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A VTOL TRANSLATIONAL RATE CONTROL SYSTEM STUDY ON A SIX-DEGREES-OF-FREEDOM MOTION SIMULATOR

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SUMMARY

A linearized translational rate system for near hover flight was optimized on a large motion simulator under the constraints of no disturbances and limited control power. Both lateral and longitudinal modes were considered with the primary variables of investigation being control sensitivity and response "stiffness" and secondarily system damping. Yaw and height control characteristics were represented by an angular rate and acceleration system, respectively. General regions of desired sensitivity and stiffness for the longitudinal and lateral modes were determined under VFR conditions for both the rapid maneuver task and the station keeping/mild maneuver task.

TABLE OF SYMBOLS

I_x, I_y, I_z	aircraft moment of inertias about x_b y_b z_b slug-ft^2
K_δ	stick feed forward gain
K_θ, K_ϕ	pitch and roll attitude feedback gain rad/sec^2/rad
$K_{\dot\theta}$, $K_{\dot\phi}$	pitch and roll rate feedback gain rad/sec^2/rad/sec
K_{v_x}, K_{v_y}	long. and lateral feedback gain rad/sec^2/ft/sec
K_1, K_2	cubic polynomial coefficients
$L_{(\ )}/I_y$	rolling moment due to ( ), r/sec^2/ ( )
$M_{(\ )}/I_y$	pitching moment due to ( ), r/sec^2/( )
$N_{(\ )}/I_z$	yawing moment due to ( ), r/sec^2/ ( )
T	thrust, lbs
T_δ	total control sensitivity, r/sec^2/in
Tv	total velocity sensitivity, ft/sec/in
V_x, V_y	linear velocities along x and y, ft/sec
g	gravitational constant, ft/sec^2
x_b, y_b, z_b	aircraft body axes
x, y, z	inertial axis
δ	control input, in
ζ	damping ratio
σ	real axis s-plane
$j\omega$	imaginary axis s-plane
ω_o	natural frequency, 1/sec

Acronyms

PR	Pilot rating
RM	Rapid maneuver
SK/MM	Station keeping/mild maneuver
SR	Saturation ratio
TR	Translational rate

INTRODUCTION

It has long been recognized that proper control stabilization of a hovering VTOL vehicle can significantly reduce the pilot compensation required to perform a given task. This reduced work load is a function of both the magnitude of the stabilization and its degree (i.e., rate stabilization, rate plus attitude stabilization, etc.). This is true since a variation in the magnitude of the stabilization influences the system's dynamic behavior (e.g., damping, rise time, final value, etc.) while a change in the degree influences the number of control integrations the pilot must perform himself. The work of Reference 1, which studied roll acceleration, roll rate, and roll attitude stabilized VTOL control systems indicated that when optimized, added degrees of stabilization yield improved pilot ratings or, alternatively reduced control power requirements. A natural extension to that work would be the study of a translational rate (TR) system, a system obtained by adding translational rate feedback to the attitude system. Such systems have been the subject of several studies (References 2, 3, 4, and 5); most of these involved simulations conducted on fixed base or small motion simulators and were for specific systems.

While it is true that the ultimate design of any control system often depends highly on the vehicle to which it is to be applied, certain basic handling qualities criteria or system dynamics are none-the-less sought. It is in the area of basic system characteristics for a translational rate control system which achieves translation through attitude changes, that the effort of this simulation was slanted. That is, this more generalized simulation, conducted on a large motion simulator, addressed the problem of identifying optimum bands of control sensitivity, stiffness, and damping for a TR system. The study considered two near hover VTOL control tasks, one relating to terminal area VTOL transport type maneuvering and the other to precision hover or crane type maneuvering.

DESCRIPTION OF SIMULATION

Aircraft model and simulation conditions. This simulation, like the study from which it stems (Reference 1), was conducted on the Ames large motion six-degrees-of-freedom simulator (Figure 1). This simulator has motion freedom within an 18 ft. cube.

For the present simulation, the generalized rigid-body, near-hover equations of motion developed in Reference 6 were used in both the lateral and longitudinal modes. These equations were then augmented by the inclusion of feedback terms to form the systems studied in this simulation. Throughout the simulation the yaw characteristics remained at a satisfactory angular rate control system of sensitivity N_δ/I_Z = .5 r/sec^2/in and damping N_r/I_z = -3.5 1/sec. Height control was considered to be decoupled from all other controls and was accomplished by manual throttling of a single vector acting along the z body axis.

The controller configuration and other conditions of the simulation are given below.

Conditions:

VFR

Calm air (no gusts, cross-winds, or ground effects)

Ideal system (no actuator dynamics, etc.)

No gyroscopics or cross-coupling

Constant control geometry

Controller:

	Displacement (in.)	Force Gradient (lb/in)	Breakout Force (lb)	
Roll	±4.5	1.5	1.5	center stick
Pitch	±4.5	3.0	1.5	
Yaw	±3.0	8.0	6.0	rudder pedal
Throttle	Left hand throttle lever			

Two pilots participated in this study. One pilot had had experience as a test pilot on a variety of VTOL aircraft and the other had had extensive helicopter experience. Each pilot was given similar systems and tasks and in most cases these were repeated. Also both pilots were occasionally exposed to an optimal attitude control system (ω = 2 r/sec, ζ = .7, and T_δ = .5 r/sec^2/in) during the simulation so as to maintain a reference between that type system and the TR system.

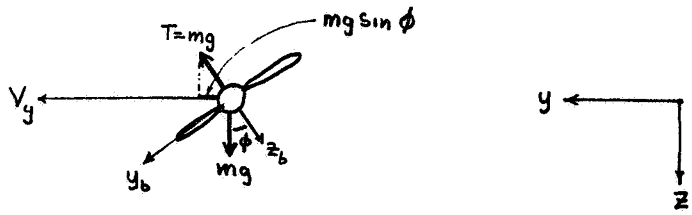
<u>System Equation Form</u>. The equation form for the TR system under consideration was constructed by assuming rate, attitude and velocity feedback around the basic aircraft as shown on Figure 2. The basic decoupled hover equation for roll as given in Reference 6 is,

$$L_\delta/I_x \ \delta = s(s - L_p/I_x)\,\phi - L_v/I_x \ V_{y_b} \tag{1a}$$

Then with the addition of stabilization as shown in Figure 2 (i.e., K_δ, K_ϕ, $K_{\dot\phi}$, K_{v_y}), Equation (1a) becomes

$$K_\delta \ L_\delta/I_x \ \delta = (s^2 - (K_{\dot\phi} + L_p/I_x)s - K_\phi)\phi - (K_{v_y} + L_v/I_x)V_{y_b} \tag{1b}$$

For a fixed thrust vector where transition rates are derived via attitude changes, as shown below, the relation of ϕ to $\dot V_y$ is approximated by



$$\dot{V}_{y_b} \simeq \dot{V}_y = g \ \mathrm{Sin}\phi \ = \ g\phi \ \text{(small angles)} \tag{2}$$

Then substituting this relation for ϕ in Equation 1b yields

$$gK_\delta L_\delta/I_x\delta = (s^3 - (K_{\dot{\phi}} + L_p/I_x)s^2 - K_\phi s - g(K_{V_y} + L_v/I_x))\,V_y \tag{3}$$

and similarly the Equation for longitudinal motion is

$$-gK_\delta \ M_\delta/I_y\delta = (s^3 - (K_{\dot{\theta}} + M_u/I_y) \ s^2 - K_\theta s + g(K_{V_x} + Mu/Iy))\,V_x \tag{4}$$

Equations 3 and 4 form monic polynomials of third order with all the K terms being independent. Note that each of the coefficients of the polynomials incorporates one of these K terms. Because of this flexibility and also for mathematical convenience these equations were related to the standard cubic polynomial form, which in roll becomes,

$$gT_\delta\delta = (s^3 + K_1\omega_o s^2 + K_2 \ \omega_o^2 \ s + \omega_o^3) \ V_y \tag{5}$$

and in pitch becomes,

$$gT_\delta\delta = (s^3 + K_1 \ \omega_o s^2 + K_2 \ \omega_o^2 s + \omega_o^3) \ V_x \tag{6}$$

where T_δ is the control sensitivity, K_1 and K_2 are "damping" terms, and ω_o (the natural frequency) is a measure of stiffness. Note the cubic has two "damping" terms and thus is somewhat more complex with regards to damping, than is a second order polynomial which has only one damping term ζ(i.e., $s^2 + 2\zeta\omega_o s + \omega_o^2$). Therefore, this simulation did not treat K_1 and K_2 as entirely independent terms but rather considered cubic polynomial forms with known "damping" characteristics. Although several forms exist, this study, which had the limited objective of showing a region of preference, considered only two forms. The two forms considered were the Binomial form, which exhibits a well damped transient behavior, and the Butterworth form with a medium damped behavior (Reference 7). Figure 3 illustrates the characteristics of these two forms. With the damping characteristics restricted to the two forms above, the primary variables of this simulation thus became control sensitivity, (T_δ) and stiffness (ω_o).

The simulation was conducted entirely under VFR conditions and evaluations were made on two categories of tasks. The first category was a rapid maneuver task appropriate for all classes of VTOL aircraft, and the second category was a station keeping/mild maneuver task which would be of concern for a crane or slung load operation. Pilot ratings based on the revised Cooper-Harper rating scale, Figure 4, were obtained separately for each category.

Initial System. So as to reduce the region requiring investigation in this simulation, the initial or base case TR system was one constructed from an attitude system with desirable handling qualities. This was done by first considering an optimized attitude system in roll and pitch of $T_\delta = .5 r/sec^2/in$, $\zeta = .7$, and $\omega = 2$ r/sec (Reference 1) which yields the second order equation,

$$.5\delta = (s^2 + 2(.7)\ (2)\ s + (2)^2)\ \phi \quad \underline{\text{roll}} \tag{7}$$

Then by including velocity feedback and by making the substitution for ϕ established by Equation 2 (i.e., $\phi = sV_y/g$) Equation 7 becomes first

$$.5\delta = (s^2 + 2.8\ s + 4)\ \phi + K_{V_y}\ V_y \tag{8}$$

and finally

$$g(.5)\ \delta = (s^3 + 2.8s^2 + 4s + g\ K_{V_y})\ V_y \tag{9}$$

Equation 9 represents a cubic polynomial which can be approximated by either the binomial or Butterworth form. For example, by letting $\omega_o = 1.1$ the binomial form is,

$$T_\delta\ \delta = (s^3 + 3.3s^2 + 3.6s + 1.33)\ V_y \tag{10}$$

which, with the proper choice of K_{V_y}, roughly approximates Equation 9. Thus $\omega_o = 1.1$ represents the initial guess for omega and Equation 10 the base case binomial form for this simulation.

Test Program. This simulation covered four phases

1. System "damping" - An assessment of desirable values of system "damping" was made by pilot evaluations in which the base case binomial form ($\omega_o = 1.1$) was compared with its Butterworth counterpart. This was repeated for other omegas.
2. System stiffness and control sensitivity - Starting with the base case (Equation 10) a parametric search for the optimum band of ω_o (stiffness) and T_δ (control sensitivity) was made. The arbitrary minimum range control power limits of 1.4 r/sec^2 in roll, .7 r/sec^2 in pitch, and .4 r/sec^2 in yaw (Reference 8) were imposed throughout this segment. Longitudinal and lateral dynamics were changed together and no disturbances were introduced.
3. Saturation - Control saturation was monitored throughout the simulation and assessments made, via pilot rating, as to saturation tolerances for this type of a translation rate system.

4. Control power - Selecting an optimum system, determined by Part 1, the control power limits in roll were varied over a range of values to determine the level required for both the rapid maneuver and station keeping/mild maneuver tasks.

RESULTS AND DISCUSSION

System Damping. The initial phase of the simulation involved the comparison of the base case to the lesser damped Butterworth form. This comparison established a preference by the pilots for the more heavily damped characteristics of the binomial form. The somewhat medium damped characteristics of the Butterworth form caused attitude overshoots that were unnatural to the pilots and thus resulted in additional pilot compensation. This was reflected as a difference in the pilot rating of approximately one point for $\omega_o = 1.1$. The comparison was repeated later in the simulation for other omegas with similar results. This is illustrated in Figure 5 where the binomial versus Butterworth forms are compared through pilot rating for the rapid maneuver task. On the basis of these results attention was focussed in the remainder of the program on the binomial system.

T_δ vs ω_o. The results of tests in which the stiffness (ω_o) and control sensitivities (T_δ) were varied are shown in Figure 6 and 7. Figure 6 shows data for the rapid maneuver (RM) and Figure 7 the station keeping/mild maneuver (SK/MM) tasks. These figures represent the average of several runs. The dispersion of pilot rating between runs for the same pilot was seldom greater than 1/2 point and between pilots seldom greater than one point.

One subtlety of this simulation which bears discussion is the representation of stick sensitivity. The control sensitivity in terms of angular acceleration, T_δ ($r/sec^2/in$) was chosen as the primary variable. This representation, of course, most directly relates the vehicle controller to the angular control power. However, other sensitivities such as the resulting linear velocity and vehicle attitude response are important characteristics in the pilot's evaluation of a given system. The relationship of control sensitivity to velocity sensitivity can be expressed directly as a function of T_δ and the stiffness parameter as follows:

$$T_V(\text{fps/in}) = \frac{gT_\delta}{\omega_o^{\,3}}$$

Lines of constant T_V are shown on Figures 6 and 7.

The peak attitude response is also a factor that the pilot considers in the evaluation of a system. This response, however, is a transient, and can be only approximated mathematically. For a step control input, the peak attitude response can be roughly approximated by

$$Att_{peak}\ (\text{rad/in}) \propto \frac{T_\delta}{K_2\omega_o^{\,2}}$$

where K_2 is the coefficient of the cubic polynomial, Equation 5 or 6. The expression for Att_{peak} indicates that for the same ω_o and T_δ a Butterworth form ($K_2 = 2$) yields a higher bank angle transient than does a binomial form ($K_2 = 3$). This is a characteristic of lower damping and may in part explain the preference for the binomial over the Butterworth response.

A consolidation of the data on Figures 6 and 7 is given on Figure 8. Here the PR $\leq$ 3 envelopes for both the RM and the SK/MM tasks are shown, with the surrounding bounds being based on pilot comments of major deficiencies noted in those regions. It should be emphasized that in many cases there were considerable overlap of these deficiencies.

It can be noted from Figure 8 that the desired RM and SK/MM envelopes very nearly coincide. The larger PR $\leq$ 3 bound for the SK/MM task indicates the preference the pilots had for slightly higher omegas when performing that task. This of course, enchanced the precision with which a position could be held. The preference for higher omegas is also consistent with pilot commentary recorded during the simulation. However, the general utility of the higher omegas is severly constrained by the rapid degradation in PR of the RM task (Figure 6).

Also, as can be seen on Figure 8, the PR bounds indicate the tolerance for lower velocity sensitivities the pilots had when performing the SK/MM task. The optimum velocity sensitivity for this task was somewhere around 5fps/in. By contrast, higher velocity sensitivities were found to be more desirable for the RM task. Based on commentary, the pilots preferred a velocity sensitivity for this task of around 10 fps/in and were unable to perform rapid maneuvers below 2 fps/in.

The narrow region of PR $\leq$ 2.0, shown on Figure 8, indicates a system with overall optimum characteristics to be one with a stiffness of around $\omega_o = 2.0$ and a velocity sensitivity of about 5 fps/in ($T_\delta = 1.0$ r/sec^2/in).

Saturation. An overall concern of this simulation was that of saturation of the control moments. The interest here was not in establishing design criteria but in making some assessments, in terms of pilot opinion, of the effect of saturation on a TR system in an undisturbed environment. Therefore, throughout the simulation the occurence of saturation of the available control power was monitored.

A useful measure for making assessments is provided by the system saturation ratio (SR) which is defined in Reference 1 as,

$$SR = \frac{\text{Maximum command moment } (r/S^2)}{\text{Maximum control moment } (r/S^2)}$$

With the control moment (or control power) limits cited earlier it can be determined that many of the systems tested were significantly in excess of SR = 3. In fact, as can be seen on Figure 9, all of the systems with a pilot rating better than 3 had a SR $\geq$ 3 in the longitudinal mode. Reference 1 indicated that for an attitude system saturation ratios of up to around 3 can not only be tolerated but offer certain advantages in the way of higher bank angle response and lower control power requirements. The present simulation indicates that for a translational rate system the level of tolerable SR appears to be considerably higher. This tolerance of a higher SR is further substantiated by previous indications that added stabilization tends to reduce the control power requirements.

On Figure 9 a region where saturation actually occurred is shown. Systems tested above the shaded line resulted in momentary saturation of the control moments in roll and/or pitch (usually both) during some portion of the simulation. This saturation generally occurred on rapid piloted inputs of $\pm$1.2 in. or greater in pitch and $\pm$2.5 in. or greater in roll. In general, the magnitude of piloted inputs into roll tended to be twice those in pitch and since the control power available in roll was also twice that in pitch the onset of saturation in the two axis usually coincided. Thus, the single shaded line on Figure 9 serves both pitch and roll for this simulation.

<u>Pilot Rating vs. Control Power.</u> The last part of this simulation considered an optimum TR system of ω_o = 2.2 and T_δ = 1.25 r/S^2/ in. for several runs in which the available control power was varied. The effect on pilot rating for a reduction in control power for both theSK/MM and RM tasks was recorded. These results are superimposed on those for other systems from Reference 1 and 9 and shown on Figure 10. This figure indicates

that for a control power greater than .8 r/s^2 the TR system is rated by the pilots as better than an attitude system. However, as the control power is reduced from 1.0 to about .7, the effects of control moment saturation indicated pilot opinions of an unacceptable level for the RM task. This sharp degradation occurred at a saturation ratio of around 7 and greater. This would indicate that for a TR system under ideal conditions, a reduced control power can no longer be used effectively when the system saturation ratio is above 7.

The data for the acceleration, rate, and attitude systems on figure 10 were taken with the saturation ratio held to one; thus it is not meaningful at the low control power settings to draw a comparison between those curves and the curve for the RM task of the translational rate system. However, the data for the SK/MM task, which is less demanding on control power and thus did not result in saturation, can be compared. Figure 10 shows this comparison to be reasonably consistent.

CONCLUSIONS

A piloted simulation study was conducted to determine the basic control system dynamic characteristics needed for an attitude derived translational rate command system for an aircraft in near-hover flight. The desired characteristics determined by this simulation are summarized below.

- The attitude response should be well damped (the dynamic response of the binomial form of the TR system was found preferrable to the lesser damped Butterworth form).
- The optimum cubic natural frequency (ω_o) was 1.5 - 2.5 r/sec. The pilots generally favored the lower frequencies for the RM task and slightly higher frequencies for the SK/MM task.

- The optimum command sensitivity (T_δ) was .6 - 1.5 r/s^2/in. This yields a velocity sensitivity (depending on ω_o) of from 2 to 20 fps/in. The optimum velocity sensitivity for the RM task was 5 to 20 fps/in and for the SK/MM task 2 to 10 fps/in.
- With reference to the RM task and under ideal conditions, the translational rate system appears to have lower control power requirements than does an attitude system and tolerates higher saturation ratio systems (approximately SR $\leq$ 7 as opposed to SR $\leq$3for attitude systems (Reference 1)).

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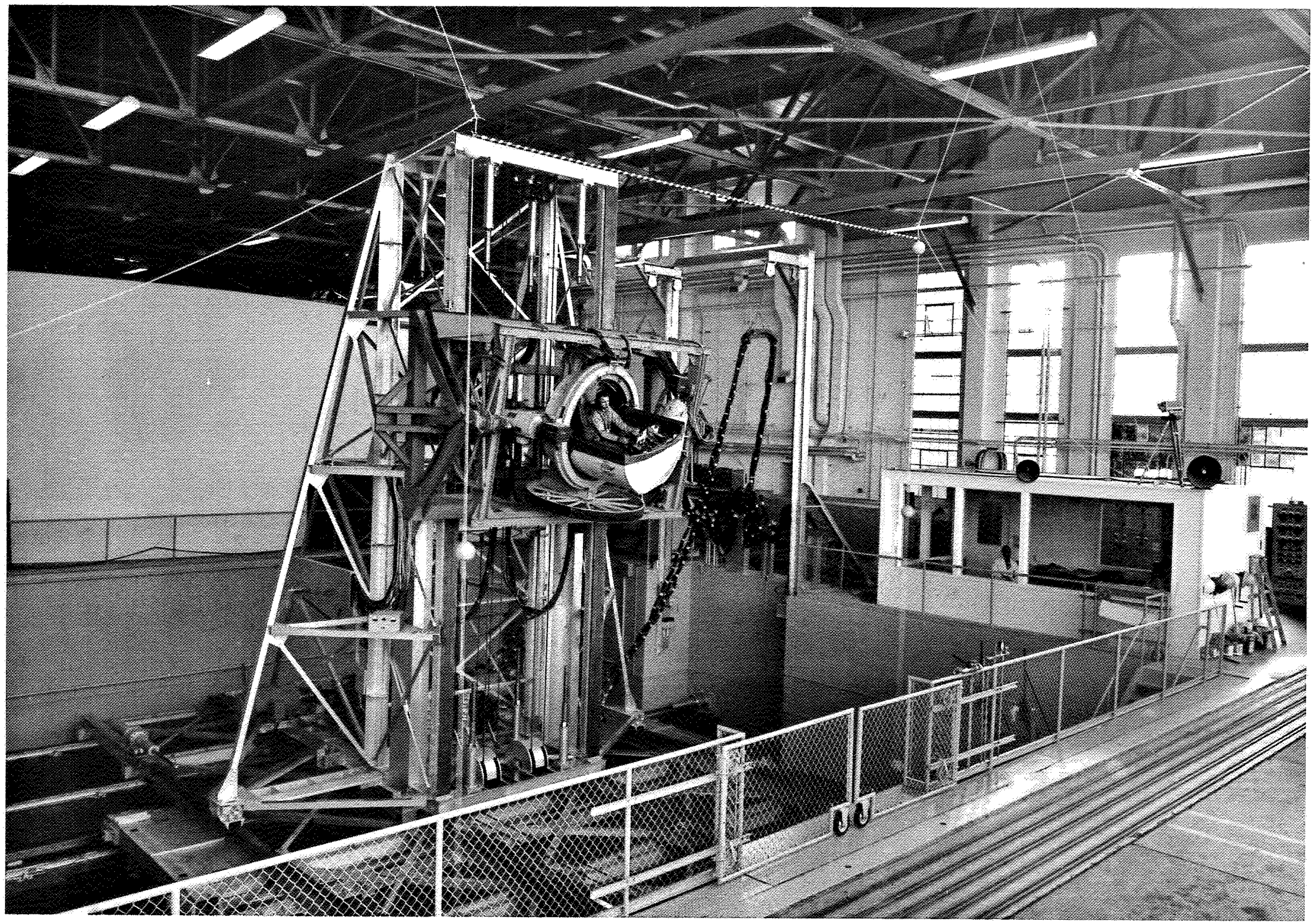


Figure 1. Ames Six-Degrees-of-Freedom Simulator

ROLL TRANSLATIONAL RATE SYS.

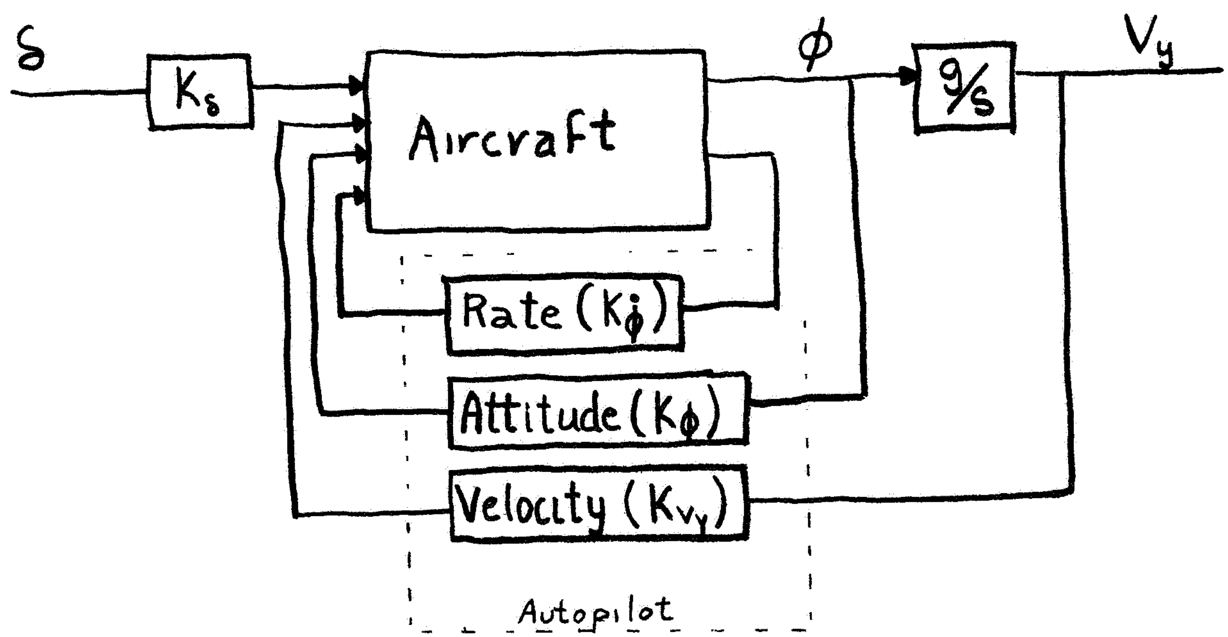
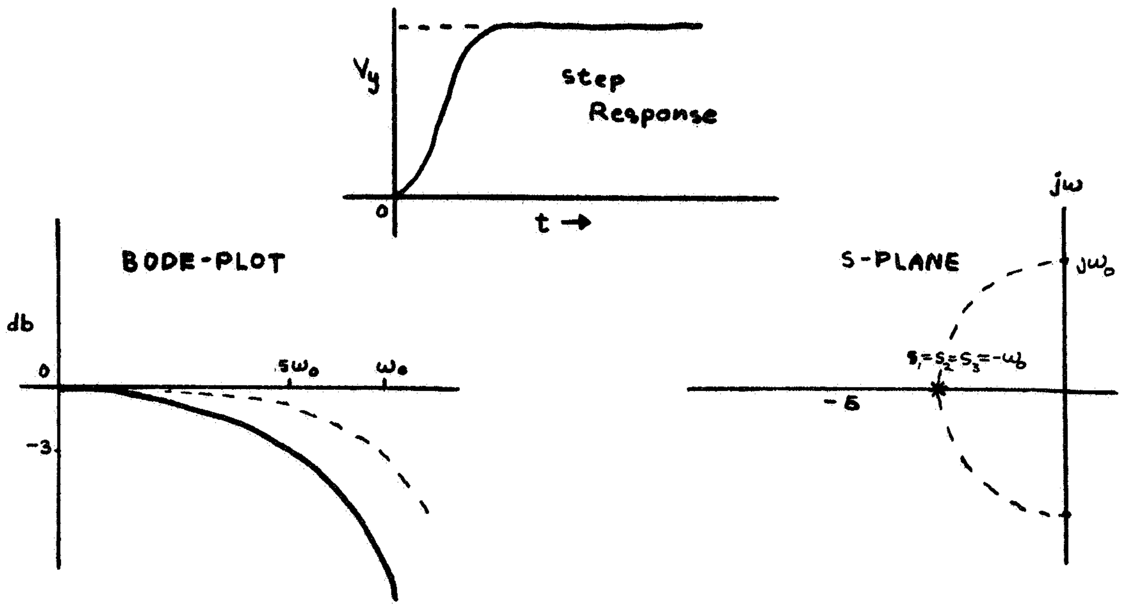


Figure 2

BINOMIAL FORM ($K_1 = K_2 = 3$)

$$s^3 + 3\omega_o s^2 + 3\omega_o^2 s + \omega_o^3 = (s+\omega_o)^3$$



BUTTERWORTH FORM ($K_1 = K_2 = 2$)

$$s^3 + 2\omega_o s^2 + 2\omega_o^2 s + \omega_o^3 = (s^2 + 2(.5)\omega_o s + \omega_o^2)(s+\omega_o)$$

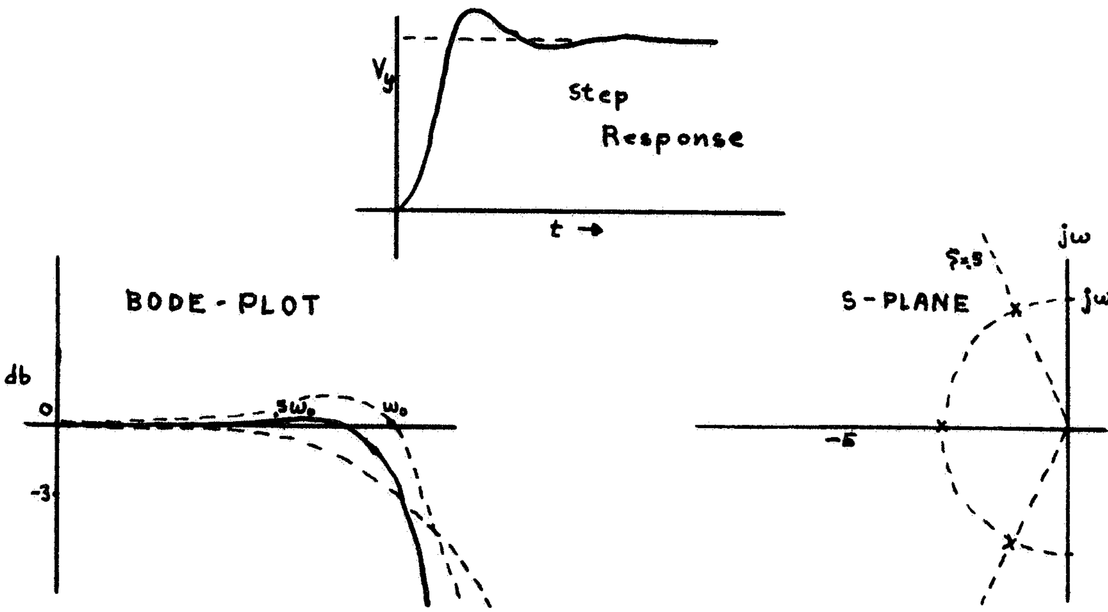


Figure 3

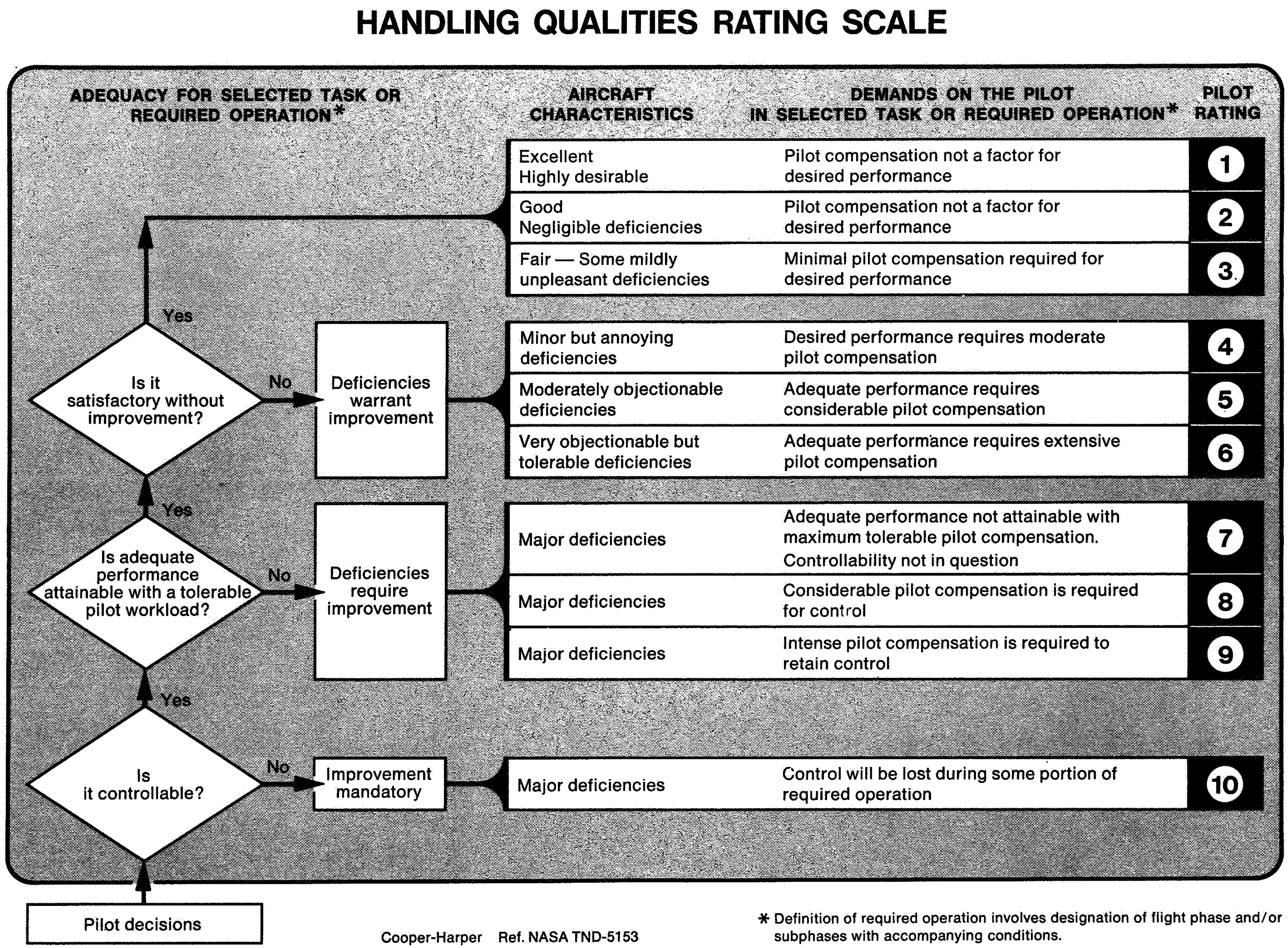

HANDLING QUALITIES RATING SCALE
ADEQUACY FOR SELECTED TASK OR REQUIRED OPERATION*
AIRCRAFT CHARACTERISTICS
DEMANDS ON THE PILOT IN SELECTED TASK OR REQUIRED OPERATION*
PILOT RATING
Excellent
Highly desirable
Pilot compensation not a factor for desired performance
1
Good
Negligible deficiencies
Pilot compensation not a factor for desired performance
2
Fair — Some mildly unpleasant deficiencies
Minimal pilot compensation required for desired performance
3
Yes
Is it satisfactory without improvement?
No
Deficiencies warrant improvement
Minor but annoying deficiencies
Desired performance requires moderate pilot compensation
4
Moderately objectionable deficiencies
Adequate performance requires considerable pilot compensation
5
Very objectionable but tolerable deficiencies
Adequate performance requires extensive pilot compensation
6
Yes
Is adequate performance attainable with a tolerable pilot workload?
No
Deficiencies require improvement
Major deficiencies
Adequate performance not attainable with maximum tolerable pilot compensation.
Controllability not in question
7
Major deficiencies
Considerable pilot compensation is required for control
8
Major deficiencies
Intense pilot compensation is required to retain control
9
Yes
Is it controllable?
No
Improvement mandatory
Major deficiencies
Control will be lost during some portion of required operation
10
Pilot decisions
Cooper-Harper Ref. NASA TND-5153
* Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions.

Figure 4

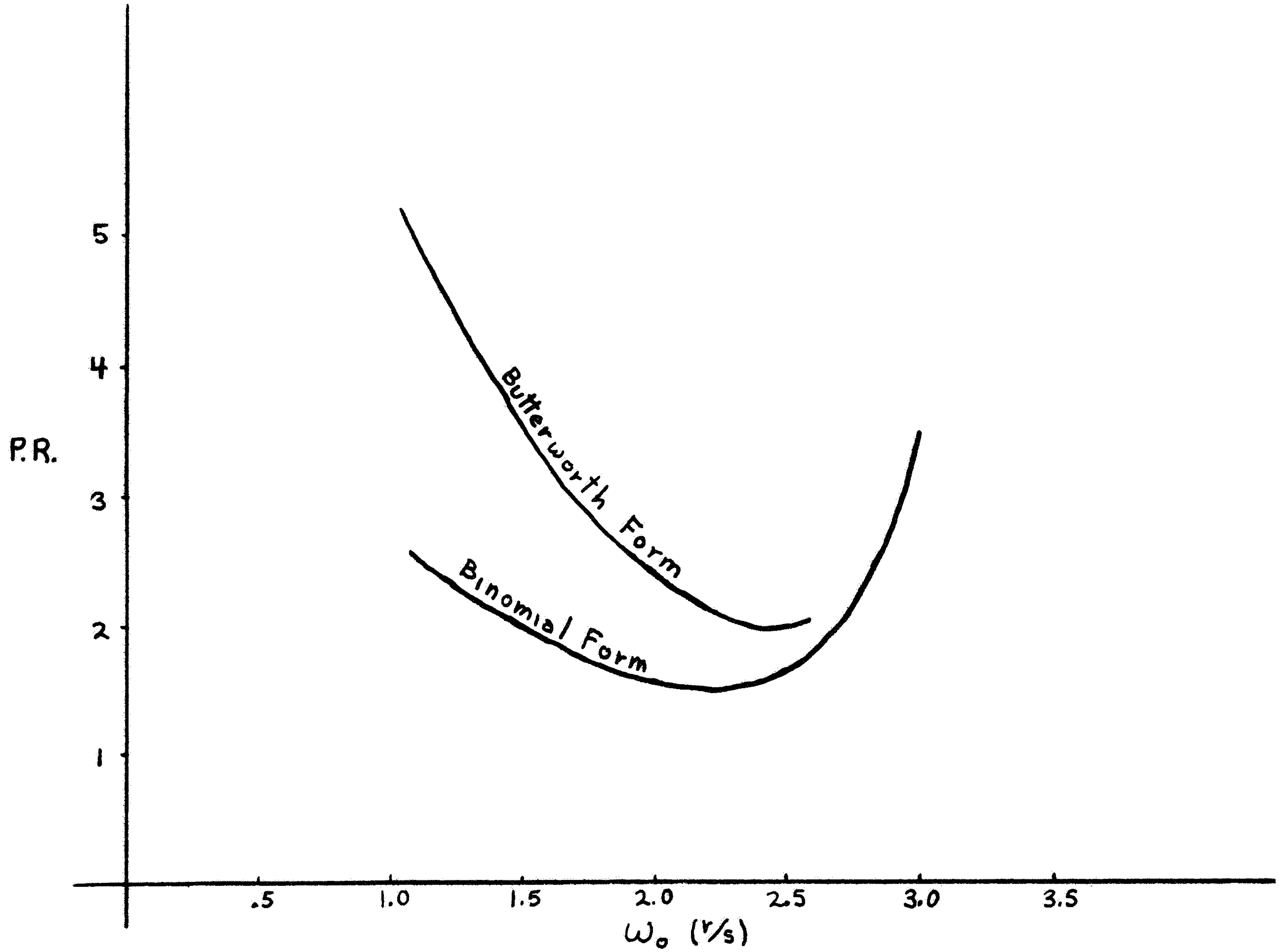


Figure 5. System Damping (Butterworth vs. Binomial)

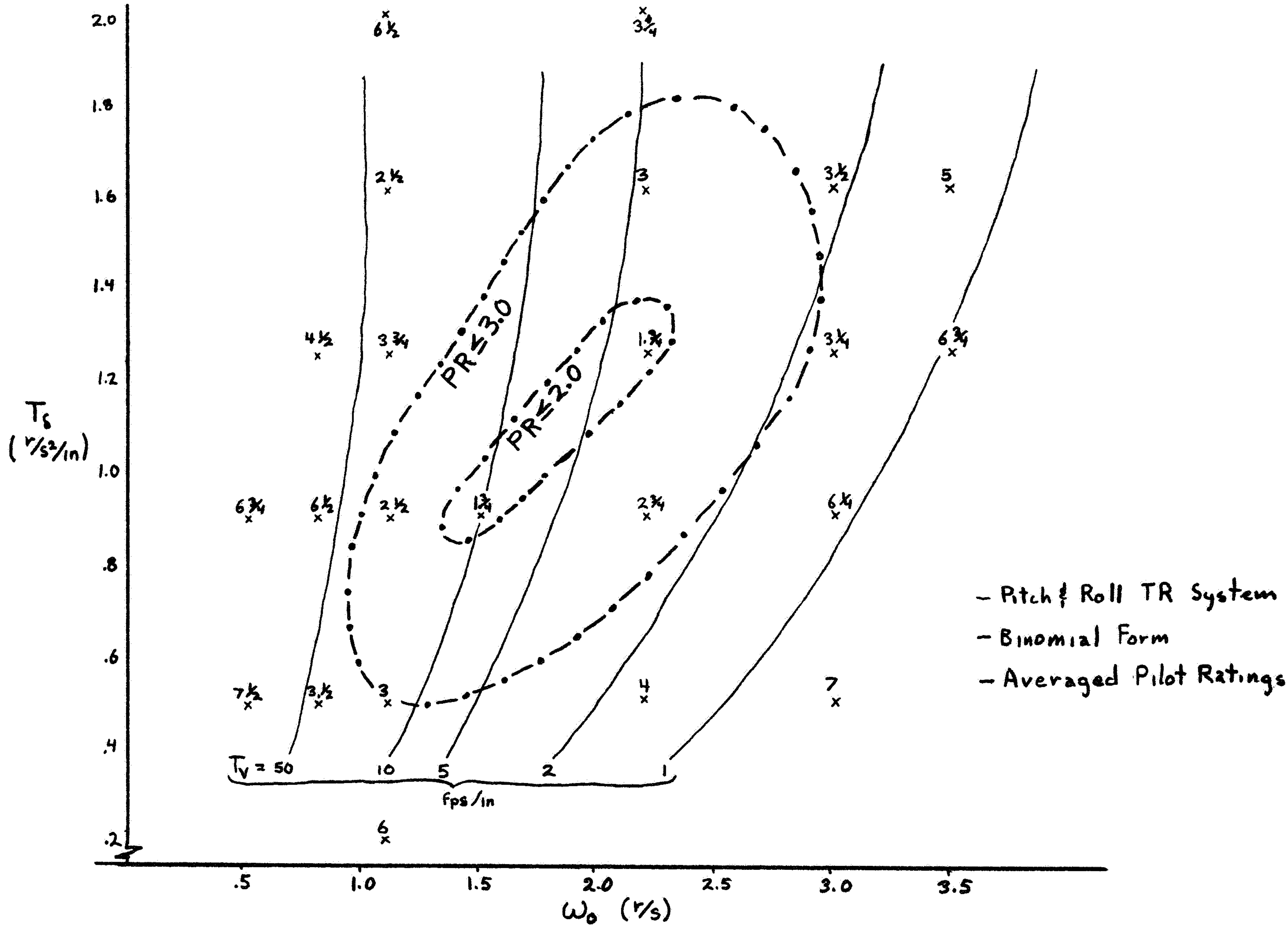


Figure 6. Rapid Maneuver

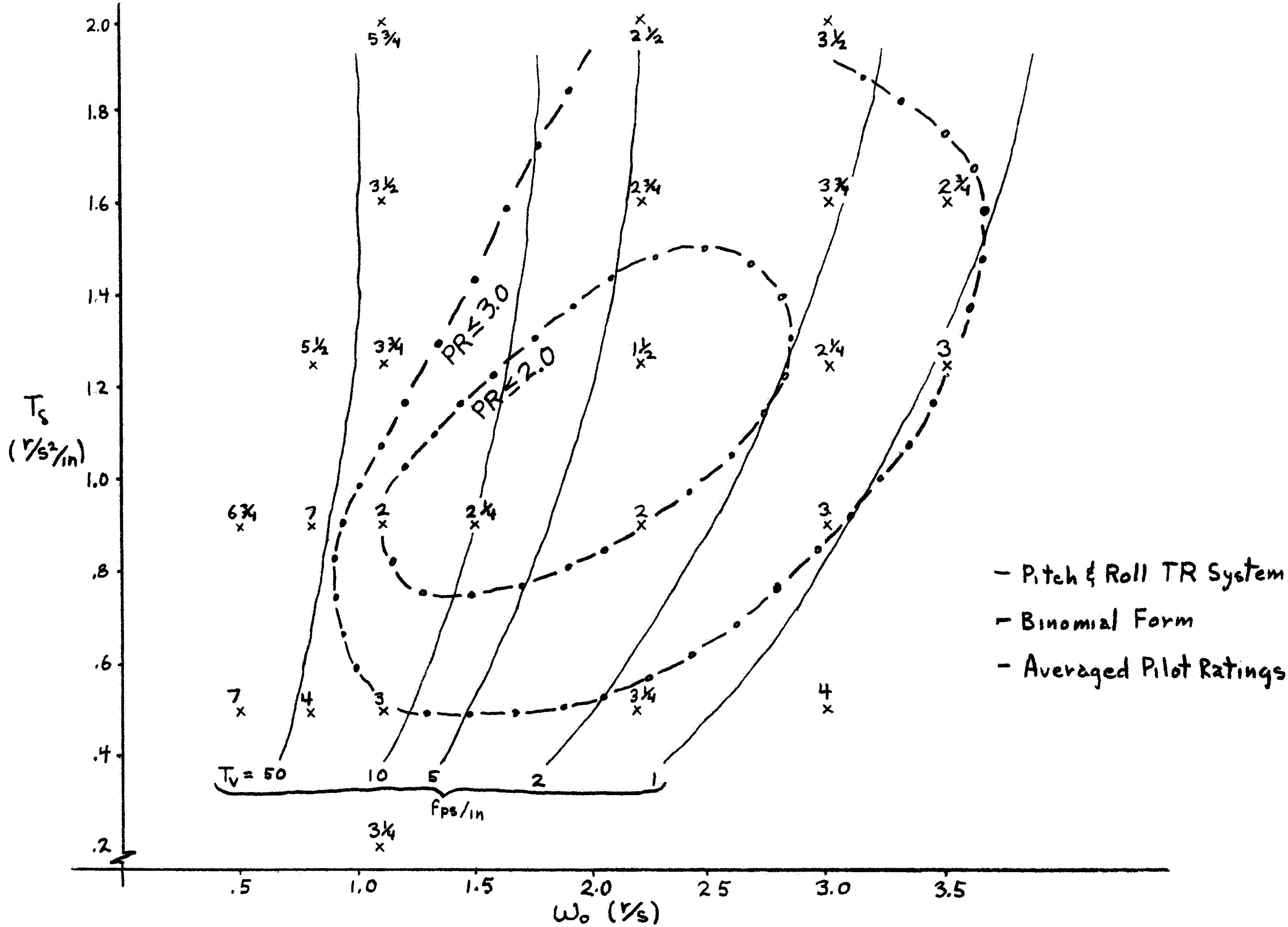


Figure 7. Station Keeping/Mild Maneuver

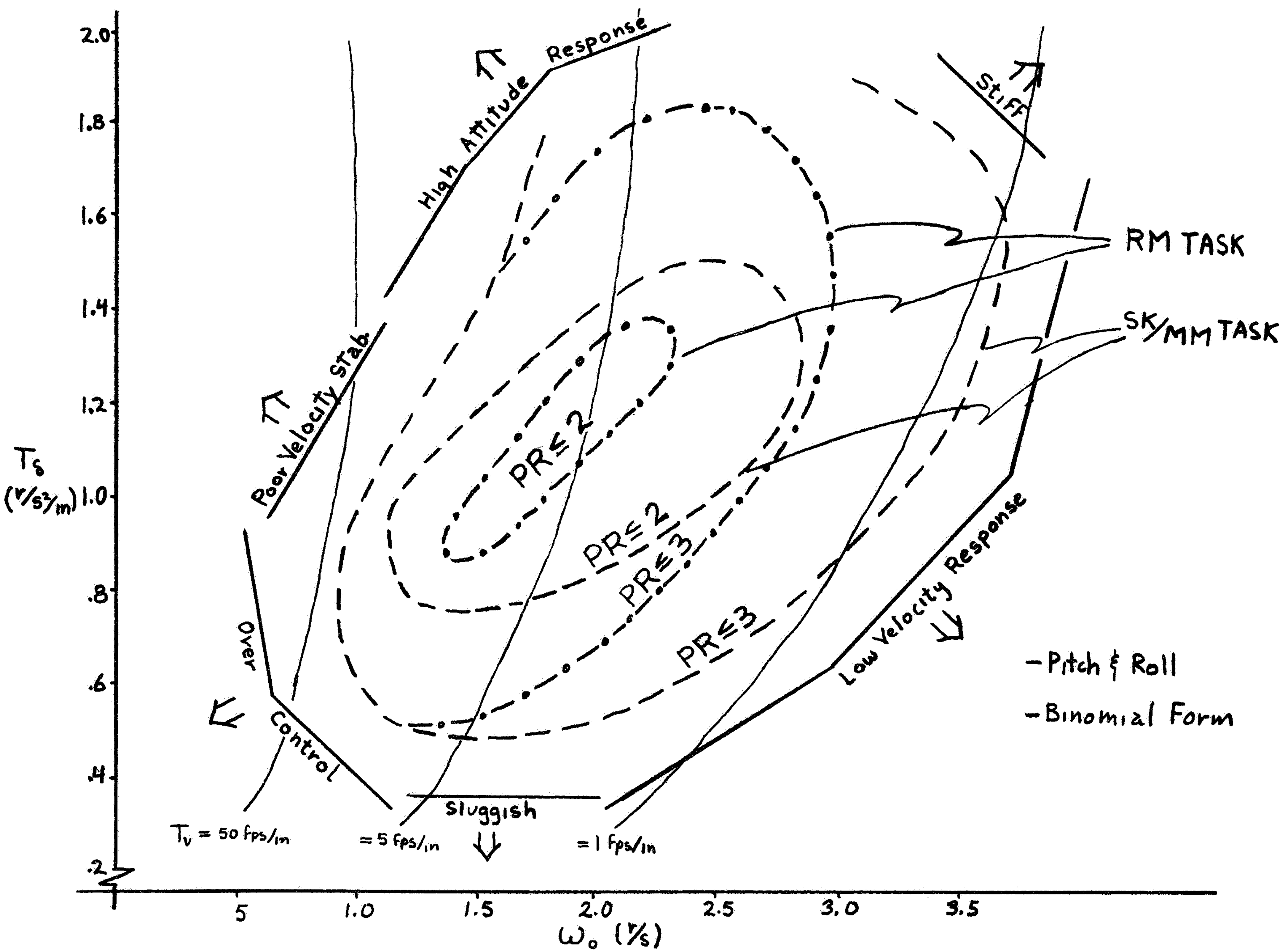


Figure 8. Op timum TR System

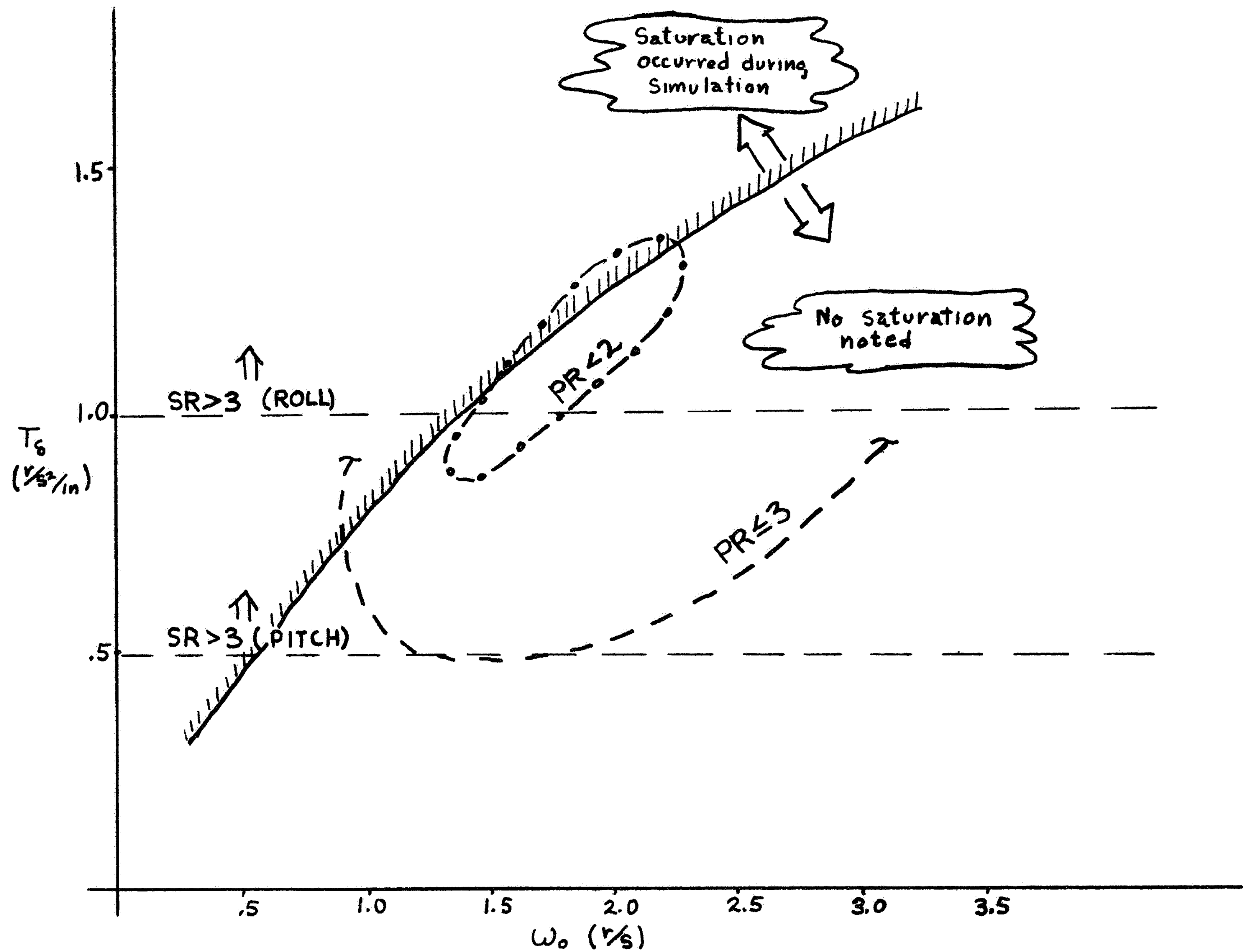


Figure 9. Regions of Saturation Indicated in Study of TR Systems.
Control power available 1.4 r/s^2 in roll, .7 r/s^2 in pitch.

SIMULATOR COMPARISON OF ACCELERATION, RATE, ATTITUDE, AND TRANS. RATE CONTROL SYSTEM

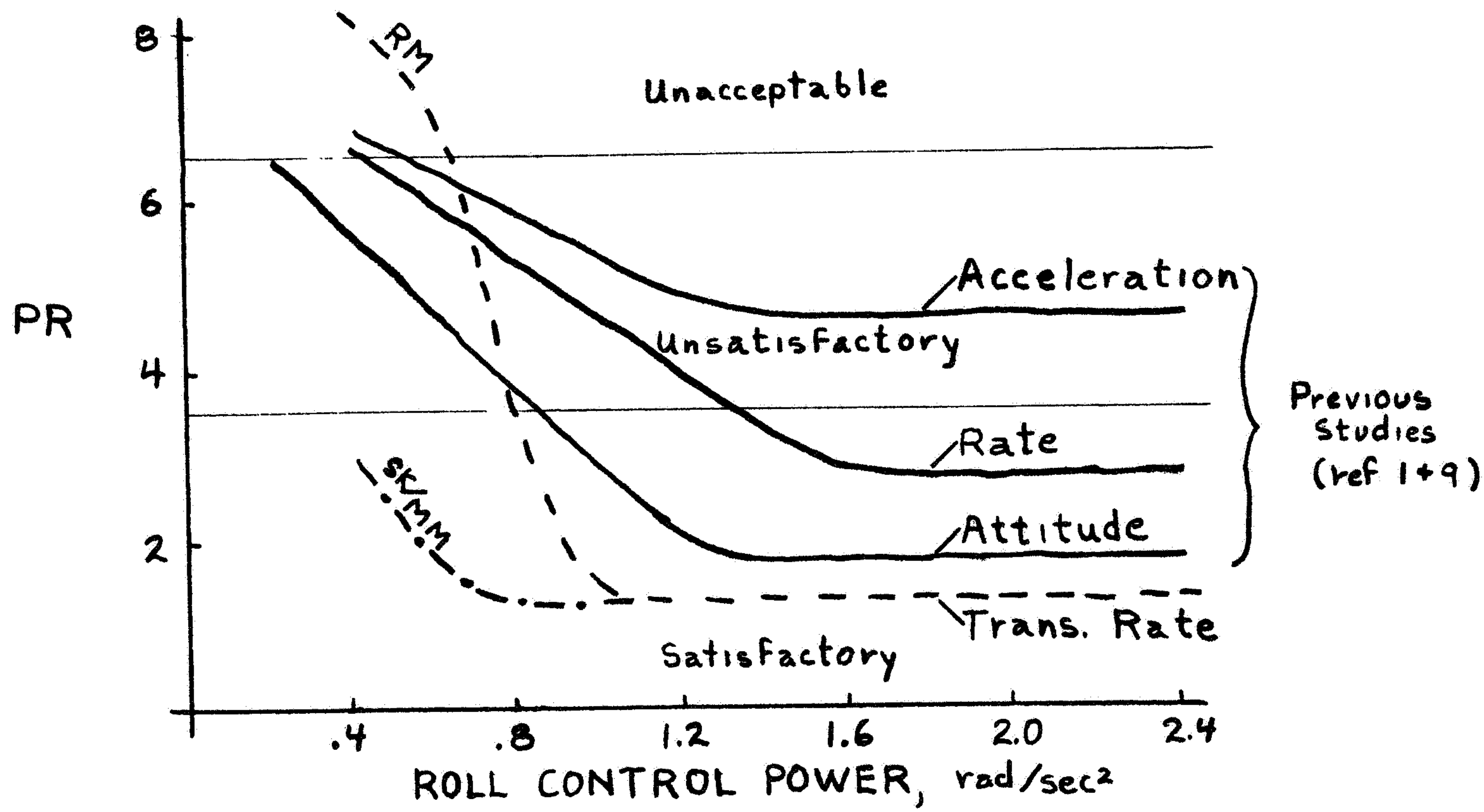


Figure 10