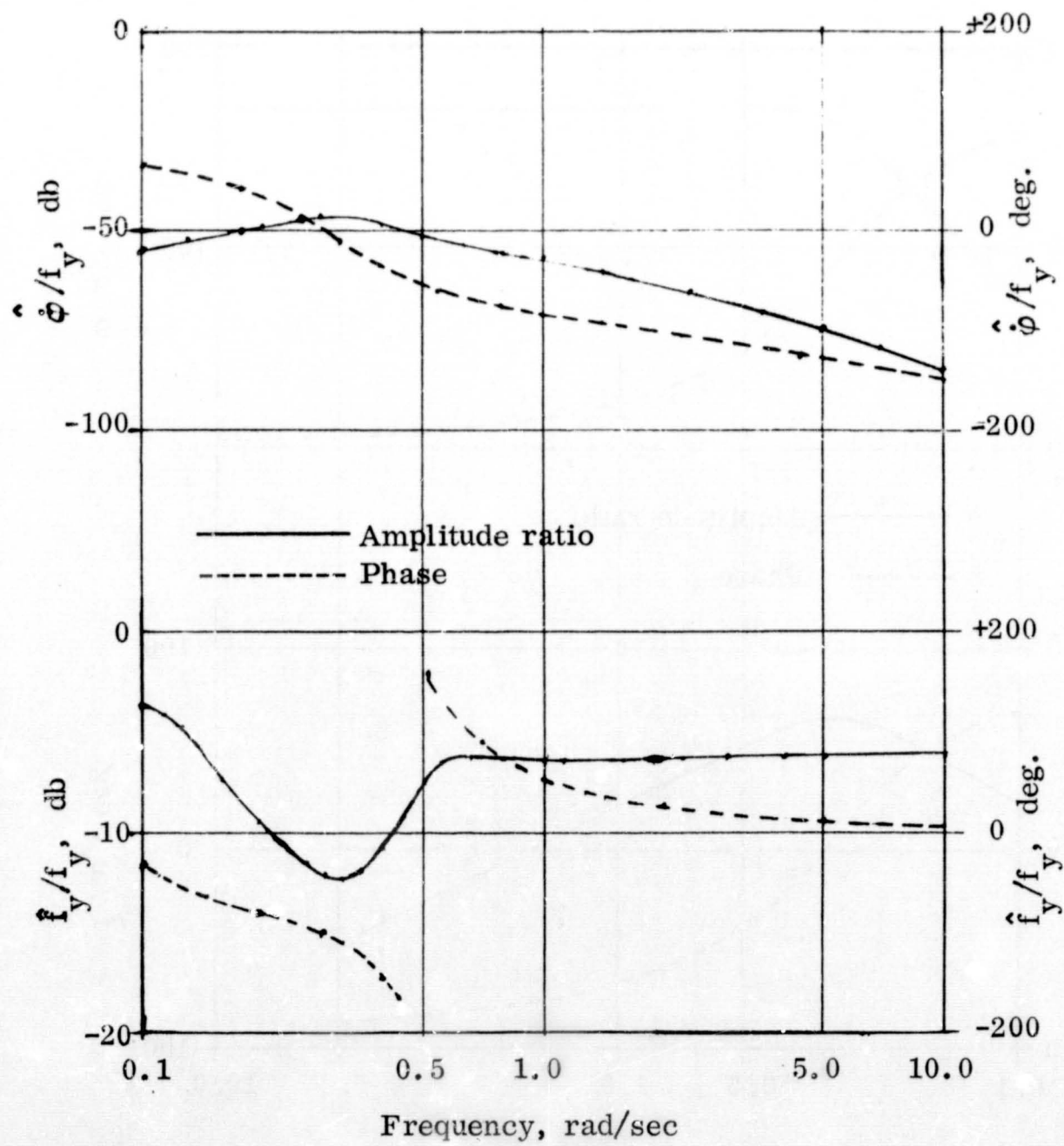
The transfer functions have a higher order and a different form than is generally encountered with classical circuits. Frequency responses associated with several of the transfer functions are presented in Figure A. 4. The frequency response plots associated with coupling between the force and angular rate are dimensional, with force considered in feet per second per second and angular rate in radians per second. The ideal simulator would have no cross-coupling and a flat response for force-to-force and rate-to-rate transfers.

Figure A. 5 presents the transient response characteristics of translation position, \hat{y} (in feet), rotation angle, $\hat{\phi}$ (in degrees), rotation rate, $\dot{\hat{\phi}}$ (in degrees per second), and y-force, \hat{f}_y (in feet per second per second), to two different inputs: a one ft/sec² force step in f_y occurring at five seconds and a 2.5 deg/sec pulse of one-second's duration occurring at five seconds. These plots were made with a simulation program rather than with the operational subroutine listed in Figure A. 6.

A. 3 Coordinated Circuit

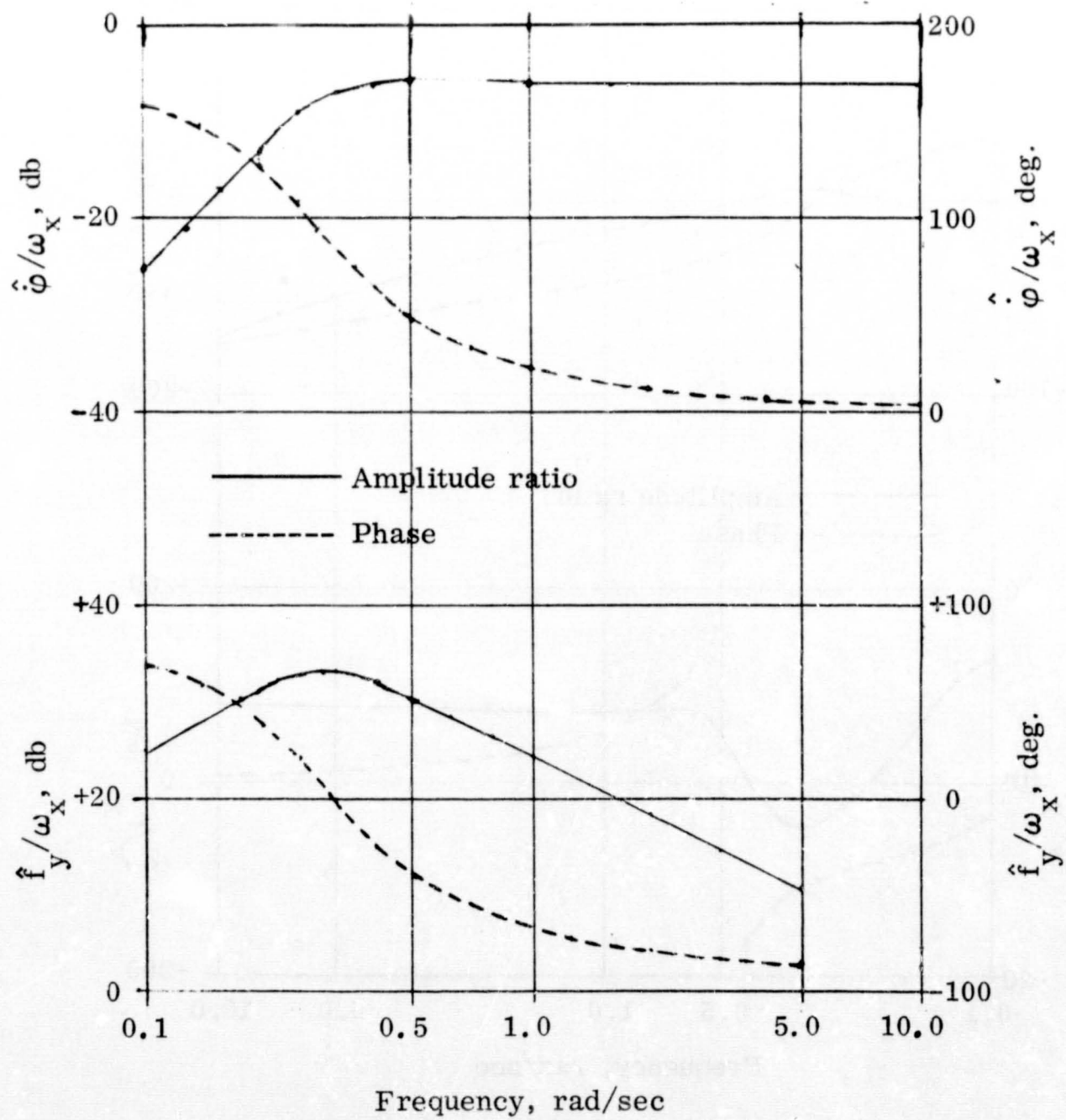
Figure A. 7 presents the coordinated circuit. This circuit takes the same inputs and provides the same outputs as the uncoordinated circuit. The principal differences between this and the uncoordinated circuit are:

- Side and longitudinal (x and y) force commands are smoothed with a second-order low-pass filter having a five radian/second natural frequency, to reduce undesirable rate responses which result from rapid force variations.
- The filtered x and y force commands are fed directly to a residual tilt loop based on a nonlinear feedback control law which attempts to null the cross-product.
- Side forces which are not immediately generated by the residual tilt loop are obtained by an appropriate error signal which drives the translation channels. This produces coordination between tilt-produced and translation-produced forces.



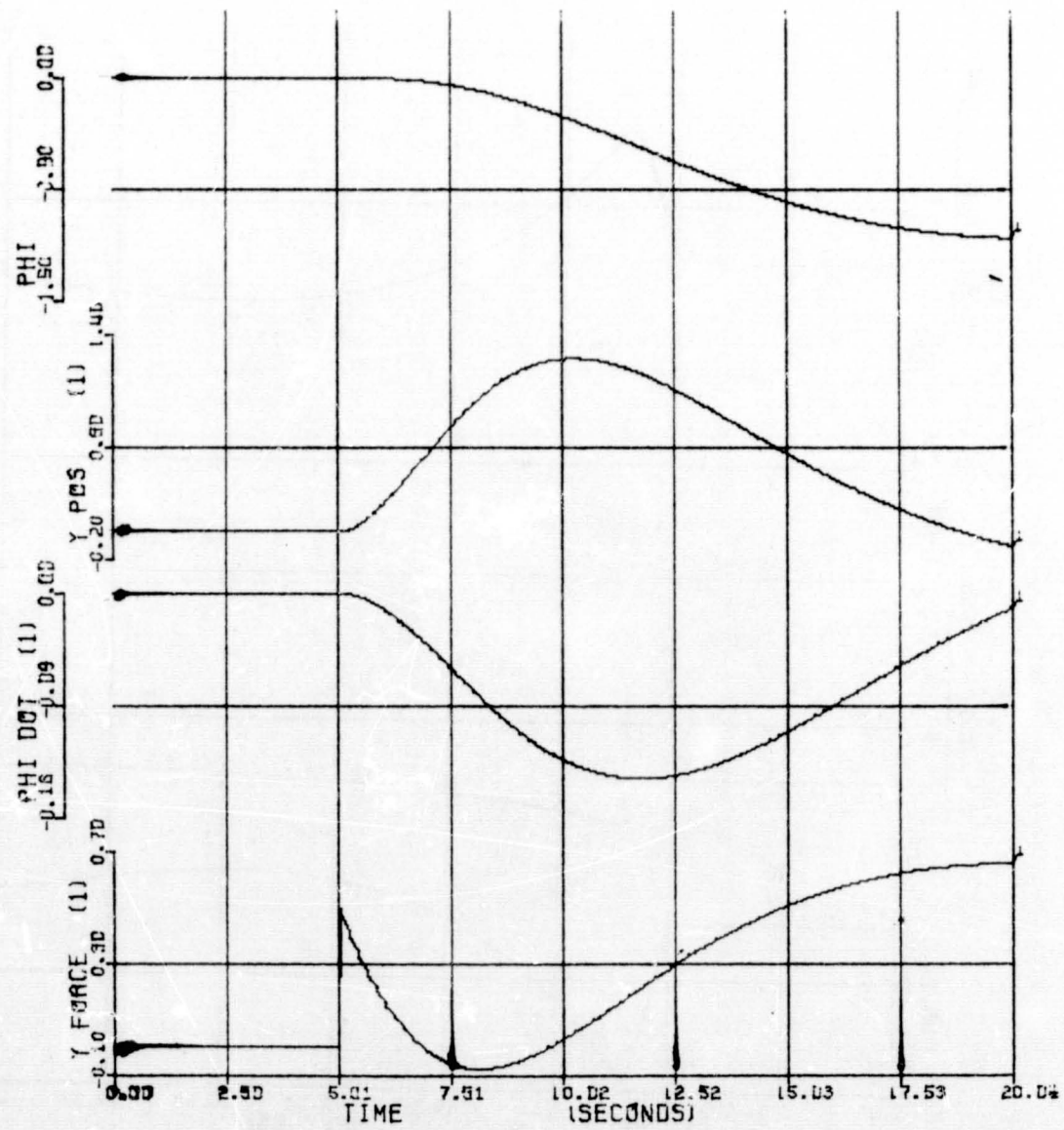
(a) Force Input

Figure A. 4 - Frequency Response of Uncoordinated Circuit



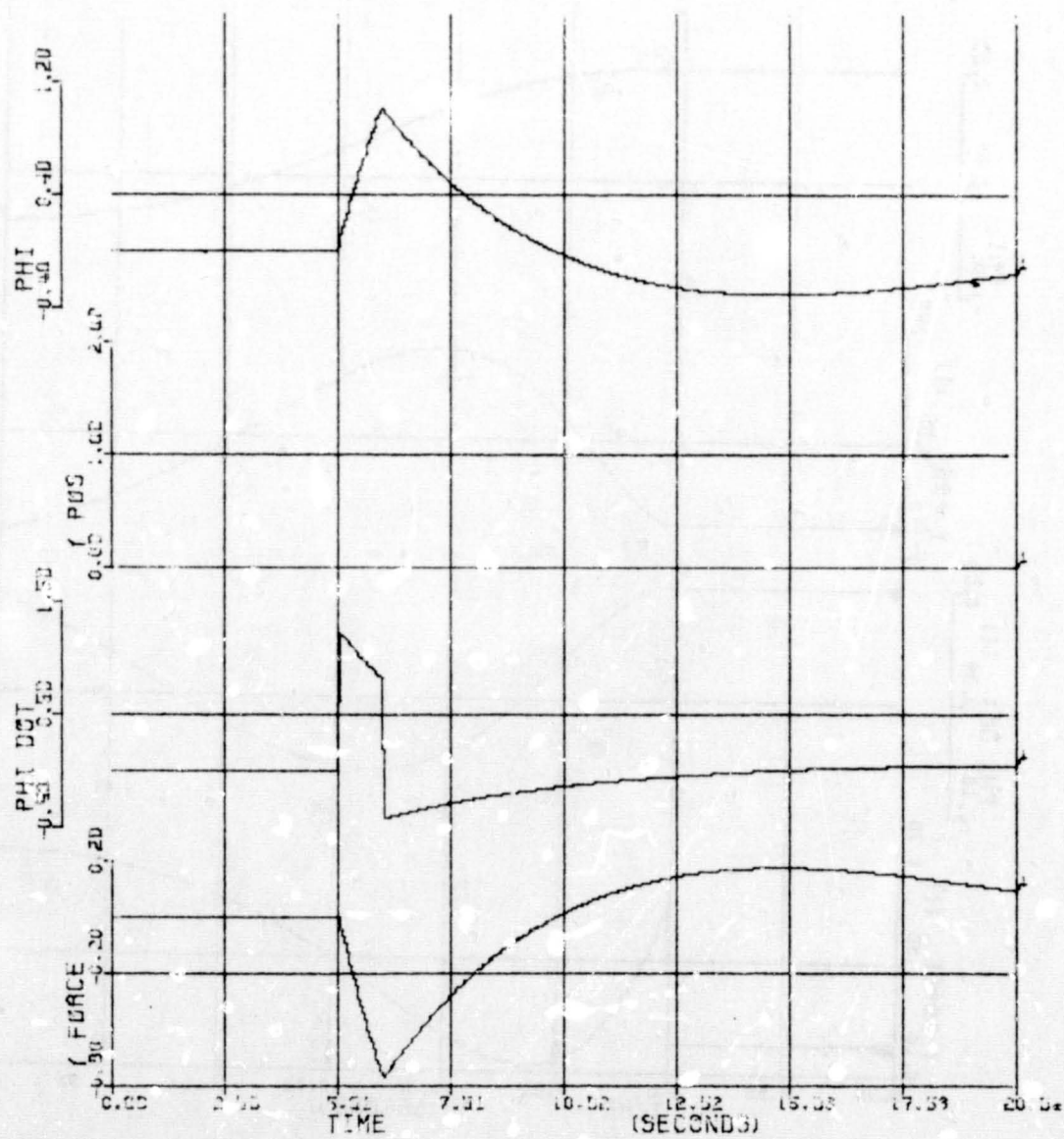
(b) Rate Input

Figure A.4 (cont)



(a) Responses to a Step Force Input

Figure A. 5 - Transient Responses of Uncoordinated Circuit



(b) Response to Pulse in Angular Rate

Figure A.5 (continued)


```

SUBROUTINE WASHRO (MODE,P,Q,R,PHIGC,THETGC,PSIGC,DT1)
COMMON/WASHOT/TG(3,3),WRT(3),PSIG
DIMENSION XW(3),WPQR(3),WR(3),WRC(3),L1WINT(50)
REAL KW
DATA CG1,CG2,CG3/.08,0.,0./
DATA KW,TAUW/0.5,2.5/
IF (MODE) 100,6300,220
100 PHIG=0.0
    PSIG =0.
    THETG=0.
    WRT(1)=0.
    WRT(2)=0.
    WRT(3)=0.
    †CALL MGRATE(3,DT1,L1WINT,4,0.0,ERR)
C
C     BODY ANGULAR RATE WASHOUT
C
    TW=EXP(-DT1/TAUW)
    GW=TAUW*(1.-TW)
C
C     IC CONDITIONS ON FILTER
C
    XW(1)=TAUW*P
    XW(2)=TAUW*Q
    XW(3)=TAUW*R
220 CONTINUE
    WPQR(1) = P
    WPQR(2) = Q
    WPQR(3) = R
C
C     WASH INPUT RATES
C
    DO 250 IFR=1,3
    XW(IFR)=TW*XW(IFR)+GW*WPQR(IFR)
    WR(IFR)=KW*(WPQR(IFR)-XW(IFR)/TAUW)
250 WRC(IFR)=WR(IFR)+WRT(IFR)
280 CONTINUE
    PSIGD = CR*WRC(3) +SR*WRC(2)
    THETGD= (CP*WRC(2) -SR*WRC(3))/CY
    PHIGD = WRC(1) -THEGD*SY
    IF (MODE.NE.1) GO TO 300

```

† See footnote page 45

(a) Subroutine WASHRO

Figure A.6 - Uncoordinated Circuit Subroutine Listings

```

      †CALL GRATON (L1WINT,PSIGD,PSIG,THETGD,THETG,PHIGD,PHIG)
300 CONTINUE
      PHIGC = PHIG +CG1*PHIGD
      THETGC= THETG+CG2*THETGD
      PSIGC = PSIG +CG3*PSIGD

C
      CR = COS(PHIG)
      SR = SIN(PHIG)
      CP = COS(THETG)
      SP = SIN(THETG)
      CY = COS(PSIG)
      SY = SIN(PSIG)
      † See footnote page 45

C      DIRECTION COSINES
      TG(1,1) = CP*CY
      TG(1,2) = SP*SR -CP*SY*CR
      TG(1,3) = SP*CR +CP*SY*SR

C
      TG(2,1) = SY
      TG(2,2) = CY*CR
      TG(2,3) = -CY*SR

C
      TG(3,1) = -SP*CY
      TG(3,2) = SP*SY*CR +CP*SR
      TG(3,3) = CP*CR -SP*SY*SR
6300 CONTINUE
      RETURN
      END

```

(a) Subroutine WASHRO (continued)

Figure A.6 (continued)


```

SUBROUTINE WASHTO (MODE,FP,XDV,YDV,ZDV,DT2)
COMMON/WASHOT/TG(3,3),WRT(3),PSIG
REAL KA,KS1,KS2,KOTT,KR
DIMENSION TMO(3),TMOD(3),FP(3),FCP(3),L2WINT(50),XHP(3),XHP2(3),
1      XRT1(3),XRT2(3),WXP(3),FSTAR(3),TAB(3),TRLIM(3),XHP1(3),
2      ACCLIM(3),TMODD(3),TMOddb(3),THP(2,2),TUHP(2),AB(3)
DATA KA,ZET,WN,FLAG,KS1,KS2,KR,TR1,TR2,/.5,.7,.5,0.0,.5,.0078,.2,
1 3.0/
DATA TRLIM/8.,8.,8./,ACCLIM/7.,7.,6./
DATA AW1,AW2,AW3,BW1,BW2,BW3/.16,.14,.23,.0375,.0376,0./
DATA CTDD,AL,BL/5.,.14,.01/
IF (MODE) 100,6300,200
100 CONTINUE
C      TRANSITION AND SENSITIVITY MATRICES
C      HIGH PASS FILTER
SROMZ2 = SQRT(1.-ZET**2)
WSROMZ = WN*SROMZ2*DT2
XPZWN = EXP(-ZET*WN*DT2)
SPZWN = SIN(WSROMZ)
CPZWN = COS(WSROMZ)
C
TUHP(1) = XPZWN*SPZWN*WN/SROMZ2
THP(1,2) = -TUHP(1)
THP(2,1) = (XPZWN*SPZWN)/(WN*SROMZ2)
THP(1,1) = XPZWN*(CPZWN - SPZWN*ZET/SROMZ2)
THP(2,2) = THP(1,1) - THP(1,2)*2.*ZET/WN
TUHP(2) = 1.-(XPZWN/SROMZ2)*(ZET*SPZWN + SROMZ2*CPZWN)
ZOWHP = 2.*ZET/WN
C
C      RESIDUAL TILT LOW PASS FILTER
C
TRT11=EXP(-DT2/TR1)
TRT22=EXP(-DT2/TR2)
TURT1=TR1*(1.-TRT11)
TURT2=TR2*(1.-TRT22)
KOTT=KR/(TR1-TR2)
DO 105 J=1,3
TMO(J) = 0.
105 TMOD(J) = 0.
+CALL MGRATE (6,DT2,L2WINT,J,0.0,ERR)
FCP(3)=-32.2
200 CONTINUE
FCP(1)=KS1*FP(1)
FCP(2)=KS2*FP(2)
C      FCP(3)=-32.2 SET IN DATA ALWAYS
C      NOW COMPUTE CROSS PRODUCT
WXP(1)=TG(3,2)*FCP(3)-TG(3,3)*FCP(2)

```

[†] See footnote page 45

(b) Subroutine WASHTO

Figure A.6 (continued)

```

WXP(2)=TG(3,3)*FCP(1)-TG(3,1)*FCP(3)
WXP(3)=TG(3,1)*FCP(2)-TG(3,2)*FCP(1)
WXP(3)=WXP(3)-PSIG*32.2
IF (MODE) 210,6300,300
C
C     HERE FOR FILTER IC
C
210 DO 6153 KFR=1,3
    XHP1(KFR)=0.0
    XHP2(KFR)=FP(KFR)
    XRT1(KFR)=TR1*WXP(KFR)
6153 XRT2(KFR)=TR2*WXP(KFR)
    300 CONTINUE
C
C     LOW PASS THE TILT RATES
C
DO 6170 JFR=1,3
    XRT1(JFR)=TRT11*XRT1(JFR)+TURT1*WXP(JFR)
    XRT2(JFR)=TRT22*XRT2(JFR)+TURT2*WXP(JFR)
6170 WRT(JFR)=KOTT*(XRT1(JFR)-XRT2(JFR))
C
C     HIGH PASS CAB REFERENCE FILTER ON FORCES
C
DO 6210 KFR=1,3
    XHPD1=THP(1,1)*XHP1(KFR)+THP(1,2)*XHP2(KFR)+TUHP(1)*FP(KFR)
    XHPD2=THP(2,1)*XHP1(KFR)+THP(2,2)*XHP2(KFR)+TUHP(2)*FP(KFR)
    XHP1(KFR)=XHPD1
    XHP2(KFR)=XHPD2
6210 FSTAR(KFR)=KA*(FP(KFR)-ZOWHP*XHP1(KFR)-XHP2(KFR))
C
C     CONVERT TO INERTIAL COORDINATES
DO 6220 KK1=1,3
    ABD=0.
    DO 6219 KK2=1,3
6219 ABD=ABD+TG(KK1, KK2)*FSTAR(KK2)
6220 TAB(KK1)=ABD
C
C     PUT IN ONE G IF CAR REFERENCE WASHOUT ON FORCES
TAB(3)=TAB(3)+FLAG*32.2
C     LIMITING SCHEME
DO 280 IL=1,3
    TAB(IL) = TAB(IL) -AL*TMOD(IL) -BL*TMO(IL)
256 TMODD(IL) = TAB(IL)
    IF(ABS(TAB(IL)).GT.ACCLIM(IL)) TMODD(IL)=SIGN(ACCLIM(IL),TAB(IL))
258 ABD = ABS(TMO(IL)) -TRLIM(IL)
    IF(ABD) 263,259,259
259 TMODL = 0.

```

(b) Subroutine WASHTO (continued)

Figure A.6 (continued)


```

GO TO 276
263 IF(TMOD(IL)) 264,280,272
264 TMDL = -SQRT(14.*(TMO(IL) +TRLIM(IL)))
IF(TMOD(IL)-TMDL) 276,280,280
272 TMDL = SQRT(14.*(TRLIM(IL) -TMO(IL)))
IF(TMOD(IL) -TMDL) 280,280,276
276 TMODD(IL) = TMODD(IL)-CTDD*(TMOD(IL)-TMDL)
IF(ABS(TMODD(IL)).GT.ACCLIM(IL)) TMODD(IL)=SIGN(ACCLIM(IL),
1 TMODD(IL))
280 CONTINUE
C INTEGRATION OF MOTION (TRANSLATIONAL) SIGNALS
IF (MODE.NE.1) GO TO 305
+CALL GRATON (L2WINT,TMOD(1),TMO(1),TMOD(2),TMO(2),TMOD(3),TMO(3),
1 TMODD(1),TMOD(1),TMODD(2),TMOD(2),TMODD(3),TMOD(3))
305 CONTINUE
XDV = TMO(1) +AW1*TMOD(1) +BW1*TMODD(1)
YDV = TMO(2) +AW2*TMOD(2) +BW2*TMODD(2)
ZDV = TMO(3) +AW3*TMOD(3) +BW3*TMODD(3)
325 CONTINUE
6300 CONTINUE
RETURN
END

```

⁺ See footnote page 45

(b) Subroutine WASHTO (continued)

Figure A.6 (continued)

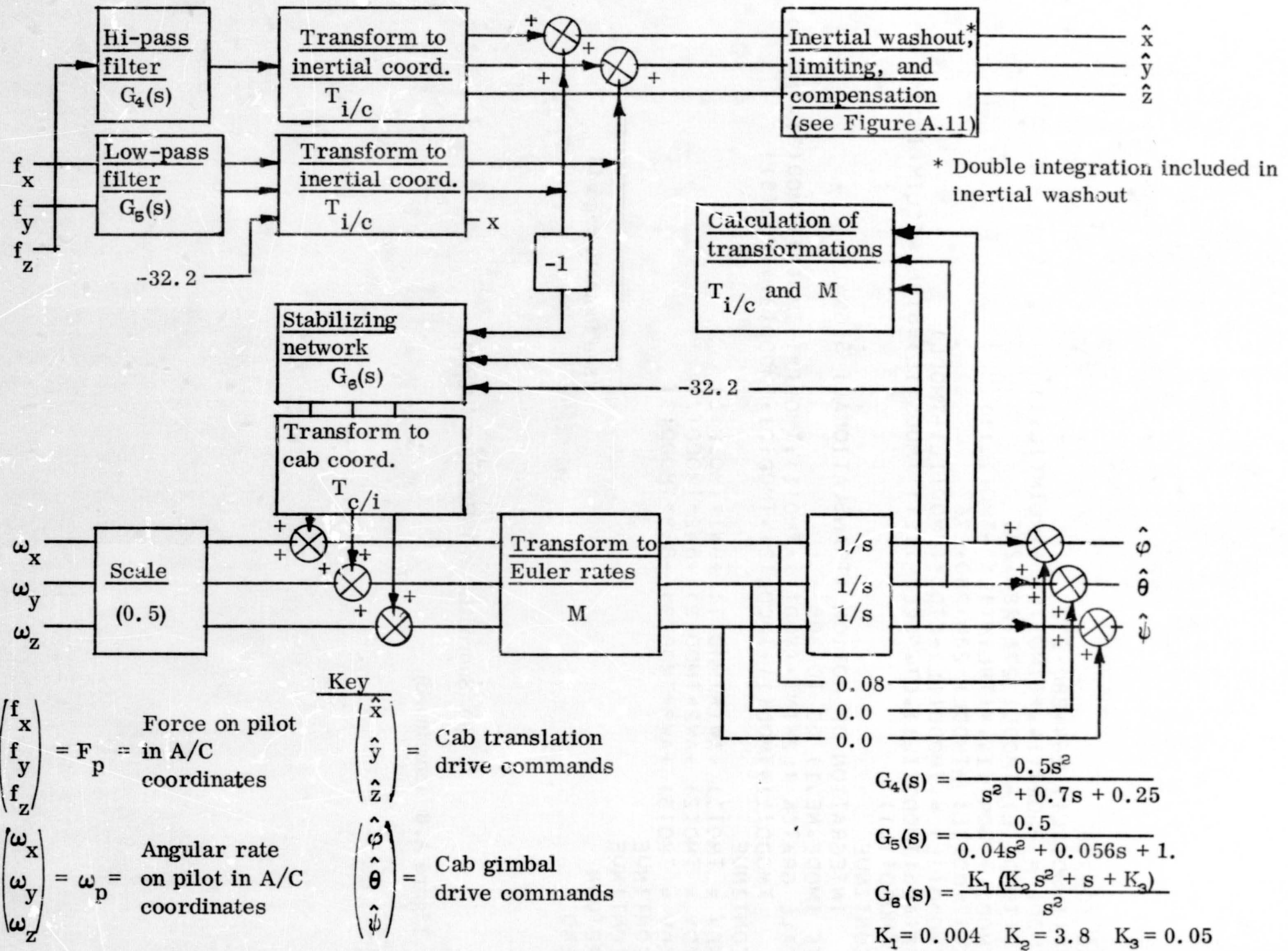


Figure A.7 - Block Diagram of Coordinated Washout Circuit (nominal parameter values shown)

- The cross-product feedback law is calculated in an inertial coordinate system requiring only the interchange of two channels to obtain the cross-product. However, some coordinate transformations must also be performed.
- All angular-rate washout is obtained from the residual tilt feedback circuit.

Inertial washout, limiting, and compensation for this circuit (Section A. 4) is identical to that in the uncoordinated circuit.

Important transfer functions describing several input-output relationships in the linearized coordinated circuit are given in Table A.2. Figure A.8 presents frequency response associated with some of the important transfer functions, while Figure A.9 gives transient responses. Transient response inputs, dimensions and other information related to the coordinated plots are the same as for the uncoordinated circuit. Three cases are plotted for this circuit, however. These correspond to the table below.

CASE	PARAMETER		
	K_1	K_2	K_3
1	.004	3.8	.05
2	.009	2.6	.05
3	.017	1.83	.05

A FORTRAN listing of the operational circuit is given in Figure A.10.

A.4 Limiting Logic, Inertial Washout, and Compensation

All three circuits accomplish most of their translation-attenuating motion by scaling and filtering variables coordinatized in an aircraft-fixed frame. It is pointed out in Reference 1, however, that this type of motion attenuation does not

TABLE A. 2

TRANSFER FUNCTIONS FOR THE LINEARIZED COORDINATED CIRCUIT

INPUT	OUTPUT			
	Position, \hat{y}	Angle, $\hat{\phi}$	Specific Force, \hat{f}_y	Angular Rate, $\dot{\hat{\phi}}$
Specific Force f_y	$\frac{0.5s^3}{D_5(s)D(s)D_1(s)}$	$\frac{0.5K_1(K_2s^2+s+K_3)}{D_5(s)D(s)}$	$\frac{0.5(s^5+D_1(s)D_6(s))}{D_6(s)D_1(s)D(s)}$	$\frac{0.5sK_1(K_2s^2+s+K_3)}{D_5(s)D(s)}$
Angular Rate ω_x	$\frac{-16.1s^2}{D(s)D_1(s)}$	$\frac{0.5s^2}{D(s)}$	$\frac{-16.1s^2(s^2-D_1(s))}{D(s)D_1(s)}$	$\frac{0.5s^3}{D(s)}$
	Position, \hat{z}	Angle, $\hat{\psi}$	Specific Force, \hat{f}_z	Angular Rate, $\dot{\hat{\psi}}$
Specific Force \hat{f}_z	$\frac{0.5s^2}{D_0(s)D_1(s)}$	---	$\frac{0.5s^4}{D_0(s)D_1(s)}$	---
Angular Rate ω_z	---	$\frac{0.5s^2}{D(s)}$	---	$\frac{0.5s^3}{D(s)}$

Key

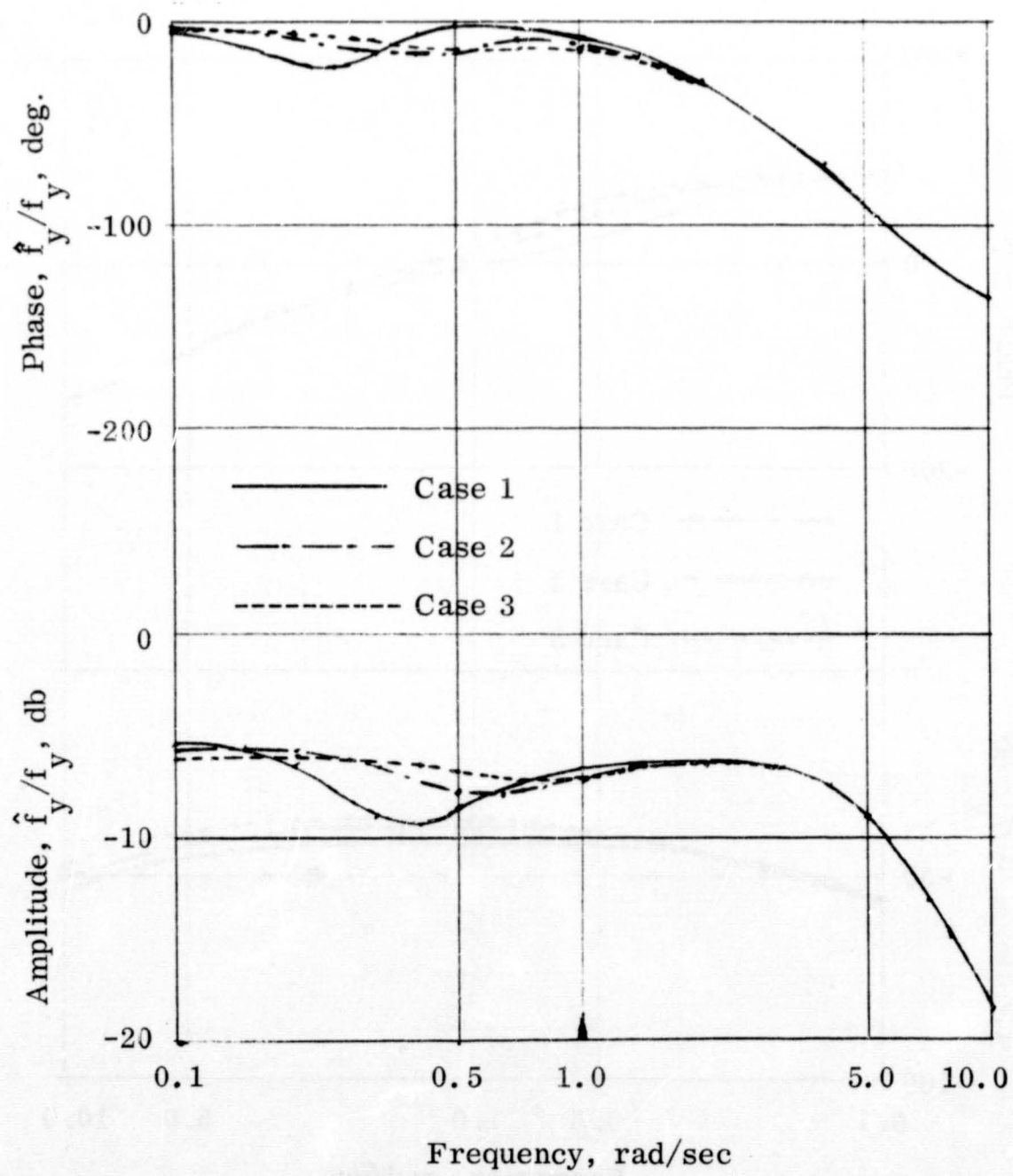
$$D(s) = s^3 + 32.2K_1(K_2s^2 + s + K_3)$$

$$D_0(s) = s^2 + 0.7s + 0.25$$

$$D_1(s) = s^2 + 0.14s + 0.01$$

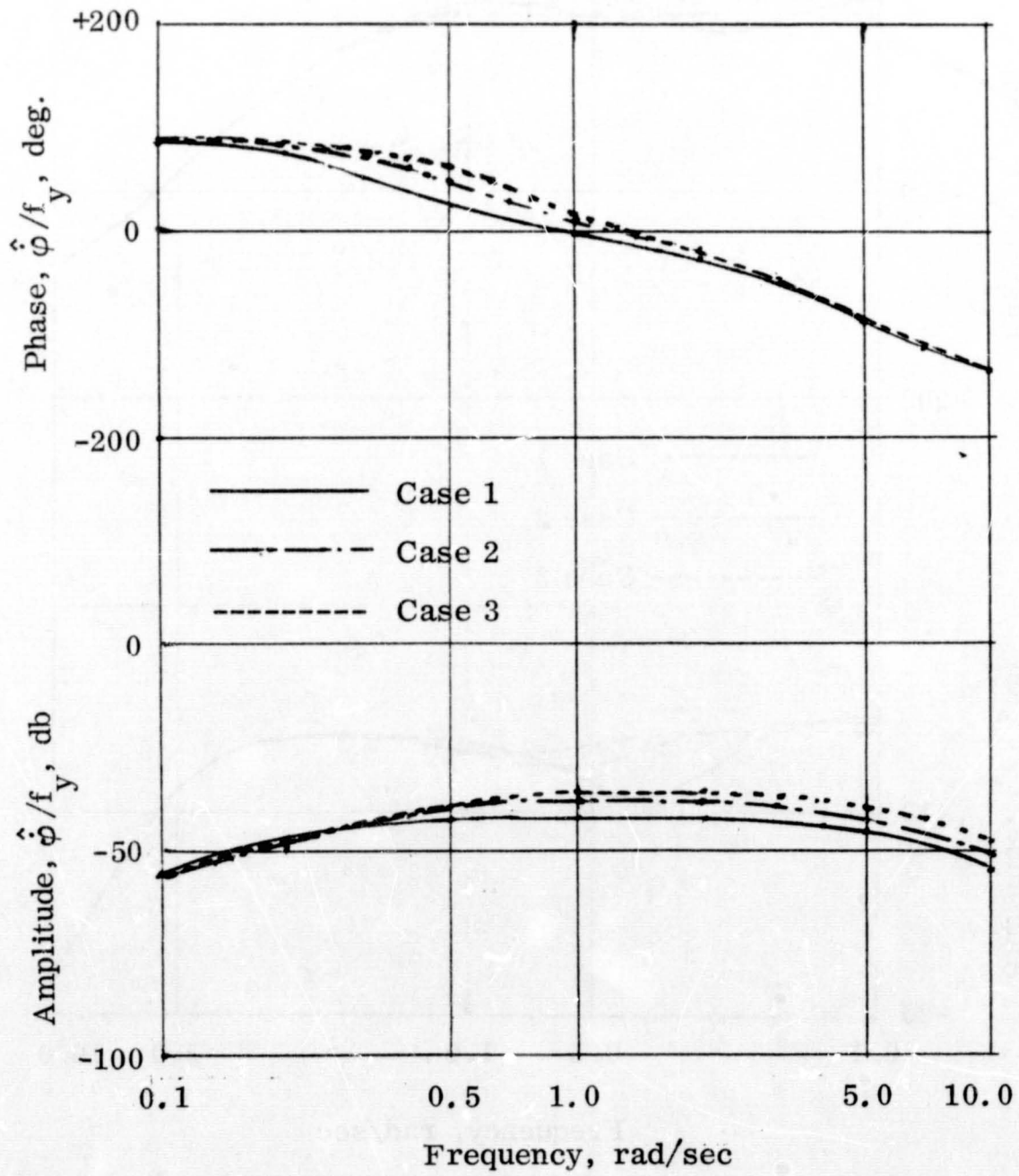
$$D_5(s) = 0.04s^2 + 0.28s + 1$$

$$D_6(s) = 32.2K_1(K_2s^2 + s + K_3)$$



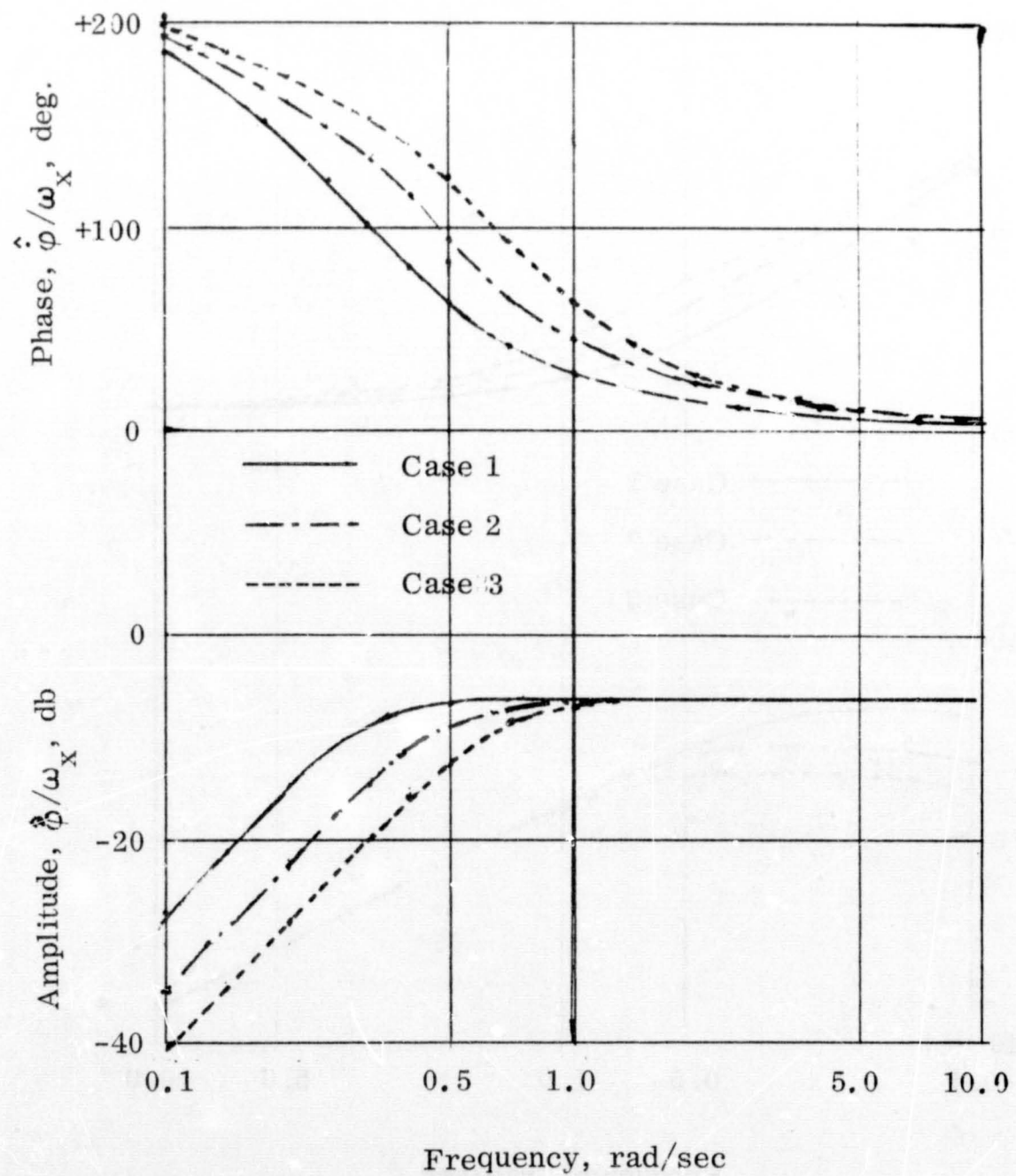
(a) Force Input - Force Output

Figure A.8 - Frequency Responses for Three Coordinated Circuit Configurations



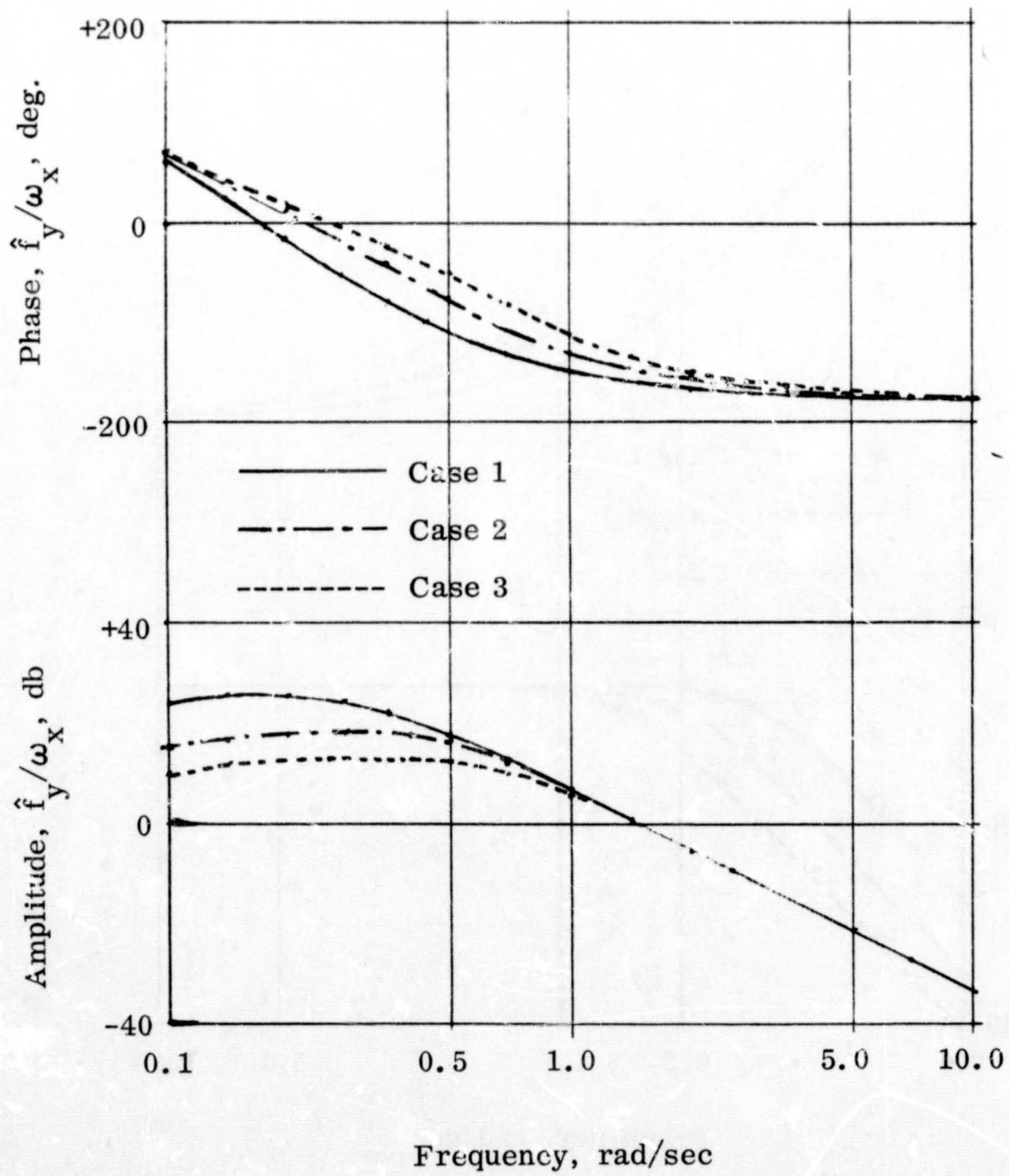
(b) Force Input - Rate Output

Figure A.8 (cont)



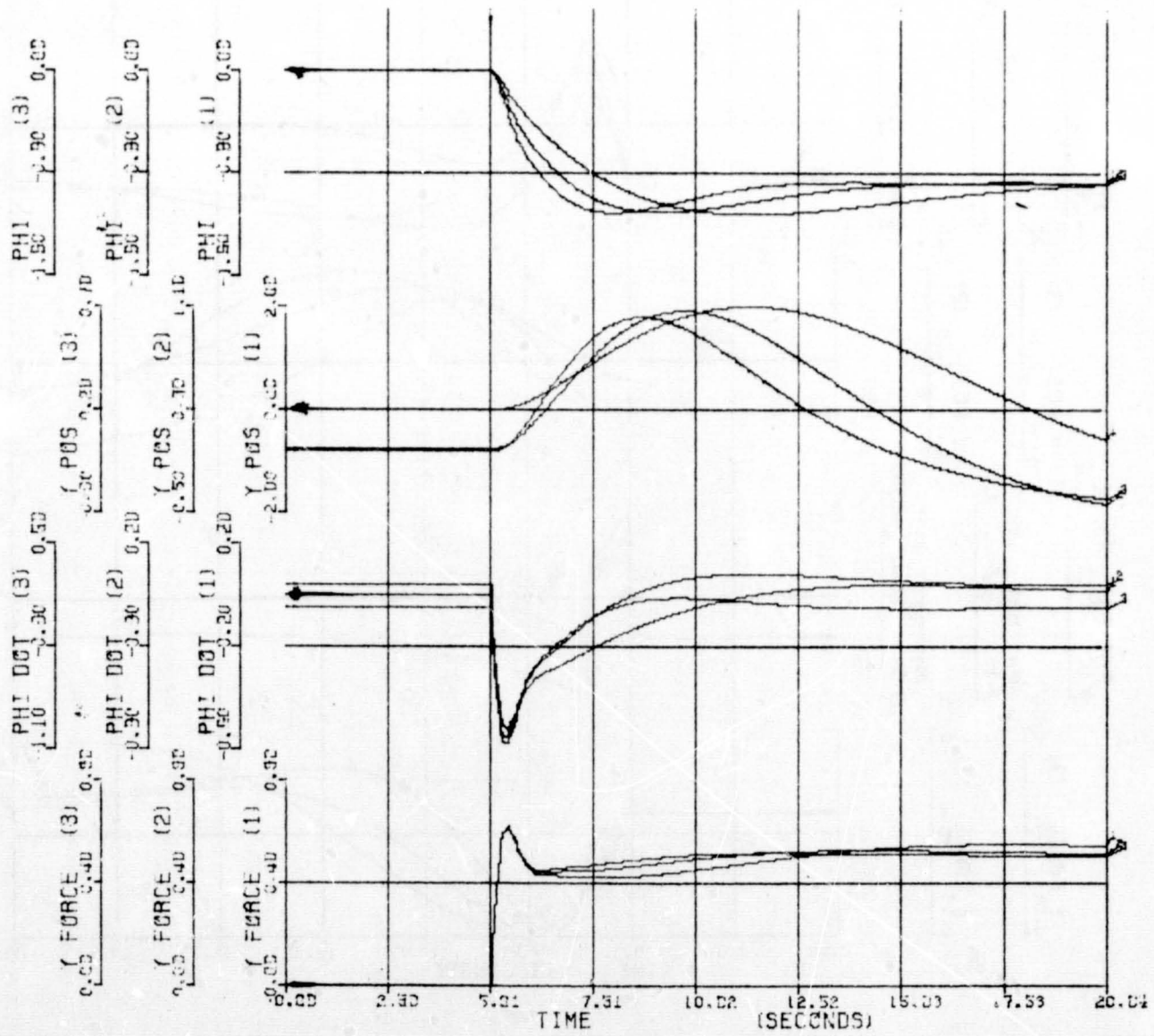
(c) Rate Input - Rate Output

Figure A.8 (cont)



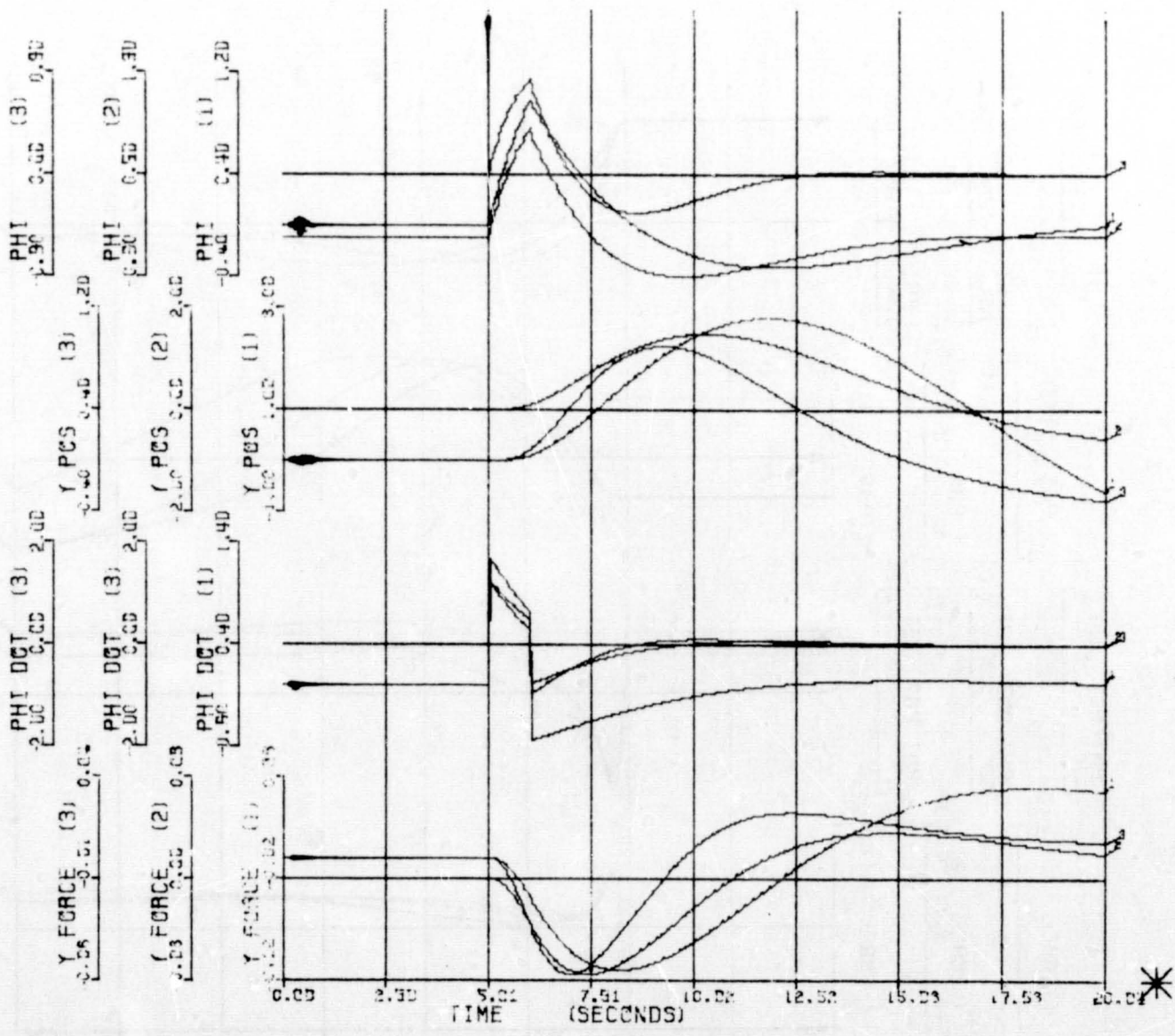
(d) Rate Input - Force Output

Figure A.8 (cont)



(a) Responses to a Step Force Input

Figure A.9 - Transient Responses of Coordinated Circuit



(b) Responses to an Angular Rate Pulse

Figure A.9 (continued)

```

SUBROUTINE WASHRN (MODE,P,Q,R,PHIGC,THETGC,PSIG,DT1)
COMMON/WASHO/TG(3,3),WRT(3),PSIG
REAL KW
DIMENSION WPQR(3),WRC(3),L1WINT(50)
DATA KW/.5/
DATA CG1,CG2,CG3/.08,0.,0./
IF (MODE) 100,6300,220
100 PHIG=0.0
PSIG =0.
THETG=0.
+CALL MGRATE (3,DT1,L1WINT,4,0.0,ERR)
220 CONTINUE
WPQR(1) = P
WPQR(2) = Q
WPQR(3) = R
DO 230 IFR=1,3
230 WRC(IFR)=KW*WPQR(IFR)+WRT(IFR)
PSIGD = CR*WRC(3) +SR*WRC(2)
THETGD= (CP*WRC(2) -SR*WRC(3))/CY
PHIGD = WRC(1) -THEGD*SY
IF (MODE) 240,6300,235
235+CALL GRATON (L1WINT,PSIGD,PSIG,THETGD,THETG,PHIGD,PHIG)
240 CONTINUE
PHIGC = PHIG +CG1*PHIGD
THETGC= THETG+CG2*THETGD
PSIGC = PSIG +CG3*PSIGD
C
CR = COS(PHIG)
SR = SIN(PHIG)
CP = COS(THETG)
SP = SIN(THETG)
CY = COS(PSIG)
SY = SIN(PSIG)
C
DIRECTION COSINES
TG(1,1) = CP*CY
TG(1,2) = SP*SR -CP*SY*CR
TG(1,3) = SP*CR +CP*SY*SR
C
TG(2,1) = SY
TG(2,2) = CY*CR
TG(2,3) = -CY*SR
C
TG(3,1) = -SP*CY
TG(3,2) = SP*SY*CR +CP*SR
TG(3,3) = CP*CR -SP*SY*SR
6300 CONTINUE
RETURN
END

```

+See footnote page 45

(a) Subroutine WASHRN

Figure A.10 - Coordinated Circuit Subroutine Listings


```

SUBROUTINE WASHTN (MODE,FP,XDV,YDV,ZDV,DT2)
DIMENSION TMO(3),TMOD(3),FP(3),FCP(3),L2WINT(50),XHP(2),FSTAR(3),
1      WRTI(3),X1SS(3),X2SS(3),AB(3),TAB(3),TRLIM(3),ACCLIM(3),
2      THP(2,2),TUHP(2),FRT(3),THS(2,2),TUHS(2),TMODD(3),
3      TMOddb(3),DS(2),XLP(2,2)
COMMON/WASHO/TG(3,3),WRT(3),PSIG
REAL KA,K1SS,K2SS,K3SS,KF
DATA KF,ZES,WS,K1SS,K2SS,K3SS,KA,ZET,WN/
1      .5,.7,5.,.004,3.8,.05,.5,.7,.5/
DATA TRLIM/8.,8.,8./,ACCLIM/7.,7.,6./
DATA AW1,AW2,AW3,BW1,BW2,BW3/.16,.14,.23,.0375,.0376,0./
DATA CTDD,AL,BL/5.,.14,.01/
IF (MODE) 100,6300,220
100 DO 105 J=1,3
    TMO(J) = 0.
105 TMOD(J) = 0.
+ CALL MGRATE (6,DT2,L2WINT,J,0.0,ERR)
    FRT(3)=0.0
    FSTAR(3)=-32.2
C      TRANSITION AND SENSITIVITY MATRICES
C      HIGH PASS FILTER
    SROMZ2 = SQRT(1.-ZET**2)
    WSROMZ = WN*SROMZ2*DT2
    XPZWN = EXP(-ZET*WN*DT2)
    SPZWN = SIN(WSROMZ)
    CPZWN = COS(WSROMZ)
C
    TUHP(1) = XPZWN*SPZWN*WN/SROMZ2
    THP(1,2) = -TUHP(1)
    THP(2,1) = (XPZWN*SPZWN)/(WN*SROMZ2)
    THP(1,1) = XPZWN*(CPZWN - SPZWN*ZET/SROMZ2)
    THP(2,2) = THP(1,1) - THP(1,2)*2.*ZET/WN
    TUHP(2) = 1.-(XPZWN/SROMZ2)*(ZET*SPZWN + SROMZ2*CPZWN)
    ZOWHP = 2.*ZET/WN
C
C      LOW PASS SMOOTHING FILTER FOR 1G FORCES
    SROMZ2 = SQRT(1.-ZES**2)
    WSROMZ = WS*SROMZ2*DT2
    XPZWN = EXP(-ZES*WS*DT2)
    SPZWN = SIN(WSROMZ)
    CPZWN = COS(WSROMZ)
C
    TUHS(1) = XPZWN*SPZWN*WS/SROMZ2
    THS(1,2) = -TUHS(1)
    THS(2,1) = (XPZWN*SPZWN)/(WS*SROMZ2)
    THS(1,1) = XPZWN*(CPZWN - SPZWN*ZES/SROMZ2)
    THS(2,2) = THS(1,1) - THS(1,2)*2.*ZES/WS

```

+ See footnote page 45

(b) Subroutine WASHTN

Figure A.10 (continued)


```

TUHS(2) = 1.-(XPZWN/SROMZ2)*(ZES*SPZWN +SROMZ2*CPZWN)
C
C      RESIDUAL TILT FILTER
C      SET ONE SIGNAL SHAPING FILTER TERM
G2SS=DT2*DT2/2.0
XHP(1)=0.0
XHP(2)=FP(3)+32.2
DO 6151 II=1,2
XLP(1,II)=0.0
6151 XLP(2,II)=0.0
DO 6152 II=1,3
X1SS(II)=0.0
6152 X2SS(II)=0.0
220 CONTINUE
C      APPRX 1 G FORCE WITH SMALL HORIZONTAL COMPONENTS
C
C      APPROXIMATE 1 G FORCE, SCALE AND SMOOTH
DO 6160 II=1,2
DS(1)=XLP(1,II)
DS(2)=XLP(2,II)
DO 6157 JJ=1,2
6157 XLP(JJ,II)=THS(JJ,1)*DS(1)+THS(JJ,2)*DS(2)+KF*TUHS(JJ)*FP(II)
FSTAR(II)=XLP(2,II)
6160 CONTINUE
C      FSTAR(3)=-32.2 SET IN DATA ALWAYS
C
C      TRANSFORM FSTAR TO GET FIRST TWO COMP. IN INERTIAL COOR
DO 6170 IWT=1,2
FRT(IWT)=0.0
DO 6170 JWT=1,3
6170 FRT(IWT)=FRT(IWT)+TG(IWT,JWT)*FSTAR(JWT)
FRT(3) ALWAYS SET TO ZERO
C
C      HIGH PASS THIRD COMP. OF NON 1 G FORCES
DUMMY=FP(3)+32.2
DO 6205 LFHP=1,2
XHPD=0.0
DO 6200 KFHP=1,2
6200 XHPD=XHPD+THP(LFHP,KFHP)*XHP(KFHP)
6205 XHP(LFHP)=XHPD+TUHP(LFHP)*DUMMY
DUMMY=KA *(DUMMY-ZOWHP*XHP(1)-XHP(2))
C
C      COMPUTE TRANS SPECIFIC FORCES BEFORE INERTAIL WO AND LIMITING
DO 6210 IFHP=1,3
6210 TAB(IFHP)=FRT(IFHP)+DUMMY*TG(IFHP,3)
C
C

```

(b) Subroutine WASHTN (continued)

Figure A.10 (continued)

```

C      SIGNAL SHAPING FOR RESIDUAL TILT RATES ,3 CHANNELS)
FCP(1)=-FRT(2)
FCP(2)= FRT(1)
FCP(3)=-32.2*PSIG
DO 6250 IFHP=1,3
X1SSD=X1SS(IFHP)+DT2*FCP(IFHP)
X2SSD=DT2*X1SS(IFHP)+X2SS(IFHP)+G2SS*FCP(IFHP)
  X1SS(IFHP)=X1SSD
  X2SS(IFHP)=X2SSD
6250 WRTI(IFHP)=K1SS*(X1SSD+K3SS*X2SSD+K2SS*FCP(IFHP))
C
C      TRANSFORM RESIDUAL TILT RATES TO BODY COORDINATES
DO 6270 IFHP=1,3
WRT(IFHP)=0.0
DO 6270 LFHP=1,3
6270 WRT(IFHP)=WRT(IFHP)+TG(LFHP,IFHP)*WRTI(LFHP)
C      LIMITING SCHEME
DO 280 IL=1,3
TAB(IL) = TAB(IL) -AL*TMOD(IL) -BL*TMO(IL)
256  TMODD(IL) = TAB(IL)
IF(ABS(TAB(IL)).GT.ACCLIM(IL)) TMODD(IL)=SIGN(ACCLIM(IL),TAB(IL))
258  ABD = ABS(TMO(IL)) -TRLIM(IL)
IF(ABD) 263,259,259
259  TMODL = 0.
GO TO 276
263  IF(TMOD(IL)) 264,280,272
264  TMODL = -SQRT(14.*(TMO(IL) +TRLIM(IL)))
IF(TMOD(IL)-TMODL) 276,280,280
272  TMODL = SQRT(14.*(TRLIM(IL) -TMO(IL)))
IF(TMOD(IL) -TMODL) 280,280,276
276  TMODD(IL) = TMODD(IL)-CTDD*(TMOD(IL)-TMODL)
IF(ABS(TMODD(IL)).GT.ACCLIM(IL)) TMODD(IL)=SIGN(ACCLIM(IL),
1 TMODD(IL))
280  CONTINUE
IF (MODE.NE.1) GO TO 300
+CALL GRATON (L2WINT,TMOD(1),TMO(1),TMOD(2),TMO(2),TMOD(3),TMO(3),
1 TMODD(1),TMOD(1),TMODD(2),TMO(2),TMODD(3),TMO(3))
300  CONTINUE
XDV = TMO(1) +AW1*TMOD(1) +BW1*TMODD(1)
YDV = TMO(2) +AW2*TMOD(2) +BW2*TMODD(2)
ZDV = TMO(3) +AW3*TMOD(3) +BW3*TMODD(3)
325  CONTINUE
6300 CONTINUE
RETURN
END

```

⁺ See footnote page 45

(b) Subroutine WASH TN (continued)

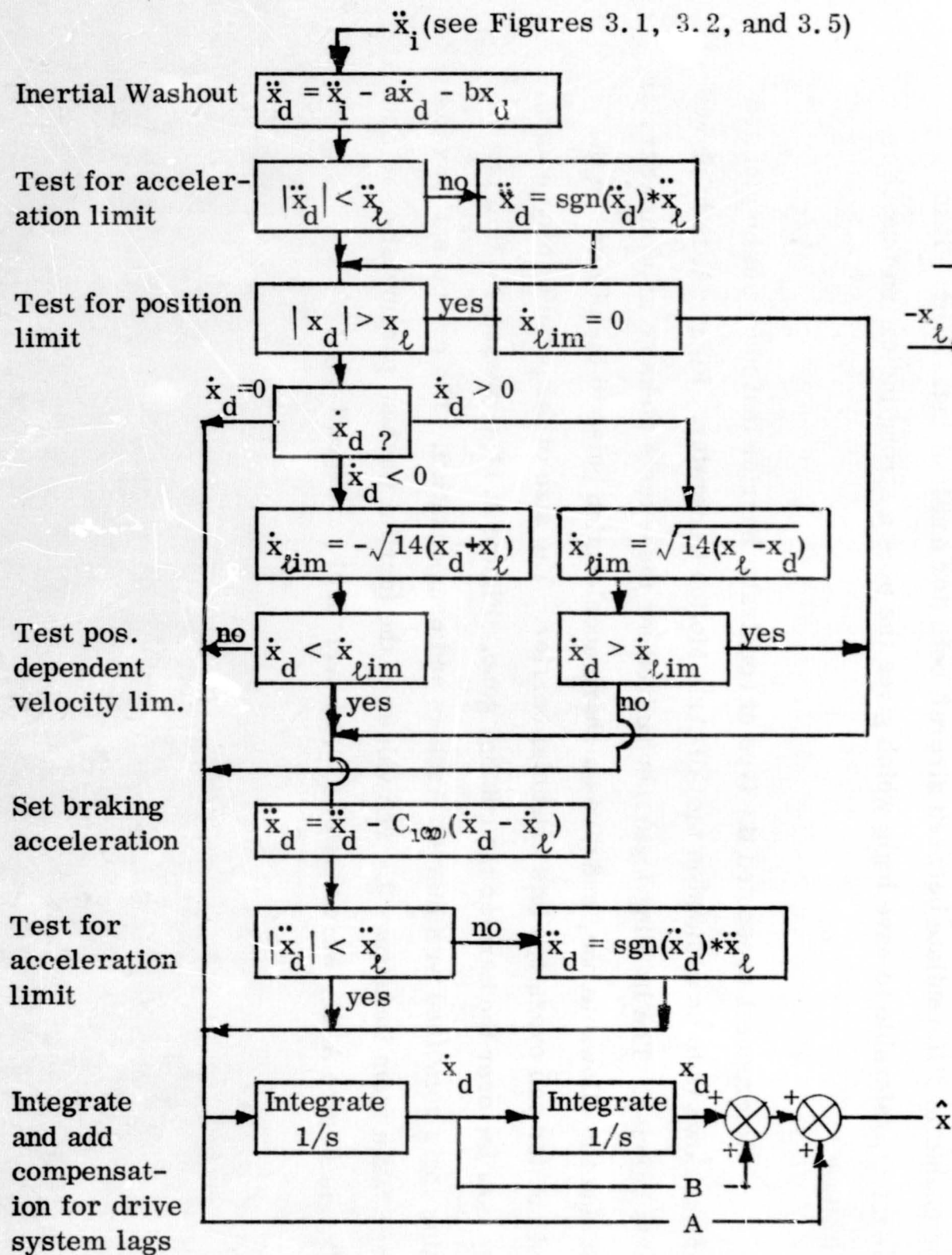
Figure A.10 (continued)

guarantee a bounding of simulator position commands. Furthermore, integrators used to obtain translation drive commands can drift. Hence, high-pass filtering has been added to the three circuits described in the previous sections. This filter takes the form:

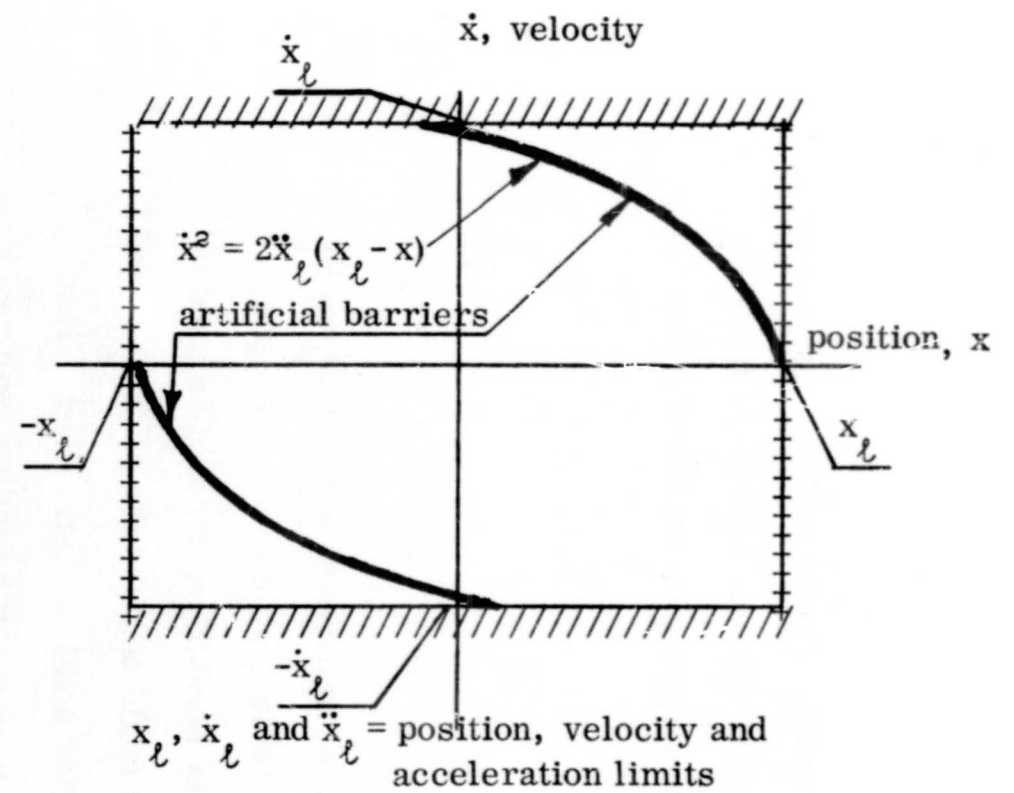
$$\frac{s^2}{s^2 + .14s + .01}$$

Since the All-Axis Motion Generator experiences a time-consuming shutdown whenever certain translation bounds are exceeded, it is desirable to have limiting logic which keeps the simulator off these bounds. Very smooth logic could be used to keep the simulator off shutdown bounds, but this could confuse the pilot who would be unable to differentiate between aircraft behavior and limiting. Hence, it is deemed preferable to have logic which gives the pilot a strong indication that he is limiting.

Reference 1 presented the type of constraint barrier that must not be violated if shutdown is to be avoided in the All-Axis Motion Generator. Figure A.11(b) shows this barrier. The limiting logic mechanized for these tests picks an artificial barrier inside the allowable one, and gives a sharp acceleration pulse to the pilot when the simulator cab oversteps this artificial barrier. The size of the pulse is proportional to how far over the barrier the cab has gone. Figure A.11(a) presents a flow chart of this logic combined with inertial washout and compensation. The compensation values are taken from Reference 3. The values of the inertial washout parameters, a and b , in Figure A.11, were taken as 0.14 and 0.01, respectively.



(a) Logic Mechanization



(b) Inequality Barriers

Lead Compensation Parameters for Ames All-Axis Motion Generator

Channel	A	B
Longitudinal	.0375	0.16
Lateral	.0376	0.14
Vertical	0.0	0.23

Figure A.11-Translational Drive Systems Inertial Washout, Soft Limiting and Lead Compensation Logic

REFERENCES

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2. Bergeron, H. P. ; "The Effects of Motion Cues on Compensatory Tracking Tasks," presented at the AIAA Visual and Motion Technology Conference, AIAA Paper No. 70-352, Cape Canaveral, Florida, March 1970.
3. Fry, E. B. et al. ; "Use of a Six-Degrees-of-Freedom Motion Simulator for VTOL/ Hovering Tasks," NASA TN D-5383, August 1969.
4. Stapleford, R. L. et al. ; "Experiments and a Model for Pilot Dynamics with Visual and Motion Inputs," Systems Technology, Inc. Technical Report No. 168-2 for Contract No. NAS 2-3650.