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THE CALCULATION OF MOTION DRIVE SIGNALS FOR PILOTED FLIGHT SIMULATORS

By Stanley F. Schmidt and Bjorn Conrad

October 1969

Prepared under Contract No. NAS2-4869 by

ANALYTICAL MECHANICS ASSOCIATES, INC.

Palo Alto, California

for

AMES RESEARCH CENTER

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SECTION 1

Introduction

Piloted flight simulators are used extensively for both research[1] and pilot training purposes. It is well known[2,3,4,5] that the addition of motion in these simulations provides realism and gives a greater consistency of research results between simulations and flight tests. Motion simulators have highly restricted movement, however, and techniques which make an optimal usage of this restricted motion are not well understood.

The command signals for the motion simulator cannot be taken directly from a computer simulation of the real aircraft's motion but first, must be modified by logic which is traditionally referred to as "washout" circuits. The traditional approach[6] to designing such circuits is of an empirical nature which uses pilot subjective opinion to arrive at an acceptable compromise.

This report summarizes the results of a research investigation whose overall objective was to improve the techniques for designing such circuits. A specific objective was to provide washout logic for the Ames All-Axis Motion Generator described in the Appendix. These objectives can be accomplished only after solving some closely related problems. These include finding answers to such questions as:

1) What type of motion is important to the pilot?

2) At what level does anomolous motion become distracting?

3) How can the effectiveness of washout circuits be tested?

Hence, a great deal of effort was expended on these areas as well as on the design of operational logic.

Section 2 reviews the overall motion simulation problem and some fundamental assumptions about pilot sensed motion. Difficulties imposed by motion constraints inherent in motion simulators and traditional washout circuits are also described. Section 3 expands on the traditional solutions to obtain washout circuits for multi-degree of freedom motion simulators. Particular attention is given to the problem of coupling which arises with multi-degree of freedom simulators. A new concept incorporating certain feedback control principles is also developed. With this concept, the resultant washout circuitry provides coordinated drive signals for rotational and translational motions. This coordination permits a more accurate representation of longitudinal and lateral force cues than previously used concepts.

Section 4 discusses the overall problem associated with experimental validation of washout circuitry. The various considerations discussed there lead to the development of a simulated formation flying task. The results of an evaluation of this task are presented in this section. These results compare fixed base (no motion) and nearly ideal motion. Section 5 reviews the overall research investigation and makes several recommendations for continued research.

SECTION 2

Fundamental Considerations

2.0 Review of overall problem. — In order to obtain a perspective on the work discussed in this report a brief review of a piloted flight simulator, with specific emphasis on the inherent difficulties with which this research is concerned, is presented.

Conceptually a piloted flight simulator consists of the following blocks:

1. A cockpit ("cab") which can be moved about via commands issued to servo drive systems.
2. Airplane control devices (stick, rudder pedals, etc.) located in the cab.
3. A computer which takes input signals from the controls and solves the aircraft's equations of motion to determine its states (e.g., positions, velocities, attitudes and angular velocities).
4. Assorted aircraft instrumentation and other visual indicators which provide a measure of the aircraft's state (as determined by the computer) to the pilot.

The instruments and visual display can be commanded to move in accordance with the computed aircraft state. Ideally, the cab would also be commanded to move about in accordance with the states that the real aircraft would possess. Generally, it is impossible to do this since the cab is mounted in a mechanical structure with limited motion. In particular, such a cab can only move a few feet in any direction with limited velocity and accelerations. Similar limitations exist on angular rotations and rotation rates.

Now the following dilemma rises. The pilot manipulates the controls of the simulator. The computer determines the resultant motion of the aircraft being simulated and sets the visual display to show this motion. The computer also commands the cab to move, preferably just as the aircraft would. However, since only limited motion of the cab is possible some modification of the computer motion is necessary before it is used to command cab motion.

The object of this research project was to investigate ways of using the computed motion values to obtain signals representing similar motions compatible with the cab's limitations. In general, the movement of the cab must be inconsistant with the pilot's instruments and other visual displays. However, a pilot's motion senses are also limited and he may attach far more importance to some motion cues than others. The most desirable signal modification scheme would involve choosing an allowable motion which gives the pilot the best sensed motion cues possible. Under some circumstances, for example, the best solution could be to give the pilot no motion at all. This may occur when any allowable cab motion would be too inconsistant with visually indicated motion and hence unrealistically confusing the pilot.

Two major problem areas are now defined. First, which motions can a pilot sense and which are important to flying in a particular aircraft performing a given task? Second, what logic scheme (if any) will produce reasonable pilot sensations compatible with the cab motion limitations? Answers to these questions require a great deal of experimental as well as mathematical development and the results frequently can be given only qualitative interpretation. The design of such experiments and of evaluation procedures which interpret their outcome are in themselves difficult tasks.

2.1 Discussion of pilot sensed motion. — The exact motion sensed by a pilot is difficult to isolate. However, a combination of empirical, theoretical and practical considerations leads to the working assumption that a pilot can "sense" exactly the same motions as would a set of inertial instruments mounted in his body. These instruments are three linear accelerometers and three angular accelerometers, which sense specific force (a vector) and angular accelerations (a vector), respectively.[1] In subsequent mathematical development it will be simpler to assume the angular instruments are rate gyros rather than angular accelerometers. Part of the reason for this is that some of the forces the pilot can sense are caused by centripetal type terms which depend on angular rates.

The following definitions and notation is used in subsequent mathematical development.

- x a 3 component vector representing the pilot's position with respect to inertial space (taken as earth fixed).
- g a 3 component vector representing the force/unit mass exerted on the pilot by gravity.
- f specific force, a 3 component vector of force/unit mass exerted on the pilot; represents all non-field forces such as the force on the pilot exerted by his seat.

---

[1] References 5, 7, and 8 contain some of the theoretical and empirical reasons for these sensing assumptions.

ω a 3 vector representing rotation rates of the pilot.

$\underset{p}{f}_1$ a letter under a vector indicates the frame in which the vector is to be coordinatized while a numerical subscript refers to a component of the vector. Hence $\underset{p}{f}_1$ is the first component of f in the "p" frame.

$T_{c/p}$ is a 3x3 matrix which converts a vector expressed in the p frame to its characterization in the c frame. Hence $\underset{c}{x} = T_{c/p} \underset{p}{x}$.

$(\dot{\ })$ A dot over a vector represents its time derivative taken in some inertial coordinate frame but possibly expressed in some other frame as is indicated by the letter under it.

$f^{(d)}$ A superscript is used to indicate a particular vector as defined in the text. For example, $f^{(d)}$ could mean the desired specific force.

Two coordinate frames are particularly important. The cab frame, indicated by a c, represents a frame attached to the cab (pilot). The approximately inertial frame of most interest is fixed to the pit in which the cab drives are mounted and will be denoted by p for pit frame. With this notation, we can write the equations of motion relating the cab acceleration, gravity, and the specific force. The translational equation of motion is

$$\underset{p}{\ddot{x}} = \underset{p}{f} + \underset{p}{g} = T_{p/c} \underset{c}{f} + \underset{p}{g}$$

$$\underset{p}{g} = \begin{Bmatrix} 0 \\ 0 \\ 32.2 \end{Bmatrix} \text{ ft/sec}^2 \qquad (1)$$

where g is the force of gravity per unit mass acting on the cab and f is the sum of all the nongravitational forces, called the specific force, which the pilot senses. The transformation T obeys the differential equation

$$\dot{T} = T(\omega \times) \tag{2}$$

where the cross product operator is used to refer to the anti-symmetric matrix corresponding to the regular vector cross product.

The transformation from the cab to the pit axis-system is defined using the three angles (see figure A.1 of Appendix)

$$\varphi = \text{roll angle}$$

$$\theta = \text{pitch gimbal angle}$$

$$\psi = \text{yaw gimbal angle.}$$

Then

$$T_{p/c} = \begin{bmatrix} c(\theta) & 0 & s(\theta) \\ 0 & 1 & 0 \\ -s(\theta) & 0 & c(\theta) \end{bmatrix} \begin{bmatrix} c(\psi) & -s(\psi) & 0 \\ s(\psi) & c(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & c(\varphi) & -s(\varphi) \\ 0 & s(\varphi) & c(\varphi) \end{bmatrix} \tag{3}$$

where c and s refer to cosine and sine respectively.

If we define

$$\omega = \begin{pmatrix} p \\ q \\ r \end{pmatrix} \tag{4}$$

then by differentiating (3) to obtain $\dot{T}$ and substituting $\dot{T}$, T, and ω in (4) and expanding the result, nine (9) differential equations in the dependent variables φ, θ, ψ can be obtained (elements of the 3x3 matrix on each side of the equation are equated). These nine (9) equations reduce to the three gimbal angle differential equations

$$\dot{\varphi} = p - (c(\varphi)q - s(\varphi)r)\tan(\psi)$$

$$\dot{\psi} = c(\varphi)r + s(\varphi)q$$

$$\dot{\theta} = \frac{1}{c(\psi)} (c(\varphi)q - s(\varphi)r) \tag{5}$$

The pilot actually feels the specific force (in the cab reference system).

$$f_c = T_{c/p} (\ddot{x}_p - g_p) \tag{6}$$

As a consequence of the previously stated assumptions regarding what a pilot feels and does not feel, the numerical value of f_c should be as close as possible to the specific force vector at the pilot's location of the aircraft simulated by the computer. The pilot has no sense of the individual terms on the right hand side of equation (6) (attitude as represented by T, cab acceleration, $\ddot{x}$, and gravity, g) so that these taken individually do not have to agree with the corresponding relations for an actual airplane. This fact allows some trading of one motion for another.

The cab control system accepts as commands position signals and gimbal angle commands. (In fact, the cab cannot respond perfectly to these commands but time delays, inertias etc., will be ignored here). The calculation of cab drive system signals requires a double integration of equation (1) and a single integration of equation (5). The initial conditions on velocity ($\dot{x}$), position (x) and attitudes (θ, ψ and φ), are all free to the extent that (5) and (6) have values consistent with comparable values for the simulated airplane.

2.2 Mathematical description of motion constraints. — The Ames All-Axis Motion Generator contains motion limits which can be (to a good approximation) mathematically depicted by magnitude restrictions on translational positions, velocities and accelerations, as well as the rotational angles, rates and accelerations. As an example of these limitations consider the lateral translational drive system. If we denote lateral motion of the cab in the pit frame by the scalar y [2], the constraints for this motion are

$$
\begin{aligned}
|y(t)| &\leq 9\text{ft} \\
|\dot{y}(t)| &\leq 14\text{ft/sec} \\
|\ddot{y}(t)| &\leq 7\text{ft/sec}^2
\end{aligned}
\qquad (7)
$$

Since the constraints involve derivatives (termed first - and second-order constraints in some optimization literature) only certain regions of the phase space determined by y and $\dot{y}$ are permitted at any given time unless we are willing to bounce against a constraint at a later time. Figure 2.1 depicts the portion of the phase space which equations (7) dictate, as well as the region which must be maintained to avoid hitting hard stops at a later time.

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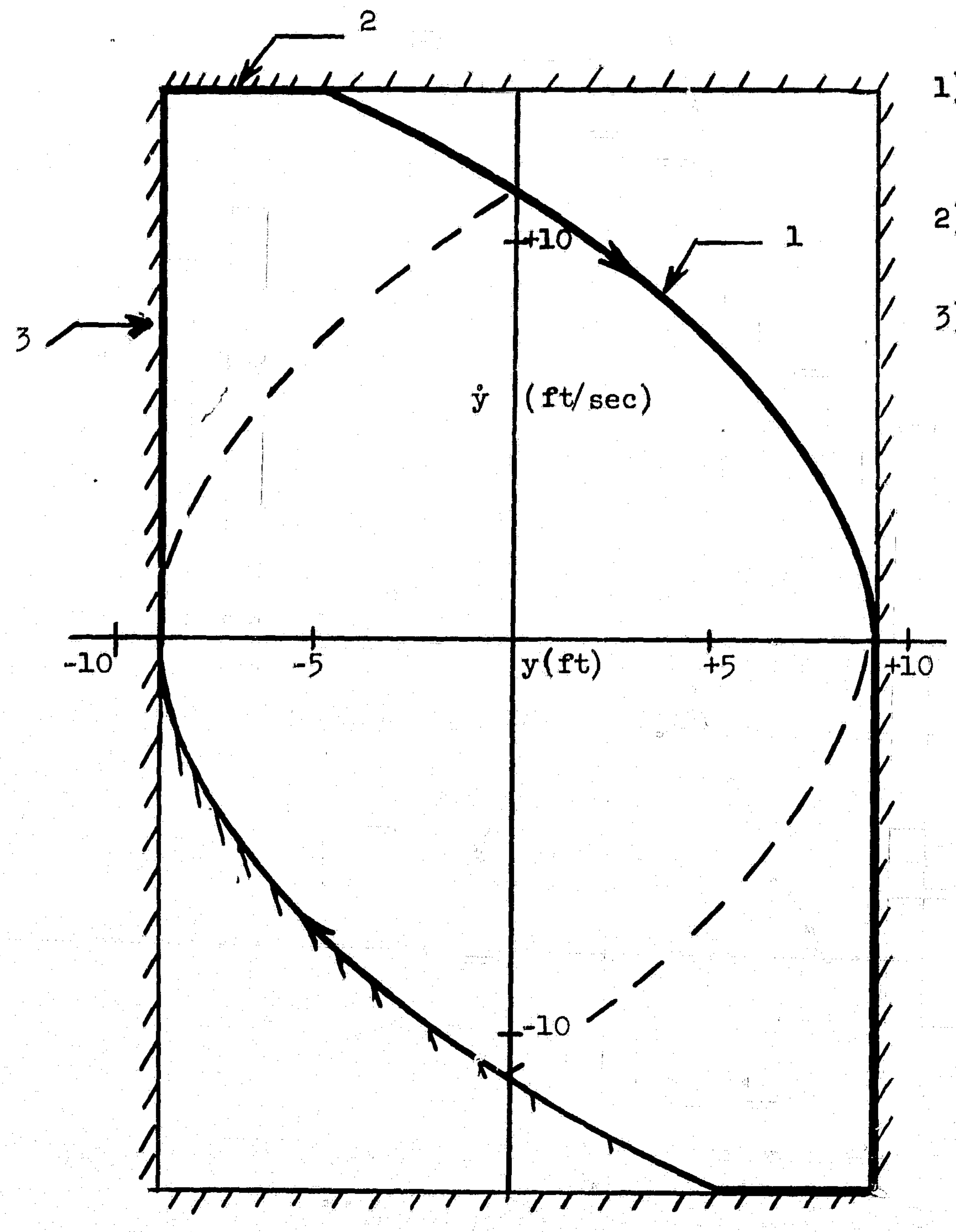
[2] The scalar y is the second component of x_p. That is $y = x_{p_2}$.



1) velocity constraint imposed by acceleration and position limits
2) velocity constraint imposed by the drive system servos
3) position constraint on travel

Figure 2.1 - Phase Plane Representation of All-Axis Lateral Drive Constraints.

In this figure, boundaries 2 and 3 are determined directly from equations (7). Boundary 1 is obtained by considering the maximum accelerations which can be used to offset the velocity the cab has at a given position. If the cab position strays from the inner region enclosed by the curved lines, it is committed to a hard cutoff.

It is instructive to consider the simulation problems associated with the constraints of equation (7) if only this channel were being used (no tilts, forward accelerations etc.) and the computer indicated a constant side force on the pilot for a long duration of time. Figure 2.2 depicts what would have to be done to simulate a specific side force of 2 ft/sec^2.

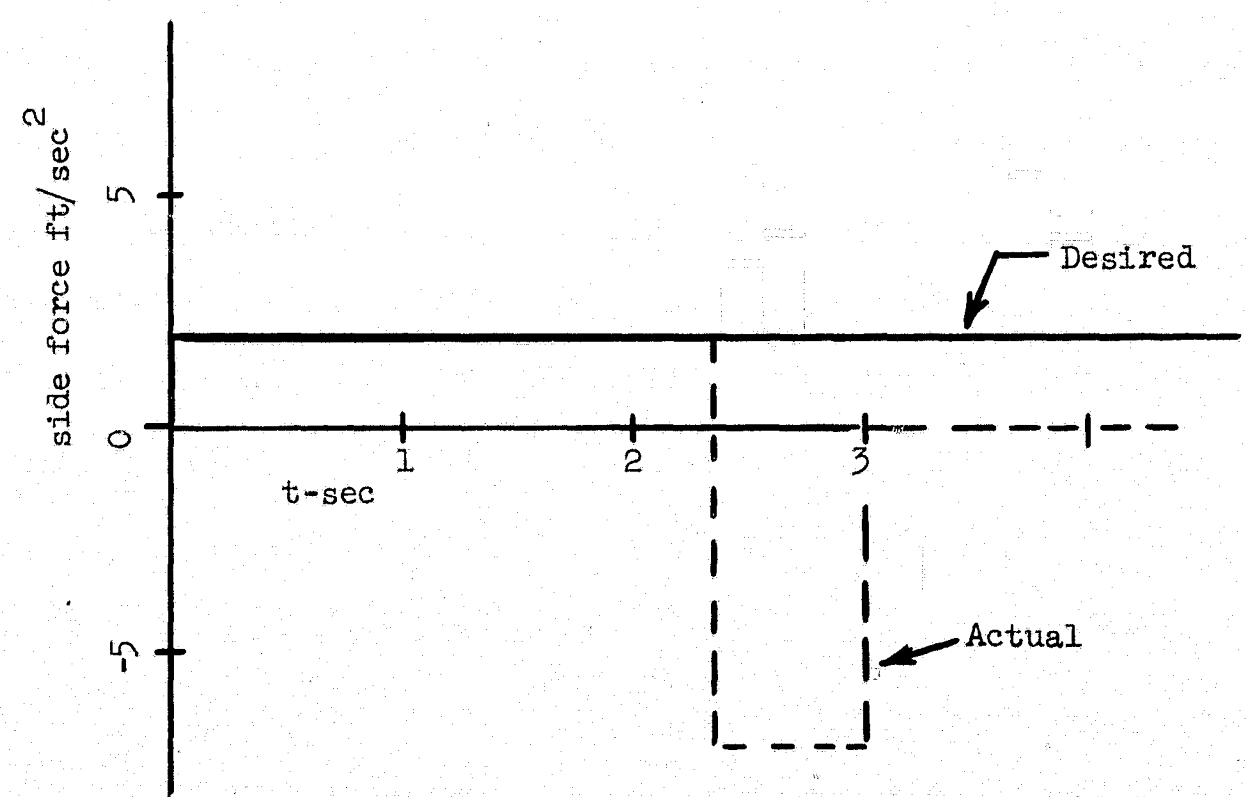


Figure 2.2 — Effects of Constraints on Ability to Generate a Constant Side Force.

As can be seen, after 2.4 seconds, boundary 1 is reached and full negative acceleration of 7 ft/sec^2 is applied for approximately 0.68 seconds to stop the cab just before hitting the position limits. This abrupt deceleration would give the pilot a totally anomolous motion cue. Given only this degree of freedom the only compromise would be to scale down the constant acceleration and possibly change its profile somewhat although eventually the acceleration must go negative and then to zero or else the cab hits the position limits. Alternatively, long constant accelerations could be abandoned entirely.

2.3 <u>Traditional approach to motion drive signal shaping.</u> – The simple example cited in the previous section illustrates the problem created by constraints and suggests the possible motion cue modifications which must be made. The most widely used modification consists of passing the computed accelerations through linear networks, historically referred to as washout circuits, which attenuate low frequency accelerations and allow rapidly varying terms (i.e., those with small integrals) to pass through. The term washout in this report is used to apply to any computer signal modification to obtain acceptable motion command signals.

The purpose of a washout filter in a translational channel is somewhat different from that in an attitude (rotational) channel. To facilitate understanding both types of washout, an example of each type is presented.

2.3.1 <u>Washout for a translational channel.</u> – Because the specific force and gravity on an aircraft are bounded, it follows that its acceleration is also bounded (see equation (1)) so acceleration limiting may not be a problem. However, as with the simple example discussed previously, specific force can be applied for a long time in one direction so that large positions (much larger than the motion simulator limits) can build up. A typical washout filter used to reject these long, slowly varying (low frequency) accelerations is shown in figure 2.3.

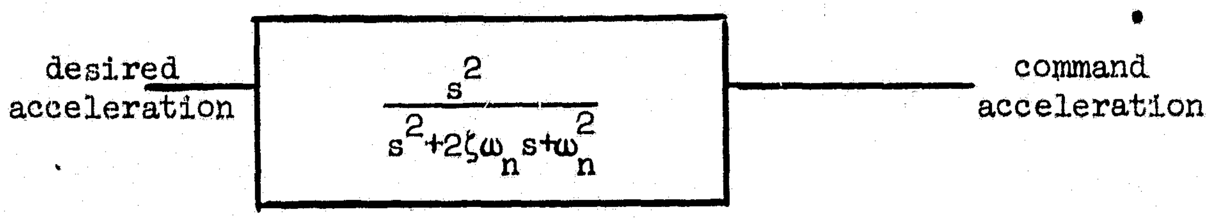
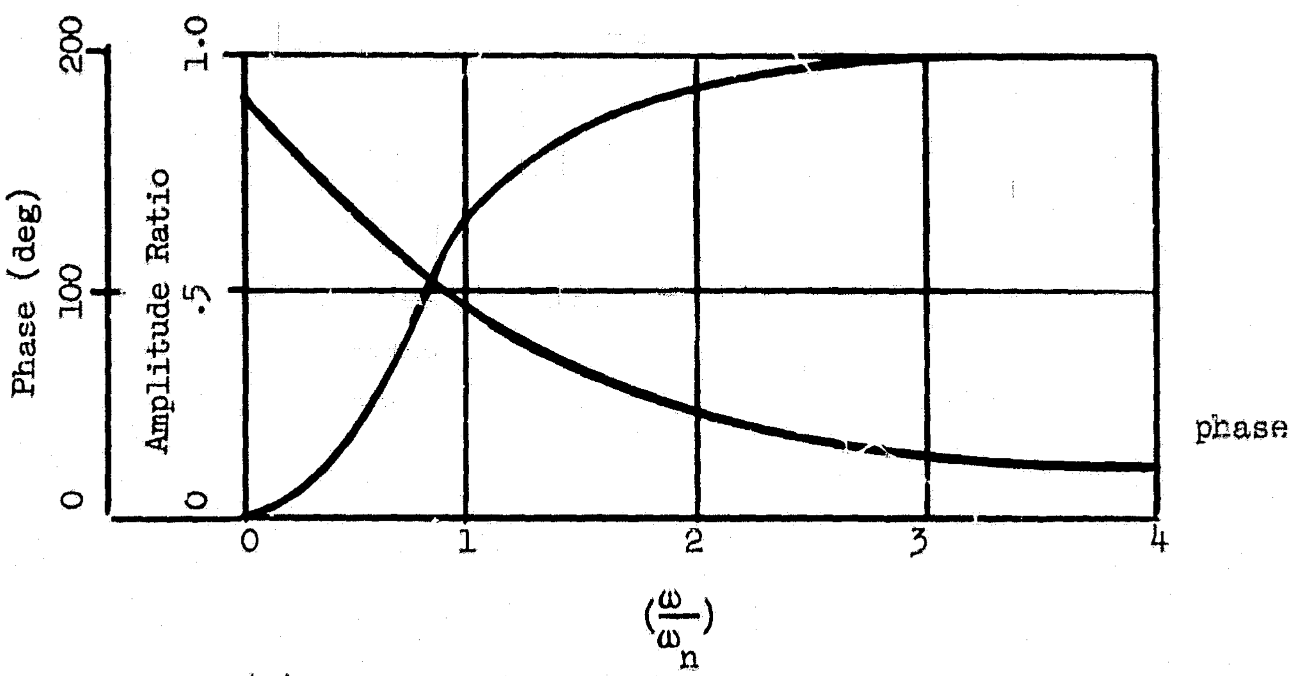
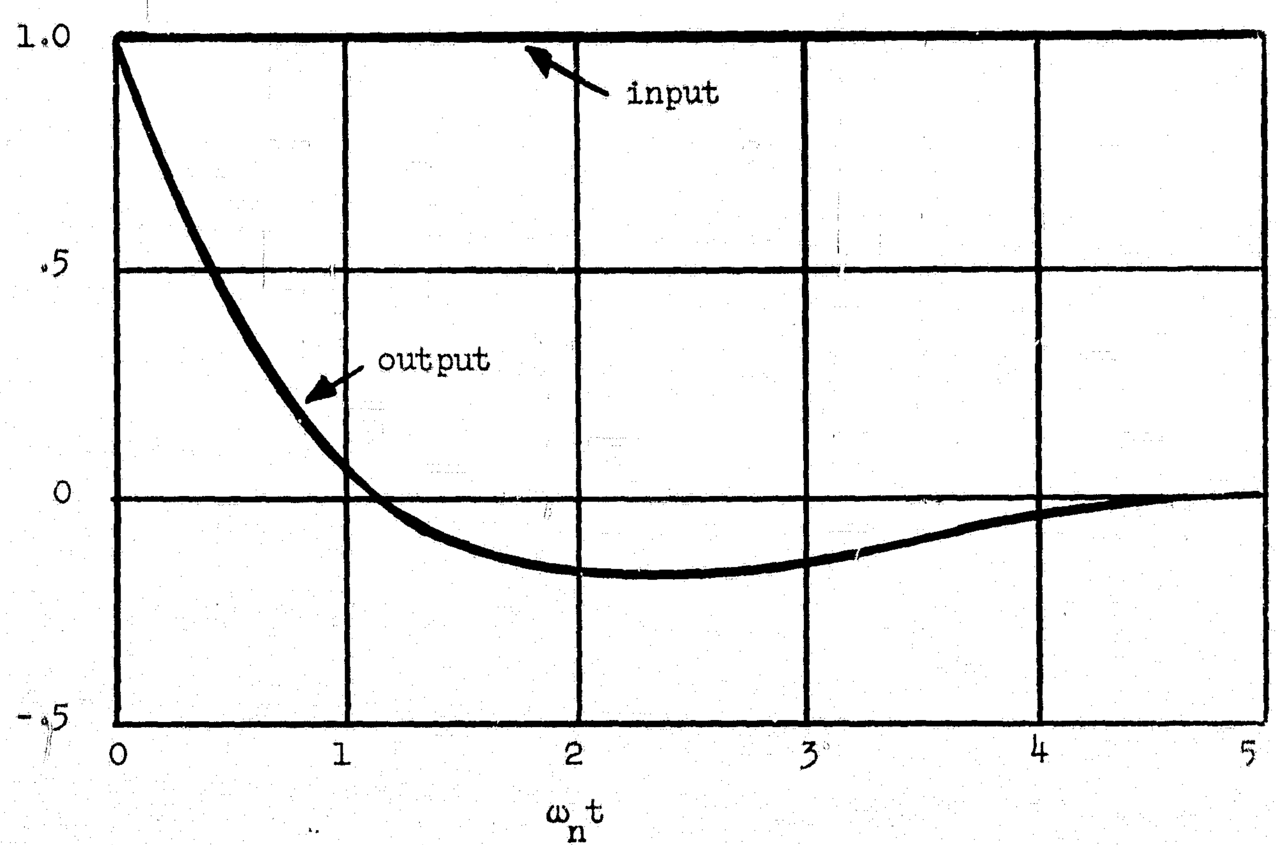


Figure 2.3 - Washout filter for a linear drive channel.

The frequency and transient response characteristics of such a filter are illustrated in figure 2.4. The damping ratio was selected at the numerical value $\zeta = 0.75$ for illustrative purposes. In order to interpret these graphs, we need to choose a value of ω_n. It should be noted from figure 2.3 that the steady state position for a constant desired acceleration is (assuming zero initial conditions)



(a) Frequency response for linear washout filter.



(b) Unit step response for linear washout filter.

Figure 2.4 - Frequency and step response characteristics for translational channel washout filter.

$$\text{Position} = \frac{\text{Desired Acceleration}}{\omega_n^2} .$$

If we assume a constant desired acceleration of 7 ft/sec^2 then to stay within the 9 foot position limits of the All-Axis Generator (see Appendix) ω_n must be about

$$\omega_n = \sqrt{7/9} = .882 \text{ rad/sec}$$

From figure 2.4a, it can be seen that if ω/ω_n is larger than about 2, the amplitude response is nearly constant. This ratio, $\omega/\omega_n = 2$, corresponds to $\omega = 1.76$ rad/sec or a frequency of 0.38 H_z. The phase lead at this frequency is still high (approximately 45°). In a pilot control problem the phasing of the signal is also very important. From figure 2.4a it is seen that the frequency must be greater than about 1H_z before the motion reproduction of the pilot command signals are appropriately presented.

The step response time history shown in figure 2(b) illustrates the output of the high pass filter subjected to a step input in acceleration (and sensed force) must occur to stop the cab. This reversal occurs when $\omega_n t$ is approximately 1.2.

In addition to high pass filtering, force scaling may also be used. For example, if a scaling factor of 1/4 is used, then ω_n can be reduced by a factor of 1/2. Such scaling allows the preservation of correct direction at lower frequencies but with less than true amplitude.

2.3.2 Washout for a rotational channel. – With the possible exception of stunt flying (barrel rolls, spins, etc.), the pitch and roll attitudes are usually constrained in the real or simulated aircraft. Yaw is not constrained since steady turns are part of normal flying. Euler angle rates for all cases are constrained. Hence, for many normal problems the attitude cues could be exactly represented with the gimbal angle capability of the All-Axis Motion Generator. If only tilt channels are used, however, the pilot will experience peculiar specific force sensations when coordinated steady turns or other similar maneuvers are simulated. This effect can be most easily demonstrated by considering a maneuver involving small angle deviations from a level flight condition. In this case the gimbal angles will be small and are conveniently depicted by the vector

$$\rho = \begin{Bmatrix} \varphi \\ \theta \\ \psi \end{Bmatrix}$$

For this case, the cab and pit axis are closely aligned and the transformation between them can be approximated by

$$T_{c/p} \approx I - (\rho x) \qquad (8)$$

In a trim condition, the airplane lift provides specific forces primarily along the aircraft's (normal) axis, that is, f_c should be approximately of the form

$$f_c = \begin{Bmatrix} 0 \\ 0 \\ -32.2 \end{Bmatrix}$$

However, substituting (8) into (6) without any translational motion $(\ddot{\underline{p}} = 0)$ gives

$$\underline{f}_c \approx \begin{Bmatrix} 0 \\ 0 \\ -32.2 \end{Bmatrix} + \begin{Bmatrix} 32.2\theta \\ -32.2\varphi \\ 0 \end{Bmatrix} \tag{9}$$

We see that the undesired specific force from attitude-only motions is

$$\underline{f}_c^{(e)} = \rho \times \underline{g}_p = \begin{Bmatrix} \theta|g| \\ -\varphi|g| \\ 0 \end{Bmatrix} \tag{10}$$

Equation (10) shows that rotations other than about the gravity vector create undesired forces. In simple physical terms, the unwanted forces are proportional to the tilt angles.

If we only have a rotation channel, then this undesired force must be accepted. However, we can reduce the effects of the force by using a washout filter to gradually restore the cab to an upright position ($\rho = 0$). A circuit appropriate for this is illustrated in figure 2.5.

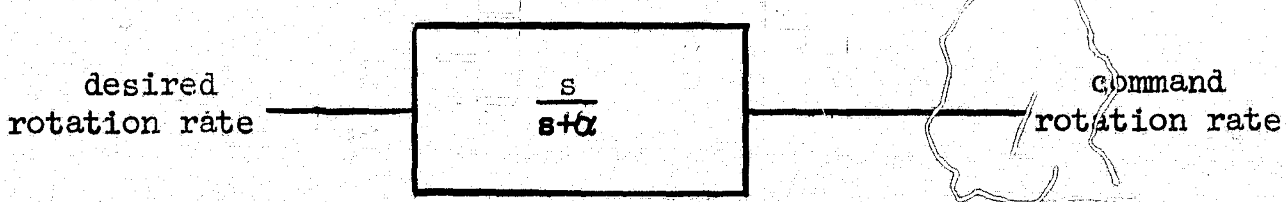


Figure 2.5. - Washout filter for a rotational channel.

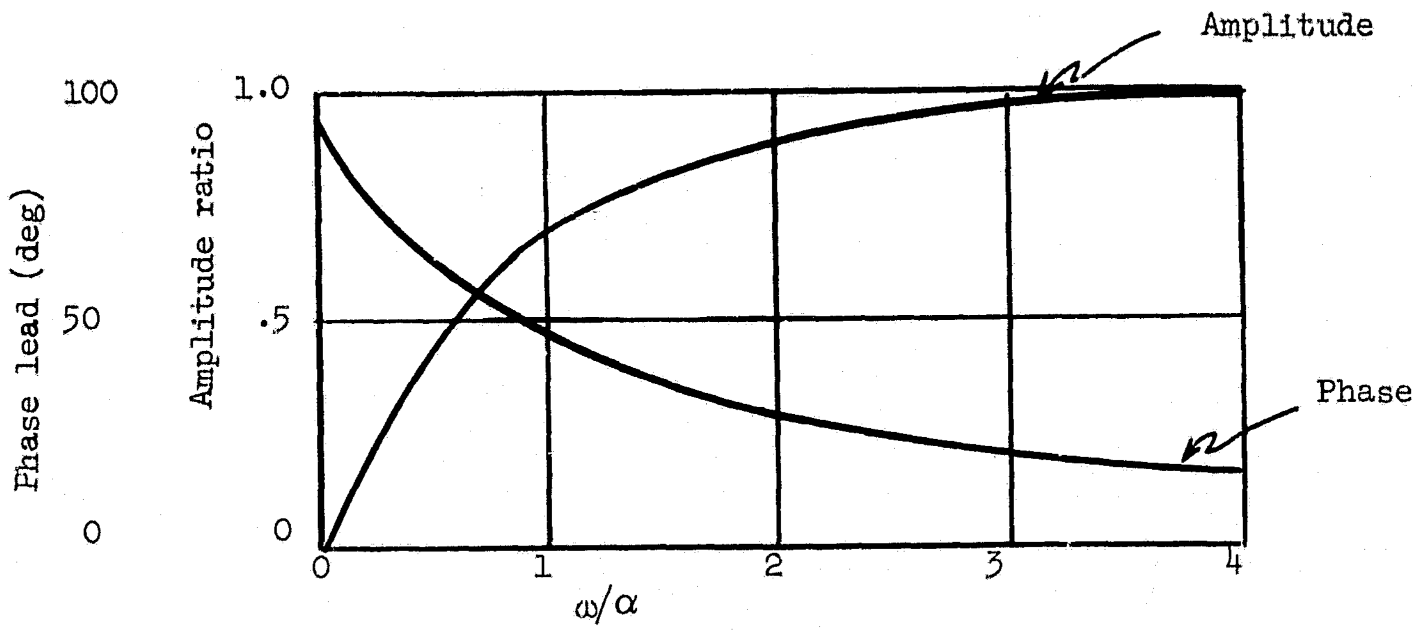
The frequency and unit pulse response for this first-order filter are illustrated in figure 2.6. Shown in figure 2.6(b) is the rotation angle which produces the undesired forces. As an example let the input pulse amplitude be .2 rad/sec and the reciprocal time constant α, equal 0.5. Then the maximum undesired specific force, f_{max}, occurs at $t \approx 4$ seconds and has a value of

$$f_{max} = (.2)(2)(.9)(32.2) = 11.6 \text{ft/sec}^2$$

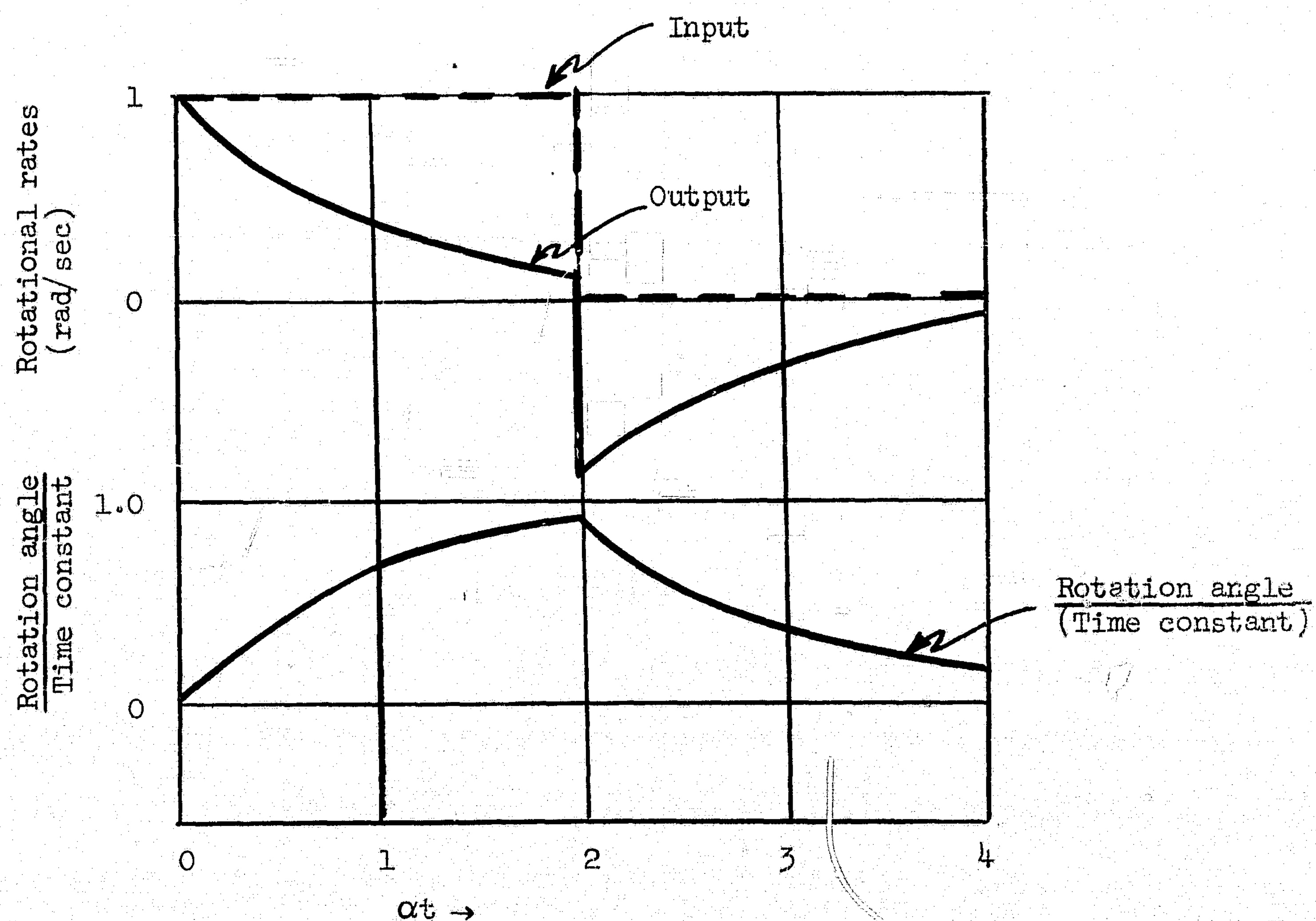
This undesired specific force reduces with time since the cab gradually restores to an upright position.

The removal of the undesired force is accomplished by the added anomolous rotation rate (difference between input and output of figure 2.6(b)). We see therefore that at best only a compromise can be obtained since in attempting to remove one anomolous "cue" we have introduced a second anomolous motion. One may also reduce the gain in the rotational channel. This permits a reduction in anomolous forces as well as anomolous rotation motions at the penalty of a reduced amplitude.

2.4 <u>Cab tilts for the representation of longitudinal and lateral force</u>. – As was noted in section 2.3.1, the translational drives of a motion simulator cannot provide the cues associated with the low frequency components of a specific force. It is possible to provide a "feel" of longitudinal and/or lateral force by tilting the cab. For small angles, equation (10) shows that the force is proportional to the product of the tilt angles and the magnitude of the gravity vector. For a single rotation channel φ, for example, we could utilize the roll command logic illustrated



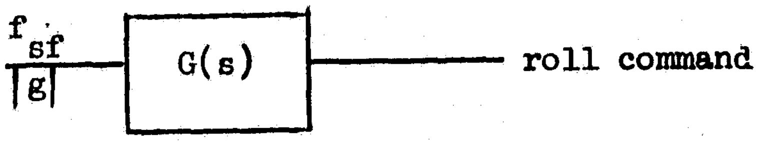
(a) Frequency response for rotational washout filter.



(b) Unit pulse responses for rotational washout filter.

Figure 2.6 - Frequency and time responses for a rotational channel washout filter.

in figure 2.7.



f_{sf} = desired side force

$|g|$ = magnitude of gravitational attraction per unit mass

Figure 2.7. - A roll command circuit for generating side force.

The transfer function G(s) has been included in the command logic to provide a means of suppressing some of the undesired rotation cues. In the conventional aircraft the pilot sensed lateral force is primarily associated with side-slip and yawing acceleration. The lateral force due to yaw acceleration arises from the displacement of the cockpit from the c.g. of the aircraft. Unless at least a second-order lag network is used for G(s) abrupt inputs as from rudder pulses (causing yawing acceleration) will cause excessive cab rolling acceleration. Even with the second-order network this anomolous rolling acceleration cue could be felt by the pilot as an unusual rolling moment due to rudder motion. A somewhat similar problem can exist in the pitch channel. In this case unwanted pitching acceleration would result from such inputs as throttle movements.

In spite of these limitations, this technique is used successfully with the appropriate selection of G(s) (time lags) for particular situations.

SECTION 3

Washout Circuits for Multi-Degree of Freedom Motion Simulators

The procedure used to generalize the washout circuit design problem to the multi-degree of freedom case will be considered in three steps. First, we try to provide the specific force cues with the translation drive channels. Second, we try to obtain good rotational acceleration cues using the rotational channels. Third, compromises between the channels are made so that rotations, for example, can be used to create side force cues using coordinated washout logic.

3.1 Washout circuits for the translation drive channels. — In normal flying tasks a pilot seems to resolve acceleration in a cab reference frame. In level or trimmed flight conditions the specific force vector lies approximately normal to the seat. If anomolous motion cues must be introduced it would seem desirable that the anomolies arising in a given cab reference channel be restricted to that channel. For example, some anomolous normal acceleration motion associated with a high g acceleration in the normal axis of the aircraft can probably be tolerated. Some anomolous lateral motion associated with essentially the normal force phenomena (as caused by normal force washout) is likely to be unpleasant. This coupling phenomenon adds an additional degree of complication to the multi-degree of freedom simulator which is not inherent in the simpler cases of section 2.

3.1.1 Washout in the pit (inertial) system reference axis. – As was shown in Section 2, the desired cab translation may be computed from knowledge of what the specific force, f, at the simulated cockpit should be. If f is specified in a cab fixed coordinate frame the relevant equation for computing translational motion is

$$\ddot{x}_p = T_{p/c} f_c + g_p \tag{11}$$

As has been previously noted $|\ddot{x}_p|$ is bounded but the position, x_p, may get arbitrarily large. Hence the signal $\ddot{x}_p$ must be modified rather than just integrated to give a cab position command signal which we will denote by

$x^{(c)}$ = cab translational drive (position command signal)

A washout circuit which will accomplish this end is depicted in figure 3.1. The quantities K_a, ω_n, and ζ of the figure are scalar gain, natural frequency and damping ratio respectively. The damping ratio, ζ, must be positive from stability considerations.

Assuming the translational drive system is perfect, the specific force felt by the pilot, which will be denoted by $f^{(p)}$, would be

$$f_c^{(p)} = T_{c/p}(\ddot{x}_p^{(c)} - g_p)$$

$$= T_{c/p}(K_a \ddot{x}_p - \omega_n^2 x_p^{(c)} - 2\zeta\omega_n \dot{x}_p^{(c)} - g_p) \tag{12}$$

Substituting (11) into (12) gives the pilot sensed specific force as a function of the desired specific force. In particular

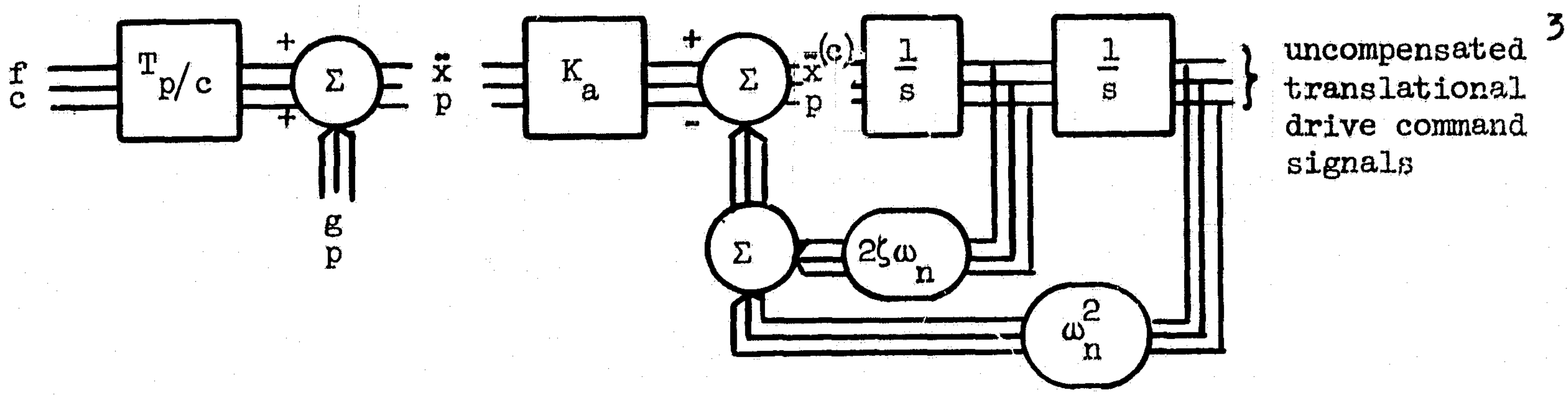


Figure 3.1 - Translational Washout Circuit in Pit Reference.

$$f_c^{(p)} = K_a f_c + T_{c/p}[(K_a - 1)g_p - \omega_n^2 x_p^{(c)} - 2\zeta\omega_n \dot{x}_p^{(c)}] \quad (13)$$

From this equation, it is apparent that only for the special case of $K_a = 1$ and $\omega_n = 0$ will the specific force on the pilot be identical to the true specific force cue.

If K_a is arbitrarily specified as unity in equation (13), the anomolous force sensed by the pilot, called $f^{(e)}$, can be written

$$f_c^{(e)} = T_{c/p}[\omega_n^2 x_p^{(c)} + 2\zeta\omega_n \dot{x}_p^{(c)}] \quad (14)$$

---

[3] The word uncompensated means without the lead compensation for minimizing the effects of drive servo lags (see Appendix).

If the cab is aligned with the inertial system (i.e., no rotation angles so $T_{c/p} = I$) then the specific force error time history in any channel resulting from a step desired force command would be unity minus the time history shown in figure 2.4. If, on the other hand, a rotation angle exists, the transformation $T_{c/p}$ will cause error coupling to occur. That is, the error quantities for any channel in the brackets of equation (14) will couple into all the channels of the specific force error as sensed in a cab reference frame.

If the scaling K_a is not unity, the error in the pilot sensed specific force can be written as

$$f_c^{(e)} = (1-K_a)[f_c - T_{c/p}\, g_p] + T_{c/p}(\omega_{n_p}^2 x^{(c)} + 2\zeta\omega_{n_p} \dot{x}^{(c)}) \qquad (15)$$

The second term is identical to equation (14) with the coupling effect described above. It should be noted that the first term will also produce coupling effects as the result of the use of the pit frame for washout. If we assume small angles so that the approximation of equation (8) can be utilized, and let $\omega_n = 0$, then equation (15) becomes

$$f_c^{(c)} \approx (1-K_a)[f_e - g_p - \rho \times g_p] \qquad (16)$$

The cross product term is a coupling effect. As a result, rotations about a vector in the level plane of the pit will in general produce coupled lateral and longitudinal forces analogous to those of the tilt of section 2.4.

The coupling problems inherent in these examples might be partially alleviated by some modification to this straight-forward scheme of washout directly in the pit frame.

3.1.2 Scaling of specific force in cab reference. - The coupling problem associated with scaling can be removed by appropriately scaling the specific force vector in the cab reference frame. If the commanded specific force vector is redefined as being one g along the cab normal axis plus the scaled perturbations of the desired specific force from one g, the coupling problem is removed. Figure 3.2 illustrates this type of scaling.

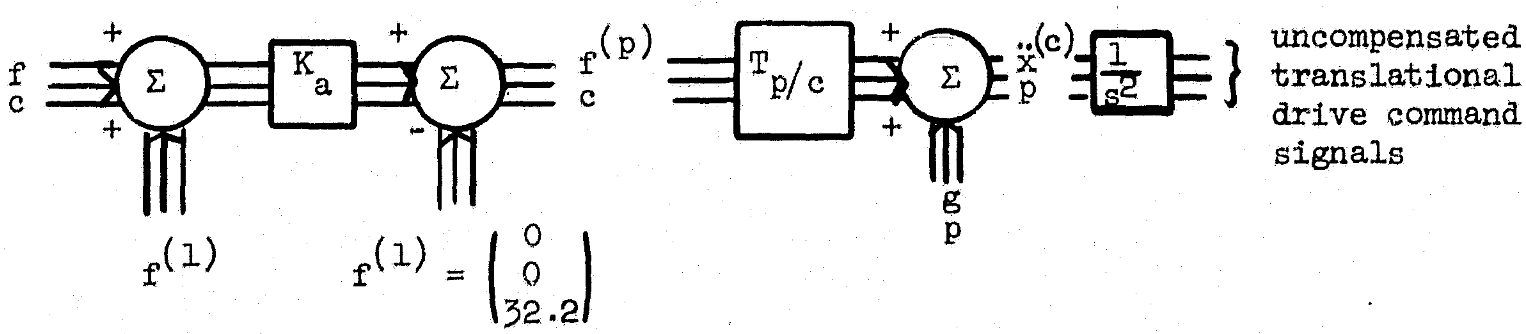


Figure 3.2. - Translational Washout Circuit With Simple Scaling.

With this logic the actual force felt by the pilot is given by

$$f_c^{(p)} = K_a[f_c + f^{(1)}] - f^{(1)} \tag{17}$$

The actual specific force is the scaled sum of desired specific force and one g normal force minus the one g normal force, $f^{(1)}$. If we assume small rotations again

$$\ddot{x}_p^{(c)} = K_a[I+\rho\times]\{f_c + f^{(1)}\} - \rho\times f^{(1)} \tag{18}$$

The first term of equation (18) is approximately the scaled linear acceleration. If the task were such that the scaled relative position were bounded, then the contribution of this term of $x_p^{(c)}$ can be made arbitrarily small by the setting of K_a. The second term of equation (18) is the drive signal acceleration required to eliminate coupling due to rotations. This term would cause unreasonable displacements unless limitations on the rotation time histories which constrain the double integral of this term occur.

Although such a design can potentially remove the coupling, it forces the rotation channels to be carefully designed to avoid the limiting of the translational channels.

3.1.3 Washout in cab reference. - It may appear that some of the coupling problems could be removed by using an appropriate high pass filter on the desired specific force vector in the cab reference frame.

An example of such a scheme is shown in figure 3.3.

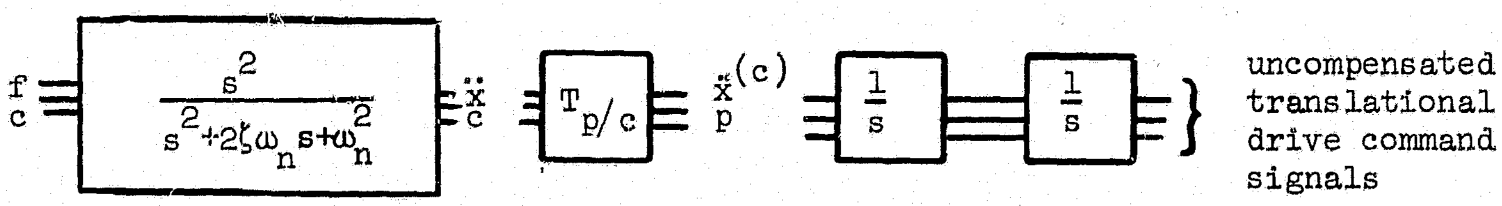


Figure 3.3 - Translational Drive Washout Circuit in Cab Reference.

Since the washout dynamics are in the cab reference, we see that the rotation transformation does not cause a coupling. For example, the distracting force felt in the normal channel will not be transformed to the side force channel as a result of rolling motions.

This circuit has other problems, however, two of which are:

1) The specific force felt by the subject depends on the rotation (gimbal quantities)

$$f_c^{(p)} = \ddot{x}_c^{(c)} - T_{c/p}\, g_p \tag{19}$$

The vector $\ddot{x}_c^{(c)}$ can have a zero value and the unwanted side force of the cab rotations is felt by the pilot.

2) The fact that the double integral of $\ddot{x}_c$ is bounded does not imply that $x_p^{(c)}$ is bounded. This can be seen by using the small angle approximation for $T_{c/p}$ as follows

$$\ddot{x}_p^{(c)} \approx \ddot{x}_c + \rho \times \ddot{x}_c \tag{20}$$

Although the double integral of the first term of equation (20) is bounded it is obvious that if ρ is arbitrary it could be so selected that the double integral of the second term is not bounded.

This problem might be overcome by additional washout in the pit reference frame in figure 3.1. The combination of both these circuits with appropriately chosen constants could give considerably less coupling than washout in pit reference only (figure 3.1) and appears worthy of further study.

3.2 Washout for rotational channels. — Previous discussion has brought out two undesirable effects that can accompany rotational motion. First, coupling terms occur due to translational washout logic. Second, anomolous specific force vector cues of the type discussed in section 2 occur. Hence it appears desirable to maintain the cab or restore the cab to an upright position whenever possible, and keep any tilt rotations small. A compromise between the presentation of the correct rotational cues and the unwanted specific force cues which result from rotations is required but for simplicity we consider rotational motion only first.

The relationships between gimbal rates and cab rates and vice versa are given by

$$\begin{pmatrix} \dot\varphi \\ \dot\theta \\ \dot\psi \end{pmatrix} = \begin{bmatrix} 1 & c(\varphi)\tan(\psi) & s(\varphi)\tan(\psi) \\ 0 & c(\varphi)/c(\psi) & -s(\varphi)/c(\psi) \\ 0 & s(\varphi) & c(\varphi) \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} = T_{g/c}\,\omega \qquad (21)$$

$$\begin{pmatrix} p \\ q \\ r \end{pmatrix} = \begin{bmatrix} 1 & s(\psi) & 0 \\ 0 & c(\varphi)/c(\psi) & s(\varphi) \\ 0 & -s(\varphi)c(\psi) & c(\varphi) \end{bmatrix} \begin{bmatrix} \dot\varphi \\ \dot\theta \\ \dot\psi \end{bmatrix} = T_{c/g} \begin{pmatrix} \dot\varphi \\ \dot\theta \\ \dot\psi \end{pmatrix} \qquad (22)$$

Equation (21) can be used to illustrate the fact that washing out the body rates by a high pass filter does not necessarily force the cab to return to zero. Equation (22) can be used to illustrate that if washout is done in a gimbal drive reference, then a coupling between channels exists when simultaneous rates are commanded.

Figure 3.4 illustrates rotational washout wherein either washout in body axis or gimbal drive axis or a combination may be obtained.

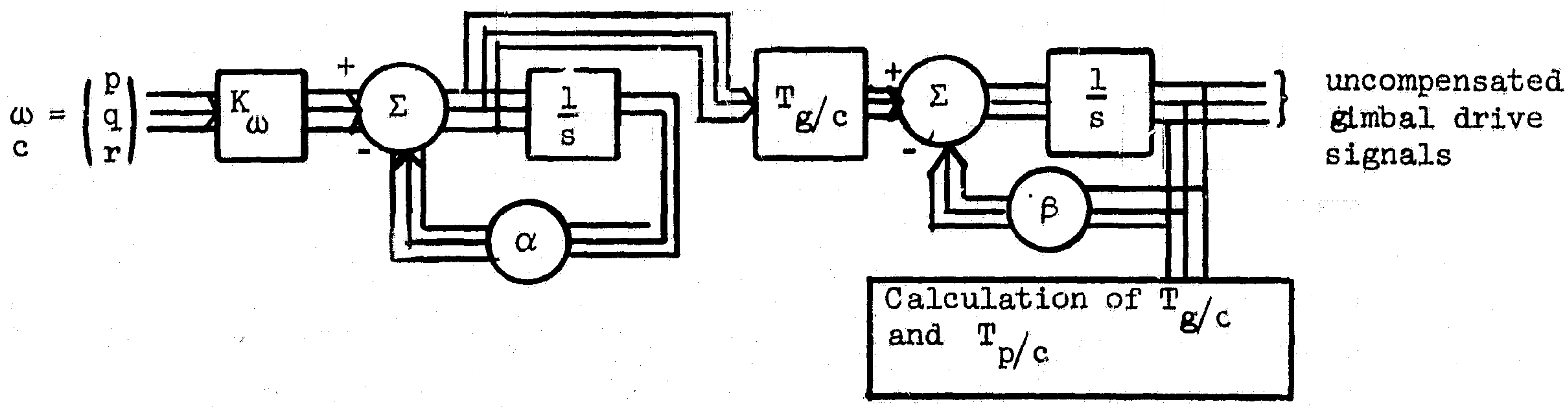


Figure 3.4 - A Washout Circuit for Rotational Channels.

This circuit represents three channels of rotational calculations. The scalar gain K_ω can be used to reduce the magnitude of the cab motions. The gain, α, permits a body axis washout whereas the gain, β, permits a cab gimbal axis washout.

As mentioned earlier some non zero value of β is necessary if we want to insure that the cab returns to the upright position. The effect of offset tilts, however, is task dependent and can be quite small.

A procedure which appears feasible for choosing K_ω, α, and β for a particular task and pilot involves the following three steps starting with $K_\omega = 1$ and $\alpha = \beta = 0$.

1) Set K_ω as small as tolerable for the task and pilot involved.
2) If K_ω is non zero then set α at the smallest tolerable level for removing unwanted specific forces created by tilts,

3) If α is non zero and some residual offsets accrue during the simulation experiments then adjust β to the smallest permissible value for compensating for the residual offset.

Typical values of $K_\omega = 0.5$ and $\alpha = 0.5$ have been used by various investigators.

3.3 Washout circuits with coordinated translational and rotational drives. - The previous sections have briefly discussed some problems associated with the rotational and translational drives considered independently. This section considers the combined problem in two steps.

First, the ideas of section 2.4 are expanded. Offset tilt angles can be used to actually provide longitudinal and side force cues for slowly varying specific forces. Second, the means of coordinating the rotational and translational drive circuitry to utilize this effect is developed. The compromises involved here will be trades between good longitudinal and lateral force motion cues and the amount of anomolous rotational motion.

3.3.1 Command signals for cab tilts. - The specific force vector felt by the pilot in cab axis reference is

$$f_c^{(p)} = T_{c/p}(\ddot{x}_p^{(c)} - g_p) \qquad (23)$$

Assuming that $\ddot{x}_p^{(c)} = 0$ and $g_p = \begin{pmatrix} 0 \\ 0 \\ 32.2 \end{pmatrix}$ then $f_c^{(p)}$ for a roll only type rotation is

$$f_c^{(p)} = \begin{pmatrix} 0 \\ -32.2 \sin\varphi \\ 32.2 \cos\varphi \end{pmatrix} \qquad (24)$$

For small angles a rotation angle (in radians) equal to

$$\varphi = - f_{c_2}/32.2 \qquad (25)$$

where f_{c_2} = desired side specific force in ft/sec^2, gives a proper force cue. This obviously only works if $|f_{c_2}|$ is modest, for example less than .2 or .3 g's. Under these circumstances the wrong sense of normal force is small.

The maximum lateral acceleration of the linear drive is about .22 g's. These small rotations are therefore compatible with the maximum side force of the lateral drive system. Rotation commands could be generated using relations like equation (25) for one axis problems. However, an alternative relation is needed to compute rotation commands for three axis problems.

To find such a relation we examine equation (25). It can be seen that when

$$g_c \times f_c = 0 \qquad (26)$$

the rotation angles produce the desired forces. But g_c in this equation can be written

$$g_c = T_{c/p} \begin{Bmatrix} 0 \\ 0 \\ 32.2 \end{Bmatrix} = \text{gravitational attraction per unit mass in the cab frame}$$

so that the choice of washout logic involves a scheme which drives the gimbal angles so that g_c will be parallel to f_c. A feedback circuit which accomplishes this is given in figure 3.5.

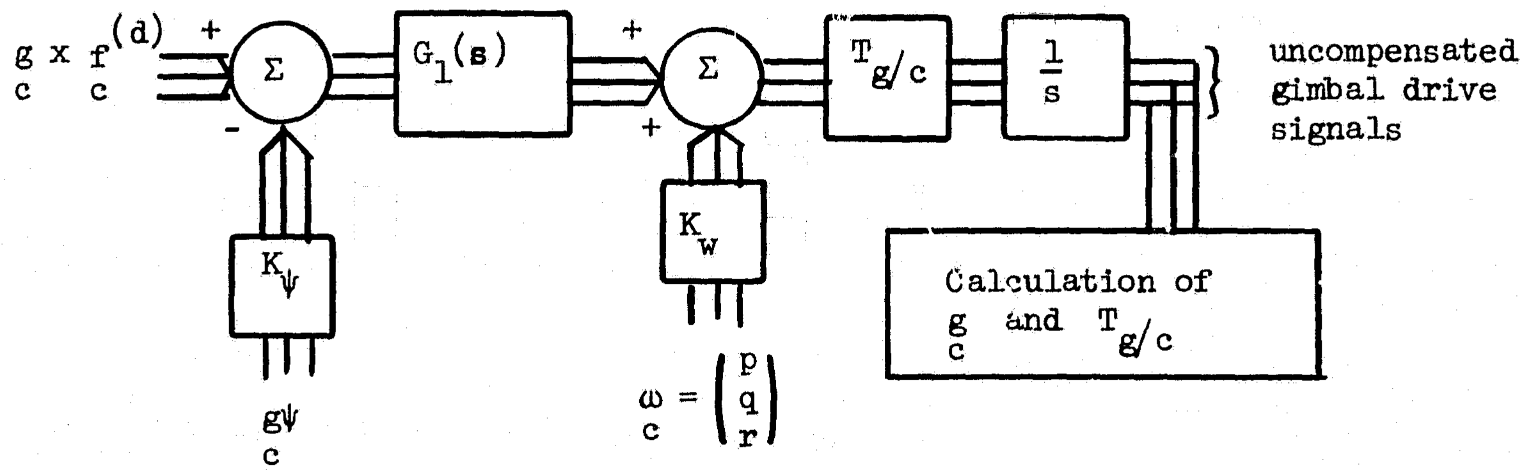


Figure 3.5 - A Washout Circuit for Rotational Drives Incorporating Cab Tilt Features.

Precautions are taken in this logic to avoid large rotation angles. In particular, the signal f_c is replaced with a scaled down version $f_c^{(d)}$.

$$f_c^{(d)} = \begin{Bmatrix} K_1 f_{c1} \\ K_2 f_{c2} \\ -32.2 \end{Bmatrix} \tag{27}$$

where K_1 and K_2 are chosen so that in any simulation maneuver of interest

$$|K_1 f_{c1}| < .2g$$

$$|K_2 f_{c2}| < .2g$$

The consequence of this definition is that

$$|f_c^{(d)}| \approx 32.2 \text{ ft/sec}^2$$

and, as usual

$$|g| = 32.2$$

so that

$$|g_c \times f_c^{(d)}| = (32.2)^2 \sin \delta \tag{28}$$

where δ equals the rotation angle error in the cross product.

In addition to commanding tilts for small specific force cues, the circuit in figure 3.5 is used to washout gimbal angles. Specifically, the $g_c \times f_c^{(d)}$ term provides negative feedback which drive gimbals to align the two vectors. The output of the $G_1(s)$ network will suppress the command rotation rate ω_c.

The cross product terms in figure 3.5 do not limit rotations in the yaw channel. The feedback, $g_c \psi$ is used for this purpose. This is a vector proportional in magnitude to the yaw gimbal angle ψ in the direction g_c. Hence, it accounts for washout normal to the $g_c \times f_c^{(d)}$ term.

$G_1(s)$ is a stable linear network selected to provide good feedback characteristics. Specifically, the network is chosen so that the overall system performance lies between the two extremes of

1) a high gain (tight) system which depicts **lateral and longitudinal** cues accurately but provides large anomolous rotation cues for rapid fluctuation of forces

and

2) a sluggish system which gives a nearly exact or proportional feel of rotational motion cues at the expense of anomolous force cues which will persist for long periods of time.

Specific choices of G_1, K_ψ etc. is accomplished by cut and try variations of the parameters.

3.3.2 Washout coordinating rotational and translational motion. — The principles developed in the previous section can be extended to yield a technique for designing a coordinated rotational and translational washout circuit. We start by transforming $f_c^{(d)}$ of equation (27) into the pit frame rather than the cab frame. This is done so that a correspondence between inputs to the translational channels (which are in a pit reference frame) and the inputs to the previously discussed rotation circuits can be obtained.

Define

$$f_p^{(d)} = T_{p/c}\, f_c^{(d)} = \begin{Bmatrix} f_1^{(d)} \\ f_2^{(d)} \\ f_3^{(d)} \end{Bmatrix} \tag{29}$$

The cab acceleration in the pit frame for the specific force given by (29) is

$$\ddot{x}_p = f_p^{(d)} + g_p \approx \begin{Bmatrix} f_1^{(d)} \\ f_2^{(d)} \\ 0 \end{Bmatrix} \tag{30}$$

The approximation that the third component of $f_p^{(d)}$ is equal to minus one g force is made in (30). This approximation is made since a normal force of one g cannot be given to the pilot continuously except for the cab in an upright position (tilt angles are zero).

From (30) we see that $\ddot{x}_p$ is in reality only a two component vector, that is, the command acceleration of the vertical drive channel is zero. If we develop a rotational error signal in the pit frame by expanding the cross product

$$g_p \times f_p = \begin{Bmatrix} -f_2^{(d)} \\ f_1^{(d)} \\ 0 \end{Bmatrix} |g| \tag{31}$$

then, we also have only two non zero components. Of particular note is that (31) can be readily formed from (30) by a sign change on one of the components, an interchange of the two components, and a scaling multiplier of $|g|$. As a result of these factors, and by making an appropriate choice of rotational error signal shaping, one can obtain a washout circuit coordinating the rotational and translational drives.

Figure 3.6 illustrates a coordinated washout circuit incorporating the various factors previously outlined. The functions of the various operations are indicated on the figure. As can be noted, the signal shaping network has been selected with an s^2 term in the denominator. This corresponds to a double integration which is the same operation used in calculation of the longitudinal and lateral position drives. Hence, two states of the shaping network correspond with the two position drives. As a matter of fact, the double integration in the position drive calculation could be omitted and these drive signals formed by the double integration

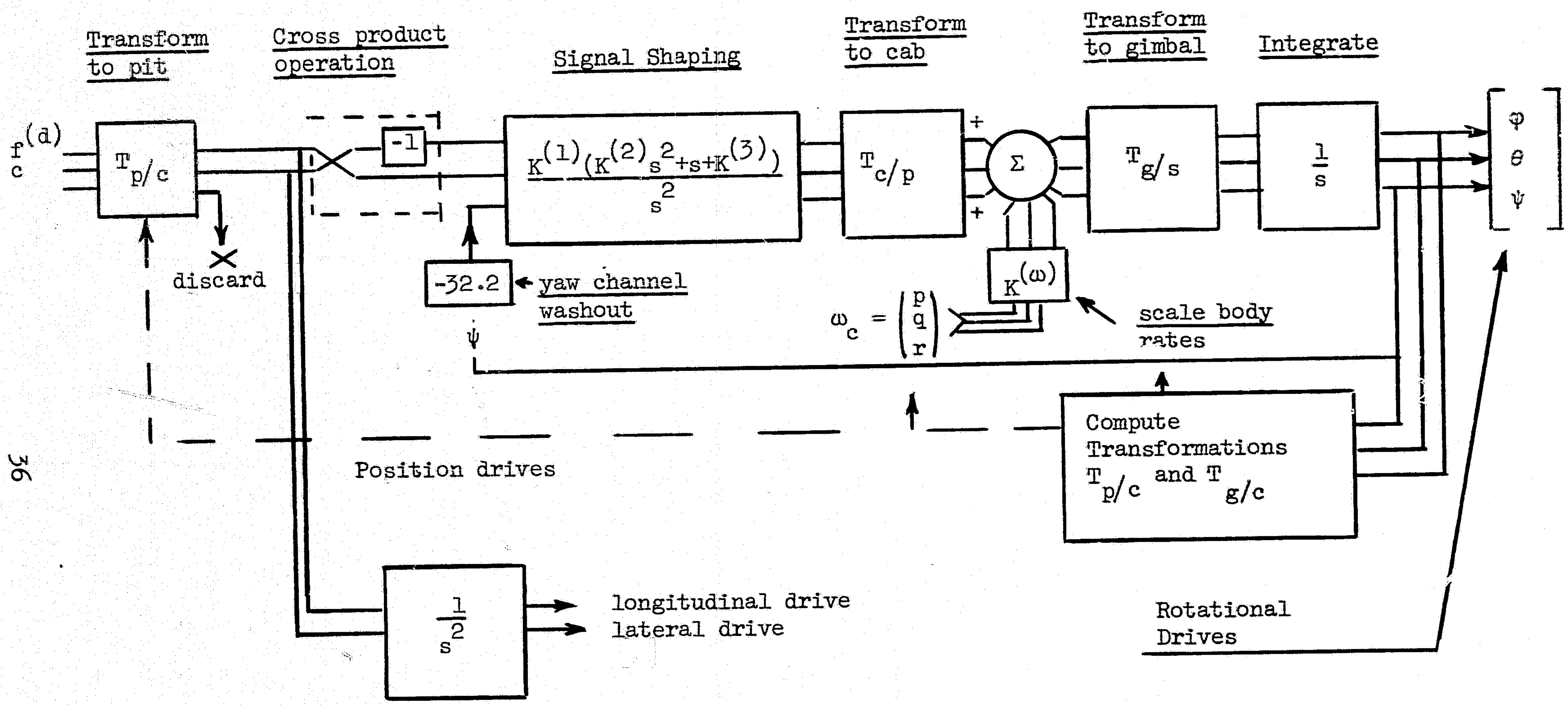


Figure 3.6 - A washout circuit coordinating rotational and translational drives.

of the shaping network. The shaping network was selected of the form indicated as a result of these considerations and that this choice forces the position drive signals to be bounded. This latter factor results from the fact that the washout circuit is a feedback control circuit. The feedback results since the transformation, $T_{p/c}$ is a function of the gimbal angles φ, θ, and ψ. This feedback will be outlined in more detail subsequently.

As was the case for the washout circuit of the previous section, there is no command from the cross product to drive the yaw gimbal to zero (washout about the g vector). This is quite obvious from equation (31) where the third component is identically zero. In figure 3.6, the quantity ψ is fed into the third channel of the shaping network to provide the required washout for rotations about the g vector (local vertical).

The output of the signal shaping network can be interpreted as the washout rates in pit axis. These rates are transformed to cab axis and summed with the desired body rates. In this washout circuit the desired body rates are defined as the product of the scale factor, $K^{(\omega)}$, and the body rates, ω_c, which come from the computer simulation of the aircraft.

The closed loop character of the washout circuit can be seen by assuming the small angle approximation for the $T_{p/c}$ transformation and examining components of the vector $f_p^{(d)}$.

$$f_p^{(d)} \approx [I + \rho\times]f_c^{(d)} = \begin{bmatrix} f_{1_c}^{(d)} - \psi f_{2_c}^{(d)} + \theta f_{3_c}^{(d)} \\ \psi f_{1_e}^{(d)} + f_{2_c}^{(d)} - \varphi f_{3_c}^{(d)} \\ -\theta f_{1_c}^{(d)} + \varphi f_{2_c}^{(d)} + f_{3_c}^{(d)} \end{bmatrix} \qquad (32)$$

With the definition of $f_c^{(d)}$ as given in equation (27) we see that the first component of $f_p^{(d)^c}$ is

$$f_{p_1}^{(d)} = (f_{c_1}^{(d)} - \psi f_{c_d}^{(d)}) - 32.2\theta \qquad (33)$$

Now if we interpret the bracketed term in (33) as the input and the θ term as the feedback we see part of the loop closure. By assuming the product transformation

$$T_{c/p} \cdot T_{g/c} = I$$

and referring to figure 3.6, the linear feedback circuit shown in figure 3.7 can be obtained for the pitch channel.

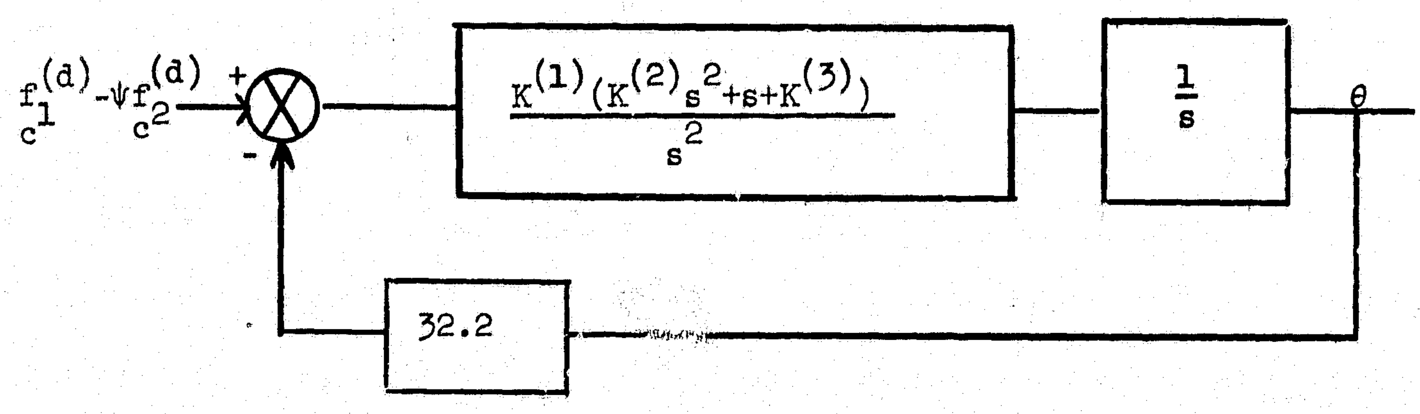


Figure 3.7 - Linearized Equivalent Circuit of Pitch Channel.

The other two channels can be shown to be equivalent to figure 3.7. For those familiar with stability analysis it should be obvious that the gains $K^{(1)}$, $K^{(2)}$, and $K^{(3)}$ can be selected to give a stable system. For the washout circuits like the above which were used in the study, the gains were set to obtain an appropriate transient response.

By examining figures 3.6 and 3.5 the following properties of this washout circuit can be summarized

a. For small amplitude disturbances the translational forces are properly presented for all frequencies.

b. Washout rates depend on the available linear travel and the rapidity of the force variations.

c. For a constant force the dynamic characteristics are such that the cab will arrive at the null linear position in the steady state. This occurs as a result of $K^{(3)} > 0$. The cab will be tilted to provide the force in the steady state solution.

d. Rate commands are washed out at a speed dependent on gain settings. No undesired specific force is felt for these rotation command inputs.

e. The third channel of the circuit is used for washout of the yaw gimbal angle ψ.

Hence, this washout circuit has many of the characteristics desired of motion command logic. Because it is recognized that long duration normal forces of other than one g cannot be commanded, we have essentially reduced the six degrees of freedom to five.

Since the normal force cues need consideration, it is recommended that they be introduced in this circuit by the use of the techniques outlined in section 3.1. In this case, we need only consider washout for the normal force in the cab reference since the remaining quantities are handled by the circuit of figure 3.6.

SECTION 4

Evaluation of Washout Circuits

Previous sections illustrated several promising techniques for washout circuitry for multi-degree of freedom motion simulators. Each technique requires the determination of various parameters such as gains (scaling of inputs), network time constants, etc. The choice of a particular technique and these parameters represents a particular compromise between the true motion that the pilot should sense and the motion cues that actually can be realized with the constrained cab. At this point, a difficult problem is encountered. We must find some testing and evaluation procedure which (a) determines the "best" set of parameters to use in a given configuration and (b) measures the effectiveness of a given configuration. This section discusses the results of research on testing and evaluation procedures.

4.0 Requirements for an evaluation procedure. - If only one washout configuration were to be tested, and 'reasonable' parameters for it were known from prior experiments, an efficient search technique for improvement might be implemented by using a particular task and trying different values of parameters. However, the more general problem involves the following considerations.

1) The procedures should always give comparisons of particular washout configurations with the two absolute extremes of real flight and fixed base simulation. The first extreme implies that a combination of real flight tests and simulations would be necessary for

evaluation unless a flight task with only limited motion (i.e. motion which the simulator can carry out completely) is used.

2) Good performance indexes to measure how well a pilot performs a given task in the simulator must be defined. This would permit analysis of the sensitivity of a pilot to motion cues and hence indicate their relative importance. Pilot opinion provides one such index but quantitative, less subjective measures such as mean-square average errors between actual and desired pilot response are also desirable.

3) Although a particular task and performance index might be found so that 1) and 2) above are satisfied, there remains the problem that the effectiveness of a washout circuit for one task may not prove its suitability for another task since the relative importance of motion cues can be task and aircraft dependent.

These considerations make the design of testing and evaluation procedures difficult. In this investigation, for example, a first attempt at defining a test and evaluation procedure employed the simulated task of performing a landing approach with a jet transport. Using pilot comments as an evaluation index, it was determined that the motion provided with a particular washout-circuit improved the overall simulator characteristics. However, moderate changes in the washout configuration did not seem to alter their opinions. It appears that this particular task (and airplane) does not require hi-fidelity motion and hence is not a good test for washout circuits.

Discussions with Ames scientists and test pilots indicated that the importance of motion cues is amplified in aircraft with degraded handling characteristics. If the landing task had been redefined with a poor aircraft, however, no comparison of simulation with realistic feel could be accomplished without actually performing the test with an airplane.

4.1 Definition of a promising evaluation procedure. — In contrast with the landing task, simulation of a relative position task, such as would occur in formation flying or refueling missions, appeared to offer better prospects. If a lead aircraft (formation flying) or a tanker (refueling) flys at a constant altitude and velocity, then the All-Axis Motion Generator can theoretically provide proper motion cues if the pilot is adept enough to stay within the 18 foot cube position limits of the simulator. The word theoretical is used since spurious (anomolous) motions will always exist due to imperfections in the mechanical systems associated with the cab drives (see Appendix).

Experiments were conducted to see if the formation flying task could be used in testing washout circuit configurations. The primary object of these experiments was to determine if this task could give comparisons between completely realistic motion and fixed base motion. Washout circuits, of course, would give intermediate motions.

Tests were conducted utilizing a variety of simulated aircraft and lead airplane motions. Several pilots took part in the tests, and, as will be seen in the subsequent descriptions, all indications are that significant differences exist between real and fixed base motion for this task. Hence, it appears quite appropriate for evaluation of washout circuits. The formation flying task and experiments conducted will now be discussed.

4.2 Description of the formation flying task. – Elements of the formation flying task simulation are illustrated in figure 4.1. The pilot in the cab is given a visual display generated by the REDIFON. The display consists of a model of the Convair 990 where the REDIFON camera is initially positioned directly behind the 990. A sketch of the TV display for initial conditions is illustrated in figure 4.2. Shown also in figure 4.2 are the approximate boundaries for the lateral and vertical drives of the All-Axis Motion Generator. When motion is used the pilot must control the simulator to remain within these boundaries or soft limits are reached which cause erroneous motion cues.

With reference to Figure 4.1, the pilot controls are stick, rudder, and throttle. These quantities plus initial conditions are the inputs to the aerodynamic simulation. A constant head wind (approximately 140 knots) is used in the problem and the aircraft is initially trimmed so that initial transients of the problem are very small. The aerodynamics used are representative of a small twin jet transport. Table 4.1 gives the characteristics of the aircraft which were simulated. The roll damping and roll coupling terms are varied to give the values of lateral handling characteristics which are referred to herein as GOOD, FAIR, and POOR. Six degrees of freedom are simulated for the aircraft and visual display. Longitudinal motion is the only motion cue not provided to the pilot. This cue was eliminated since the pilots had trouble with limits in the longitudinal channel of the motion simulator. Visual cues (depth perception) are not sufficient in the two-dimensional TV display to permit the pilot to tightly control the longitudinal separation.

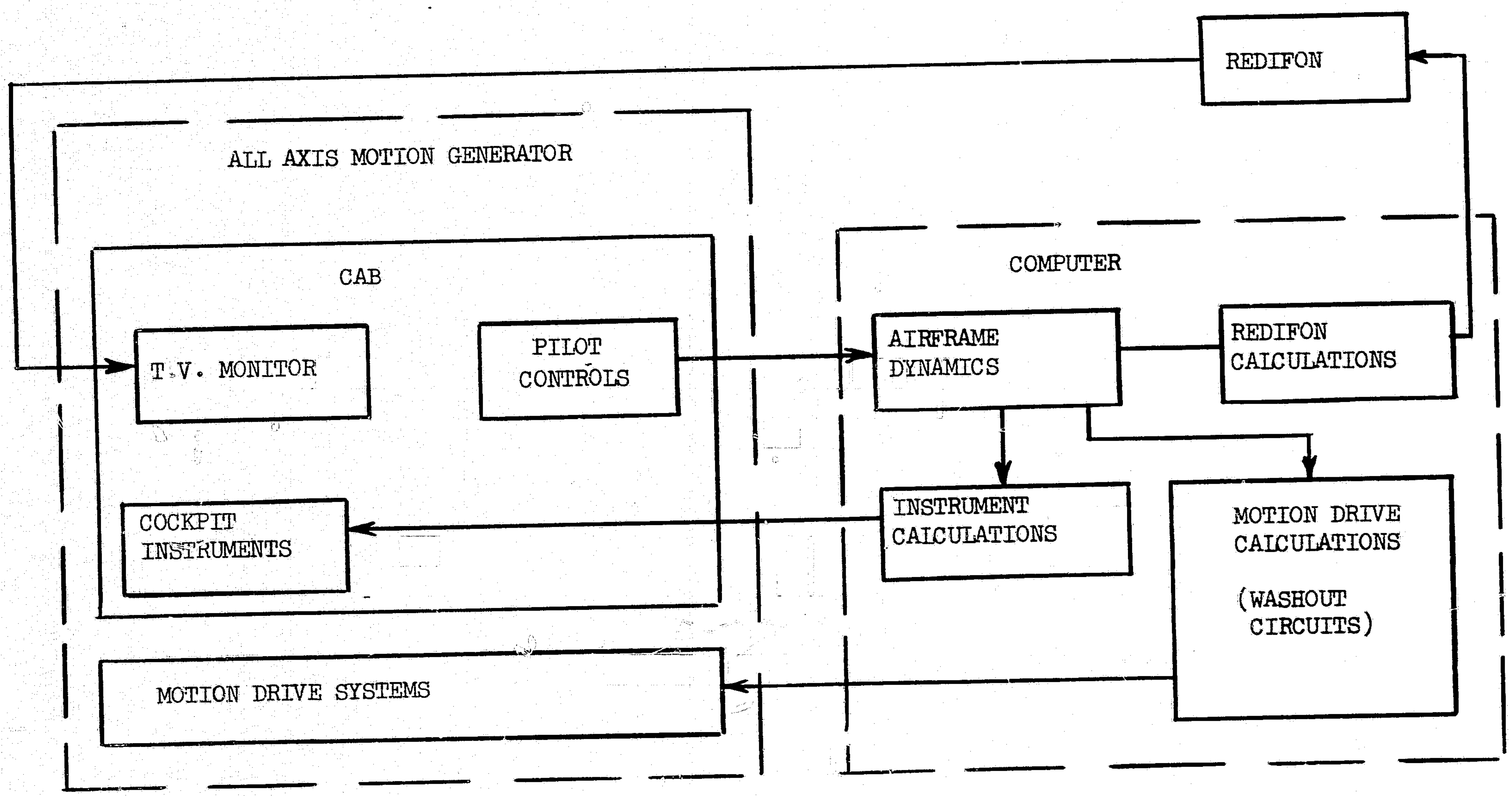


Figure 4.1 - Block Diagram of a Pilot Control Simulation Using the All Axis Motion Generator.

The motion drive calculations shown in figure 4.1 are effectively one to one relative motion. That is, no washout is used when motion is given to the subject. The motion drive systems are disengaged for the fixed base data.

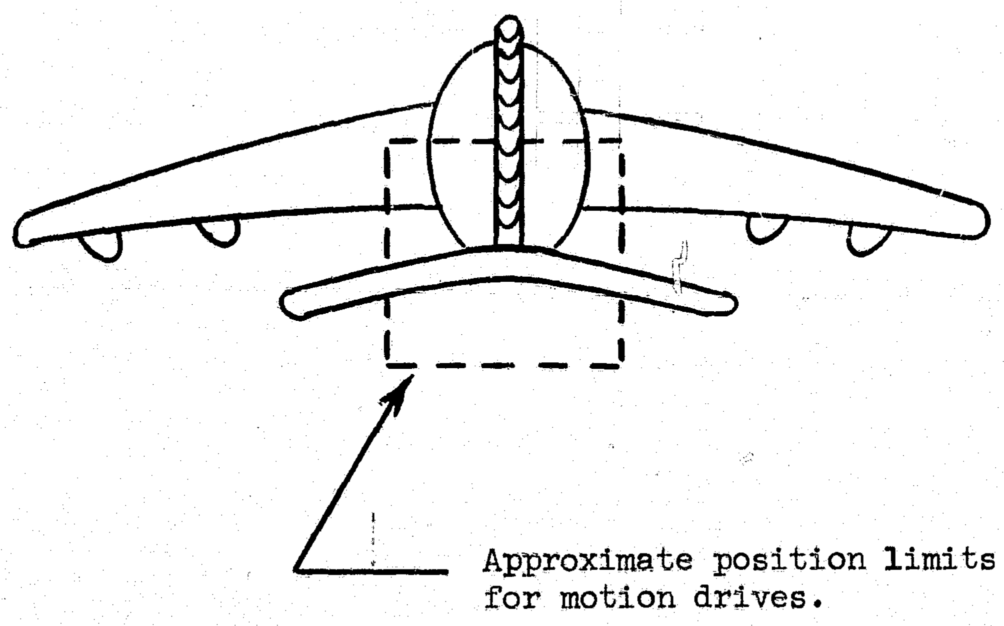


Figure 4.2 - Sketch of Visual Display for Formation Flying Task.

TABLE 4.1

CHARACTERISTICS OF SIMULATED AIRCRAFT

Physical Properties

$\bar{c}$	11.08	I_X	125000.	I_{XZ}	8.25
b	71.2	I_Y	120312.	m	777.5
s	690.	I_Z	234375.	X_p^*	30.

Derivatives** (Stability Axis)

C_{D_o} $\alpha=0$	.098			C_{ℓ_r} $\alpha=0$	.2
C_{D_α}	.377			$\partial C_{\ell_r}/\partial\alpha$	.76
$\partial C_{D_\alpha}/\partial\alpha$	1.82			C_{n_p} $\alpha=0$	-.025
C_{ℓ_β} $\alpha=0$	-.0653	-.1722	-.1722	$\partial C_{n_p}/\partial\alpha$	-.93
$\partial C_{\ell_\beta}/\partial\alpha$	-.253	-.506	-.506	C_{L_o} $\alpha=0$	.375
C_{ℓ_p}	-.44	-.22	-.11	C_{L_α}	5.35
$C_{\ell_{\delta_a}}$	-.1722			$C_{L_{\delta_e}}$	.302
$C_{\ell_{\delta_r}}$	.021			C_{m_q}	-12.3
C_{m_α}	-1.022			$C_{m_{\dot{\alpha}}}$	-4.01
$C_{m_{\delta_e}}$	-.923			C_{n_β}	.1
$C_{n_{\delta_r}}$	-.1			C_{n_r}	-.32
C_{Y_β}	-.8				

* Pilot position ahead of cg (ft).

** Where three values are given they are for the aircraft in the order GOOD, FAIR, POOR from left to right in the table.

The REDIFON calculations shown in figure 4.1 include a random forcing function for the REDIFON vertical and lateral drive. This signal has peak amplitudes of about 3 feet and could be reasonably well approximated by zero mean white noise through a 100 second time constant first order filter.

The subject's task is to hold the Convair 990 in the middle of the TV display; that is, in the initial condition position sketched in figure 4.2. For each condition of the airframe and motion type the subject is requested to perform this task for about two to three minutes. On line calculations of the performance are made of mean and variance of the three position errors where

$$\text{Mean of error} = \frac{1}{T} \int_0^T \text{error}(t)dt$$

$$\text{Variance of error} = \frac{1}{T} \int_0^T (\text{error}(t))^2 dt - (\text{Mean})^2$$

Since the random forcing function comes from a magnetic tape, the problem disturbances are nearly identical for all cases and all subjects. The standard deviation is the square root of the variance. Mean value data although available are not summarized. One should not attempt to deduce that the above quantities are statistical. They are simply a readily calculated performance measure for the experiment.

The order of airframes in carrying out the test was GOOD, FAIR, POOR. The subject was given the fixed base mode for familiarization for each airframe. In some cases the subjects requested motion for this same purpose. Following familiarization the data run with motion was attempted. If the subject could control the problem for the desired time, the next problem was begun. Otherwise, the subject was allowed additional trials with the same motion. The fixed base data were taken following the motion run for each case. Some subjects also requested more than one trial for the fixed base data run.

In addition to the performance calculations, and questionnaire data, other quantities were also noted. In particular, strip chart recordings were made of about 24 quantities and FM tape records were made of 13 relevant quantities which give time histories of pilots visual and motion cues and his control output for each case. Following the completion of the tests the subjects were interviewed for comments and were asked to fill out a questionnaire.

4.3 Discussion of pilot questionnaire data. - The results of the pilot response to the questionnaire are shown in Table 4.2. As noted on the table, the number of pilots checking a given column is indicated. Six Ames test pilots took part in the simulation tests. Two of these six flew the simulated task for data runs on two different occasions. The questionnaire results are for the first trial only.

In reviewing the answers to questions 1, 5 and 6, one sees that overall "fair" rating for motion and unacceptable rating for fixed base is indicated. Answers to questions 2a and 4 generally imply the overall impression that the motion was considered helpful. Question 2b shows that without motion there was general agreement between pilots that their performance was poor to unacceptable.

The spread in answers to question 3 is believed traceable to the simulator motion drive anomalies (See questions 9 and 10). Some pilots were more aware of these deficiencies than others.

Question 5 was introduced to see whether pilots thought a formation flying task might be useful in overall handling qualities evaluation. The reason for the question is that true relative motion (except for drive system anomalies) for such a task can be represented on the All-Axis Generator. The answers indicate that without motion such an evaluation of handling qualities is not worthwhile. With motion it appears such an evaluation is promising and the question probably should be given further attention.

The answers to questions 7 and 8 indicate a strong agreement between pilots on the difficulty of the task compared to real problems. The reasons for this difficulty are believed to be as follows:

a) The visual cues are not nearly as good as they would be in the real problem.

b) The airplane used was somewhat sluggish for such a tight formation flying problem compared with aircraft on which the pilots had flight experience.

The pilots comments indicated that both items are true to some degree and which is worst depends on the individual pilot's experience.

The answers to question 9 indicate that with motion the audible noises are both evident and distracting to the majority of the pilots. This is with one to one motion where audible noise level is to some degree correlated with visual and motion cues. With washout circuitry it is believed that these audible noises will be more distracting since they will not necessarily be correlated with visual cues.

TABLE 4.2

SUMMARY OF PILOT QUESTIONNAIRE RESULTS

Question	EXCELLENT	GOOD	FAIR	POOR	UNACCEPTABLE
1. How well do you think you could determine the boundary between UNSATISFACTORY and UNACCEPTABLE handling qualities for a formation flying task? *					
a) Moving Base		3	1	2	
b) Fixed Base			2	1	3
2.** How well did you perform the task?					
a) Moving Base		2	1	3	
b) Fixed Base				4	2
3. How realistic was the motion fidelity with respect to the visual display?	1	1	2	2	
4. How helpful was the motion in performing the task?	2	1	3		
5. If this task and simulation were used on an arbitrary aircraft not necessarily requiring formation flying, how well would it aid in evaluating handling qualities? Note: Formation flying could be simulated for many points in the flight envelope.					
a) Moving Base		2	1	1	1
b) Fixed Base		1		1	3
6. Rate your impression of the usefulness of this simulation as a training device for formation flying or refueling.					
a) Moving Base	1	2	2	1	
b) Fixed Base		1	1	2	2

* Note: Number in column indicates the number of pilots with indicated rating.

** Two of the pilots rated this question on the basis of the airplanes. That is, they rated their performance better (as it was) for the GOOD airplane than for the POOR. For simplicity, the average rating was used in the summary.

TABLE (CON'T)

		MORE DIFFICULT	SLIGHTLY MORE DIFF.	ABOUT SAME	LESS DIFFICULT	SUBSTANTIALLY EASIER
7. Rate difficulty of the task in relation to real formation flying.						
a) Moving Base		6				
b) Fixed Base	3	3				
* 8. Rate difficulty of the task in relation to a real refueling task.						
a) Moving Base		4				
b) Fixed Base	3	1				

	ALWAYS	OFTEN	OCCASIONALLY	RARELY	NEVER
9. Were audible simulation noises evident?					
a) Moving Base	1	4	1		
b) Fixed Base					6
If so, were they distracting?					
a) Moving Base		3	2		1
b) Fixed Base					6
10. Were drive vibrations evident?	1	3	2		
If, so, were they distracting?		3	2	1	
11. Did you have any tendency toward disorientation?					
a) Moving Base			2	2	2
b) Fixed Base		1	2	1	2

* Two pilots did not answer question 8 as a result of inexperience with the real refueling task.

The answers to question 10 indicate that drive vibrations are both evident and distracting to the majority of the pilots. This vibration problem is believed to be caused primarily by the lateral drive channel (See Appendix). It is recommended that some experiments be conducted to isolate this problem and correct it, if possible.

The answers to question 11 generally indicated little problems associated with disorientation, with or without motion. One pilot commented that in the fixed base cases he occasionally had problems of moving the ailerons in the wrong direction.

It is believed that the answers to question 11 will change when washout is introduced. That is, some other tests have indicated that anomolous motion can cause a feeling of disorientation.

4.4 <u>Discussion of measured tracking errors</u>. – Table 4.3 contains the standard deviation of the tracking errors for each of the pilots. The data from Table 4.3 is summarized in Figures 4.3 and 4.4. Both figures 4.3 and 4.4 indicate considerable differences between motion and fixed base. Generally speaking, with motion there was considerably less variance (scatter) in performance between the different pilots. The larger scatter with motion for the POOR aircraft is believed partially due to the soft limits. That is, two of the pilots reached the lateral or vertical limits and had problems resulting from the lack of proper linear acceleration cues. This is believed to have caused a larger transient than would have been encountered otherwise. The POOR aircraft is of course harder to control so this is a second factor contributing to the larger scatter.

Two of the pilots (C and D) actually improved performance with motion in going through the GOOD, FAIR, POOR airplane sequence. This is undoubtedly associated with the learning process about the simulation and task.

Of particular note is the large scatter in the fixed base results which generally increases with the degrading of aircraft handling qualities. One of the pilots who controlled the FAIR and POOR aircrafts well with motion could not control the aircraft in fixed base.

These data emphasize the importance of motion for this type of flight task. Hence, it should provide a means of evaluating differences between various washout circuit configurations and various parameter settings.

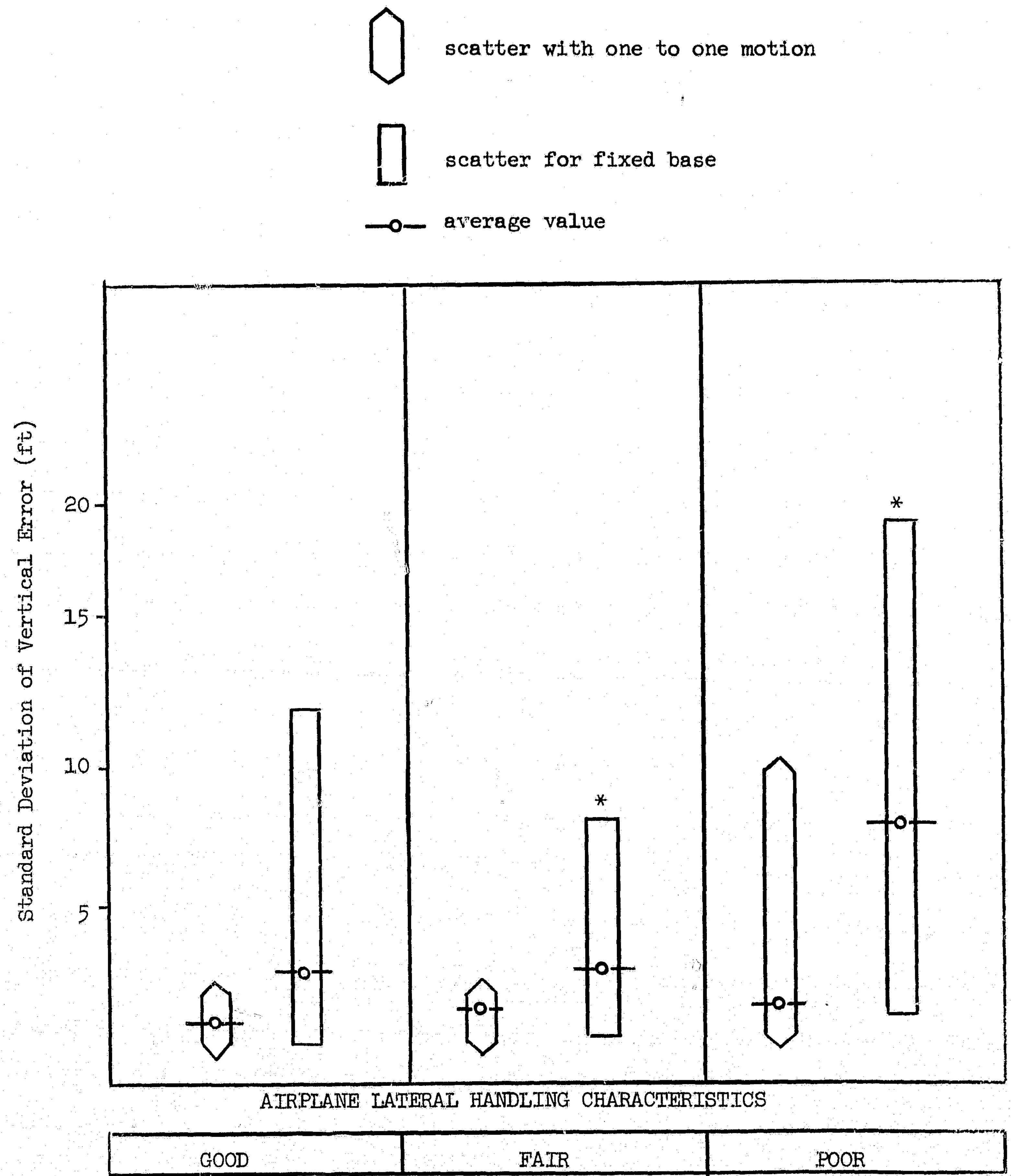
4.5 Sample time histories showing effects of motion. - As was mentioned in section 4.2, strip chart recordings were made of about 24 quantities. Figure 4.5 is a sample time history of some relevant quantities which are useful in understanding differences between fixed base and motion. The case shown is for the first sample for pilot E of Table 4.3 for the POOR aircraft. By comparing the time histories for motion versus fixed base one can note a significant difference. This difference is most evident in the yaw and roll rate time histories. Without motion cues the pilot is not able to damp the dutch roll mode. In the fixed base case the roll rate and yaw rate histories are somewhat similar to a limit cycle behavior in a non-linear feedback control system.

With motion the mode is either not excited or well damped. The additive damping possible from the motion cues is believed the most likely factor.

The characteristics shown here were present for all the pilots to some degree. Pilot D, who could not control the airframe fixed base, had a roll and yaw rate time histories characteristics of an oscillatory unstable system.

TABLE 4.3 STANDARD DEVIATION OF TRACKING ERRORS

PILOT	AIRPLANE	MOTION	COMPONENTS X ft.	Y ft.	Z ft.	Comments
A	GOOD	M	31	4.05	2.21	
		F	35.6	10	5.65	changed to no rudder
	FAIR	M		2.8		
		F	═══	21.6		
	POOR	M	74	7.1	4.37	
		F	24.6	29.6	12	Uncontrollable
B	GOOD	M	28	2.57	2.7	
		F	37.6	4.14	12.5	
	FAIR	M	10.6	2.76	2.02	
		F	73	15	5.	
	POOR	M	70.5	3.7	2.6	
		F	99	31.8	13	Uncontrollable
C	GOOD	M	27.8	3.44	3.14	
		F	14.9	3.56	2.14	
	FAIR	M	27.2	3.08	3.07	
		F	25.4	5.4	3.05	changed control technique (no rudder) lost at end
	POOR	M	32	2.88	2.75	
		F	38	12.2	2.36	
D	GOOD	M	12	4.4	.94	
		F	23.6	5.4	2.66	
	FAIR	M	16.3	3.34	2.78	
		F	12.4	12	3.2	Uncontrollable
	POOR	M	19.2	2.12	2.07	
		F	——	11.7	7.5	Uncontrollable
E	GOOD	M	——	——	——	Not available
		F	13.1	2.93	1.54	
	FAIR	M	16.2	2.4	.995	
		F	15	4	1.4	
	POOR	M	13.4	3.4	1.76	
		F	22.8	20.6	2.9	
E	GOOD	M	9.6	2.06	.945	
		F	7.65	2.61	1.01	
	FAIR	M	8.6	2.25	1.0	
		F	19.6	5.6	1.66	
	POOR	M	13.4	3	1.0	
		F	29.8	8.3	2.17	
F	GOOD	M	156.	4.0	2.22	↑
		F	500	4.3	1.73	
	FAIR	M	343	4.37	3.22	Disturbance
		F	79	8.4	3.18	of target
	POOR	M	58.5	8.2	10.9	out
		F	78	33	19	↓



*One pilot could not control problem laterally.
This point neglected in scatter and average.

Figure 4.3 - Summary of Standard Deviation of Vertical Error

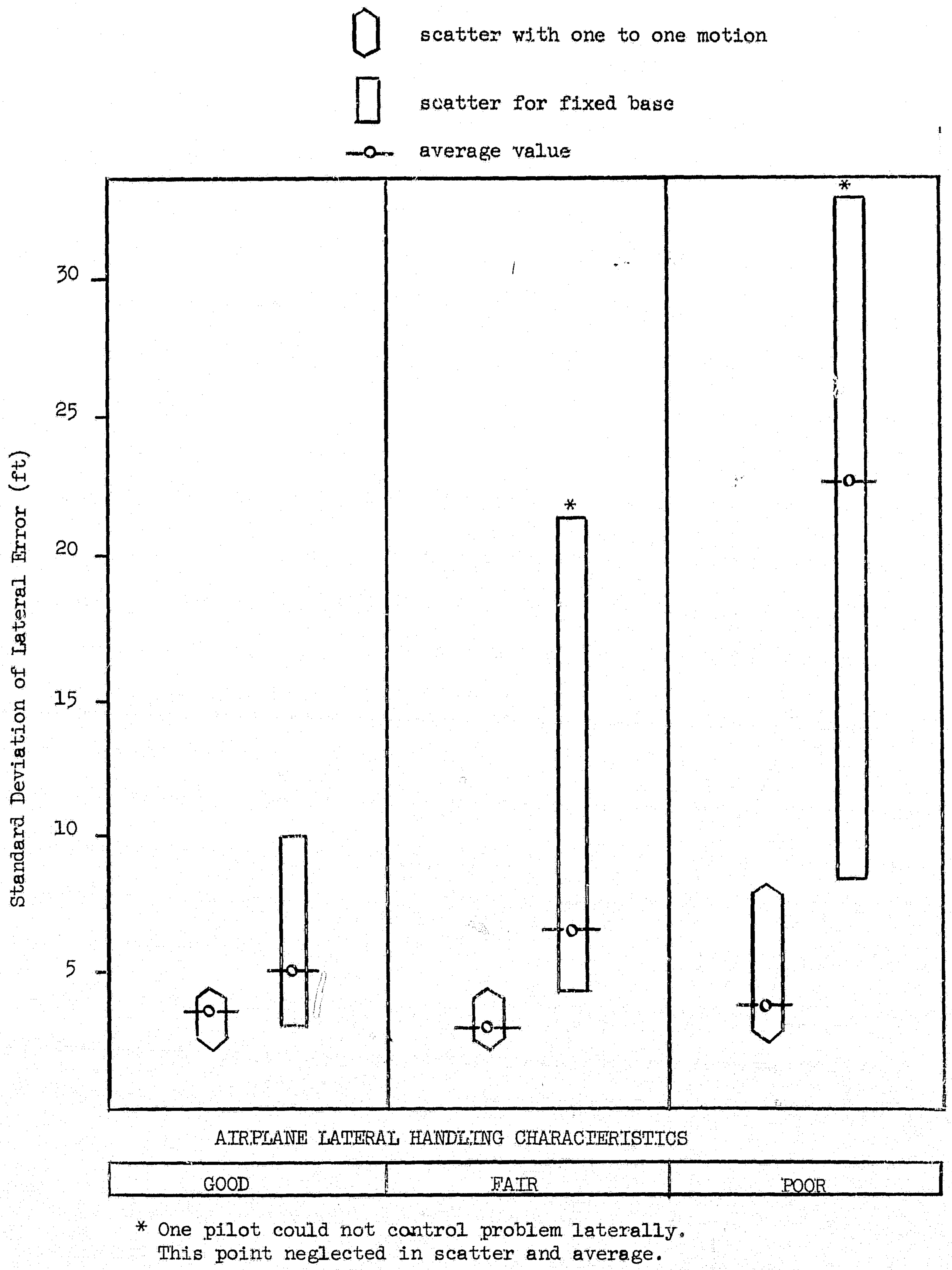


Figure 4.4 - Summary of Standard Deviation of Lateral Error.

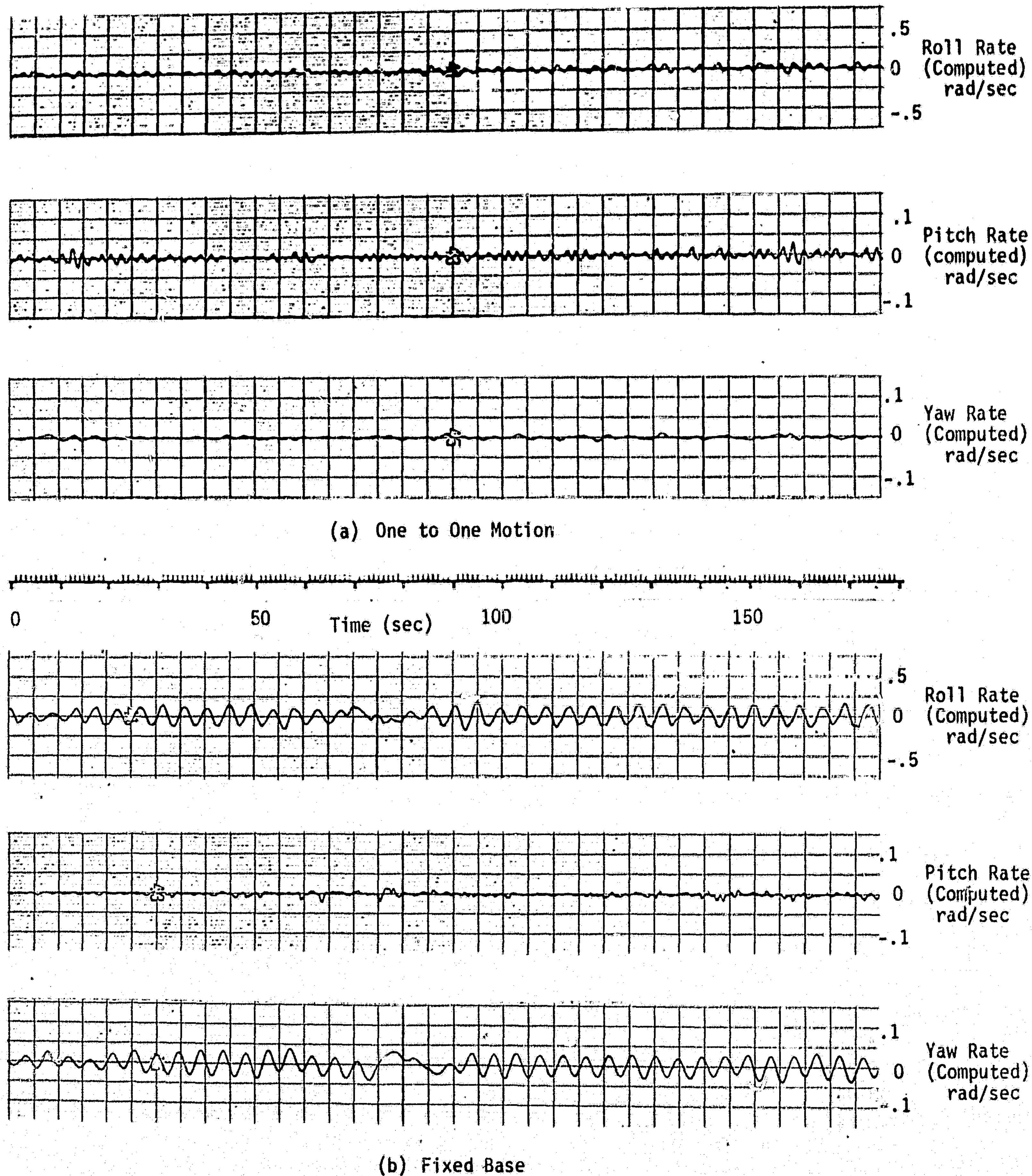


Figure 4.5-Comparative Time Histories for POOR Airplane Illustrating Effects of Motion Cues

SECTION 5

Concluding Remarks and Recommendations

One of the original objectives of the investigation described in this report included the study of the application of modern optimal control to the development of motion drive circuits. As is well known, this theory can be a powerful tool if the problem is a type which satisfies the following:

1) System input characteristics are definable in a convenient mathematical form.

2) Desired system response characteristics are specified in a convenient mathematical form.

3) System limits and other constraints are specified.

From the discussion given earlier, it should be clear that for piloted simulation problems the input characteristics of item 1) are the motion simulator drive signals which are task dependent and to some degree subject (test pilot) dependent. That is, the specific force vector and rotational acceleration vector time histories we would like to precisely match are dependent on the problem (including the airplane pilot etc.) for which the motion simulation is being used.

The desired system response characteristics (item 2) should be as close a match of forces and rotational acceleration as possible. Problems arise in specifying this in the form of a precise mathematical performance index. In particular a scalar function of the important variables is desired which is a minimum when the "best" compromise is obtained in those instances where the exact match is impossible.

Item (3) is satisfied in that the limits of the All-Axis Motion Generator are reasonably well approximated by the simple model discussed in the Appendix. However, some hidden variables which can affect the pilot's comments are not well understood. For example, both audible noise level characteristics and simulator vibrational characteristics depend on the motion simulator "state" and inputs. Furthermore, these characteristics were both noticeable and distracting in the tests described in Section 4. From optimal control theory considerations these "hidden" factors need be well enough understood so that they can be handled either as constraints or possibly included in the performance index.

After a reasonably thorough review of available literature, it became obvious that there was insufficient information to permit the direct application of optimal control theory. That is, necessary elements like the mathematical form of the performance index would have to be assumed rather than based on factual evidence. These missing elements were recognized early in the present investigation and an indirect engineering approach described was adopted with the objectives in the order of

A. Determine intermediate solutions which can be used for the All-Axis Motion Generator.

B. Utilize experiments to validate and improve the washout configurations for operational tasks.

C. Define and conduct experiments to obtain the missing information which prevent the direct application of optimal control theory.

A large portion of this report has dealt with objective A. Results of work related to this objective included:

a. A review and mathematical formulation of the basic problem of reproduction of motion cues as would be sensed in a real aircraft.

b. Examination of the influence of motion simulator constraints on the ability to reproduce the ideal motion cues. This examination has shown the following comments applicable for the Ames All-Axis Motion Generator.

Normal Force Cue - Cannot in general be precisely provided. Motion simulator constraints in the vertical channel force one to omit this cue entirely or to supply only scaled and/or high frequency components of the ideal motion.

Lateral and Longitudinal Force - For restricted ranges in magnitude these cues can be accurately provided. Requires use of cab tilts and the resultant anomolous rotations to do so, however. The magnitude of anomolous rotations in providing accurate force cues is dependent on the maximum allowed cab travel in lateral and longitudinal directions.

Rotational Cues - Can be precisely provided for many flying tasks. Problem arises since cab tilts can cause anomolous forces. This problem generally requires the use of anomolous rotation cues to reduce unwanted forces.

c. Traditional and new washout circuits have been described and developed. Both the traditional and new configurations compromise the ideal motion in satisfying motion simulator constraints. The new configurations developed appear to offer a potentially better compromise from the following considerations.

1) The translational drives are coordinated with rotational drives by means of a feedback type washout network. This allows side and longitudinal force cues to be accurately provided or modified in some arbitrary fashion such as scaling.

2) Anomolous rotational cues result. However, their magnitude would appear to be smaller than that given by the traditional washout circuit design approach.

3) The parameters one selects are related to available travel, input ranges and anomolous rotational cues. As a result, evaluation of appropriate settings for a given simulation may require less experimentation than the traditional washout circuits.

Objective B has been partially completed as follows:

a. Some experiments with a landing approach task of a jet transport were completed as discussed briefly in Section 4.

b. Two relatively general purpose subroutines for use on the EAI digital computers have been formulated. These routines compute drive signals for the All-Axis Motion Generator based on either the traditional or the new washout configurations.

c. The subroutines discussed in (b) are currently in use for a research investigation on a VTOL aircraft landing approach problem.

Objective C has been completed to the following extent:

a. A task and simulation has been defined and tested wherein motion cues have a very measurable influence.

b. Washout drive circuitry has been developed wherein a nearly independent control of motion cues is possible.

c. Applicable analysis procedures have been investigated to the extent that there appears promise in gaining information to relate:

1) Pilot subjective opinion

2) Measured pilot performance

3) Measured pilot response to real and anomolous cues

These factors on Objective C have laid the ground-work for conducting experiments and analyzing the results in order to obtain information on the performance indices for washout circuits.

Recommendations

Three recommendations for continued effort are:

1. Complete the evaluation of the washout circuits developed for the All-Axis Motion Generator. (Objective B discussed previously.) Document the results of the tests and description of the sub-routines employed in the investigation.
2. Initiate both an experimental and analytical program aimed at gaining a better understanding of the importance of the various motion cues. Particular emphasis along lines which obtain the information in a form of a performance index for washout circuits is desired. As mentioned earlier the ground work for such a study has been accomplished under Objective C.
3. Make continued improvement in the washout circuits subroutines designed for general purpose useage. As these routines are used for different tasks and aircraft by research investigators both their good and bad features will become evident. Documentation of these characteristics should permit a better understanding of the washout problem.

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Appendix

The All-Axis Motion Generator

Table A.1 gives a NASA summary of the All-Axis Motion Generator characteristics. Some additional information about the motion generator is presented here.

Limits

The limits indicated in Table A.1 are determined by protective relays in the drive system. The quantities sensed by the relays are not accelerations or velocities at the pilot's location in the cab. Rather, they are quantities such as drive motor current which is proportional to drive torque. The drive load is not a pure inertia but includes such factors as cable stretch, structure bending, friction, play in support structure and so forth.

If any limit is exceeded in any of the channels, an automatic shutdown of all drive channels is made. These shutdowns produce a nuisance factor which could be removed by incorporation of soft limiting in the drive command circuitry.

Gimballing

The cab gimballing follows the order of

Pitch - Outer Gimbal

Yaw - Middle Gimbal

Roll - Inner Gimbal

Figure A.1 is an illustration of these rotations.

TABLE A.1 - CHARACTERISTICS OF AMES ALL-AXIS MOTION GENERATOR

Motions Generated:

	Acceleration	Velocity	Displacement	
Roll	> 6 Rad/Sec^2	4 Rad/Sec	$\pm 45^{\circ}$	
Yaw	> 6 Rad/Sec^2	4.9 Rad/Sec	$\pm 45^{\circ}$	
Pitch	> 6 Rad/Sec^2	2.8 Rad/Sec	$\pm 45^{\circ}$	Maximums
Vertical	10 Ft/Sec^2	17.3 Ft/Sec	$\pm$ 9 Ft	
Longitudinal	7 Ft/Sec^2	14.1 Ft/Sec	$\pm$ 9 Ft	
Lateral	7 Ft/Sec^2	14.1 Ft/Sec	$\pm$ 9 Ft	

Drives: Ward-Leonard Electrical Servos
Torque motors drive through silent chains to rubber-faced sectors or to cable pulling drums.

Program: Closed-loop operation with analog computation.

General Comments:

Shut-down capability is provided at several stations. Electrical and electronic circuits are used to limit accelerations, velocities and displacements. Brakes are energized-to-release for fail-safe operation.

The one-man cab is fitted for vertical rising aircraft with stick, rudder, and throttle controls. Televised visual display is anticipated as an approach and landing aid. Displacement to a limit of travel programs the cab to drive to an initial condition of displacements and attitude.

The design permits installation of cabs having other configurations.

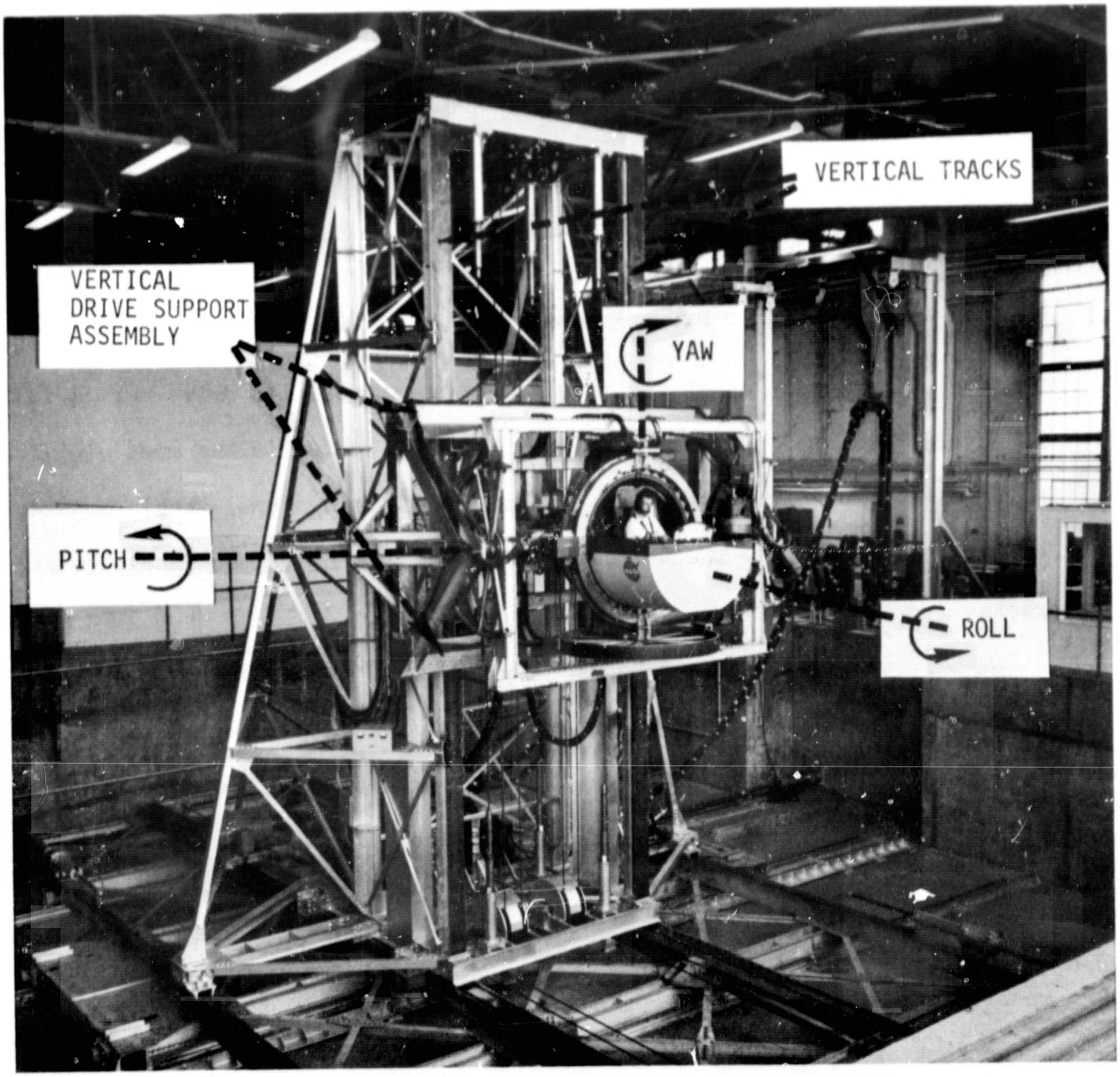

Figure A.1-The Ames All-Axis Motion Generator

Translational Drive Systems

The translational drives are track-wheel-supports driven by electrical motors through cables. The mass of the load in the various axes follows the order

Vertical - Inner Drive - Lowest Mass

Longitudinal - Middle Drive - Middle Mass

Lateral - Outer Drive - Largest Mass

The characteristics of the response of these position drive servos follows the inverse order of the mass, i.e., the lateral system is the most sluggish in response. In the longitudinal and lateral drive systems, wheels on tracks support the structure. The weight of the structure holds the wheels to the tracks.

The vertical drive has five wheels on each of two tracks to constrain the cab and gimbal structure to vertical motions. The center of gravity of the cab-gimbal structure (see Figure A.1) is considerably forward to the drive track wheel assemblies. Some evidence obtained from sinusoidal tests suggests that there is play in the drive support assembly. If the cab is driven vertically or longitudinally the weight resulting from the offset center of gravity of the cab gimbal structure would tend to hold the wheels to the vertical drive tracks. When the support structure is driven laterally, however, the offset center of gravity of the cab combined with some play in the wheels can cause anomolous side forces and yawing rates. The sinusoidal results tended to support this theory in that lateral anomolous motions are the most significant. For example, if one drives the lateral servo with about a 1 H_z signal of a very small amplitude then cab mounted lateral accelerometer output is by no means sinusoidal. Instead it appears to be dominantly damped oscillatory motion with a higher natural frequency than 1 H_z.

Such characteristics can result from the play in the actual drive assembly. Visual inspection during the 1 H_z excitation tends to support this theory. The vertical tracks appear to oscillate at 1 H_z. However, the cab lateral distance motion seen from the front of the cab has a high frequency damped oscillation excited at a 1 H_z repetition rate. Note that the visual distance measure observed includes both distance due to lateral travel of the vertical drive tracks as well as rotations about a vertical axis. Play in the wheel assembly would allow apparent lateral distance motions under the conditions tested.

Lead Compensation

The NASA tests have defined lead compensation network constants for all the drive channels. The compensation is of the form shown in equation (A.1) for the translational drives.

$$y_c = a_2\ddot{y} + a_1\dot{y} + y \tag{A.1}$$

y_c = a linear drive command

y = desired (calculated) linear drive position

$\dot{y}$ = dy/dt

$\ddot{y}$ = d^2y/dt^2

a_1 and a_2 = compensation coefficients (different numerical values for each channel). This experimentally-determined compensation causes the cab mounted accelerometer outputs to follow $\ddot{y}$ with near zero error to modest frequencies (e.g. 1-2 H_z).

Approximate Model

Assuming lead compensation is used and anomolous motions and limits neglected then the servo response is effectively perfect for the bandwidth of interest. As a result, we can use the approximate model of a perfect servo except for the limits given in Table A.1 and the anomolous motions discussed previously.

Experimental evidence has suggested that anomolous motions are less noticeable if the simulated problem contains some rough air. In this instance the subject cannot readily distinguish the rough air from the servo anomolies. Hence, the approximate model suggested becomes more accurate for simulated pilot control problems in turbulent air.