NASA TECHNICAL NOTE

NASA TN D-5358

NASA TN D-5358

FIXED-BASE SIMULATOR PILOT RATING SURVEYS FOR PREDICTING LATERAL-DIRECTIONAL HANDLING QUALITIES AND PILOT RATING VARIABILITY

by Lawrence W. Taylor, Jr., and Kenneth W. Iliff

Flight Research Center
Edwards, Calif.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • AUGUST 1969

NASA TN D-5358

FIXED-BASE SIMULATOR PILOT RATING SURVEYS FOR PREDICTING LATERAL-DIRECTIONAL HANDLING QUALITIES AND PILOT RATING VARIABILITY

By Lawrence W. Taylor, Jr., and Kenneth W. Iliff

Flight Research Center
Edwards, Calif.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – CFSTI price $3.00

FIXED-BASE SIMULATOR PILOT RATING SURVEYS FOR PREDICTING LATERAL-DIRECTIONAL HANDLING QUALITIES AND PILOT RATING VARIABILITY

By Lawrence W. Taylor, Jr., and Kenneth W. Iliff
Flight Research Center

SUMMARY

Pilot ratings of lateral-directional handling qualities were collected for a wide range of simplified aircraft characteristics through the use of a simple fixed-base simulator with a color contact analog display. The results of the general survey were obtained with an engineer as the subject and are contained in 45 plots involving five parameters. The survey results show that the handling qualities for the specific simulations used were, in general, optimum when $\frac{\omega_\varphi}{\omega_d} = 1.0$, where ω_φ is the roll control parameter and ω_d the undamped natural frequency of the Dutch roll mode, but if the roll control power is too low, a value of $\frac{\omega_\varphi}{\omega_d} > 1.0$ is desirable. Increased roll and Dutch roll damping are important in alleviating the pilot-induced-oscillation tendency for $\frac{\omega_\varphi}{\omega_d} > 1.0$ but can be a detriment if the roll response is made sluggish, particularly for $\frac{\omega_\varphi}{\omega_d} < 1.0$. The results of the general survey are used in an empirical method for predicting lateral-directional pilot ratings for most airplane configurations and flight conditions.

In another survey, utilizing the same simulation, ratings were obtained from many pilots in order to study the variability in pilot ratings among pilots and the differences in pilot rating that result from changes in mission. The standard deviation of individual pilot ratings ranged from 1.0 at the "good" end of the scale to 2.0 in the middle of the scale. Ratings for specific missions were generally numerically higher (more adverse) than those for the general mission for the same vehicle characteristics.

INTRODUCTION

The handling qualities of aircraft have been the subject of many investigations. Analytical methods and fixed-base and in-flight simulators have been used to investigate the influence of a variety of parameters on handling qualities. References 1 to 15

represent a partial bibliography of lateral-directional studies. Criteria based on these studies have been guides in airplane design and have provided a general understanding of the effects of many parameters. Increased airplane performance, larger operating envelopes, and new design considerations necessitate a continued refinement and improvement in handling-qualities knowledge.

Methods of estimating and assessing handling qualities are available as, for instance, the use of closed-loop pilot-airplane systems analysis (for example, refs. 11 to 13), ground-based flight simulators (for example, refs. 5, 14, and 15), and in-flight simulators (for example, refs. 1 to 4 and 10). The more sophisticated and reliable methods, however, require considerable time and effort; hence, a method is needed that can be easily applied. It was reasoned that an assessment of the handling qualities of all combinations of several airplane parameters over wide ranges of operating conditions would provide handling-qualities data on which predictions could be based. Such a survey was undertaken at the NASA Flight Research Center, utilizing a fixed-base simulator. The results of the survey—lateral-directional handling qualities as defined by pilot ratings—are presented in this paper. Pilot ratings were selected as the most significant criteria, for it is the pilot who must finally judge the acceptability of the airplane. The first part of the investigation was a general survey in which pilot ratings were obtained by an engineer for numerous combinations of the five most pertinent handling-qualities parameters.

Inasmuch as many factors influence pilot ratings of airplane characteristics, the second part of the investigation was a survey that utilized many pilots in order to study pilot variability for a general flight mission. In addition, the effect of mission on pilot rating was investigated by considering five other missions. These results are presented herein in order to increase the applicability of the results from the general survey.

The results of this investigation are intended to provide a rapid means of predicting airplane handling qualities in which several parameters are considered simultaneously. It is not intended, however, to replace detailed simulation investigations of the handling qualities of an airplane, such as during final design and flight testing.

SYMBOLS

g	acceleration due to gravity, ft/sec^2
L_β^*	roll acceleration due to sideslip, referenced to principal axis, per sec^2 ($\frac{1}{L_\beta^*}$ is proportional to roll-induced sideslip for constant $L_{\delta_a}\delta_{a_{max}}$, ω_φ, ω_d, and τ_r; see simplified equations of motion, p. 5)
L_{δ_a}	roll acceleration due to lateral control, referenced to principal axis, per sec^2
$L_{\delta_{a_s}}$	lateral control sensitivity, $rad/sec^2/in.$

$L_{\delta_a}\delta_{a_{max}}$	lateral control power or maximum roll acceleration due to lateral control, referenced to principal axis, rad/sec^2
N'_{δ_a}	yaw acceleration due to lateral control, referenced to stability axis, per sec^2
p	roll rate, referenced to principal axis, rad/sec
s	Laplace transform variable
V	velocity, ft/sec
Y_{δ_a}	side "force" due to aileron deflection, per sec
β	angle of sideslip, rad
δ_a	lateral control deflection, rad
$2\zeta_d\omega_d$	Dutch roll damping, per sec
$2\zeta_\varphi\omega_\varphi$	damping coefficient in the numerator of the roll rate to lateral control transfer function, per sec
σ	standard deviation
τ_r	time constant of the roll mode, sec
φ	bank angle, rad
$\left\|\frac{\varphi}{\beta}\right\|$	amplitude ratio of φ to β for the Dutch roll mode
ω_d	undamped Dutch roll frequency, rad/sec
ω_φ	undamped natural frequency of the numerator of the roll rate to lateral control transfer function, referenced to principal axis, rad/sec
$\|\|$	absolute value of a quantity

A dot over a symbol denotes differentiation with respect to time.

SIMULATION

Actual flight provides many cues and motivations important in evaluating the handling of an airplane. However, for many reasons, such as safety and cost, all handling-qualities evaluations cannot be made in flight; therefore, flight simulators (ref. 16) have been designed to substitute for flight. Efforts to increase the realism of simulations have led to the addition of motion, visual presentations, and even to tests in the actual flight environment using variable-stability airplanes as simulators. All of these means of flight simulation have deficiencies: (1) the fixed-base simulator lacks motion cues

and, often, peripheral visual cues, (2) the moving-base simulator cannot match both angular and linear accelerations except for very small displacements and, in many cases, adds the distractions of noise and jerky motion, and (3) the variable-stability airplane cannot always provide the correct relationship between attitude and linear acceleration, and the higher order and "not-quite-linear" dynamics of the variable-stability airplane prevent exact simulation. Although the fixed-base simulator is limited in the fidelity with which it can represent the flight environment, the correlation of results from a fixed-base simulator program and those from flight were generally good (ref. 14) when skilled and properly motivated pilot subjects were used.

Description of Simulator

For this investigation a simple fixed-base simulator (fig. 1) was used. A seat with a conventional center stick (4 in. maximum lateral deflection, spring gradient of 3 lb/in. in roll), dial instruments displaying roll rate and sideslip, and a three-axis attitude indicator provided the essentials for the fixed-base cockpit. A color contact analog presented simulated outside attitude information providing indications of pitch, roll, and heading, and the illusion of forward velocity. Additional dials shown in figure 1 were inactive. Rudder pedals, although available, were not mechanized in the simulation. An analog computer provided the real-time solution of the equations used to represent the simplified dynamics of the airplane. Although the pitch degrees of freedom were omitted in the simulation, some pitching was evident as a result of sideslip in a banked attitude.

Mechanization of Simulator

Simplified equations that were equivalent to the transfer functions relating roll and sideslip response to lateral control (aileron) input were mechanized on the analog computer of the flight simulator. This equivalent mechanization was utilized because of the ease with which the parameters of the survey could be changed to specific values. The derivation of the transfer functions used assumed $\frac{g}{V}$ and $Y_{\delta_a} = 0$ and cancellation of the roll mode in the sideslip transfer function. A similar derivation is contained in the appendix of reference 15. The roll-to-aileron and sideslip-to-aileron transfer functions used were, respectively,

$$\frac{\varphi(s)}{\delta_a(s)} = \frac{L_{\delta_a}(s^2 + 2\zeta_\varphi \omega_\varphi s + \omega_\varphi{}^2)}{s\left(s + \frac{1}{\tau_r}\right)(s^2 + 2\zeta_d \omega_d s + \omega_d{}^2)}$$

and

$$\frac{\beta(s)}{\delta_a(s)} = \frac{-N'_{\delta_a}}{(s^2 + 2\zeta_d \omega_d s + \omega_d{}^2)}$$

where

$$2\zeta_{\varphi}\omega_{\varphi} = 2\zeta_{d}\omega_{d}$$

$$\frac{1}{\tau_r} = 4.0(2\zeta_{d}\omega_{d})$$

$$N'_{\delta_a} = \frac{(\omega_d^2 - \omega_{\varphi}^2)L_{\delta_a}}{L_{\beta}^*}$$

The transfer functions are standard except that the spiral-mode stability is neutral (as in refs. 10 and 12) and the damping terms have been restricted as indicated. The simplified sideslip transfer function results from these restrictions.

The equations mechanized on the analog computer were

$$\dot{p} = L_{\delta_a}\delta_a - \frac{1}{\tau_r}p + L_{\beta}^*\beta$$

and

$$\ddot{\beta} = -2\zeta_{d}\omega_{d}\dot{\beta} - \omega_d^2\beta - N'_{\delta_a}\delta_a$$

These equations are not airplane equations of motion but, rather, equations which gave the simplified transfer functions relating roll and sideslip response to aileron inputs. Note that the expression for N'_{δ_a} permits the sideslip induced by lateral control application to be related to L_{β}^* as follows:

$$\frac{\beta(s)}{\delta_a(s)} = \frac{-(\omega_d^2 - \omega_{\varphi}^2)L_{\delta_a}}{L_{\beta}^*(s^2 + 2\zeta_{d}\omega_{d}s + \omega_d^2)}$$

With the other parameters, ω_{φ}, ω_d, $2\zeta_{d}\omega_{d}$, and $L_{\delta_a}\delta_{a_{max}}$, specified, the amount of sideslip induced by lateral control application is inversely proportional to L_{β}^*. Sideslip was a function only of aileron deflection, since rudder control was not available to the subject and the simulation did not include unsteady atmospheric inputs.

TEST PROCEDURES

Pilot Rating Procedure

Before a subject pilot assessed the first condition, he was briefed on the purpose of the study and the pilot rating scale shown in the following table (the same scale as that used in reference 10 and similar to that presented in reference 17):

Numerical rating	Category	Adjective description within category
1	Acceptable and satisfactory	Excellent
2		Good
3		Fair
4	Acceptable but unsatisfactory	Fair
5		Poor
6		Bad
7	Unacceptable	Bad
8		Very bad
9		Dangerous
10	Unflyable	Unflyable

The suggested maneuvers for evaluation for both surveys were 45° to 45° banks, 90° heading changes, and a precision control task with no external disturbances in which the wings were held precisely level. The evaluating pilot was allowed to use his own judgment, however, on the specific maneuver to perform and was free to modify, supplement, or repeat maneuvers he believed necessary for a proper evaluation.

In the pilot rating variability survey the pilot was briefed on the missions for which pilot ratings were desired. The missions used were as follows (only the general mission was used in the general survey):

General - No specific mission.

Fighter - An operational air superiority fighter or fighter-bomber. A fairly rapid control response is desirable.

Reentry glider - A research vehicle flown by only the most qualified pilots. Compromises in the handling qualities are required because of the extreme range of flight conditions.

Bomber - An operational bomber. Rapid response is less desirable than high stability and damping.

Supersonic transport - A supersonic transport in a commercial type of operation. Because of the passengers, control must be smooth and sure.

Light airplane - A light airplane flown with a minimum of instruments by a civilian pilot with little experience.

First, the pilot was given an easily controlled case and allowed as much time as necessary for evaluation. The next two cases were selected to be very difficult to control in order to expose the pilot to the types and extremes of the control task characteristics. This procedure helped to stabilize the pilot's ratings.

All of the pilot ratings collected during the study reported in this paper were obtained without the pilot knowing the test conditions in order to minimize biases and inconsistencies.

Pilot Subjects

Pilot ratings were collected from experienced pilots and engineers. Ratings from actual pilots were used exclusively in studying the variability among pilots and the effect of airplane type and mission on pilot ratings. The piloting experience of all the pilot subjects is summarized in the following table:

	Experience, flight hours												
	Jet				Reciprocating					Miscellaneous			
Pilot	Single-engine fighter	Multi-engine fighter	Bomber	Transport	Fighter	Single-engine light aircraft	Multi-engine light aircraft	Bomber	Transport	Helicopter	Simulator	Link trainer	Research glider
A	993	7.6	---	---	1866	297	135	86	402	----	1000	200	41
B	1329	300	12	14	1617	30	100	3	222	35	150	350	17
C	1859	2.25	---	---	44	----	----	38	42	180	----	112	--
D	500	----	---	---	----	900	----	---	600	1500	400	---	--
E	1810	1	1	---	----	----	1	---	----	----	----	---	--
F	400	----	---	---	600	1200	100	75	10	----	2000	100	--
G	1660	443	---	---	----	259	----	---	20	----	50	100	--
H	2000	31	50	---	460	----	----	---	53	400	5	150	--
I	315	30	238	273	1400	300	150	366	1125	2	100	50	1
J	3100	100	200	---	----	400	1200	20	400	10	2000	---	45
K	2450	----	---	---	----	10	200	---	600	2	400	200	--
L	857	48	127	7	1196	160	340	664	968	99	----	---	12
M	850	60	20	30	2050	650	300	80	1600	4.5	800	300	17
N	1500	500	---	---	100	----	----	---	20	----	100	---	--
O	1810	25	---	---	100	50	----	---	189	1	90	---	--
P	1443	26	---	28	----	----	183	304	120	3	161	---	--
Q	75	10	25	---	300	2300	1200	200	100	1200	25	100	3
R	1400	----	---	---	----	----	----	---	----	----	----	---	--

An engineer (non-pilot), identified as subject S, was used in the general rating survey. Correlation of the ratings of all of the individual subjects and the average ratings of all the actual pilots is discussed later. Subjects T to X were also engineers. Some, but not all, of the engineers had piloting experience.

Range of Tests

Several parameters over a wide range of values $(\omega_{\varphi}, \omega_{d}, \begin{Bmatrix} 2\zeta_{\varphi}\omega_{\varphi} \\ 2\zeta_{d}\omega_{d} \\ \frac{1}{\tau_{r}} \end{Bmatrix}, L_{\delta_a}\delta_{a_{max}}, L_{\beta}^{*})$ were studied in an effort to cover the range of values for most airplanes. Ratings were collected for many combinations of ω_{φ} and ω_{d}, both of which ranged from 0 to

6.0 rad/sec. These combinations were repeated for all possible combinations of the following values of the other parameters:

$$\begin{Bmatrix} 2\zeta_\varphi\omega_\varphi \\ 2\zeta_d\omega_d \\ \frac{1}{\tau_r} \end{Bmatrix} = \begin{matrix} 0.025 & 0.25 & 1.0 \\ 0.025 & 0.25 & 1.0 \\ 0.1 & 1.0 & 4.0 \end{matrix}$$

$$L_{\delta_a}\delta_{a_{max}} = 0.1,\ 3.0,\ 10,\ 30,\ 100$$

$$L_\beta^* = -10,\ -30,\ -100$$

The pilot rating variability survey used the following sets of parameter values:

Case number	ω_φ	ω_d	$2\zeta_d\omega_d$	$\frac{1}{\tau_r}$	L_β^*	$L_{\delta_a}\delta_{a_{max}}$
1	1.8	1.2	0.25	1.0	-30	10
2	1.6	1.4	.25	1.0	-30	10
3	1.55	1.45	.25	1.0	-30	10
4	1.5	1.5	.25	1.0	-30	10
5	1.3	1.7	.25	1.0	-30	10
6	1.0	2.0	.25	1.0	-30	10
7	.8	1.2	.25	1.0	-30	10
8	3.2	3.8	.25	1.0	-30	10
9	2.6	3.4	.25	1.0	-30	10
10	.2	.8	.25	1.0	-30	10
11	.7	.4	.25	1.0	-30	10
12	3.5	2.5	.25	1.0	-30	10
13	3.5	2.5	1.0	4.0	-30	10
14	3.5	2.5	.25	1.0	-100	10
15	3.5	2.5	.25	1.0	-30	30
16	1.9	4.1	.25	1.0	-30	10
17	1.9	4.1	1.0	4.0	-30	10
18	1.9	4.1	.25	1.0	-100	10
19	1.9	4.1	.25	1.0	-30	30
A[1]	1.5	1.5	.25	1.0	-30	10
B[1]	2.0	1.0	.25	1.0	-30	10
C[1]	.5	2.5	.25	1.0	-30	10

[1]Used for pilot orientation only.

RESULTS AND DISCUSSION

This study consisted of two surveys: (1) the general pilot rating survey on which the prediction method is based and (2) the pilot rating variability survey in which pilots rated the same set of simulated airplane characteristics for several different missions.

General Survey

The results of the general survey are presented as 45 plots (for all combinations of three values of dihedral effect L_β^*, three values of Dutch roll and roll damping, and five values of roll control power) of ω_φ versus ω_d showing lines of constant pilot

rating. The fairings of the data were made as consistent as possible through the extensive use of cross plots. The airplane parameters and the values for the parameters were selected to provide extensive coverage of the most generally applicable parameters. The plots of ω_φ versus ω_d, an example of which is shown in figure 2, were chosen because the stability and control problems of control reversal, sluggishness, induced sideslip, pilot-induced oscillations, and static stability are readily portrayed. Along the diagonal line ($\omega_\varphi = \omega_d$), there is no sideslip induced by control under the constraints of the simplified simulation in this study where $2\zeta_\varphi\omega_\varphi = 2\zeta_d\omega_d$ and $\frac{g}{V} = 0$. In general, $2\zeta_\varphi\omega_\varphi$ is only nearly equal to $2\zeta_d\omega_d$. At conditions below the diagonal, the induced sideslip due to aileron inputs retards roll and causes the rate of roll to oscillate at low damping conditions. The induced sideslip due to aileron inputs increases as ω_φ is reduced, and the roll rate decreases until, at $\omega_\varphi = 0$, zero steady-state roll rate is obtained for constant aileron deflection and only sideslip with a steady bank angle is produced. For low values of ω_d this condition was found to be completely acceptable, since the steady bank angle becomes larger as ω_d is reduced. The result is in effect a bank-angle command system with adequate authority, as can be seen by examining the resulting transfer function.

At conditions above the diagonal line in figure 2, sideslip is induced that augments roll and causes lateral oscillations as the pilot attempts to stabilize bank angle. For very low values of $L_{\delta_a}\delta_{a_{max}}$ some induced sideslip is preferred to augment the sluggish roll response. Farther above the diagonal, a greater amount of sideslip is induced, and the lateral control problem may become a pilot-induced divergence even though the basic airplane is stable. Neutral static directional stability occurs at $\omega_d = 0$. These trends are generally true, although the problem areas change in size and severity as the other parameters are changed.

Figures 3(a) to 3(ss) show the results of the pilot rating survey as plots of faired contours of constant pilot rating. The figures are presented in order of increasing values of control power $L_{\delta_a}\delta_{a_{max}}$, damping $2\zeta_d\omega_d$ and $\frac{1}{\tau_r}$, and dihedral effect L_β^* as follows:

$L_{\delta_a}\delta_{a_{max}}$					$2\zeta_d\omega_d$ (1)	$\frac{1}{\tau_r}$ (1)	$\lvert L_\beta^* \rvert$
0.1	3.0	10	30	100			
3(a)	3(b)	3(c)	3(d)	3(e)	0.025	0.1	10
3(f)	3(g)	3(h)	3(i)	3(j)	.250	1.0	10
3(k)	3(*l*)	3(m)	3(n)	3(o)	1.000	4.0	10
3(p)	3(q)	3(r)	3(s)	3(t)	.025	.1	30
3(u)	3(v)	3(w)	3(x)	3(y)	.250	1.0	30
3(z)	3(aa)	3(bb)	3(cc)	3(dd)	1.000	4.0	30
3(ee)	3(ff)	3(gg)	3(hh)	3(ii)	.025	.1	100
3(jj)	3(kk)	3(*ll*)	3(mm)	3(nn)	.250	1.0	100
3(oo)	3(pp)	3(qq)	3(rr)	3(ss)	1.000	4.0	100

[1] In the simulation, $\frac{1}{\tau_r} = 4(2\zeta_d\omega_d)$ in all cases.

A tabulation of the individual ratings obtained is available on request from the Flight Research Center.

Effect of damping. – Increased damping (both roll and Dutch roll damping in the manner indicated on page 5) generally improves lateral-directional handling qualities, especially for $\frac{\omega_\varphi}{\omega_d} > 1.0$ where a pilot-induced-oscillation tendency exists. The cross plot of figures 3(t), 3(y), and 3(dd), shown as figure 4(a), shows improvement with increased damping at all values of $\frac{\omega_\varphi}{\omega_d}$. The most striking improvement often occurs at the larger ratios; however, an increase in damping can result in poorer handling qualities for a configuration with low lateral control power if the result is sluggish roll response. This phenomenon is illustrated in figure 4(b), a cross plot of figures 3(b), 3(g), and 3(l). For very small values of $\frac{\omega_\varphi}{\omega_d}$ where the adverse (retards rolling) sideslip has reduced the maximum roll rate to an objectionably low value, the increased damping also decreases the roll rate and gives poorer handling qualities.

As noted earlier, the damping terms $2\zeta_d\omega_d$, $2\zeta_\varphi\omega_\varphi$, and $\frac{1}{\tau_r}$ were dependent, (i.e., their ratios were unchanged) in order to keep the survey to a practical size. Although it is recognized that this condition will be true for few airplanes, some observations are possible concerning the restriction. When there is a tendency for the pilot to induce oscillations $\left(\frac{\omega_\varphi}{\omega_d} > 1.0\right)$, the Dutch roll damping $2\zeta_d\omega_d$ is usually more important, and when the induced sideslip retards rolling $\left(\frac{\omega_\varphi}{\omega_d} < 1.0\right)$, $\frac{1}{\tau_r}$ becomes more important. This would suggest that for a specific application, since roll damping and Dutch roll damping cannot be matched simultaneously with the data of figure 3, roll damping should be the consideration for $\frac{\omega_\varphi}{\omega_d} < 1.0$ and Dutch roll damping the consideration for $\frac{\omega_\varphi}{\omega_d} > 1.0$.

Another result of the damping terms being dependent, in particular when $2\zeta_\varphi\omega_\varphi = 2\zeta_d\omega_d$, is that there is perfect cancellation of the Dutch roll mode in the roll transfer function when $\omega_\varphi = \omega_d$. If $2\zeta_\varphi\omega_\varphi = 2\zeta_d\omega_d$, cancellation does not take place and the Dutch roll mode would be excited even when $\omega_\varphi = \omega_d$. Fortunately, for most airplanes the fact that $2\zeta_\varphi\omega_\varphi \neq 2\zeta_d\omega_d$ is of little consequence. Figure 5 is offered as an example. There is essentially no effect on the pilot rating as a function of $\frac{\omega_\varphi}{\omega_d}$ as a result of changing $\frac{2\zeta_\varphi\omega_\varphi}{2\zeta_d\omega_d}$ from 0.08 to 2.0 with $2\zeta_d\omega_d$ fixed at 0.25.

Effect of lateral control power or sensitivity. – At conditions for $\frac{\omega_\varphi}{\omega_d} > 1.0$, increasing lateral control power aggravates the pilot-induced-oscillation problem, as is

indicated in figure 6. The pilot limits his control as much as possible with very effective lateral control inputs. With $\frac{\omega_\varphi}{\omega_d} < 1.0$, the sideslip induced by roll and the steady-state roll response are the primary considerations. Increasing $L_{\delta_a}\delta_{a_{max}}$ increases the sideslip for a particular control input but does not change the sideslip that occurs with a particular steady-state roll rate. As a result, the changes in pilot rating due to maximum control power are relatively minor for values of $L_{\delta_a}\delta_{a_{max}}$ between 3 and 30. With a low value of $\frac{\omega_\varphi}{\omega_d}$, increasing the control power can alleviate a sluggish response.

The reverse is also true: inadequate lateral control power can be augmented by favorable yaw with $\frac{\omega_\varphi}{\omega_d} > 1.0$. It is this effect that causes the most favorable pilot ratings to occur at $\omega_\varphi > \omega_d$ for values of $L_{\delta_a}\delta_{a_{max}} \leqq 1.0$.

Effect of induced sideslip. – Under the restraints of the simplified simulation reported herein, the roll task is completely defined by the parameters previously discussed, that is, ω_φ, ω_d, $2\zeta_d\omega_d$, $2\zeta_\varphi\omega_\varphi$, $\frac{1}{\tau_r}$, and $L_{\delta_a}\delta_{a_{max}}$. Dihedral effect changes only the amount of sideslip encountered during an aileron-induced roll maneuver, since its effect on roll response is already accounted for by the other parameters, ω_φ and ω_d. Since a rudder was not available and gusts were not simulated, rolling was the only source of sideslip. The sign of the resultant sideslip is of little consequence with regard to lateral control, as is evidenced by the handling-qualities parameters involving roll-to-sideslip considered in the literature (refs. 2 to 4, for example). This is not to say that L^*_β has little effect on handling qualities; on the contrary, L^*_β is very important. It is useful to note that the familiar $\left|\frac{\varphi}{\beta}\right|$ ratio is approximately equal to $\left|\frac{L^*_\beta}{\omega_d{}^2}\right|$.

With ω_φ and ω_d fixed, large values of L^*_β are desired, since the sideslip produced during maneuvering is inversely proportional to L^*_β. Little effect of L^*_β was noted during the survey in the range from 10 to 100. However, as L^*_β became smaller than 10, sideslip became large. This effect is of major concern, as indicated by the adverse pilot ratings for small values of L^*_β in figure 7. The proper interpretation of these adverse ratings is that it is desirable to minimize roll-induced sideslip by keeping ω_d constant. This is done by increasing L^*_β. If L^*_β is increased indiscriminately, however, a very undesirable gust sensitivity would result. The limiting case of $N'_{\delta_a} = 0$ consists of the single point at $\frac{\omega_\varphi}{\omega_d} = 1$ where pilot rating is not affected by L^*_β. At this condition, there is perfect cancellation of the Dutch roll terms in the roll transfer function, leaving only a first-order, uncoupled roll task. Consequently, the pilot rating is affected by only $L_{\delta_a}\delta_{a_{max}}$ and $\frac{1}{\tau_r}$.

Pilot Rating Variability Survey

Pilot ratings, being subjective measures, may have considerable variability. One source of variability is the experience of the pilot and his interpretation of the rating scale. Another source is the fluctuation of his judgment, which appears to be random. Many pilot ratings were collected for a set of characteristics representing airplane configurations (see table on page 8) for several missions (see page 6). Some aspects of the variability of these pilot ratings are discussed in the following sections.

Individual correlations. – For the general mission, ratings of each pilot subject are presented and compared with the average ratings of the 18 actual pilots in figures 8(a) to 8(x). If there were perfect correlation, the points would fall along the diagonal line. Figures 8(a) to 8(r) show the correlations for the actual pilots; figures 8(s) to 8(x) show the correlations for the non-pilot subjects. The standard deviation of the individual pilot rating from the average is noted in each figure and is summarized in the following table:

Pilot	Standard deviation σ					
	Mission					
	General	Fighter	Reentry glider	Bomber	Supersonic transport	Light airplane
A	0.88	1.00	1.34	1.25	1.26	1.53
B	1.51	----	----	----	----	----
C	1.10	----	----	----	----	----
D	.78	----	----	----	----	----
E	1.38	----	----	----	----	----
F	1.83	----	----	----	----	----
G	1.30	----	----	----	----	----
H	1.12	----	----	----	----	----
I	.78	.68	1.38	1.19	.84	.86
J	2.15	----	----	----	----	----
K	.85	----	----	----	----	----
L	1.32	1.12	1.12	.94	.91	.95
M	2.69	2.70	2.89	2.31	1.77	2.07
N	1.14	1.30	1.96	1.45	1.00	1.55
O	1.29	1.02	1.58	1.80	2.38	1.94
P	1.56	1.22	1.73	1.51	1.44	1.72
Q	1.48	1.43	1.71	1.57	1.38	1.43
R	2.34	1.46	2.74	1.69	1.31	3.03
S (engineer)	1.37	1.62	1.54	1.84	1.68	1.82
T (engineer)	1.40	1.88	1.39	1.30	1.80	1.94
U (engineer)	1.73	----	----	----	----	----
V (engineer)	1.38	----	----	----	----	----
W (engineer)	1.79	----	----	----	----	----
X (engineer)	1.02	1.19	1.66	1.62	1.66	1.40

The agreement of the individual pilot's rating with the average pilot rating is clearly indicated in figure 8. The pilot's bias is evidenced by the rating falling either above or below the diagonal line. The median standard deviation of the individual rating from the average is about 1.3, and there appears to be no significant difference between

data from the actual pilot and pilot-engineer. Inasmuch as an engineer served as the subject in the general survey, any bias indicated in figure 8(s) will be reflected in the predicted pilot rating based on the survey results. Fortunately, there is very little bias, and the correlation of ratings of subject S with the average actual pilot ratings compares well with those of most of the actual pilots.

Variability among pilots. – The total variation in pilot ratings resulting from a number of actual pilots rating the same configurations is shown in figures 9(a) to 9(f) for each of the six missions investigated. The variation in pilot rating is shown by contours of constant percentile. The band between 0 and 100 percent indicates the total variation, and the band between 25 percent and 75 percent indicates the variation of the center 50 percent of the ratings. A σ of 1.3 would have a band of plus or minus one pilot rating unit for the center 50 percent if the probability distribution were Gaussian.

A reduction of the variability at both ends of the rating scale is evident. The reduction is caused by the truncation effect of the rating scale and by the greater uncertainty of the pilot when assessing characteristics that are undesirable for more than one reason. A statistical model of the variation of pilot ratings is given in the appendix.

Effect of mission. – Figures 9(b) to 9(e) show the variation in pilot ratings for the fighter, reentry-vehicle, bomber, supersonic-transport, and light-airplane missions. There is no apparent reduction in the variability for the specific mission compared to that for the general mission shown in figure 9(a).

The average of the pilots' ratings for the general mission is correlated with the average ratings for the specific missions in figures 10(a) to 10(e) in order to assess differences due to the type of mission. The differences found were small, usually about one and only rarely greater than two pilot rating units. The points for cases having a ratio of $\frac{\omega_{\varphi}}{\omega_d} > 1.0$ have been shaded to allow further differentiation in detecting bias, but no consistent difference in the bias due to $\frac{\omega_{\varphi}}{\omega_d}$ was noted. The average ratings for the specific missions were almost always equal to or higher (less desirable) than those for the general mission because of particular requirements of the specific missions which were not met. Although the differences were found to be small, the results shown may be used to adjust the predicted pilot ratings for differences due to mission.

Prediction Method

The results of the general survey were sufficiently broad to provide information for predicting the pilot ratings of many airplane configurations. Predicted ratings may be obtained by hand computation or by use of a digital computer.

Hand computation. – Although it would be possible to use the results of figure 3 to calculate lateral-directional pilot ratings by interpolating between figures for a particular application, the procedure would be tedious and time consuming. To provide a more rapid means for hand-computing ratings, much of the information in figures 3(a) to 3(ss) is summarized in figures 11(a) to 11(c). Ratings are then obtained by interpolating between the appropriate figures. It should be noted that if a pilot rating from one figure is beyond the boundary for a rating of 10, an extrapolated value greater

than 10 must be obtained to get a proper interpolation between figures. Although the parameter coverage is necessarily more restricted than the complete survey, it is believed to encompass most airplanes.

Digital computation. – The complete results of the survey (fig. 3) are best used by mechanizing the interpolation process in a digital-computer program. Such a program is now being used at the Flight Research Center; the mechanization is illustrated in figure 12. The information from the pilot rating survey (fig. 3) and the airplane characteristics, stability derivatives, and moments of inertia for the airplane considered are fed into a digital computer. The computer determines the dimensional stability derivatives, numerous parameters of interest, and the predicted pilot ratings.

With pilot rating prediction information, many airplane configurations and flight conditions can be assessed quickly at little cost through the use of a digital computer. This is particularly important to the preliminary designer and flight-test engineer.

Limitations of applications. – Although the general pilot rating survey reported herein considers more independent parameters simultaneously over a greater range of values than previous surveys of lateral-directional handling qualities, it is important to note the remaining limitations in applying the method to specific cases. Because of the large number of combinations of values possible, it was necessary to impose several limitations and assumptions, as discussed earlier. The principal limitations and assumptions were as follows:

1. Simplified airplane dynamics. (The sideslip transfer function is simplified since $\omega_{\varphi} = \omega_d$ and $\tau_s = \infty$.)

2. Damping terms varied dependently. ($0.25 \frac{1}{\tau_r} = 2\zeta_d\omega_d = 2\zeta_{\varphi}\omega_{\varphi}$.)

3. Aileron inputs only. (Use of rudder would result in more favorable pilot ratings for adverse sideslip conditions.)

4. Control power and sensitivity varied dependently. (Cannot always differentiate between control limit and sensitivity difficulty.)

5. No gust or turbulence inputs. (Large values of L_{β}^{*} would be very undesirable had gust inputs been used.)

6. No asymmetrical trim problems. (Any additional disturbance and/or task would result in less favorable pilot ratings.)

These factors, typical of other surveys, were used to limit the scope of the investigation with the intent of gaining the most useful information for the amount of effort expended. It is essential, therefore, that these factors not be neglected. For example, an airplane having values of L_{β}^{*}, $L_{\delta_a}\delta_{a_{max}}$, and $\frac{1}{\tau_r}$ of -100, 0.1 and 0.1, respectively, is indicated by the survey to have a pilot rating as good as 2.6. When one considers the effects of even moderate turbulence, however, it would not be controllable, since a gust producing only 0.057° of sideslip would require maximum lateral control to prevent rolling.

Expected accuracy. – It was mentioned earlier that the bias and variability of the pilot ratings of subject S (the only subject used in the general survey) would be reflected in the predicted pilot ratings. The standard deviation of the individual pilot ratings of subject S from the average for the actual pilots was shown in figure 8(s) to be 1.37, which was typical of that of the actual pilots. Fairing the data of the general survey, however, reduces the effect of the variability in the ratings. Figure 13 shows the standard deviation of the computed pilot ratings (based on fig. 3) relative to the average of the ratings of the actual pilots to be 1.00. The predicted pilot ratings, therefore, are expected to have an error of this magnitude because of the inaccuracies of the general survey due to the small sample size. There may, of course, be additional errors as a result of such factors as the restriction imposed, motion effects, and mission effects.

Pilot ratings from the general survey are compared with actual pilot ratings obtained in flight for the X-15 airplane in reference 18 and for a variety of airplanes in reference 19. Predicted pilot ratings were also used with success in the final configurational design of the M2-F2 and HL-10 lifting body vehicles.

CONCLUDING REMARKS

A general pilot rating survey was conducted on a fixed-base simulator in which lateral-directional handling qualities were assessed for a large range of stability and control characteristics. The results of the survey are presented in terms of the lateral control power $L_{\delta_a}\delta_{a_{max}}$, damping $\frac{1}{\tau_r}$, $2\zeta_\varphi\omega_\varphi$, $2\zeta_d\omega_d$, dihedral effect L_β^*, undamped natural frequency of the Dutch roll mode ω_d, and roll control parameter ω_φ. These data provided the basis for calculating pilot ratings for roll control (without rudder) for a large class of airplanes by interpolating between the conditions tested. The most favorable pilot ratings usually occurred at $\frac{\omega_\varphi}{\omega_d} = 1.0$ where, under the restraints of the survey, application of lateral control produced no sideslip. For values of lateral control power less than 3.0 radians/second^2, a value of $\frac{\omega_\varphi}{\omega_d} > 1.0$ was desired to compensate for the inadequate control power. For conditions in which $\omega_\varphi + \omega_d > 3.0$, pilot ratings were affected by $\frac{\omega_\varphi}{\omega_d}$ but not by ω_φ or ω_d independently. An increase in damping generally resulted in more favorable pilot ratings except where roll response was already very sluggish due to either low lateral control power or excessive control coupling. Damping was especially effective in alleviating pilot-induced oscillations which occur when $\frac{\omega_\varphi}{\omega_d} > 1.0$. Increased lateral control power resulting in excessive sensitivity generally aggravated the pilot-induced-oscillation problem. Changes in dihedral effect when ω_φ and ω_d are fixed serve to scale the amount of sideslip encountered during a roll maneuver. In any specific application, a change in dihedral will affect ω_φ and ω_d. The effect of a small amount of induced slideslip on pilot ratings under these constraints was usually very slight.

In addition, a pilot rating variability survey was made in which several pilots and non-pilots rated 22 cases for 6 different missions. The data obtained were used to study the variability of pilot ratings and the effect of the mission and to estimate the accuracy of the results of the general pilot rating survey. The standard deviation of individual pilot ratings ranged from 1.0 at the "good" end of the scale to 2.0 in the middle of the scale. Ratings for specific missions were generally numerically higher (more adverse) than those for the general mission for the same vehicle characteristics.

A digital-computer program and a simplified technique, both based on the results of the general survey, were devised for estimating lateral-directional pilot ratings for a wide variety of airplanes. Correlation of calculated pilot rating with the average rating of the pilots indicated that the accuracy of the computed pilot ratings is comparable to that for a single pilot trial.

Flight Research Center,
National Aeronautics and Space Administration,
Edwards, Calif., December 7, 1966,
126-16-01-07-24.

APPENDIX

A STATISTICAL MODEL OF PILOT RATING VARIABILITY

In order for the significance of pilot ratings to be assessed intelligently, an estimate of the variance of the results is necessary. This requirement is satisfied to some degree by the values of standard deviation presented in the foregoing discussion of results. A more definitive measure of variability is offered in a statistical model. The model suggested consists of a Gaussian distribution ($\sigma = 2.0$) which is truncated at the end of the rating scale (1 and 10) with the area of the tails added at the respective end intervals of the histogram. Figures 14(a) to 14(i) compare histograms of the actual pilot ratings and the statistical model for several intervals of pilot rating average. Actual pilot ratings for the histograms were grouped by including the integer value of the pilot rating in the right-hand adjacent panel. The model compares well with the actual ratings but tends to have too many ratings lumped at the intervals at the numerically low end of the rating scale.

Bias in the measured pilot rating mean and variance can be demonstrated by using the statistical model suggested. Figure 15 shows the effect of truncation of the statistical model on the mean and σ. The results indicate a bias which makes the mean increase as a pilot rating of 1 is approached and decrease as a pilot rating of 10 is approached. This would imply that the "actual" average pilot rating would be more favorable than the averaged ratings at the lower values and less favorable at the higher values of pilot rating. The effect of truncation on σ is to reduce its value. For this reason, $\sigma = 2$ results in a σ of 1 to 2 after truncation. It is apparent how smaller values of σ could result from studies concentrated at highly favorable (therefore, low) values of pilot ratings.

REFERENCES

1. Kauffman, William M.; Liddell, Charles J., Jr.; Smith, Allan; and Van Dyke, Rudolph D., Jr.: An Apparatus for Varying Effective Dihedral in Flight With Application to a Study of Tolerable Dihedral on a Conventional Fighter Airplane. NACA Rept. 948, 1949.

2. Liddell, Charles J., Jr.; Creer, Brent Y.; and Van Dyke, Rudolph D., Jr.: A Flight Study of Requirements for Satisfactory Lateral Oscillatory Characteristics of Fighter Aircraft. NACA RM A51E16, 1951.

3. Moore, Norton B.: Artificial Stability Flight Tests of the XF-88A Airplane. Tech. Rep. 52-298, Wright Air Dev. Center, U. S. Air Force, July 1954. (Available from ASTIA as AD 49024.)

4. McNeill, Walter E.; and Vomaske, Richard F.: A Flight Investigation to Determine the Lateral Oscillatory Damping Acceptable for an Airplane in the Landing Approach. NASA Memo 12-10-58A, 1959.

5. Creer, Brent Y.; Stewart, John D.; Merrick, Robert B.; and Drinkwater, Fred J., III: A Pilot Opinion Study of Lateral Control Requirements for Fighter-Type Aircraft. NASA Memo 1-29-59A, 1959.

6. Crone, Robert M.; and A'Harrah, Ralph C.: A New Modified Acceptance Criterion for Lateral-Directional Flying Qualities. Aerospace Eng., vol. 19, no. 9, Sept. 1960, pp. 24-29.

7. Palmer, W. E.: A Flight Simulator Study of the Lateral-Directional Stability Requirements of Piloted Air Vehicles. Rep. No. NA-61H-241, North American Aviation, Inc., Mar. 31, 1961.

8. Vomaske, Richard F.; Sadoff, Melvin; and Drinkwater, Fred J., III: The Effect of Lateral-Directional Control Coupling on Pilot Control of an Airplane as Determined in Flight and in a Fixed-Base Flight Simulator. NASA TN D-1141, 1961.

9. Kidd, Edwin A.; and Harper, Robert P., Jr.: Fixed-Base and In-Flight Simulations of Longitudinal and Lateral-Directional Handling Qualities for Piloted Re-entry Vehicles. Tech. Doc. Rep. No. ASD-TDR-61-362, Res. and Tech. Div., Wright-Patterson AFB, U.S. Air Force, Feb. 1964.

10. Harper, Robert P., Jr.: In-Flight Simulation of the Lateral-Directional Handling Qualities of Entry Vehicles. WADD Tech. Rep. 61-147, Aero. Systems Div., Wright-Patterson AFB, U. S. Air Force, Nov. 1961.

11. Ashkenas, Irving L.; and McRuer, Duane T.: The Determination of Lateral Handling Quality Requirements From Airframe Human Pilot System Studies. WADC Tech. Rep. 59-135 (Contract No. AF 33(616)-5661), Wright Air Dev. Center, U. S. Air Force, June 1959. (Available from ASTIA as AD 212 152.)

12. Durand, T. S.; and Jex, H. R.: Handling Qualities in Single-Loop Roll Tracking Tasks: Theory and Simulator Experiments. Tech. Doc. Rep. No. ASD-TDR-62-507, Aero. Systems Div., Wright-Patterson AFB, U.S. Air Force, Nov. 1962.

13. Taylor, Lawrence W., Jr.: Analysis of a Pilot-Airplane Lateral Instability Experienced With the X-15 Airplane. NASA TN D-1059, 1961.

14. Holleman, Euclid C.; and Wilson, Warren S.: Flight-Simulator Requirements for High-Performance Aircraft Based on X-15 Experience. Paper No. 63-AHGT-81, ASME, 1963.

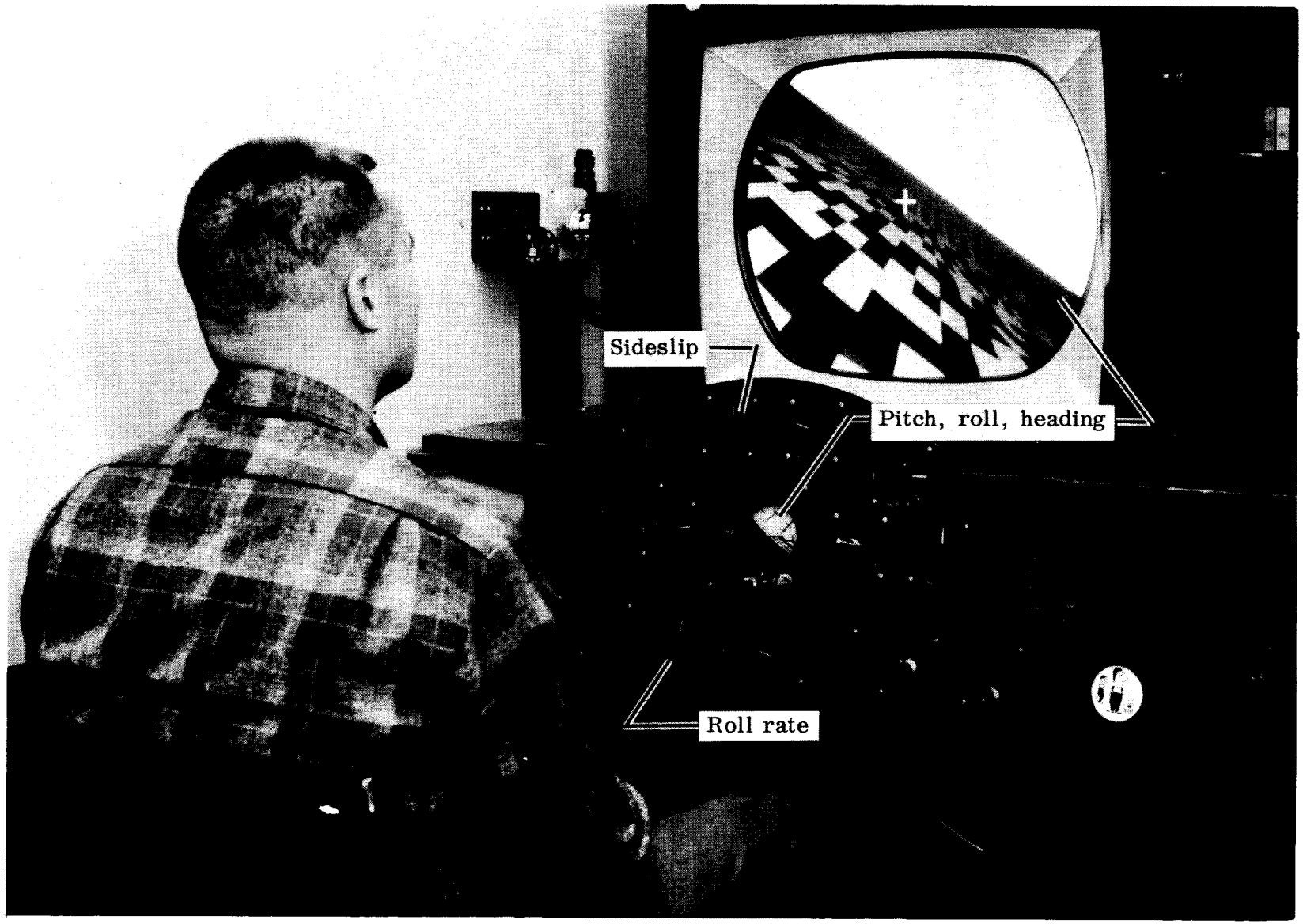
15. Taylor, Lawrence W., Jr.; and Day, Richard E.: Flight Controllability Limits and Related Human Transfer Functions as Determined From Simulator and Flight Tests. NASA TN D-746, 1961.

16. Newell, F. D.: Criteria for Acceptable Representation of Airplane Dynamic Responses in Simulators Used for Pilot Training. Tech. Rep. NAVTRADEVCEN 1146-1, Cornell Aero. Lab., Oct. 1962. (Available from ASTIA as AD 297 838.)

17. Cooper, George E.: Understanding and Interpreting Pilot Opinion. Aero. Eng. Rev., vol. 16, no. 3, Mar. 1957, pp. 47-51, 56.

18. Taylor, Lawrence W., Jr.; Robinson, Glenn H.; and Iliff, Kenneth W.: A Review of Lateral-Directional Handling-Qualities Criteria as Applied to the X-15. Progress of the X-15 Research Airplane Program, NASA SP-90, 1965, pp. 45-53.

19. Taylor, Lawrence W., Jr.; and Iliff, Kenneth W.: Recent Research Directed Toward the Prediction of Lateral-Directional Handling Qualities. Rep. No. 531, AGARD, 1966.



E-12544

Figure 1.– Photograph of cockpit and display of the ground-based simulator.

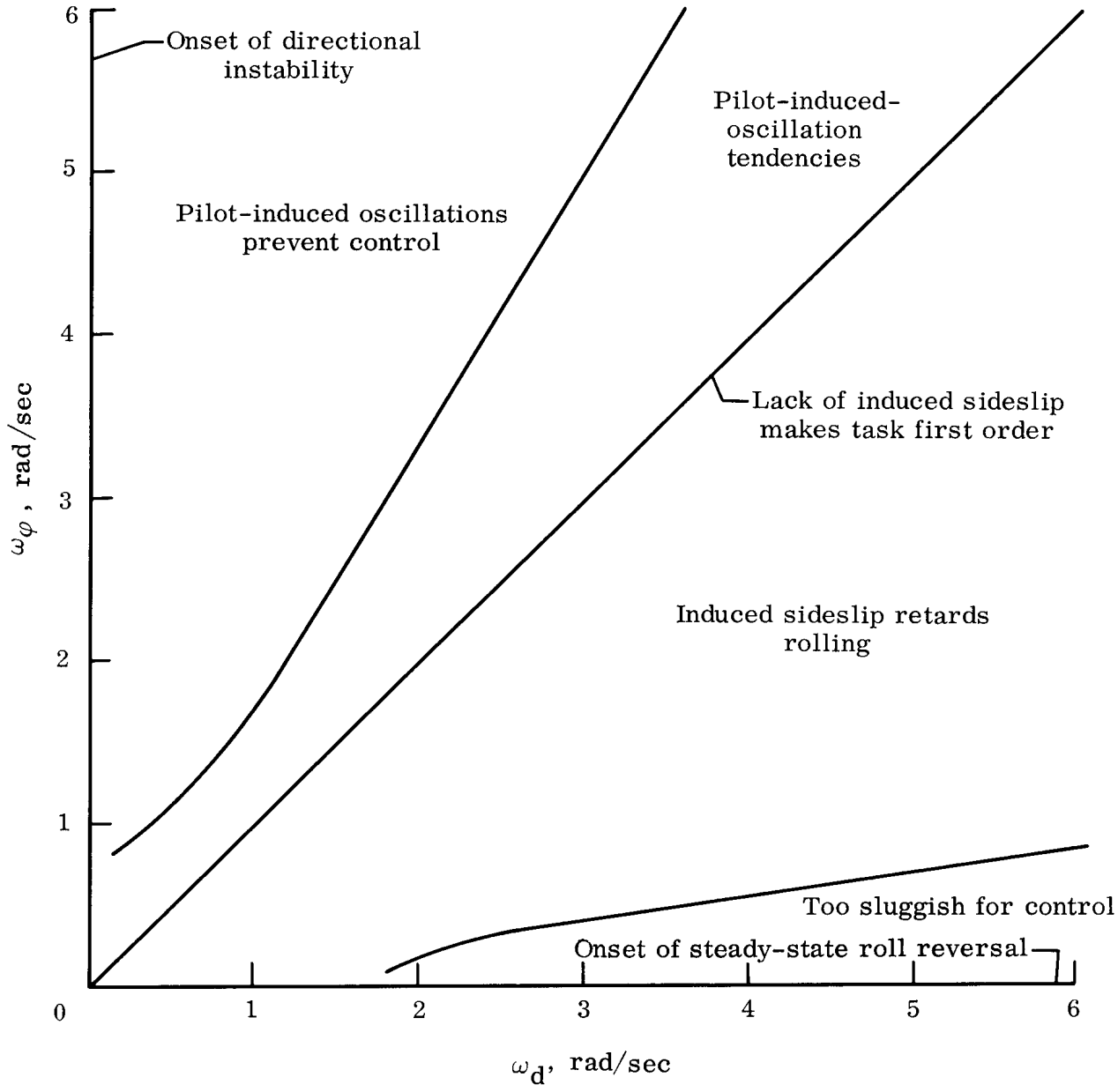
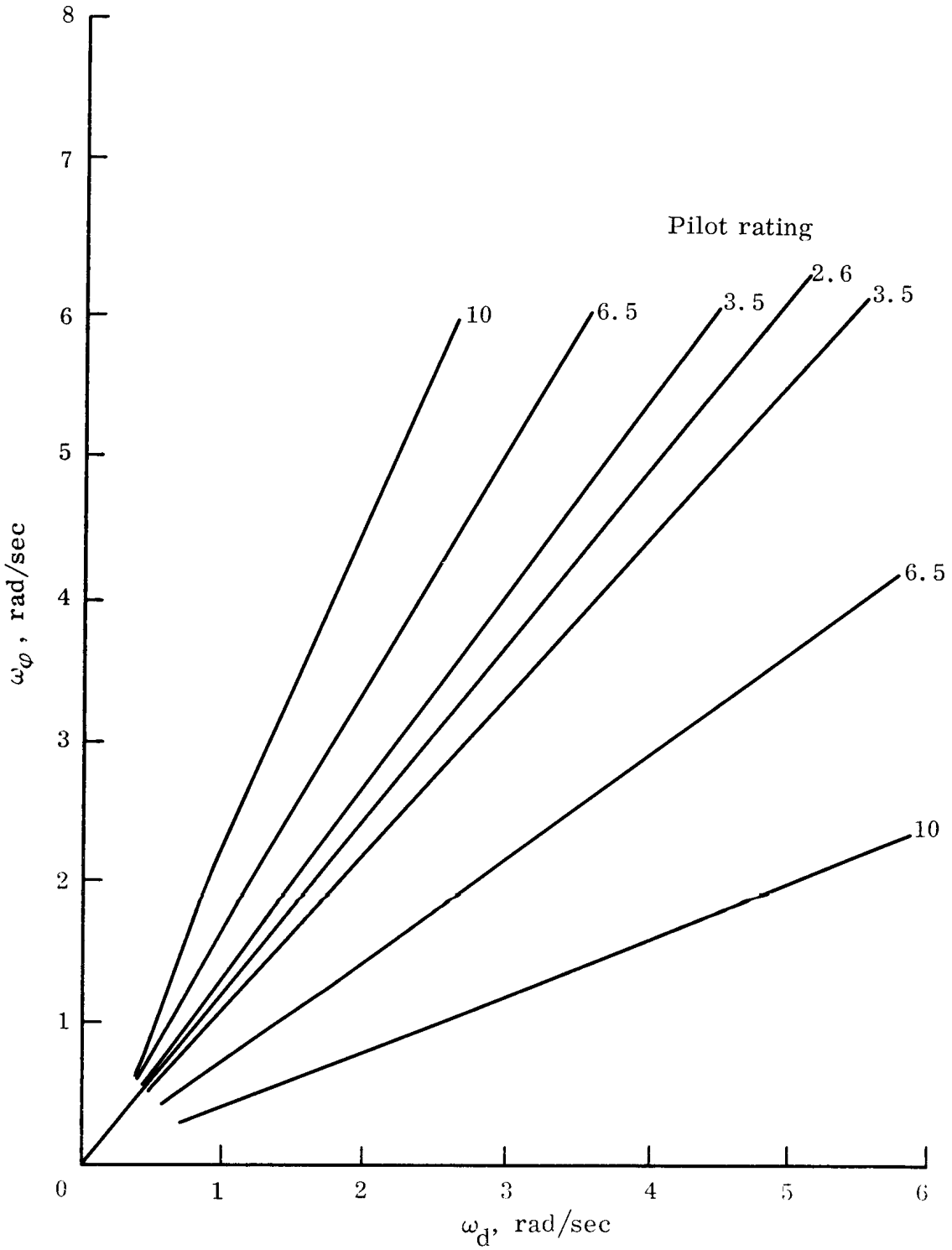
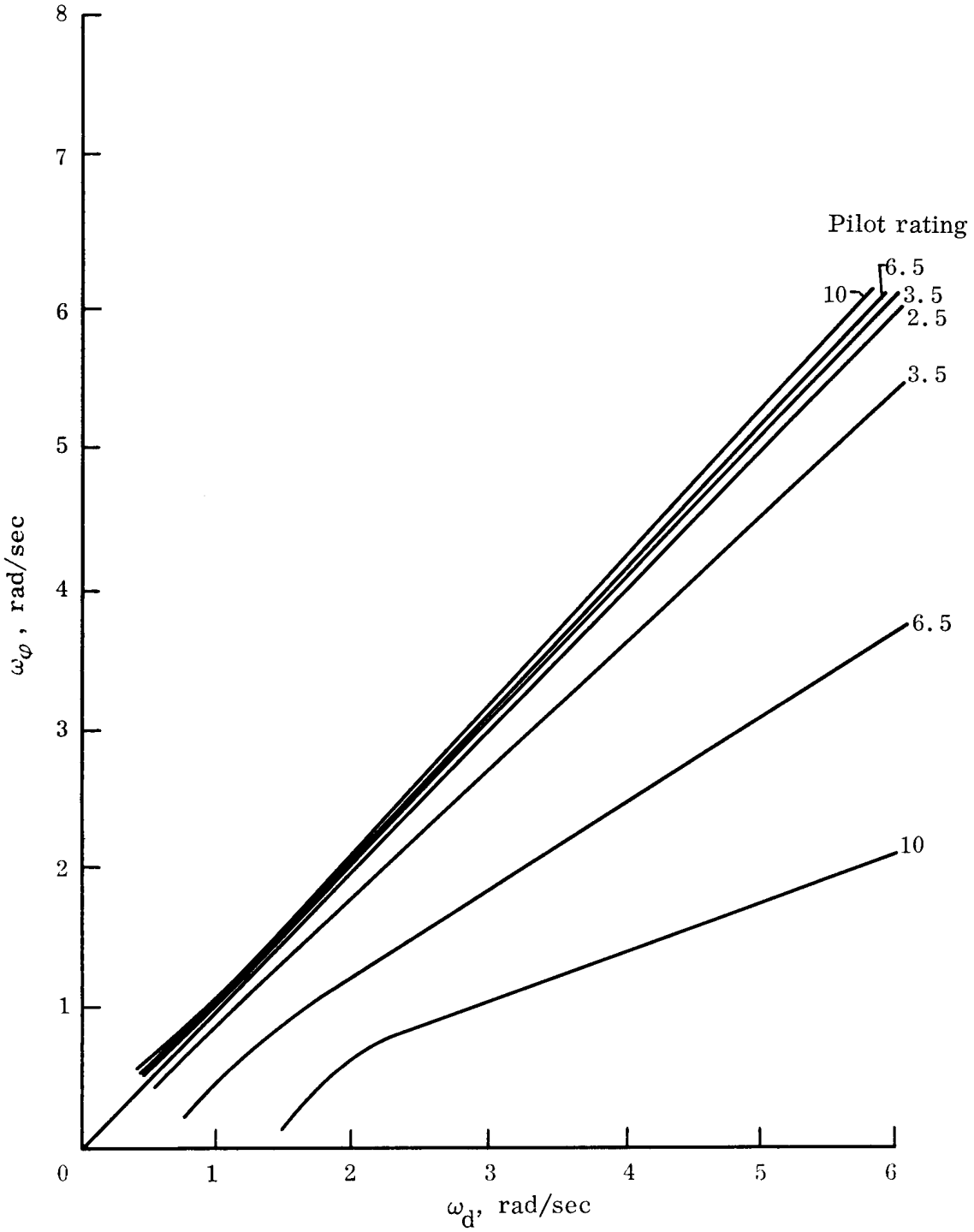


Figure 2. – General effects of ω_φ and ω_d on lateral control.



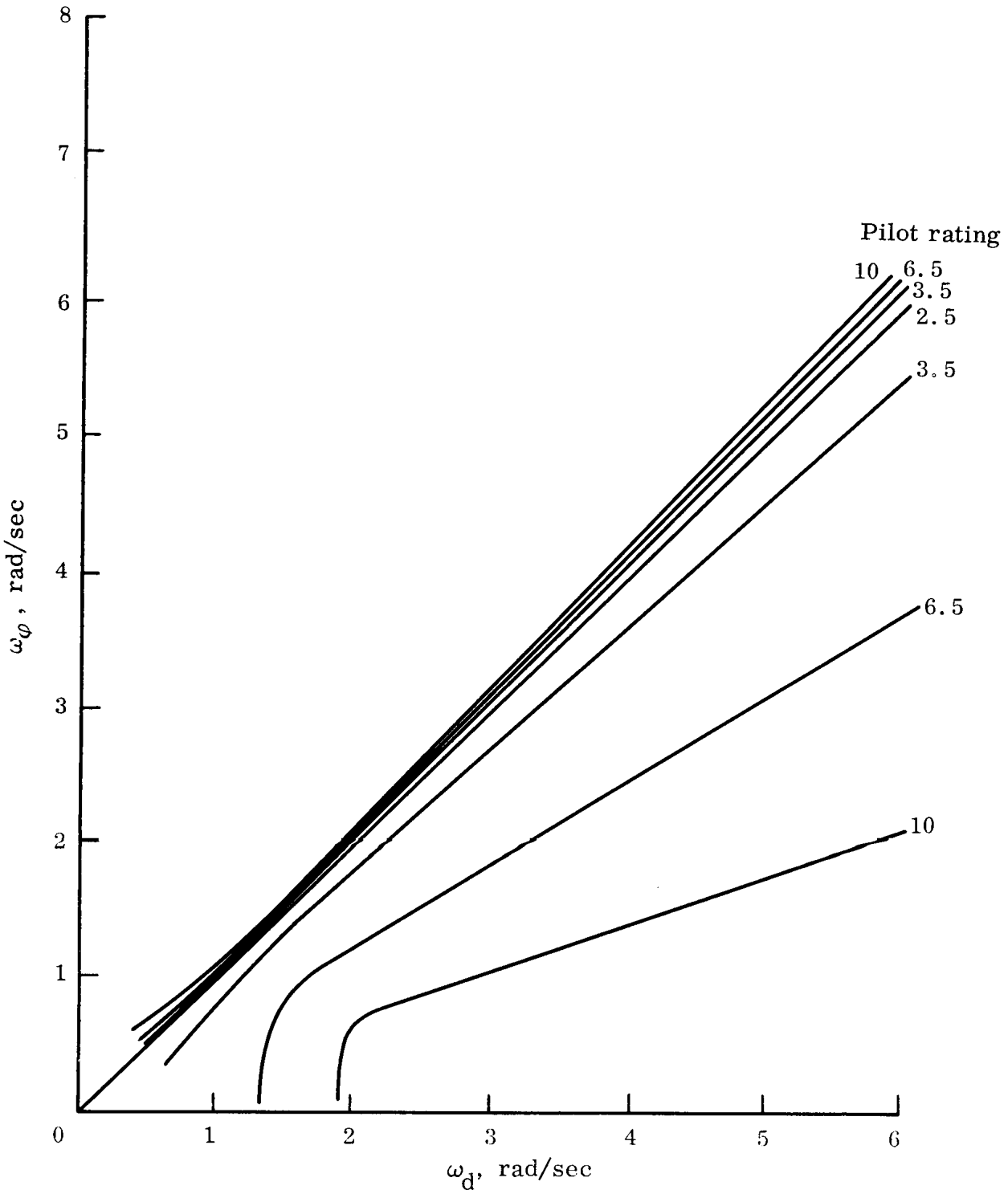
(a) $L_{\delta_a}\delta a_{max} = 0.1$, $2\zeta_d\omega_d = 0.025$, $\frac{1}{\tau_r} = 0.1$, $\left|L^*_\beta\right| = 10.$

Figure 3.– Pilot rating results of the general survey of simulated lateral-directional handling. Aileron control only.



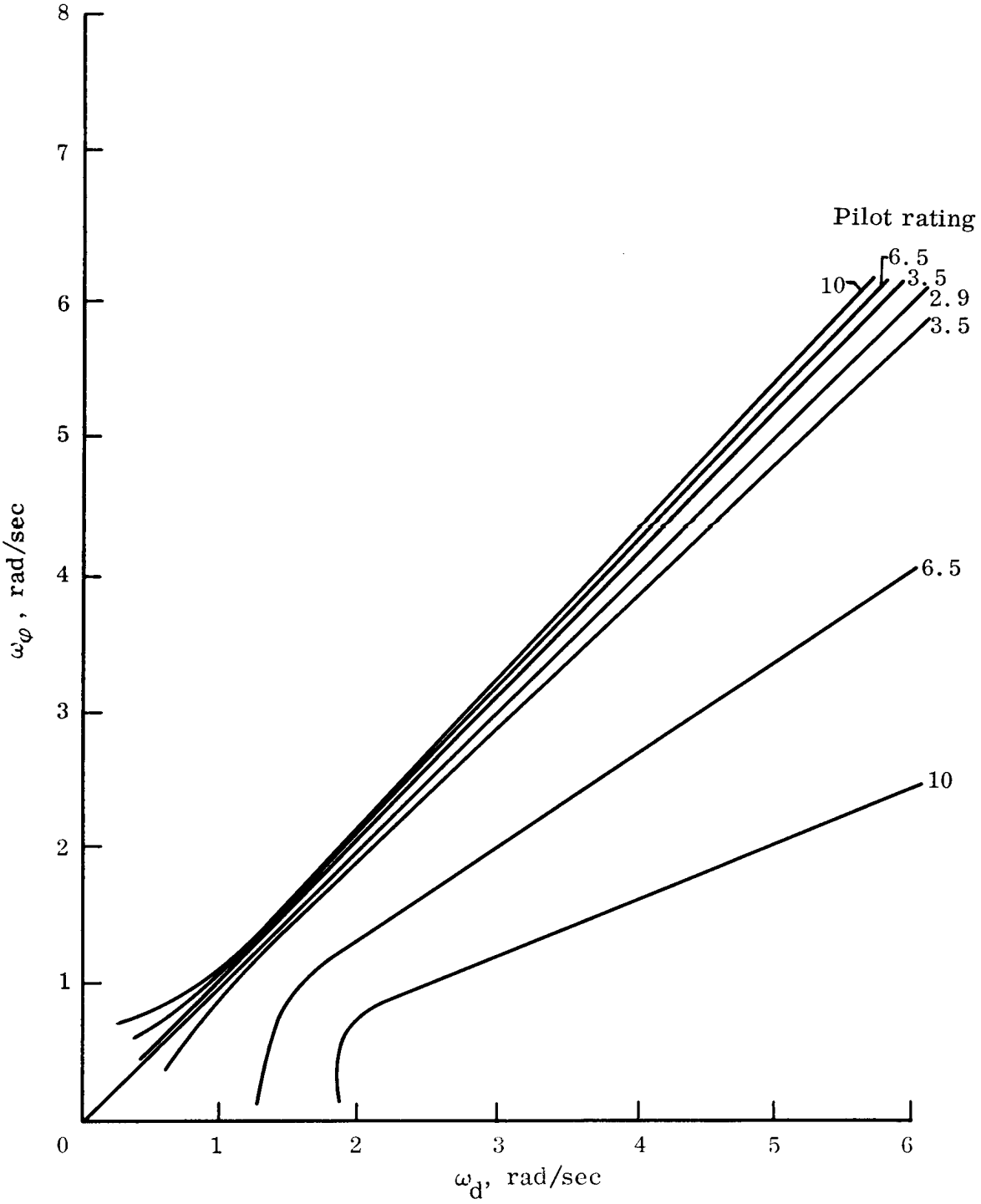
(b) $L_{\delta_a}\delta_{a_{max}} = 3.0,\ 2\zeta_d\omega_d = 0.025,\ \frac{1}{\tau_r} = 0.1,\ \left|L_\beta^*\right| = 10.$

Figure 3. – Continued.



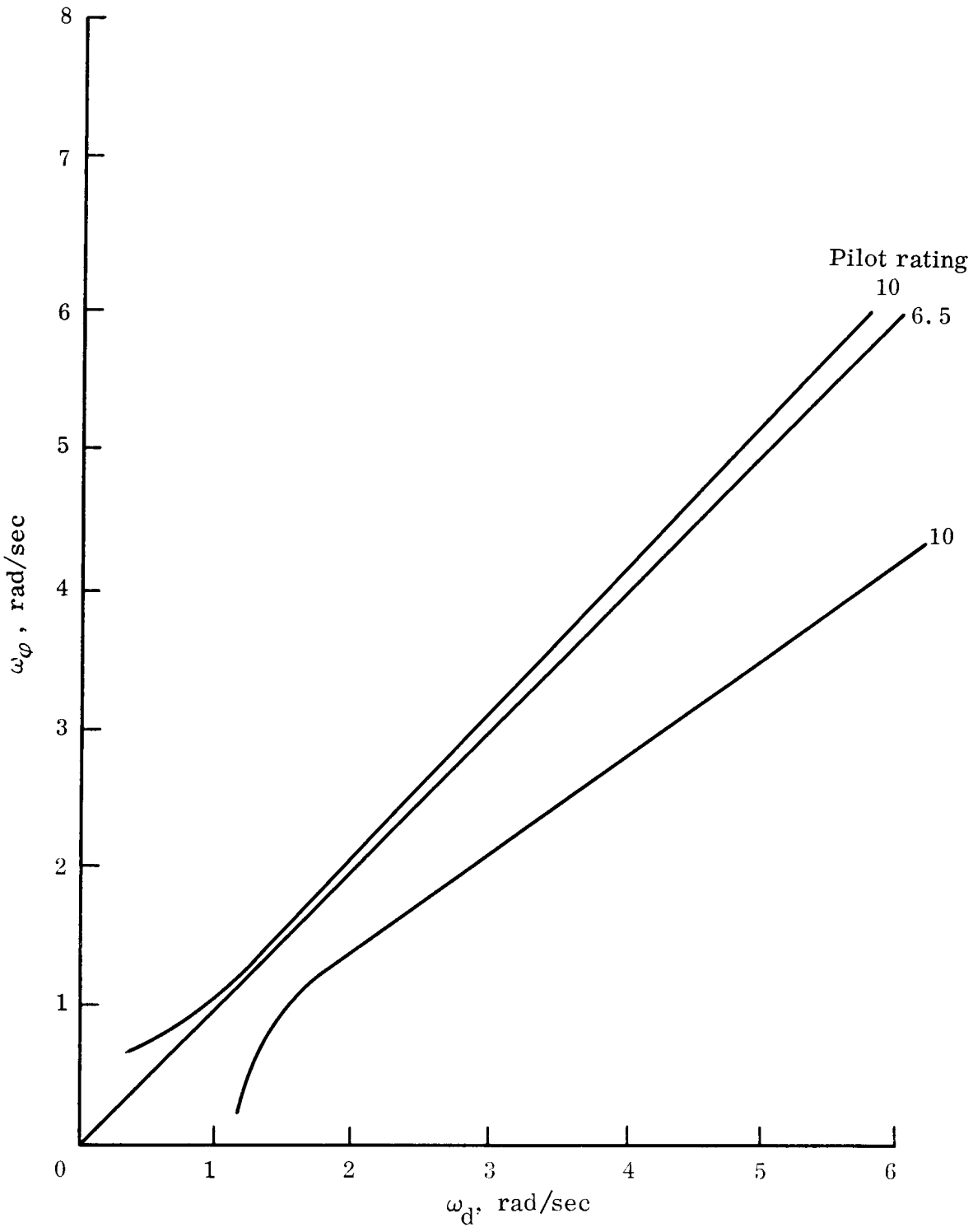
(c) $L_{\delta_a}\delta_{a_{max}} = 10.0$, $2\zeta_d\omega_d = 0.025$, $\frac{1}{\tau_r} = 0.1$, $\left|L^*_\beta\right| = 10.$

Figure 3. – Continued.



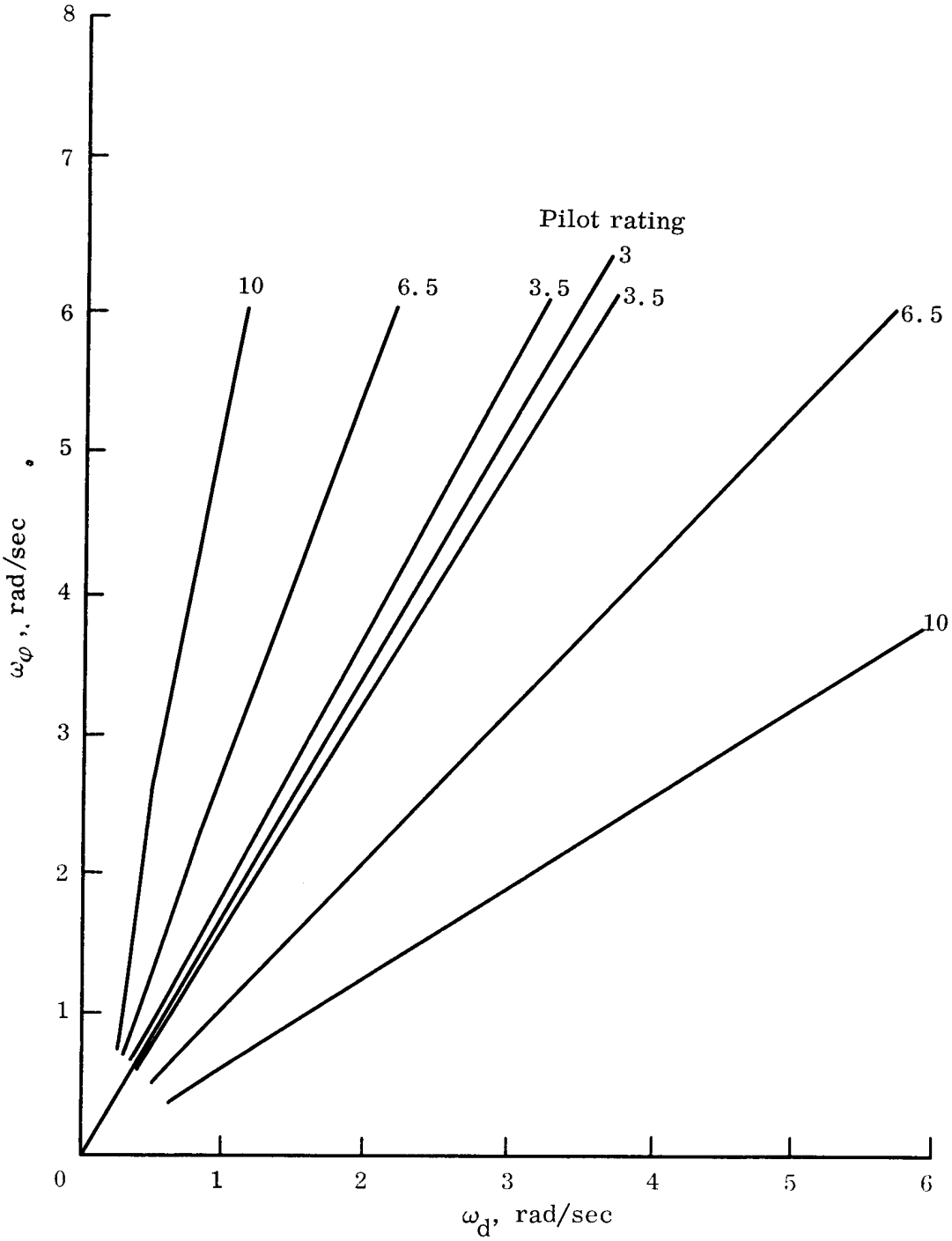
(d) $L_{\delta_a}\delta_{a_{max}} = 30.0$, $2\zeta_d\omega_d = 0.025$, $\frac{1}{\tau_r} = 0.1$, $\left|L_\beta^*\right| = 10.$

Figure 3.– Continued.



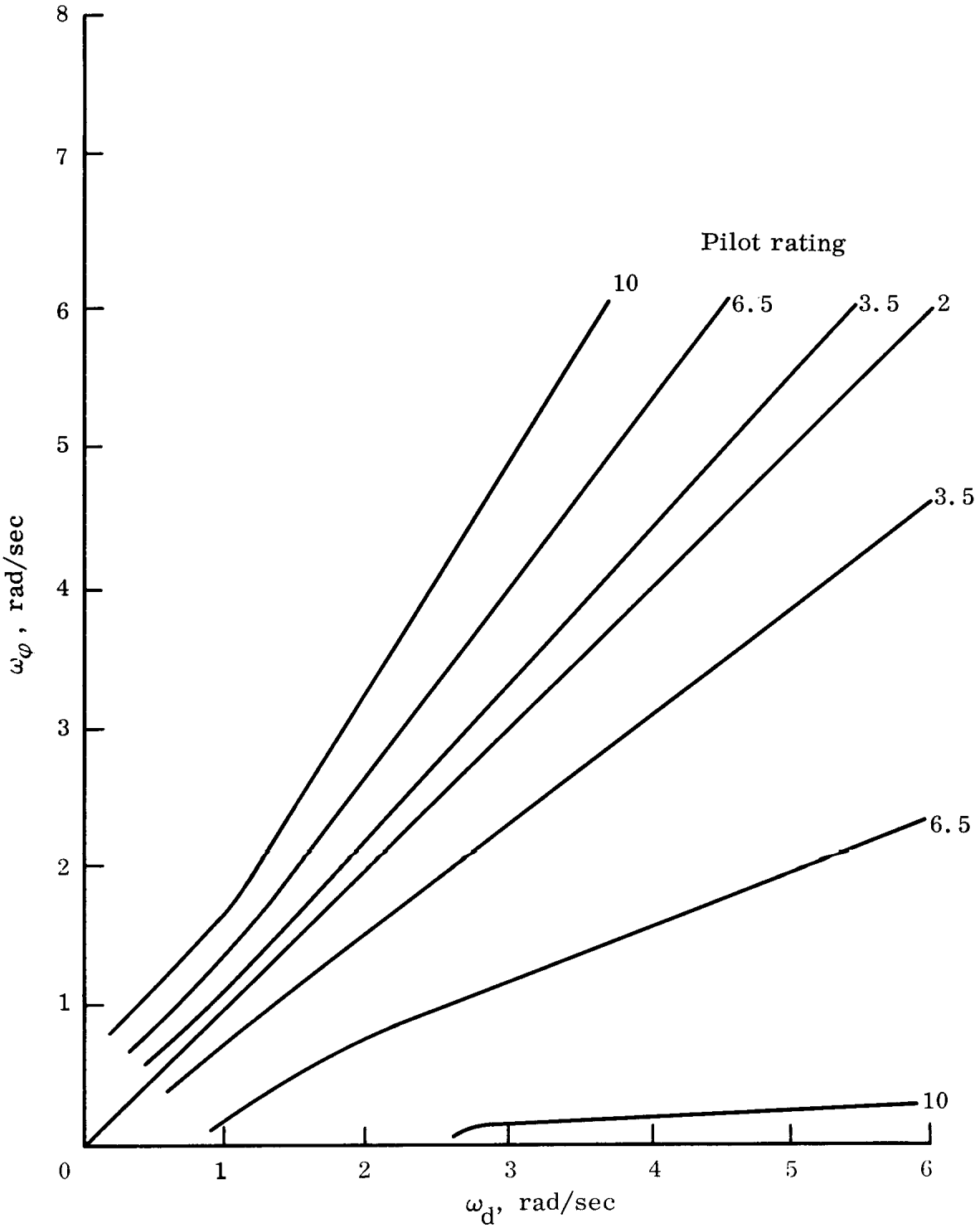
(e) $L_{\delta_a}\delta_{a_{max}} = 100.0$, $2\zeta_d\omega_d = 0.025$, $\frac{1}{\tau_r} = 0.1$, $\left|L^*_\beta\right| = 10.$

Figure 3.– Continued.



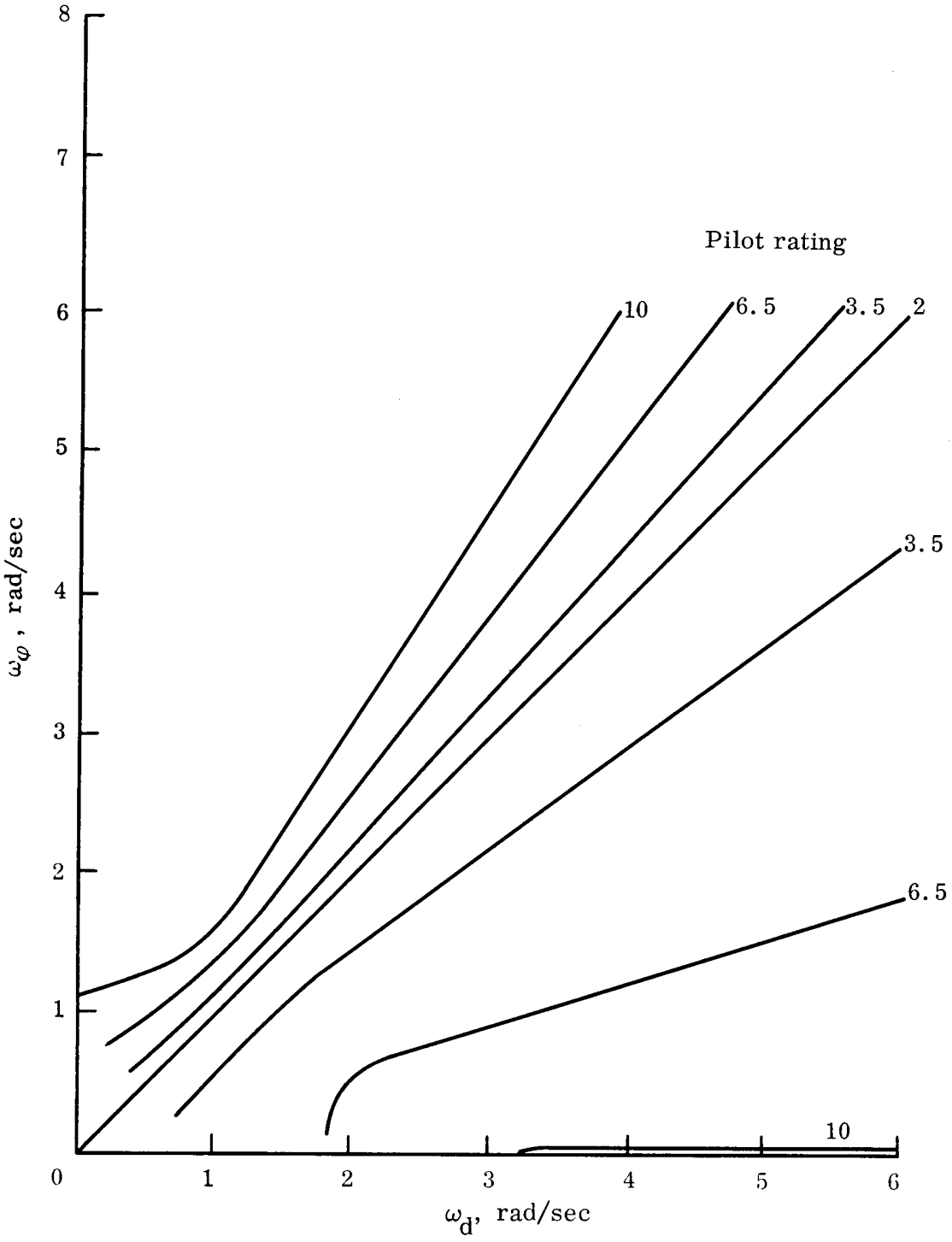
(f) $L_{\delta_a}\delta_{a_{max}} = 0.1$, $2\zeta_d\omega_d = 0.25$, $\frac{1}{\tau_r} = 1.0$, $\left|L_\beta^*\right| = 10.$

Figure 3.– Continued.



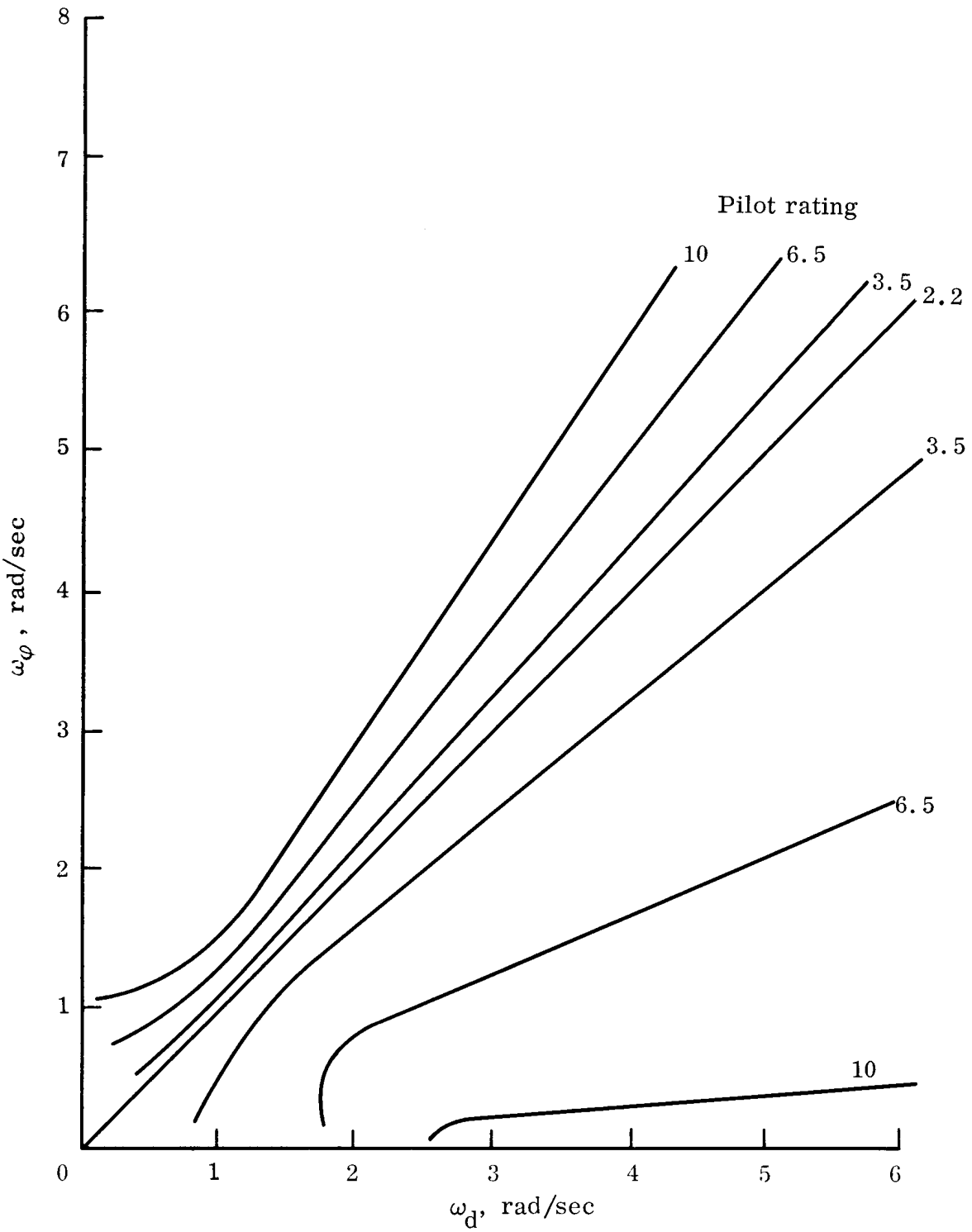
(g) $L_{\delta_a}\delta_{a_{max}} = 3.0,\ 2\zeta_d\omega_d = 0.25,\ \frac{1}{\tau_r} = 1.0,\ \left|L^*_\beta\right| = 10.$

Figure 3. – Continued



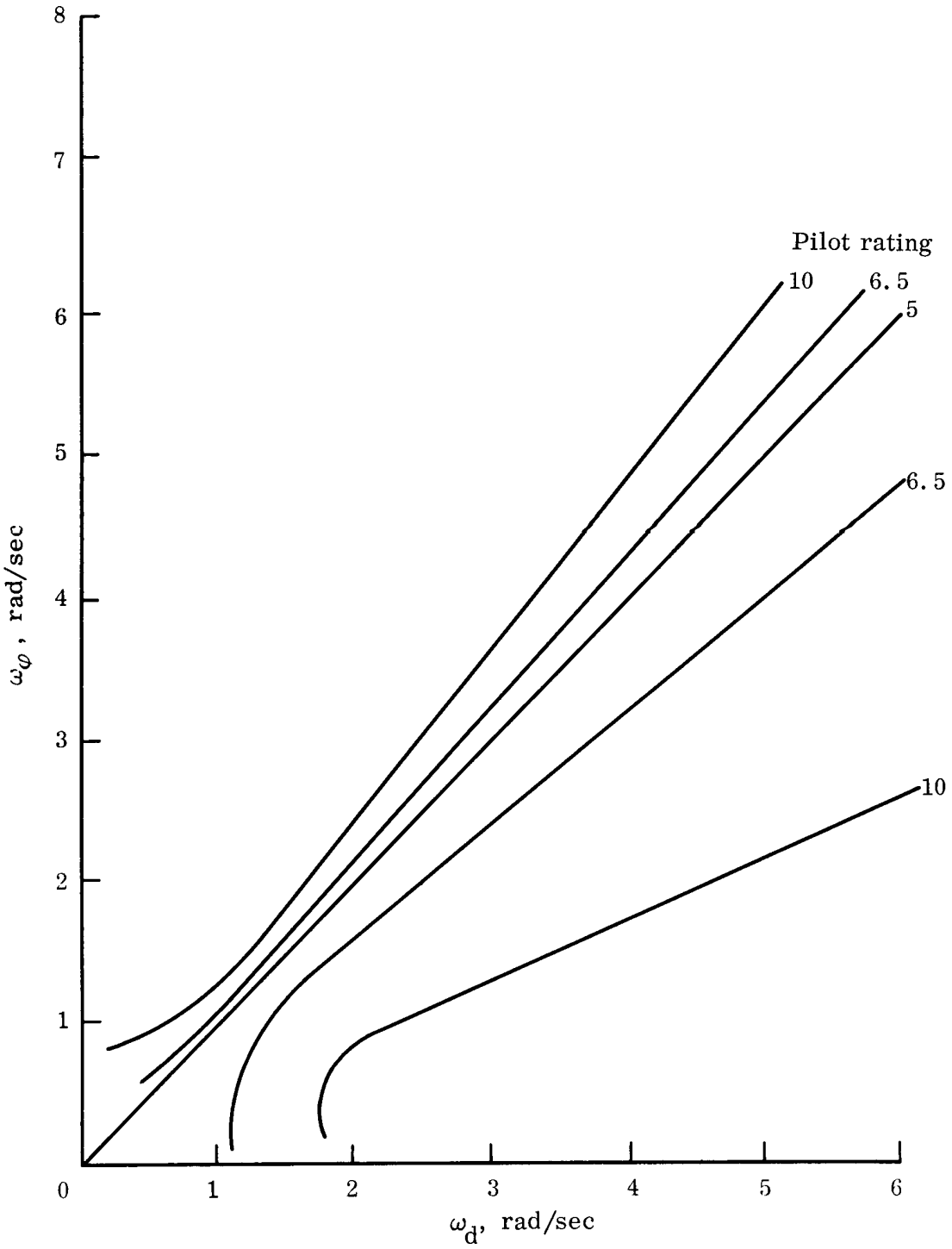
(h) $L_{\delta_a}\delta_{a_{max}} = 10.0$, $2\zeta_d\omega_d = 0.25$, $\frac{1}{\tau_r} = 1.0$, $\left|L^*_\beta\right| = 10.$

Figure 3.– Continued.



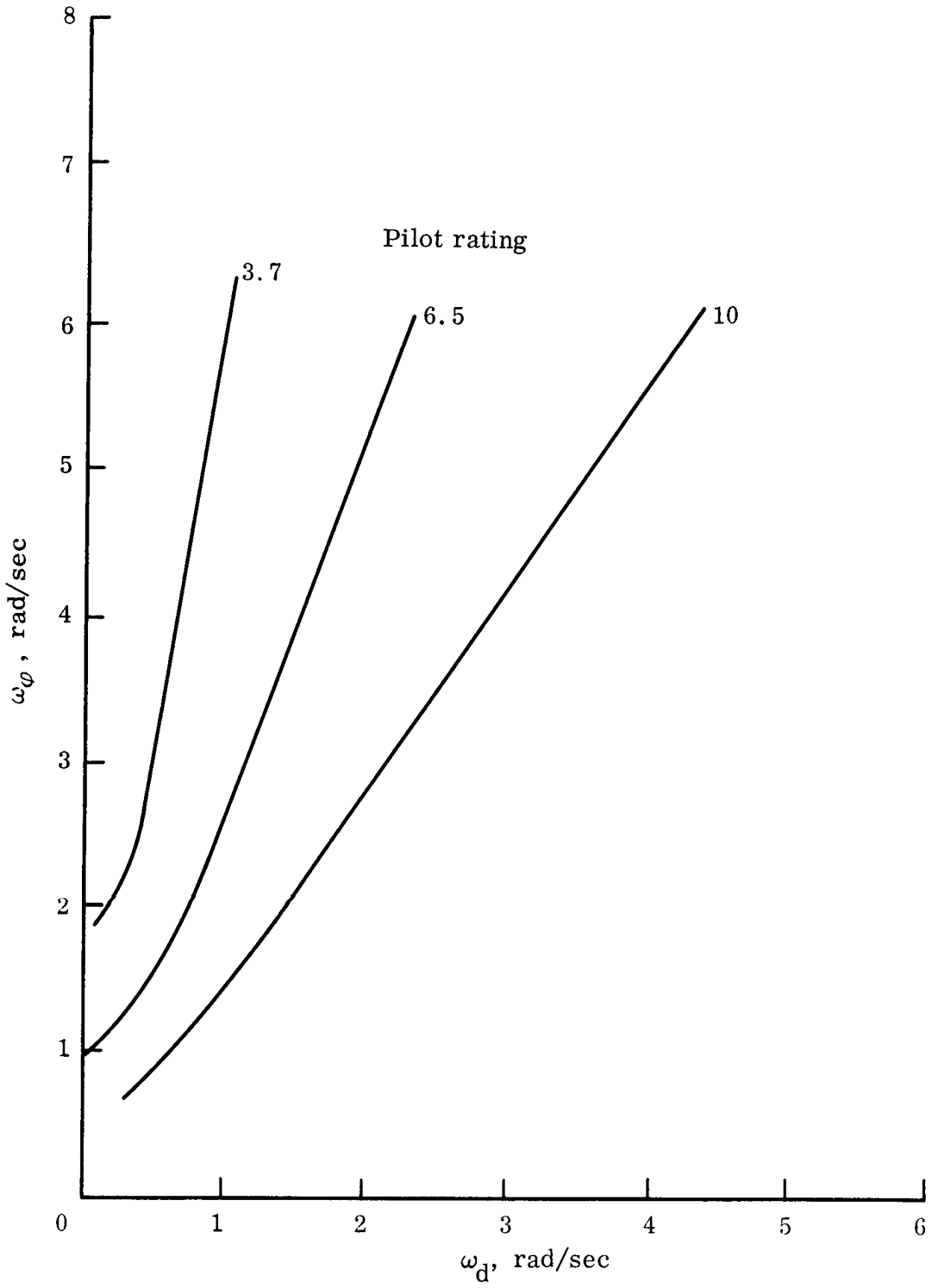
(i) $L_{\delta_a}\delta a_{max} = 30.0$, $2\zeta_d\omega_d = 0.25$, $\frac{1}{\tau_r} = 1.0$, $\left|L^*_{\dot{\beta}}\right| = 10.$

Figure 3. – Continued.



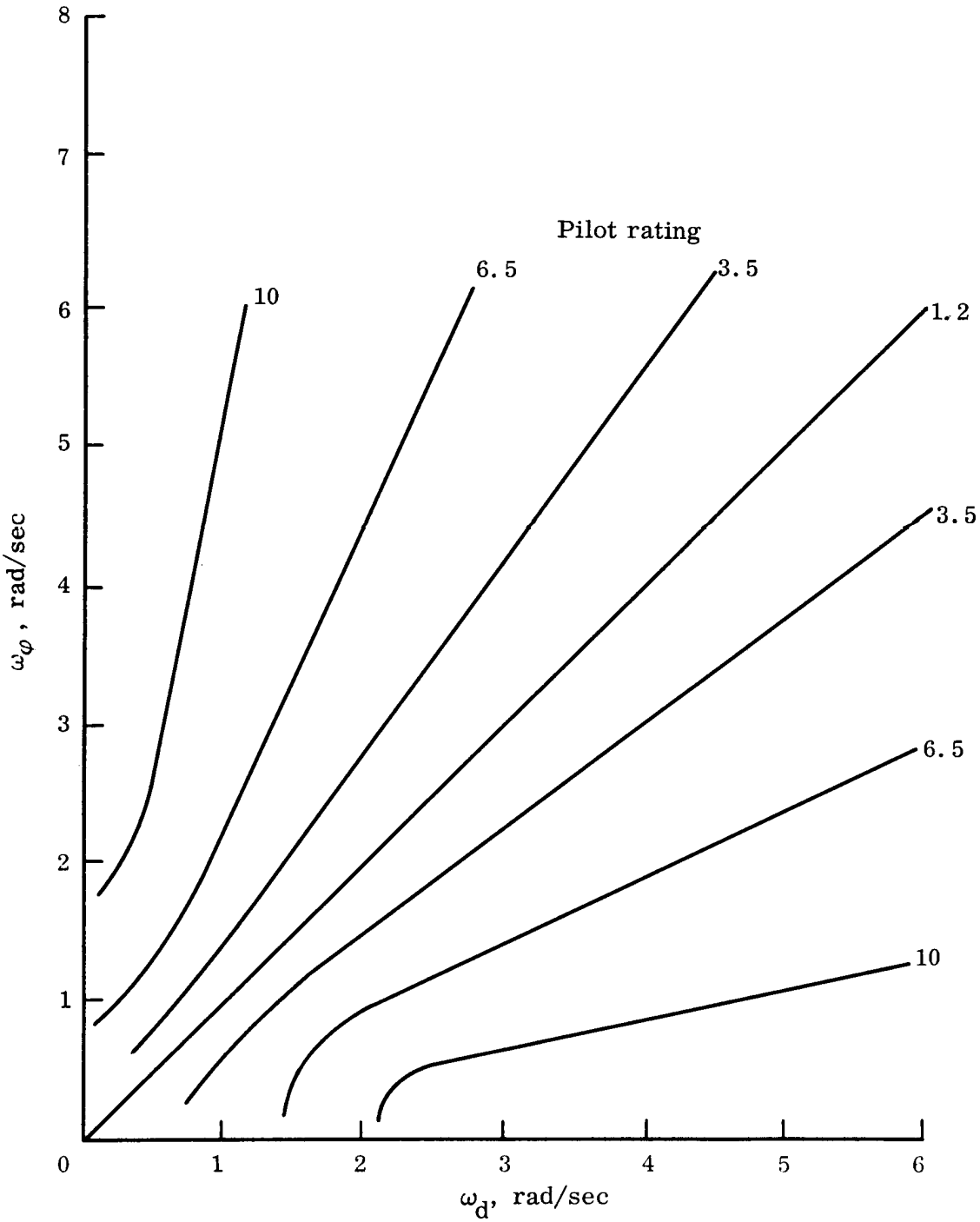
(j) $L_{\delta_a}\delta a_{max} = 100.0$, $2\zeta_d\omega_d = 0.25$, $\frac{1}{\tau_r} = 1.0$, $\left|L^*_\beta\right| = 10.$

Figure 3.– Continued.



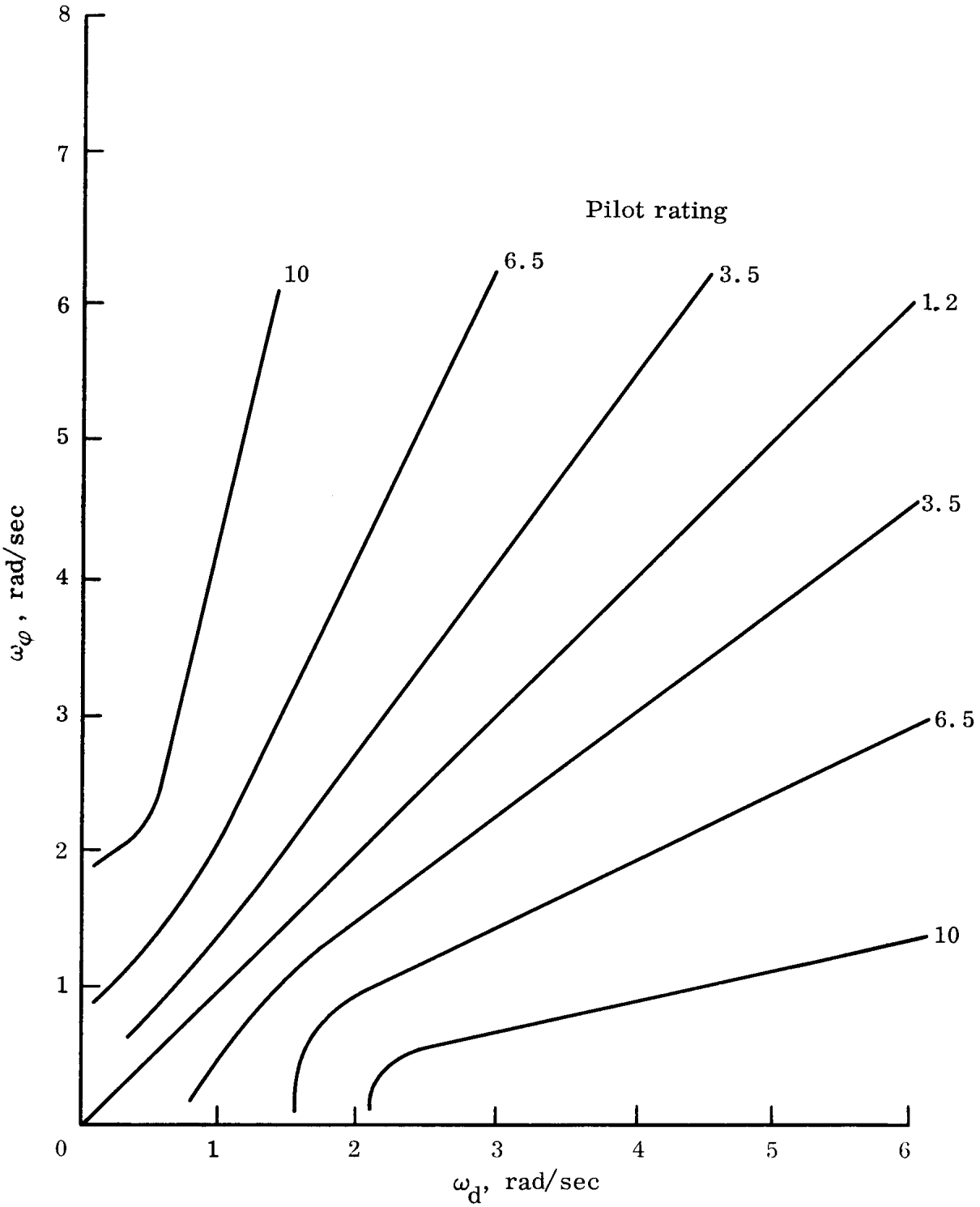
(k) $L_{\delta_a}\delta a_{max} = 0.1,\ 2\zeta_d\omega_d = 1.0,\ \frac{1}{\tau_r} = 4.0,\ \left|L_\beta^*\right| = 10.$

Figure 3.– Continued.



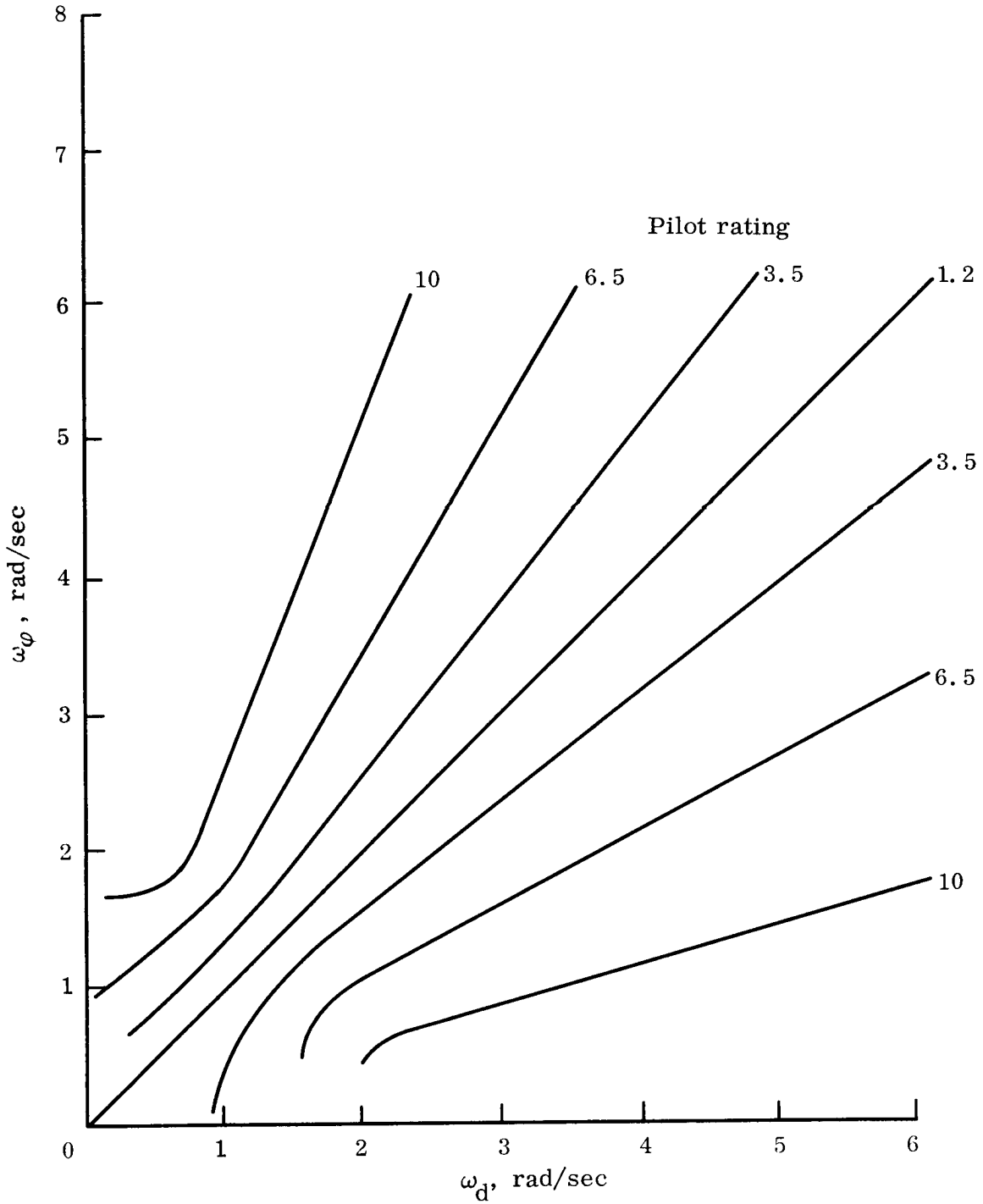
(*l*) $L_{\delta_a}\delta_{a_{max}} = 3.0$, $2\zeta_d\omega_d = 1.0$, $\frac{1}{\tau_r} = 4.0$, $\left|L_\beta^*\right| = 10.$

Figure 3.– Continued.



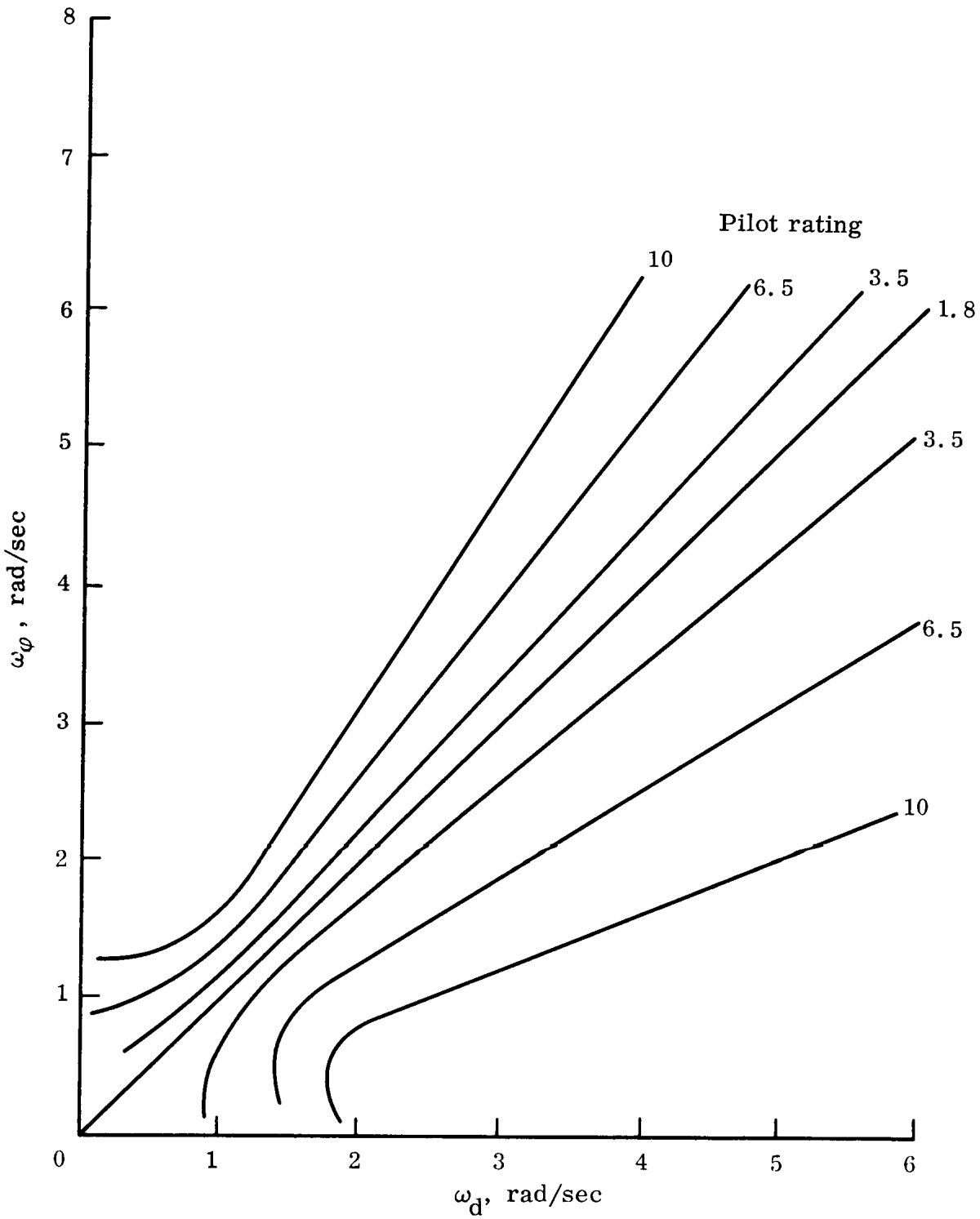
(m) $L_{\delta_a}\delta_{a_{max}} = 10.0$, $2\zeta_d\omega_d = 1.0$, $\frac{1}{\tau_r} = 4.0$, $\left|L^*_\beta\right| = 10.$

Figure 3.– Continued.



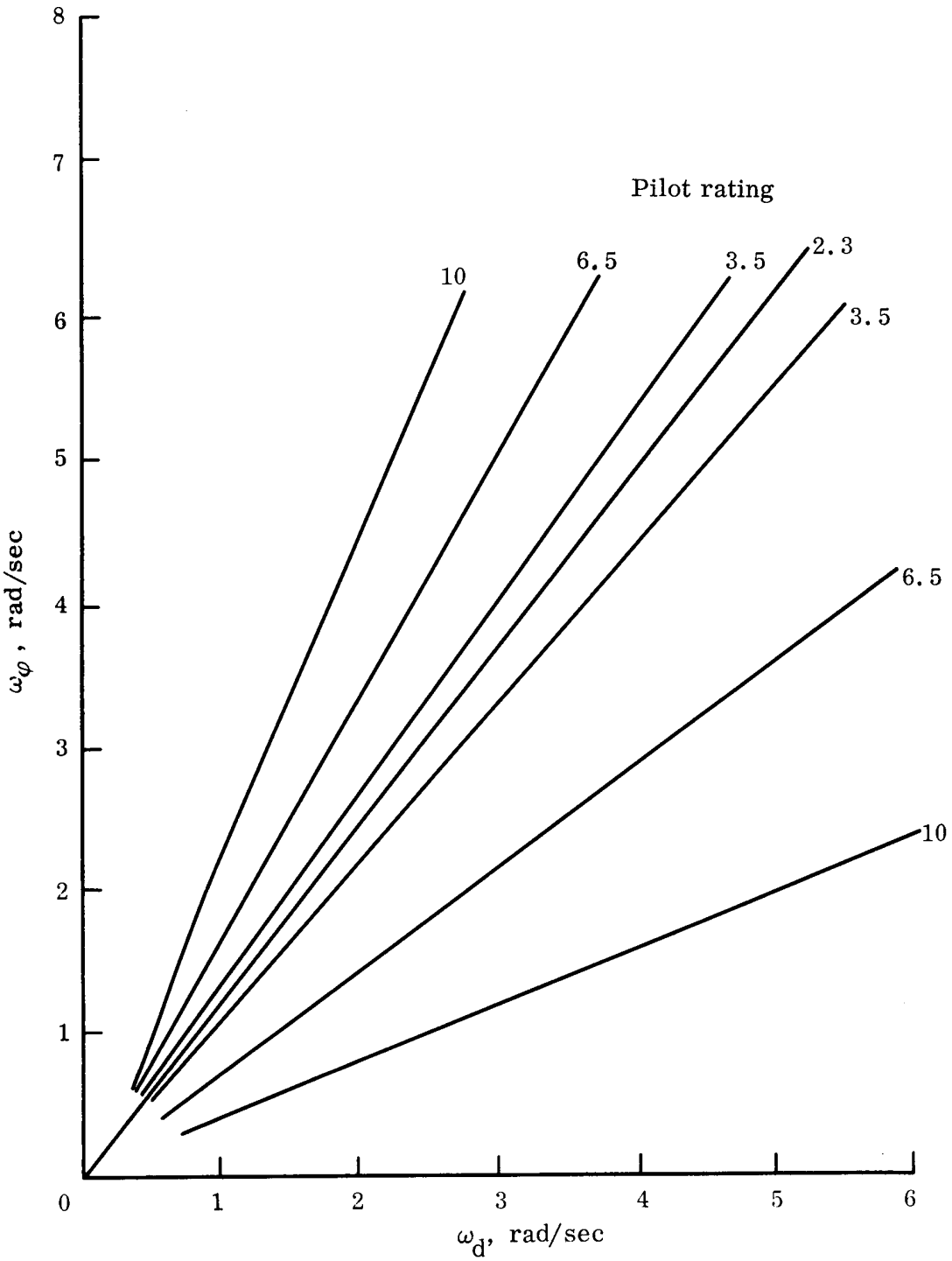
(n) $L_{\delta_a}\delta a_{max} = 30.0$, $2\zeta_d\omega_d = 1.0$, $\frac{1}{\tau_r} = 4.0$, $\left|L^*_\beta\right| = 10.$

Figure 3.– Continued.



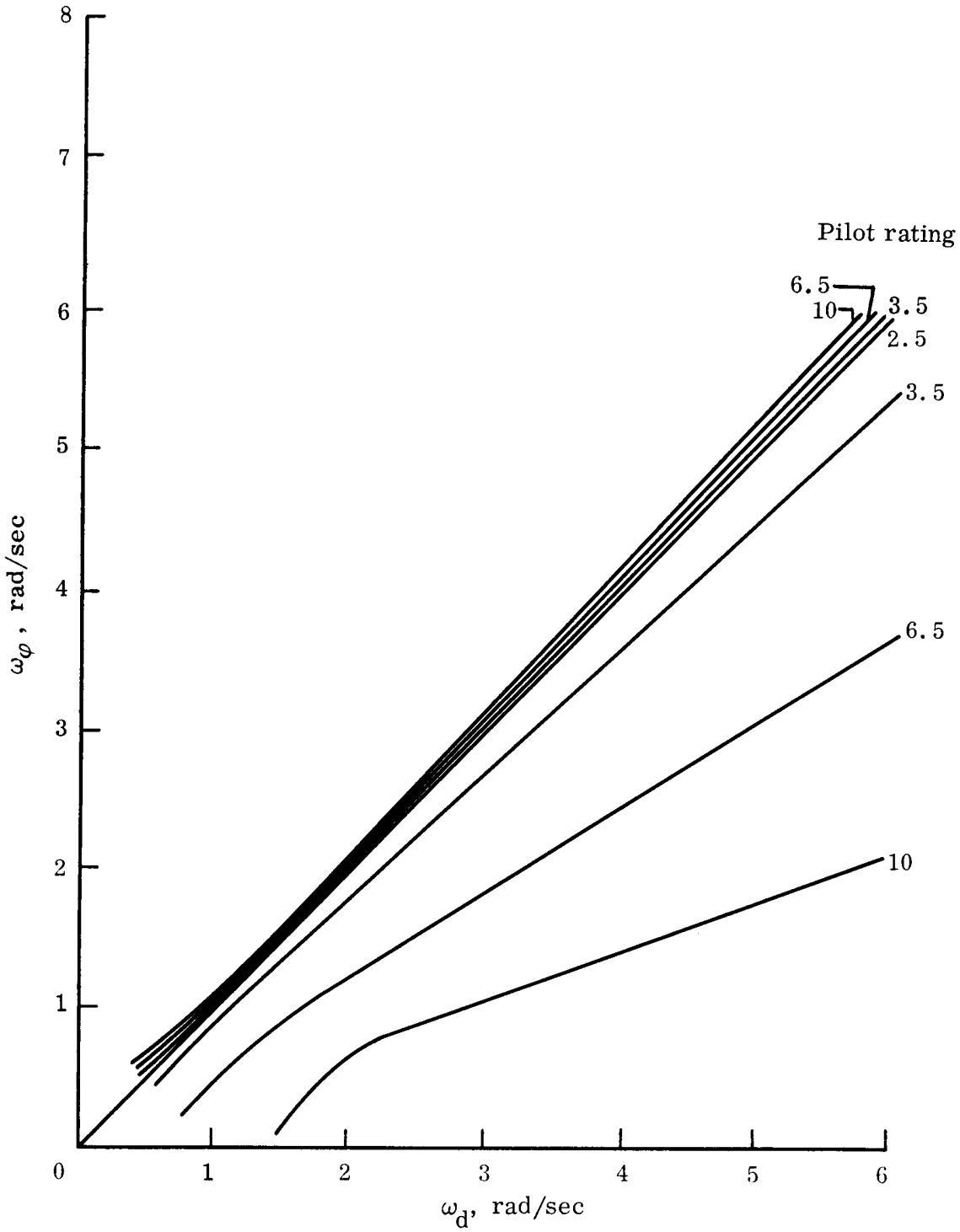
(o) $L_{\delta_a}\delta_{a_{max}} = 100.0$, $2\zeta_d\omega_d = 1.0$, $\frac{1}{\tau_r} = 4.0$, $\left|L^*_\beta\right| = 10.$

Figure 3.– Continued.



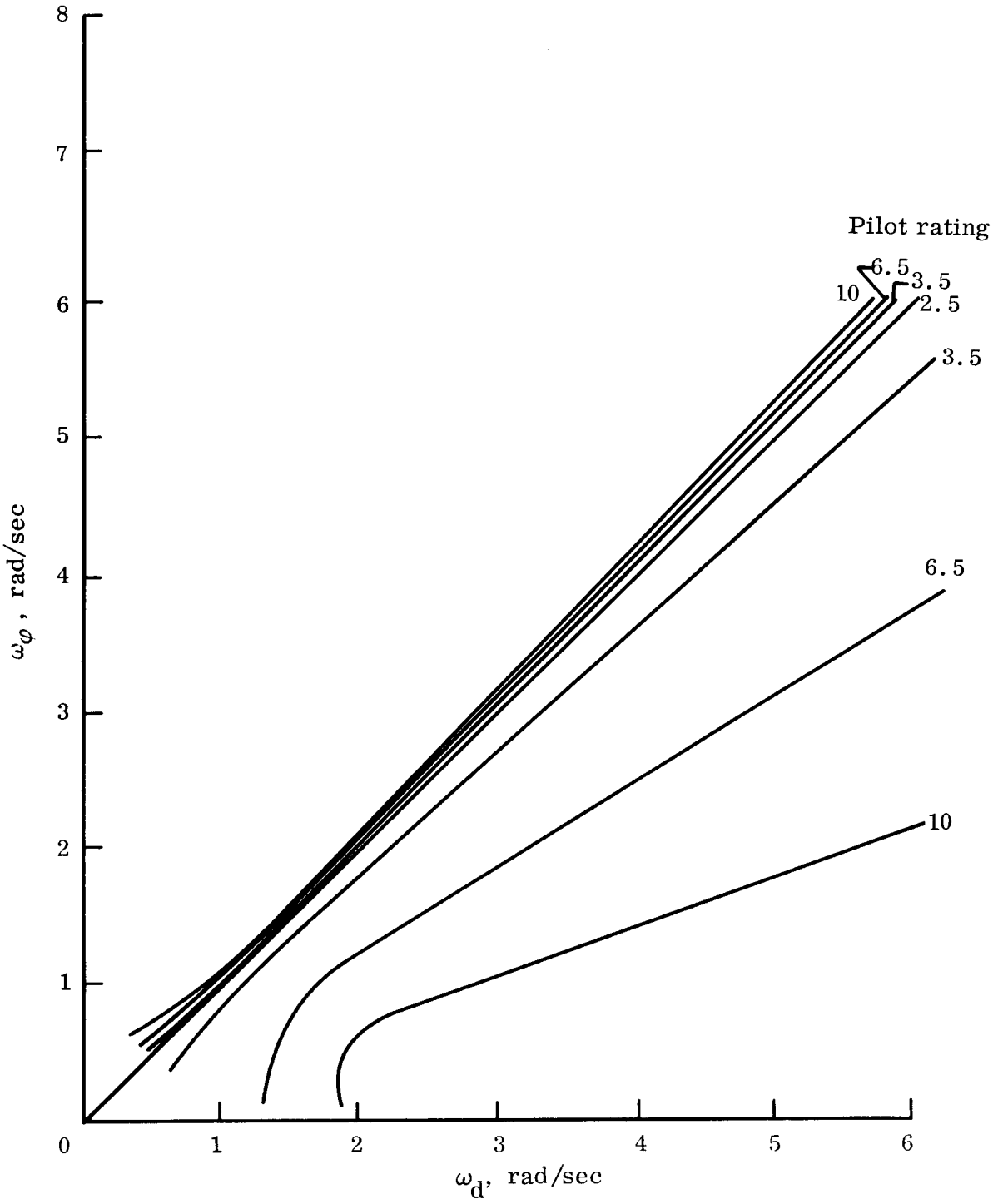
(p) $L_{\delta_a}\delta a_{max} = 0.1$, $2\zeta_d\omega_d = 0.025$, $\frac{1}{\tau_r} = 0.1$, $\left|L_\beta^*\right| = 30$.

Figure 3.– Continued.



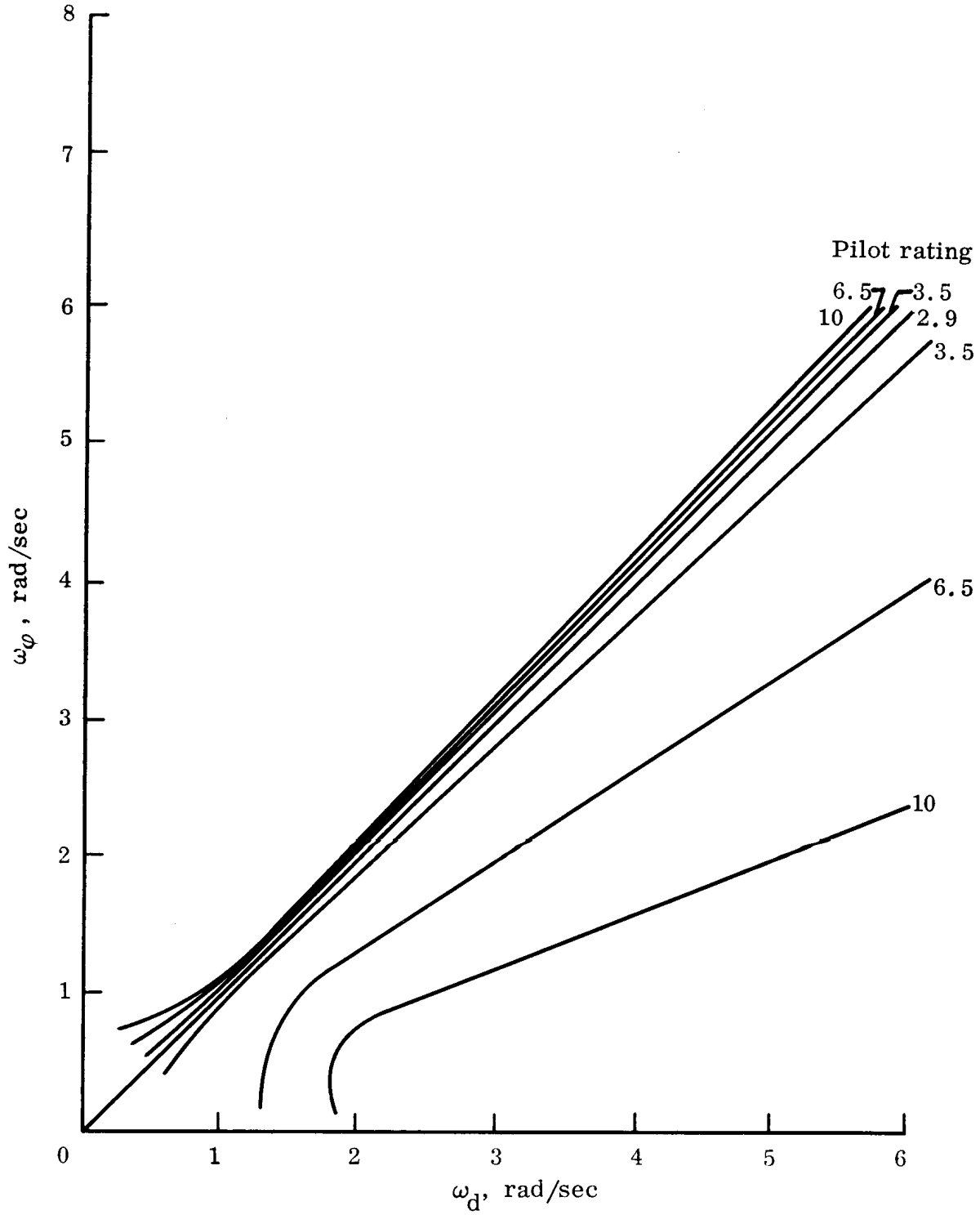
(q) $L_{\delta_a}\delta_{a_{max}} = 3.0,\ 2\zeta_d\omega_d = 0.025,\ \frac{1}{\tau_r} = 0.1,\ \left|L^*_\beta\right| = 30.$

Figure 3. – Continued.



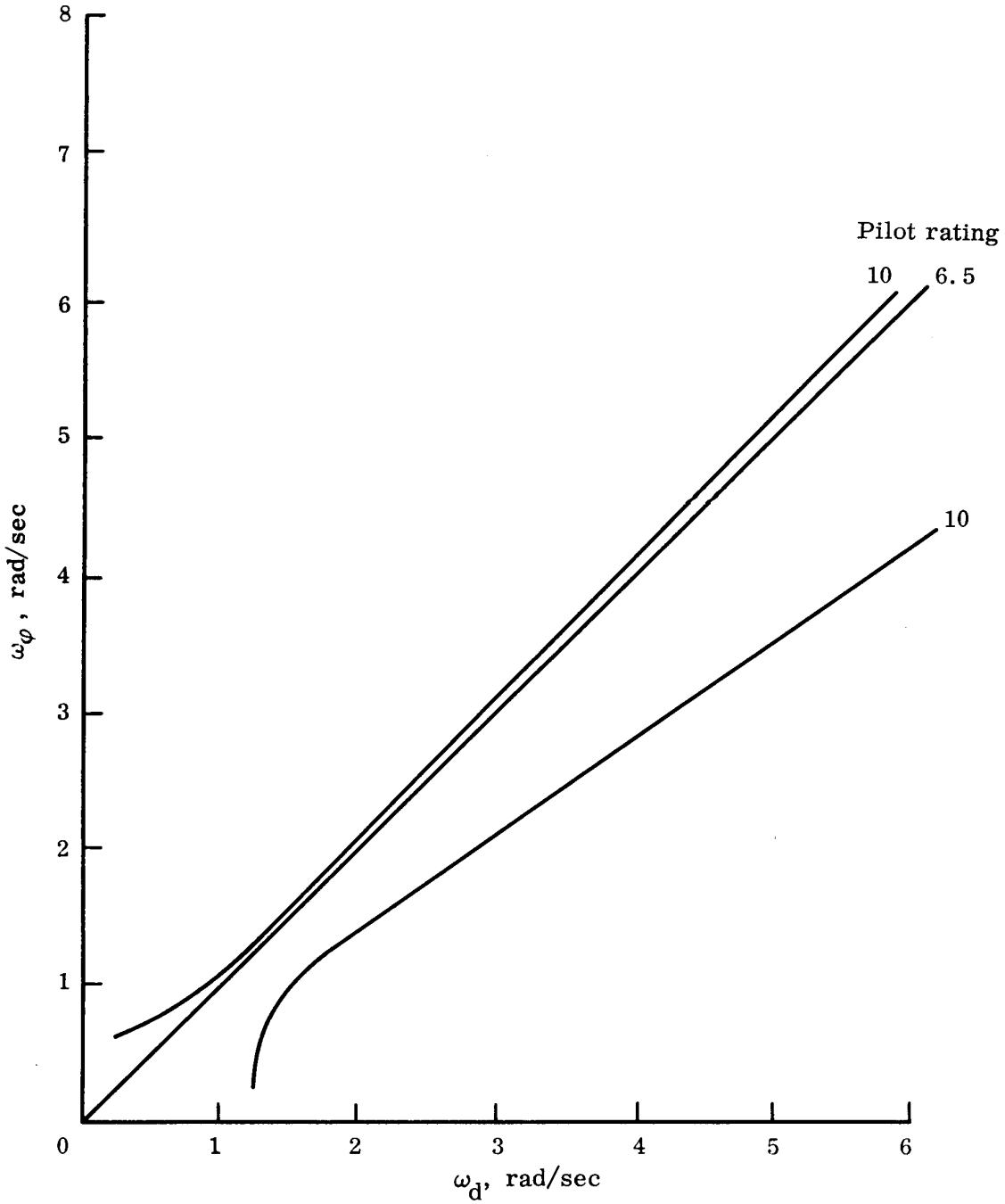
(r) $L_{\delta_a}\delta_{a_{max}} = 10.0$, $2\zeta_d\omega_d = 0.025$, $\frac{1}{\tau_r} = 0.1$, $\left|L^*_\beta\right| = 30.$

Figure 3.– Continued.



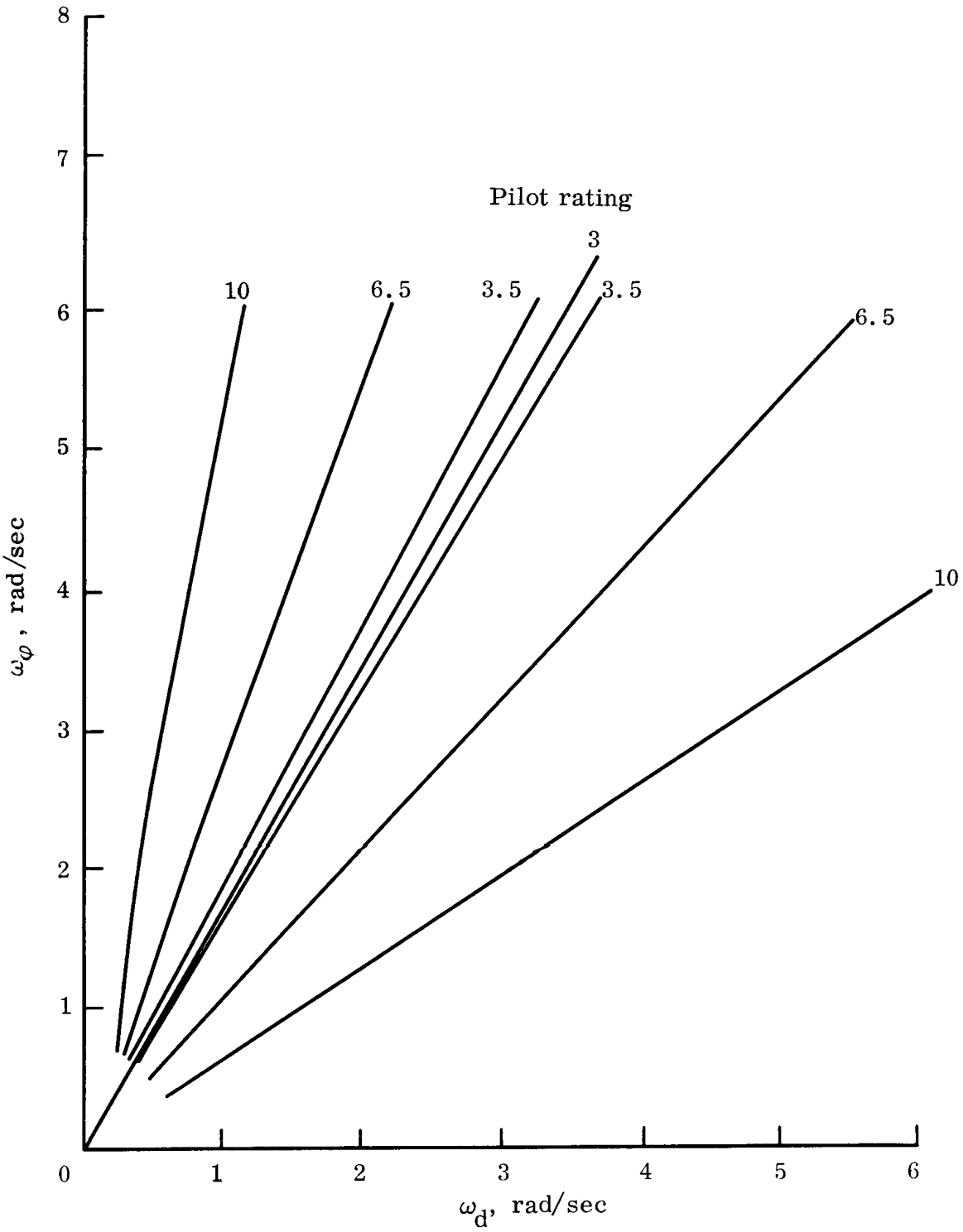
(s) $L_{\delta_a}\delta_{a_{max}} = 30.0$, $2\zeta_d\omega_d = 0.025$, $\frac{1}{\tau_r} = 0.1$, $\left|L_\beta^*\right| = 30.$

Figure 3.– Continued.



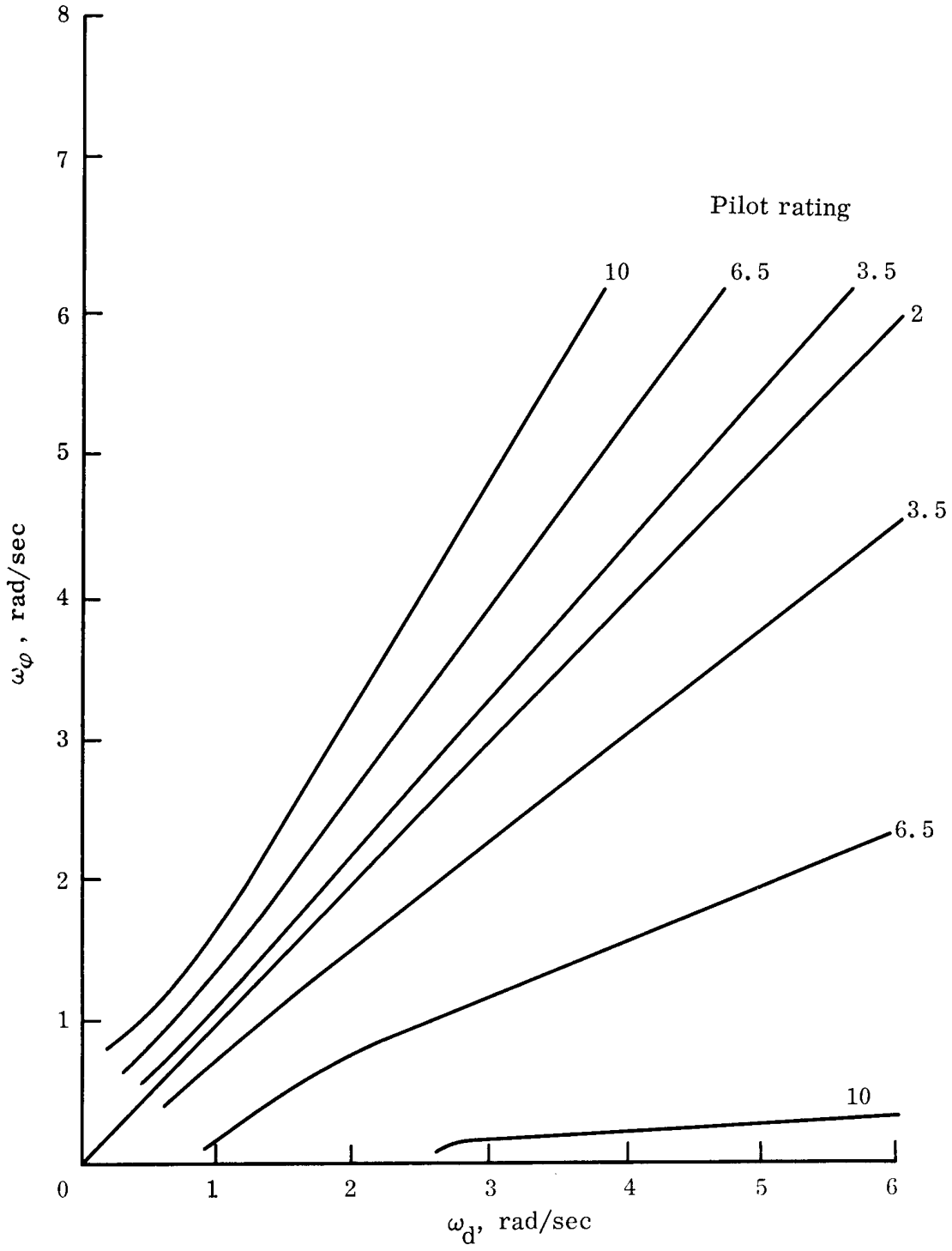
(t) $L_{\delta_a}\delta a_{max} = 100.0$, $2\zeta_d\omega_d$, $= 0.025$, $\frac{1}{\tau_r} = 0.1$, $\left|L^*_\beta\right| = 30.$

Figure 3. – Continued.



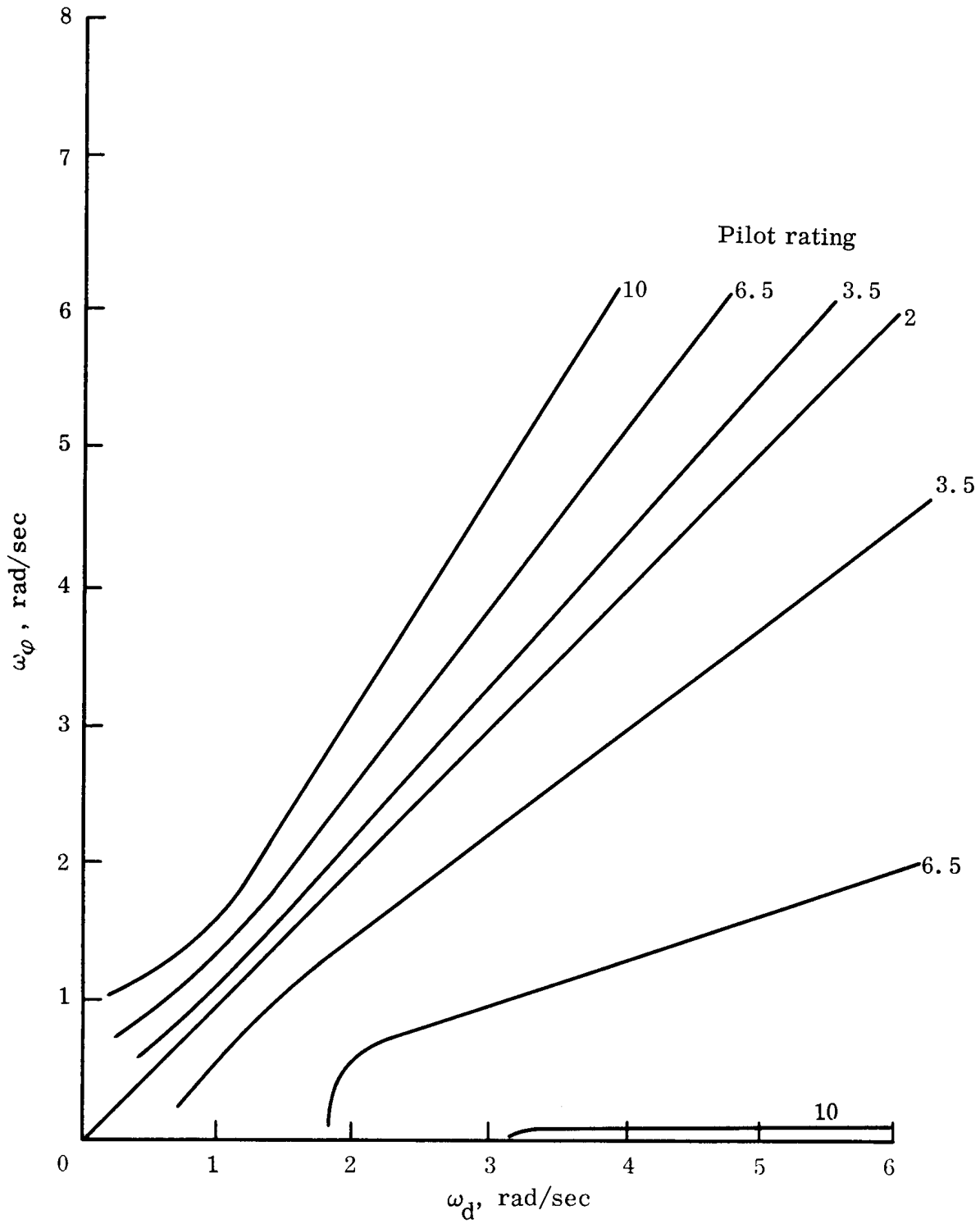
(u) $L_{\delta_a}\delta_{a_{max}} = 0.1,\ 2\zeta_d\omega_d = 0.25,\ \frac{1}{\tau_r} = 1.0,\ \left|L^*_\beta\right| = 30.$

Figure 3.– Continued



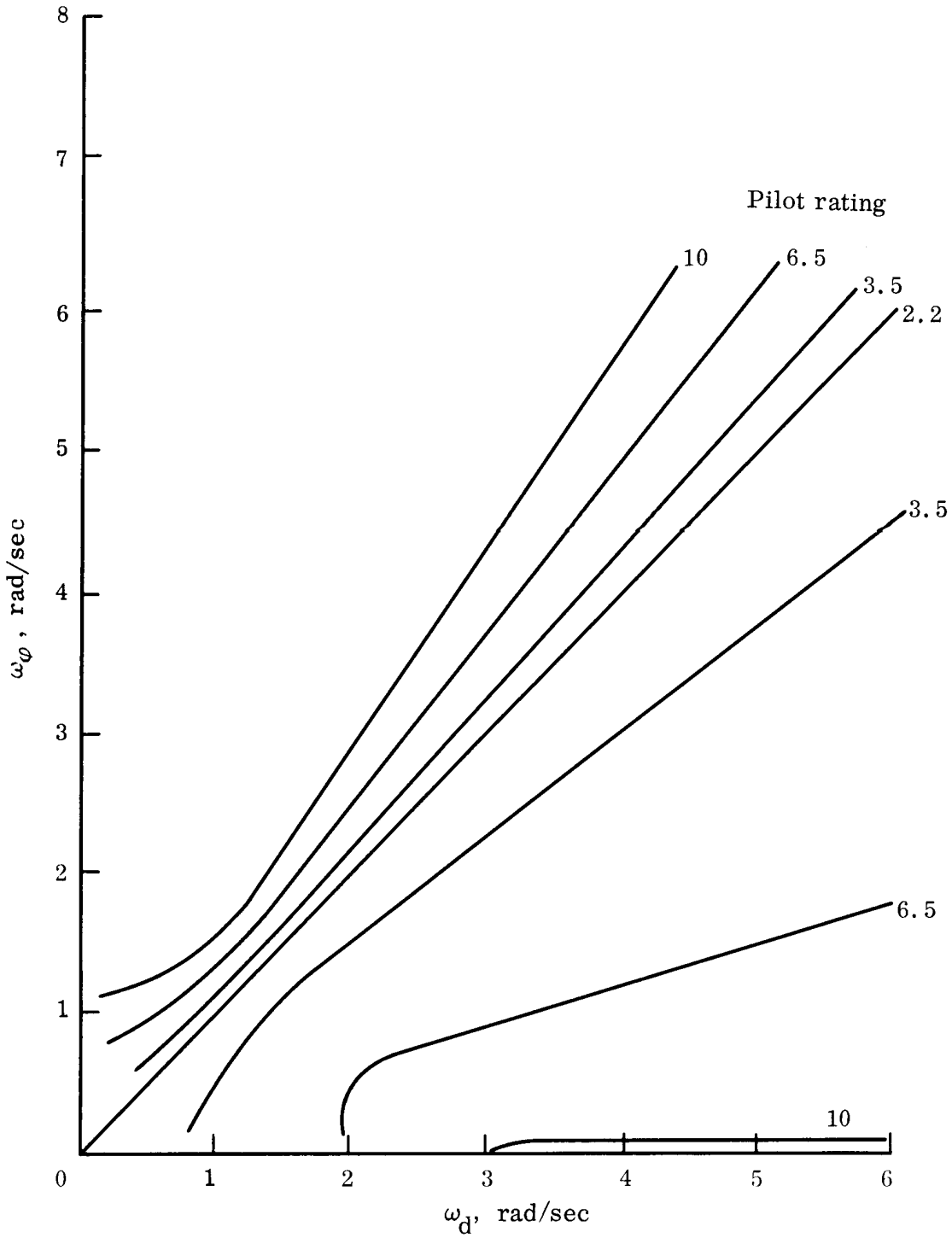
(v) $L_{\delta_a}\delta_{a_{max}} = 3.0,\ 2\zeta_d\omega_d = 0.25,\ \frac{1}{\tau_r} = 1.0,\ \left|L^*_\beta\right| = 30.$

Figure 3.– Continued.



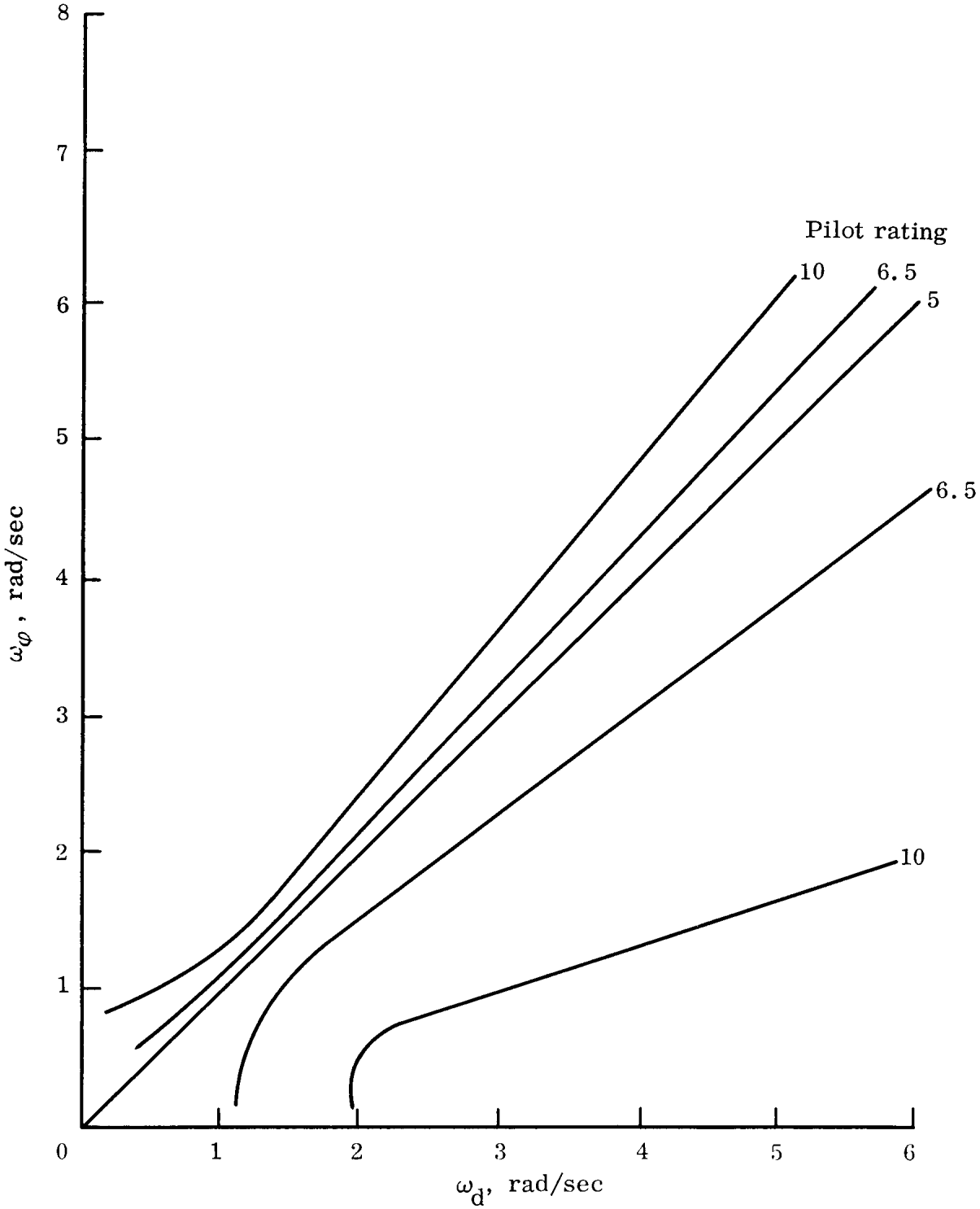
(w) $L_{\delta_a}\delta_{a_{max}} = 10.0,\ 2\zeta_d\omega_d = 0.25,\ \frac{1}{\tau_r} = 1.0,\ \left|L^*_\beta\right| = 30.$

Figure 3. – Continued.



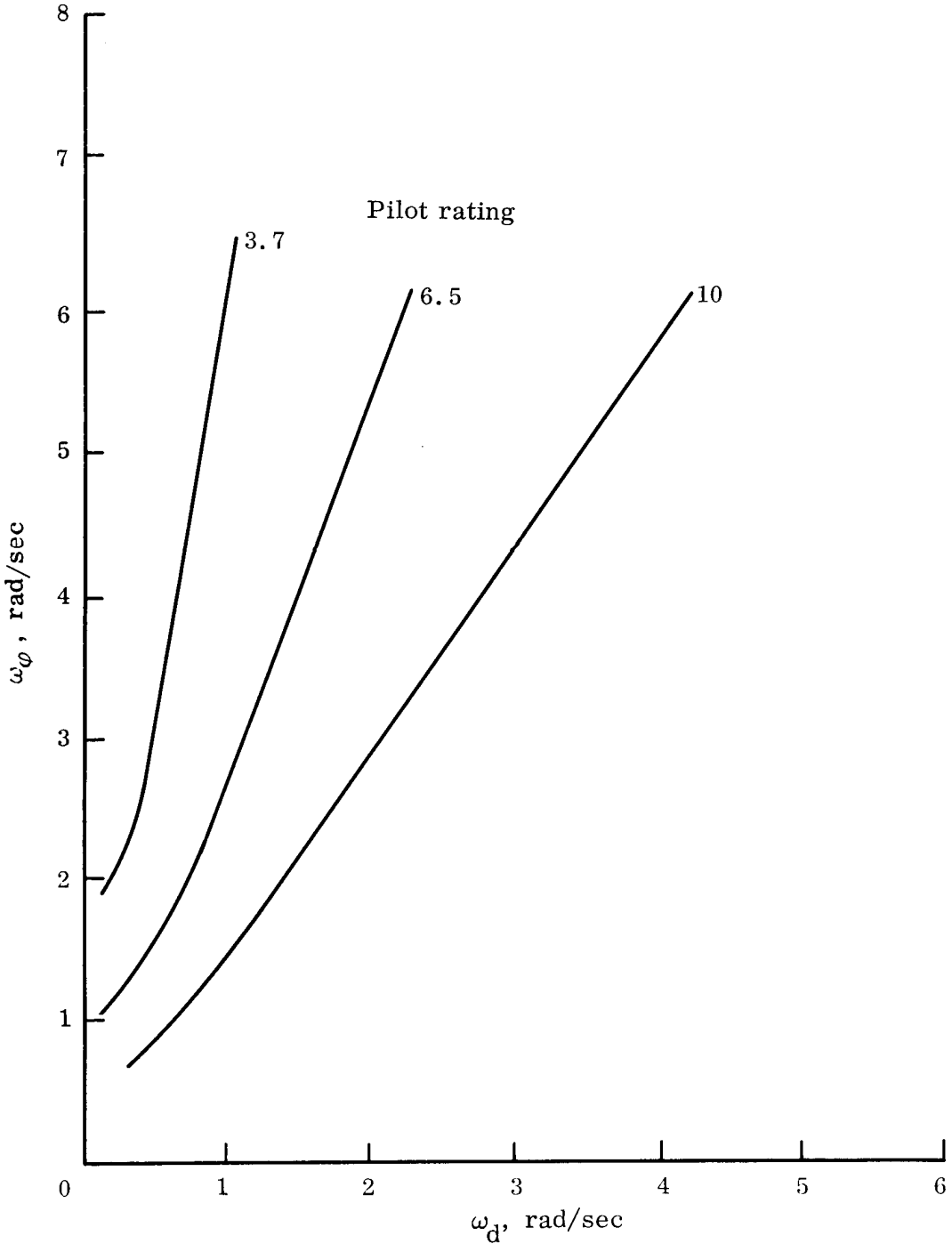
(x) $L_{\delta_a}\delta_{a_{max}} = 30.0$, $2\zeta_d\omega_d = 0.25$, $\frac{1}{\tau_r} = 1.0$, $\left|L^*_\beta\right| = 30.$

Figure 3. – Continued.



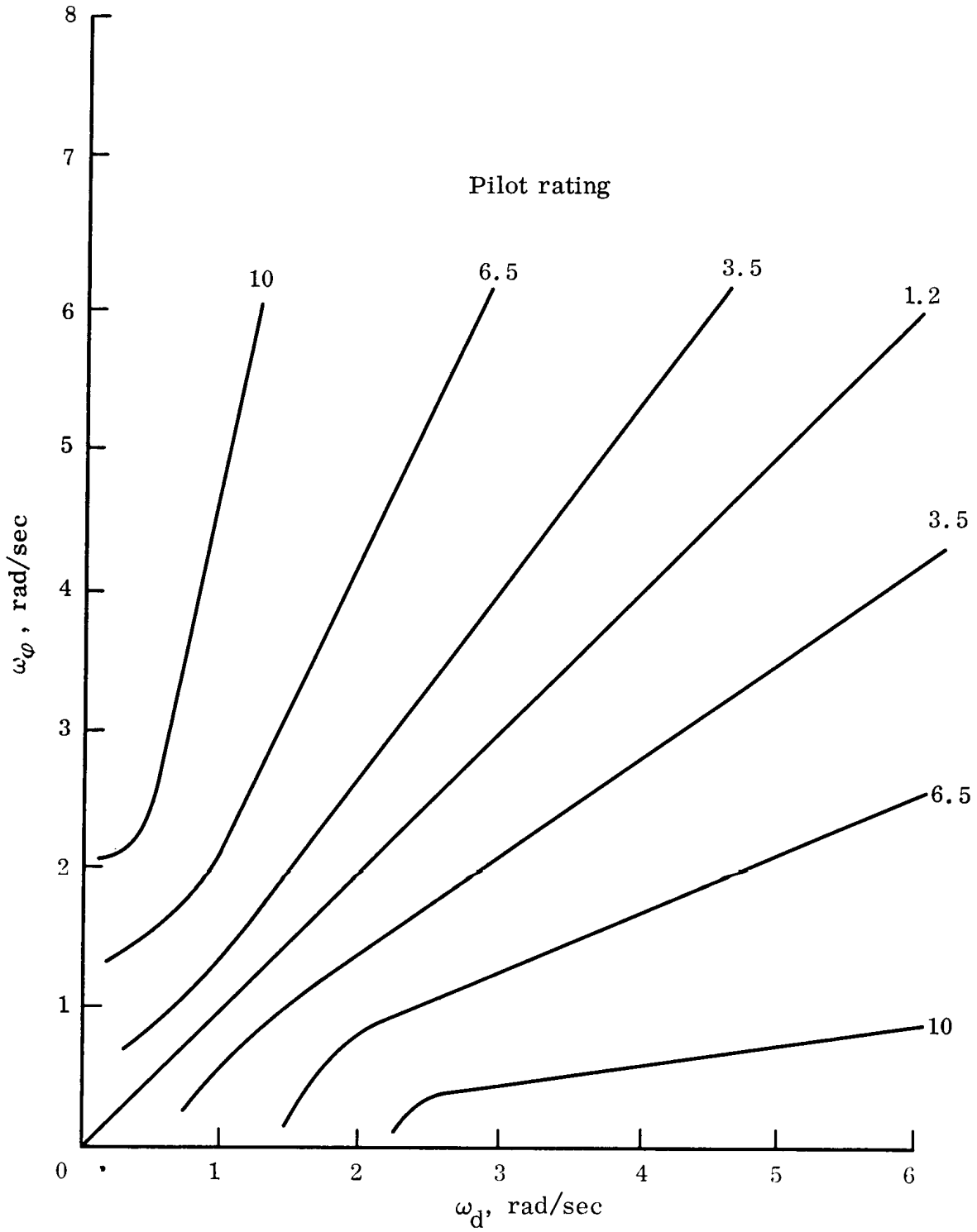
(y) $L_{\delta_a}\delta_{a_{max}} = 100.0$, $2\zeta_d\omega_d = 0.25$, $\frac{1}{\tau_r} = 1.0$, $\left|L_\beta^*\right| = 30.$

Figure 3.– Continued.



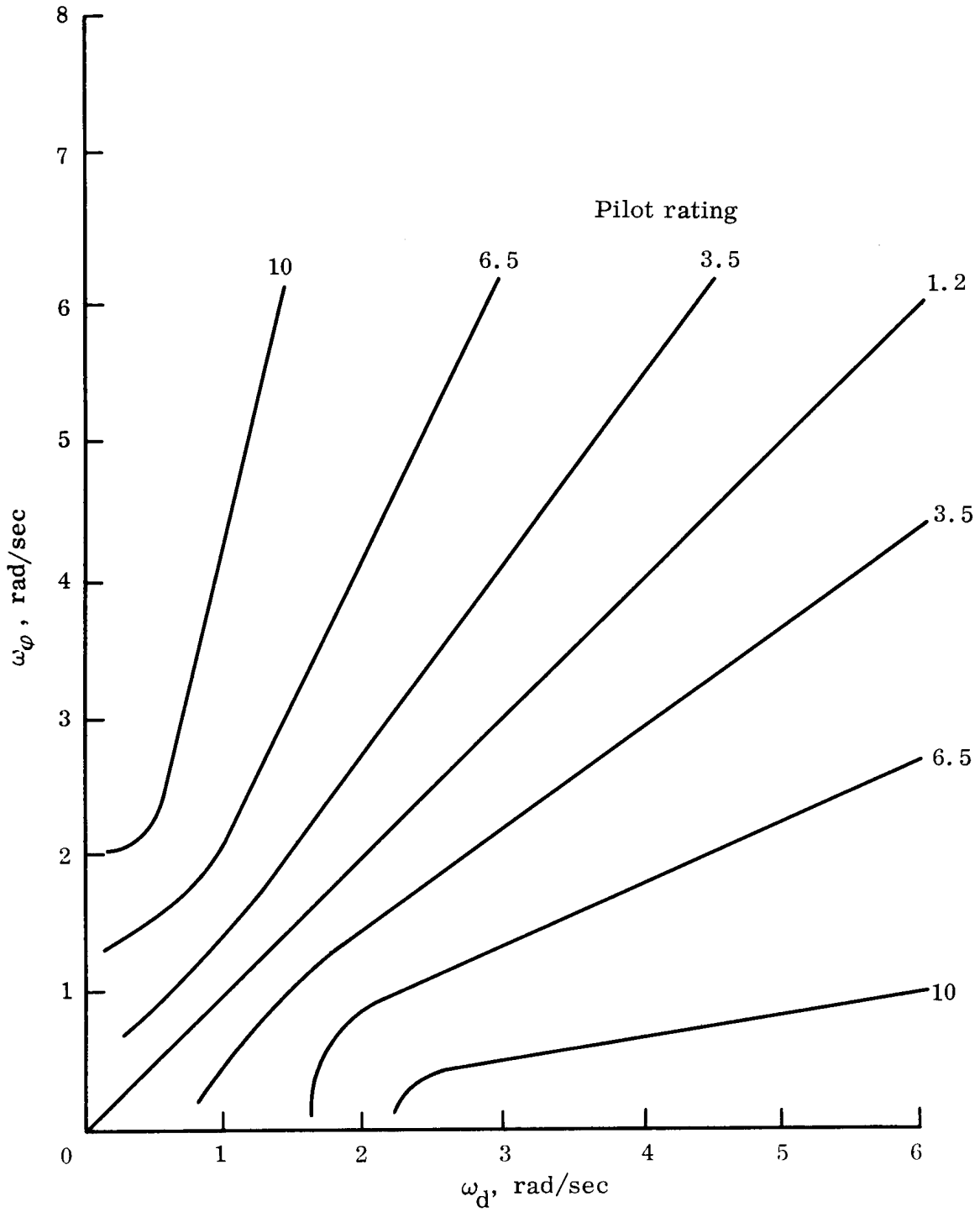
(z) $L_{\delta_a}\delta a_{max} = 0.1,\ 2\zeta_d\omega_d = 1.0,\ \frac{1}{\tau_r} = 4.0,\ \left|L^*_\beta\right| = 30.$

Figure 3. – Continued.



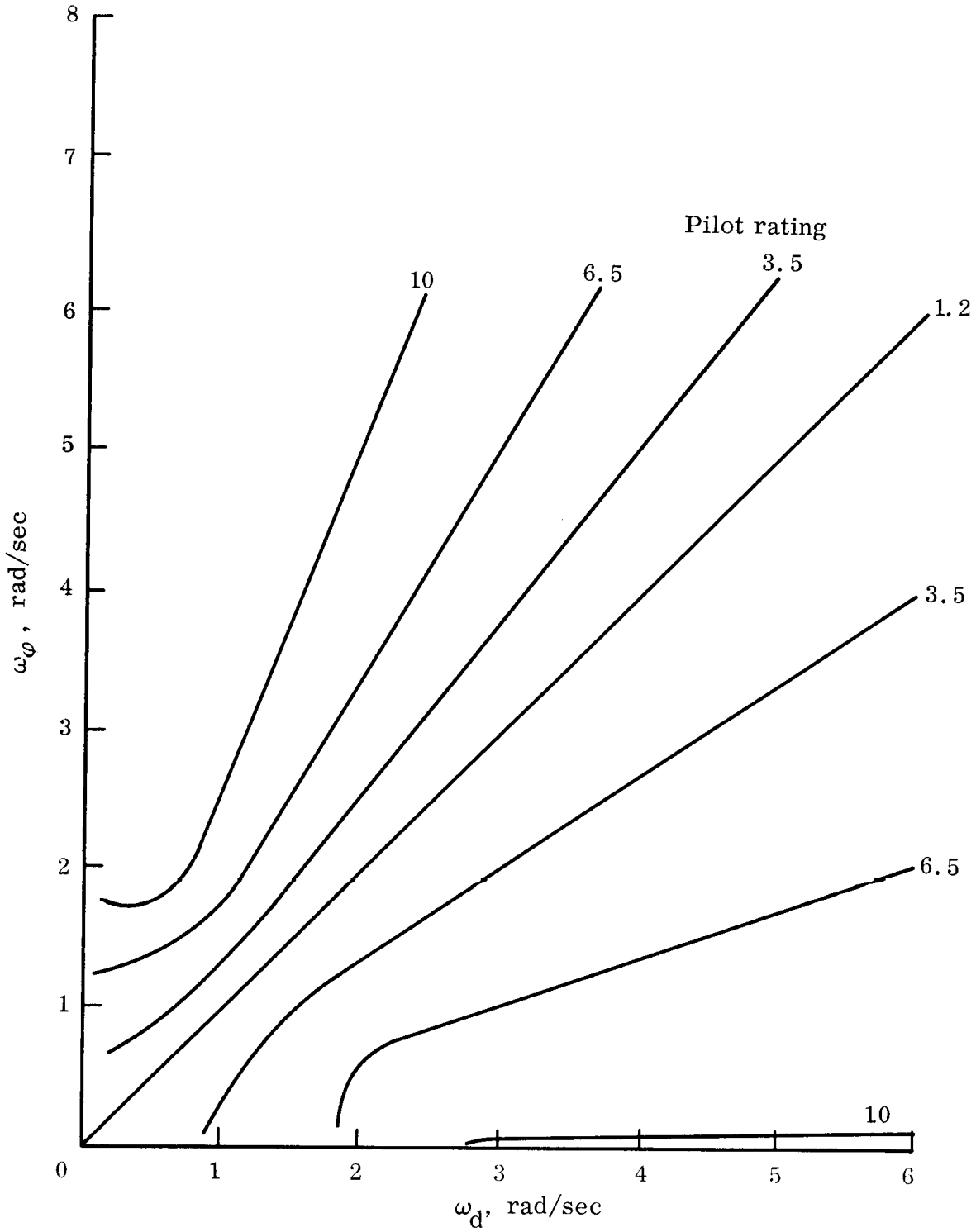
(aa) $L_{\delta_a}\delta_{a_{max}} = 3.0$, $2\zeta_d\omega_d = 1.0$, $\frac{1}{\tau_r} = 4.0$, $\left|L^*_\beta\right| = 30.$

Figure 3.– Continued.



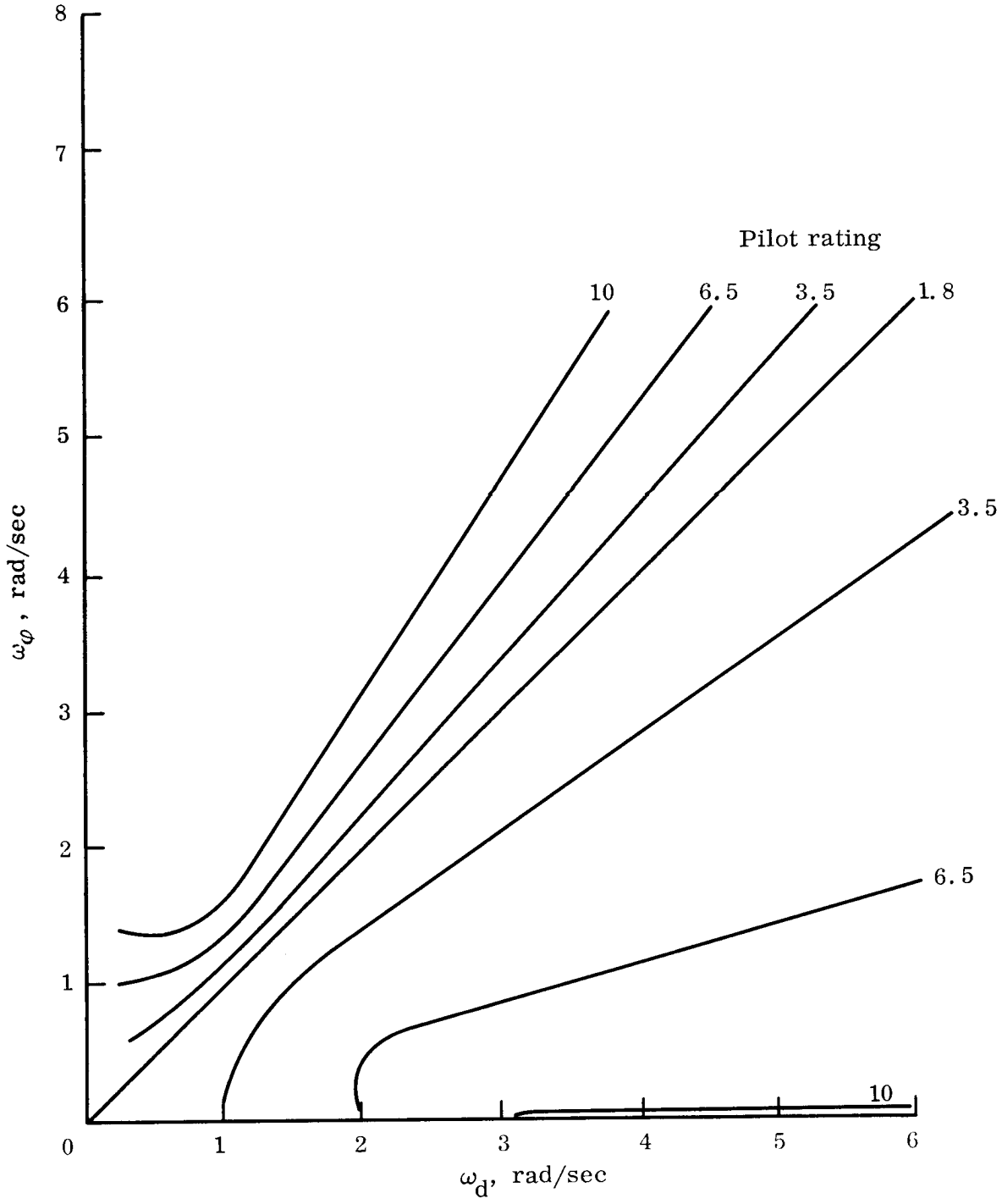
(bb) $L\delta_a\delta_{a_{max}} = 10.0$, $2\zeta_d\omega_d = 1.0$, $\frac{1}{\tau_r} = 4.0$, $\left|\frac{L^*}{\beta}\right| = 30.$

Figure 3. – Continued.



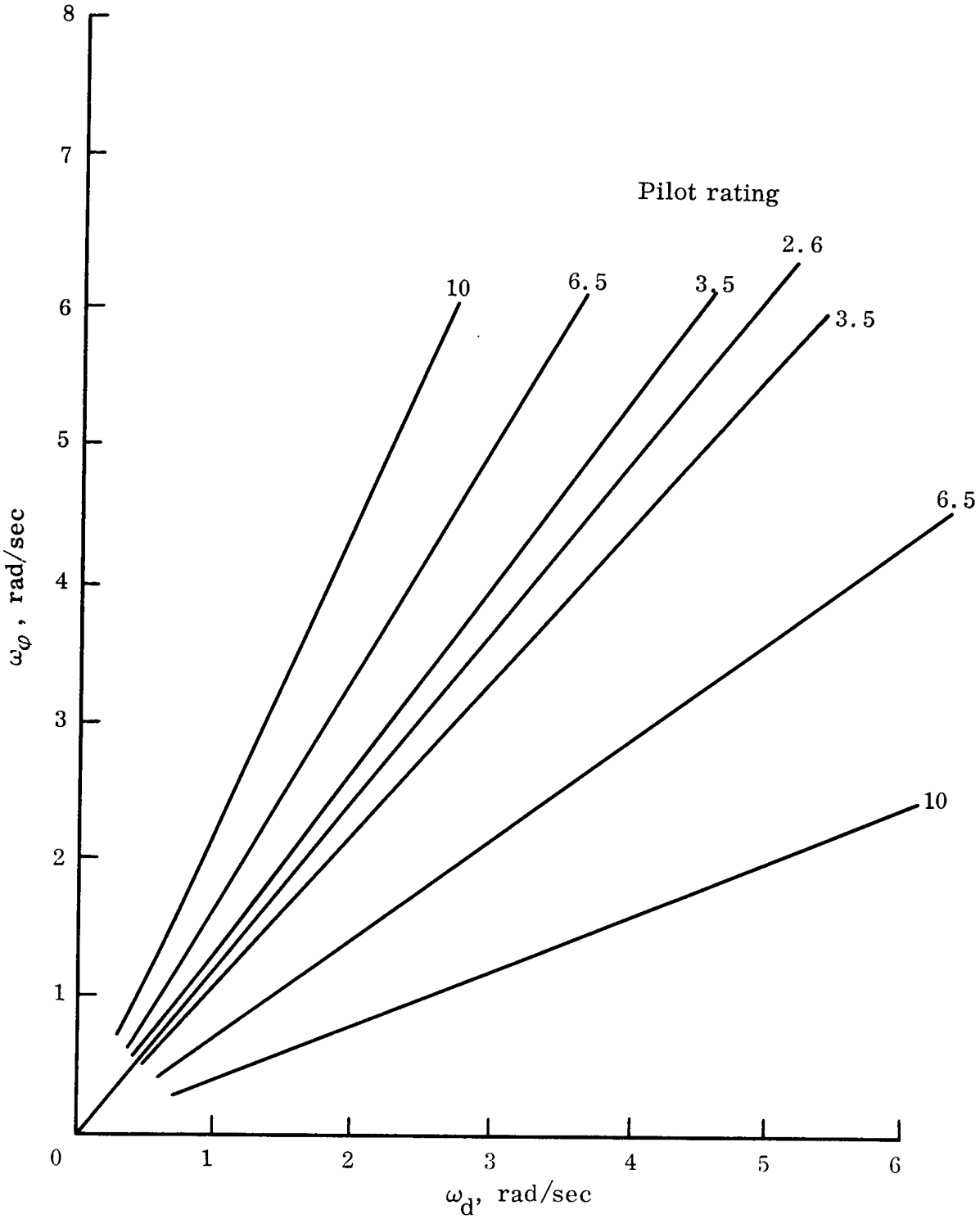
(cc) $L_{\delta_a}\delta_{a_{max}} = 30.0$, $2\zeta_d\omega_d = 1.0$, $\frac{1}{\tau_r} = 4.0$, $\left|L_\beta^*\right| = 30.$

Figure 3.– Continued.



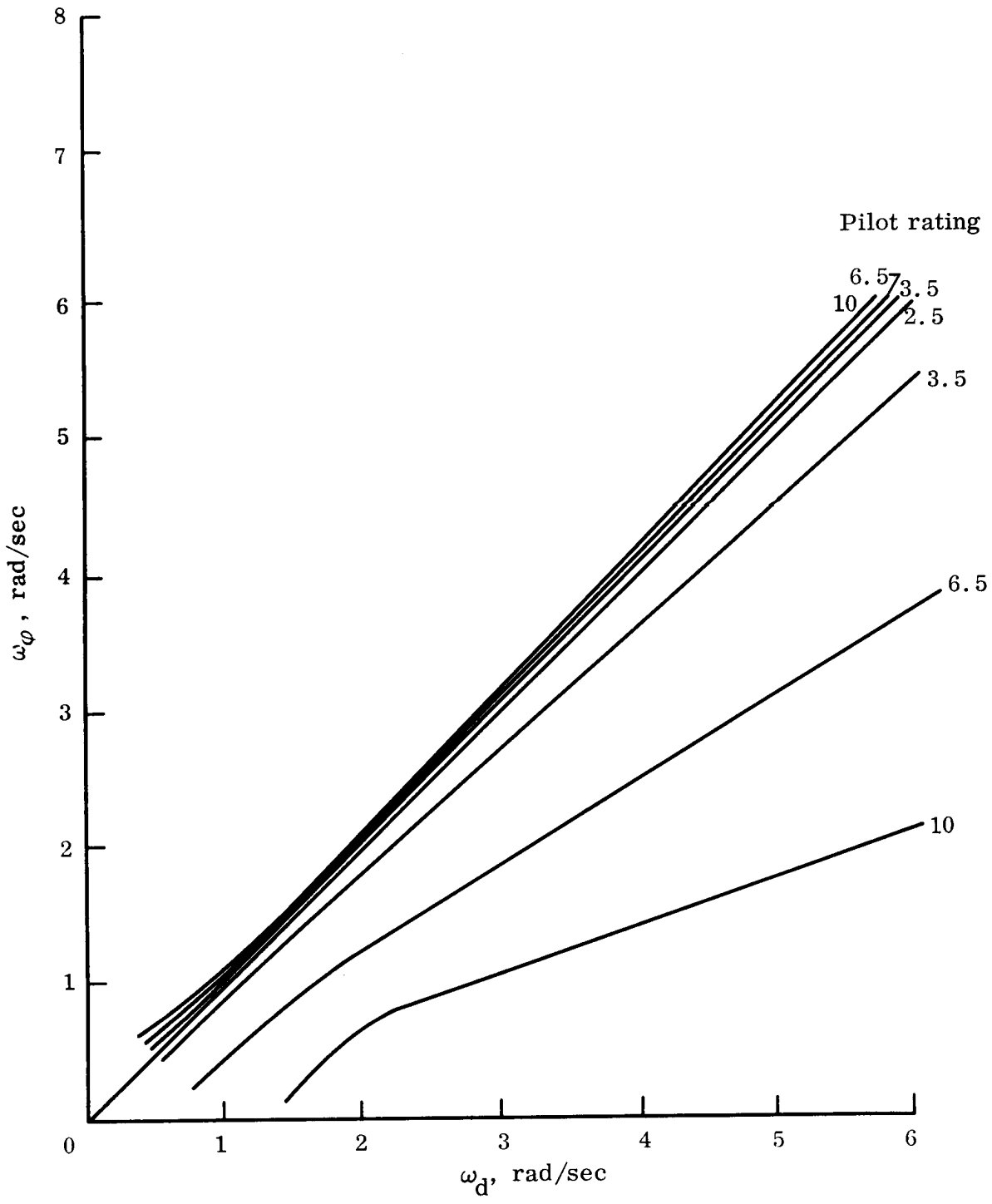
(dd) $L_{\delta_a}\delta a_{max} = 100.0$, $2\zeta_d\omega_d = 1.0$, $\frac{1}{\tau_r} = 4.0$, $\left|L^*_\beta\right| = 30.$

Figure 3.– Continued.



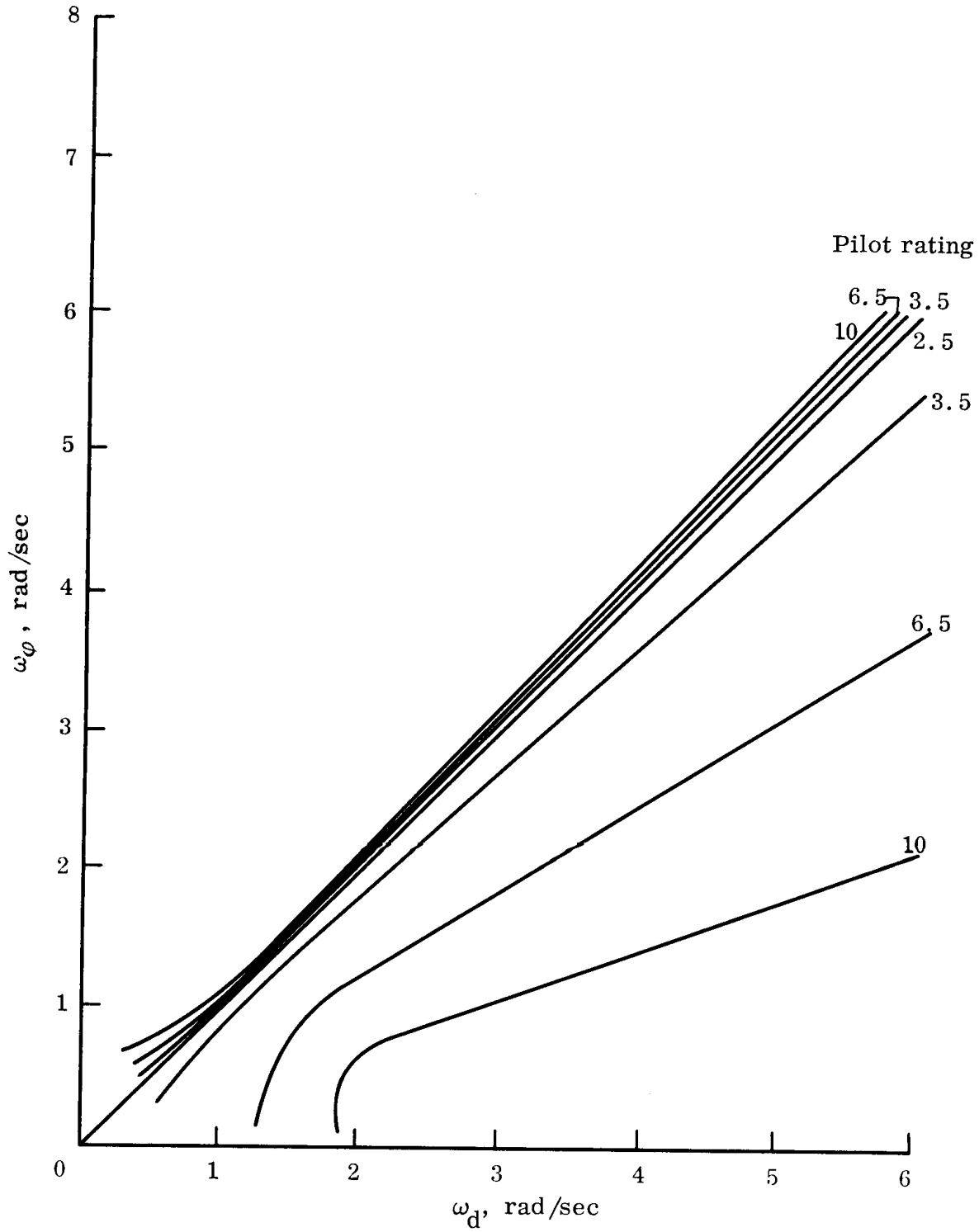
(ee) $L_{\delta_a}\delta_{a_{max}} = 0.1$, $2\zeta_d\omega_d = 0.025$, $\frac{1}{\tau_r} = 0.1$, $\left|L^*_\beta\right| = 100.$

Figure 3.– Continued.



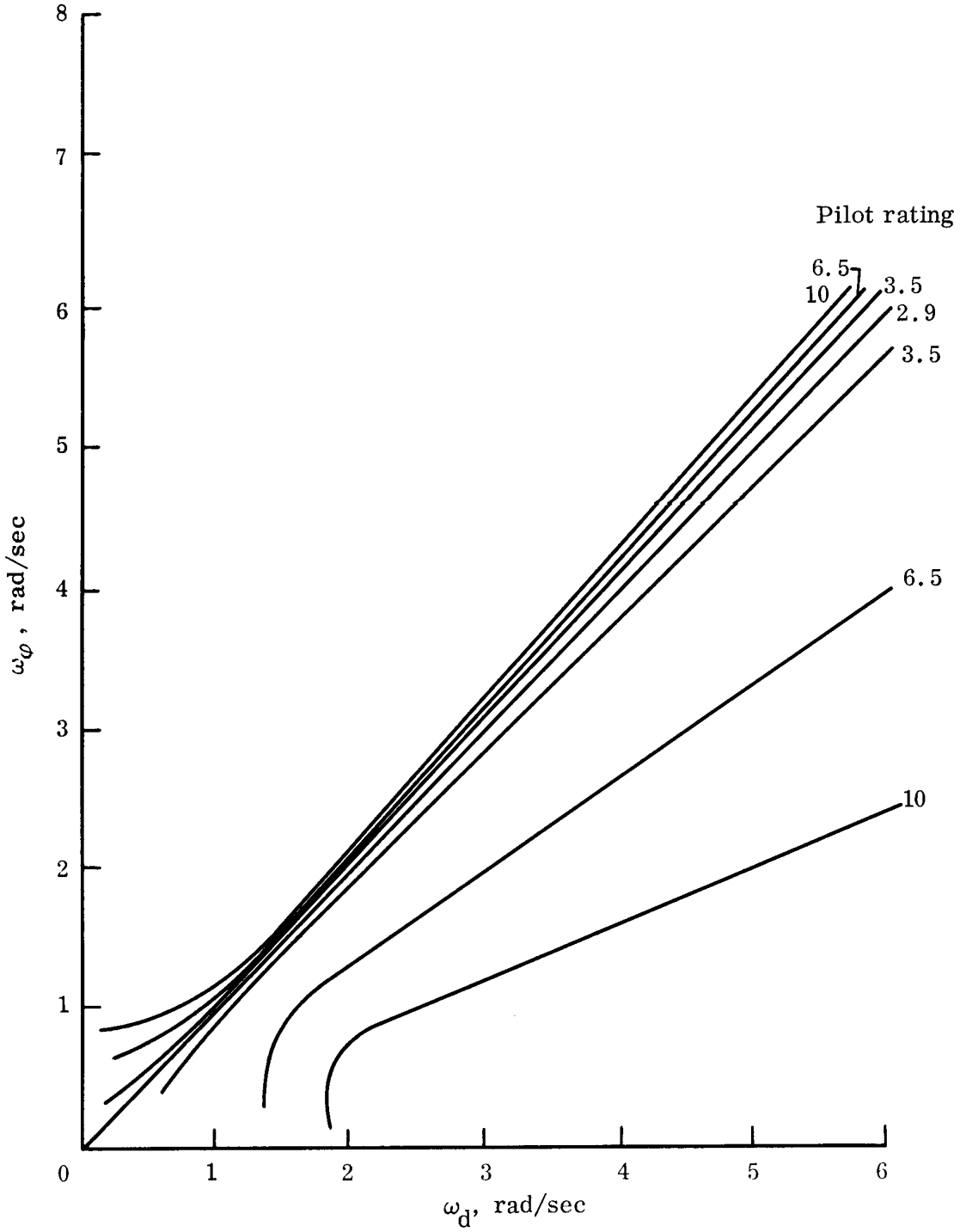
(ff) $L_{\delta_a}\delta_{a_{max}} = 3.0,\ 2\zeta_d\omega_d = 0.025,\ \frac{1}{\tau_r} = 0.1,\ \left|L_\beta^*\right| = 100.$

Figure 3.– Continued.



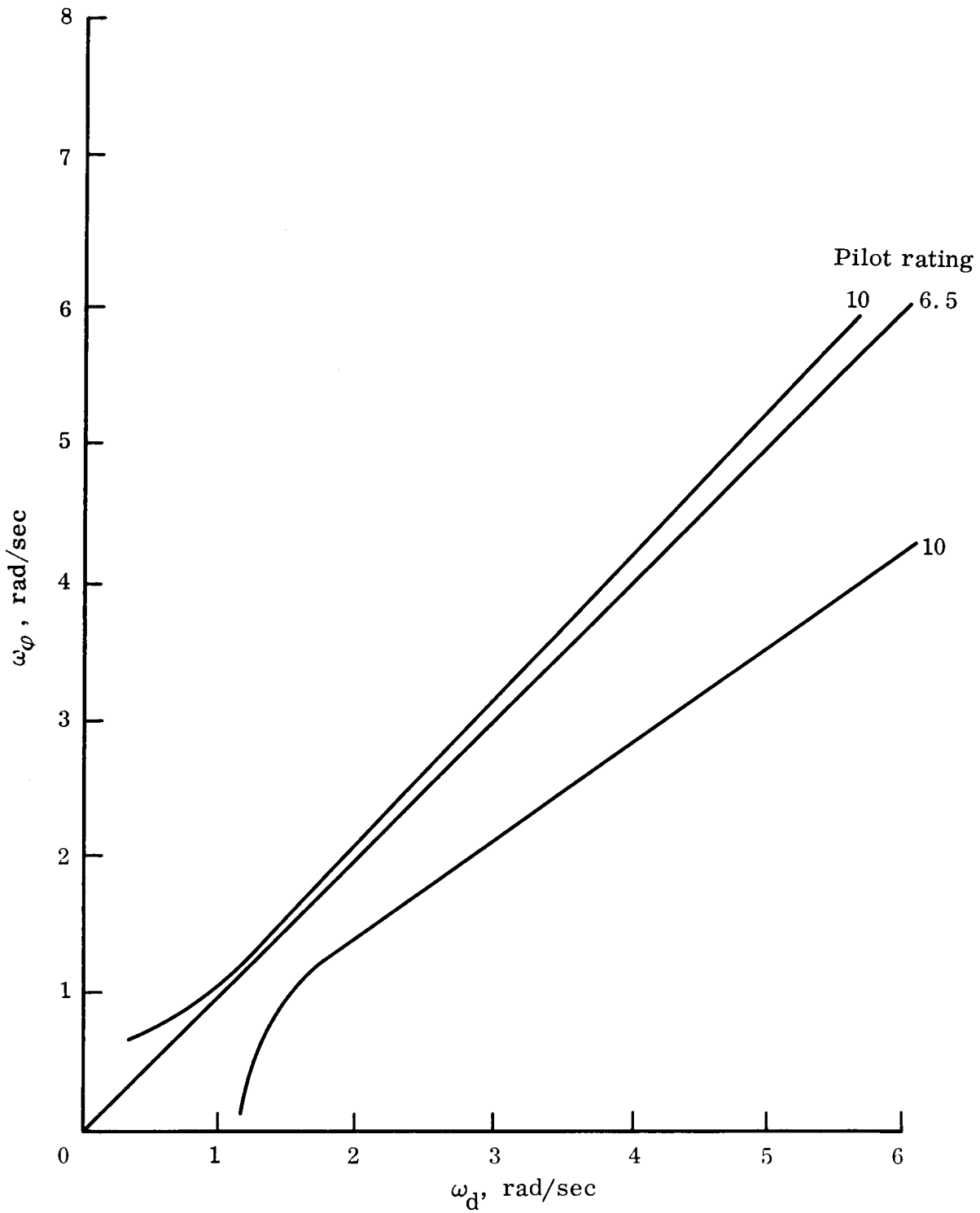
(gg) $L_{\delta_a}\delta_{a_{max}} = 10.0$, $2\zeta_d\omega_d = 0.025$, $\frac{1}{\tau_r} = 0.1$, $\left|L^*_\beta\right| = 100.$

Figure 3.– Continued.



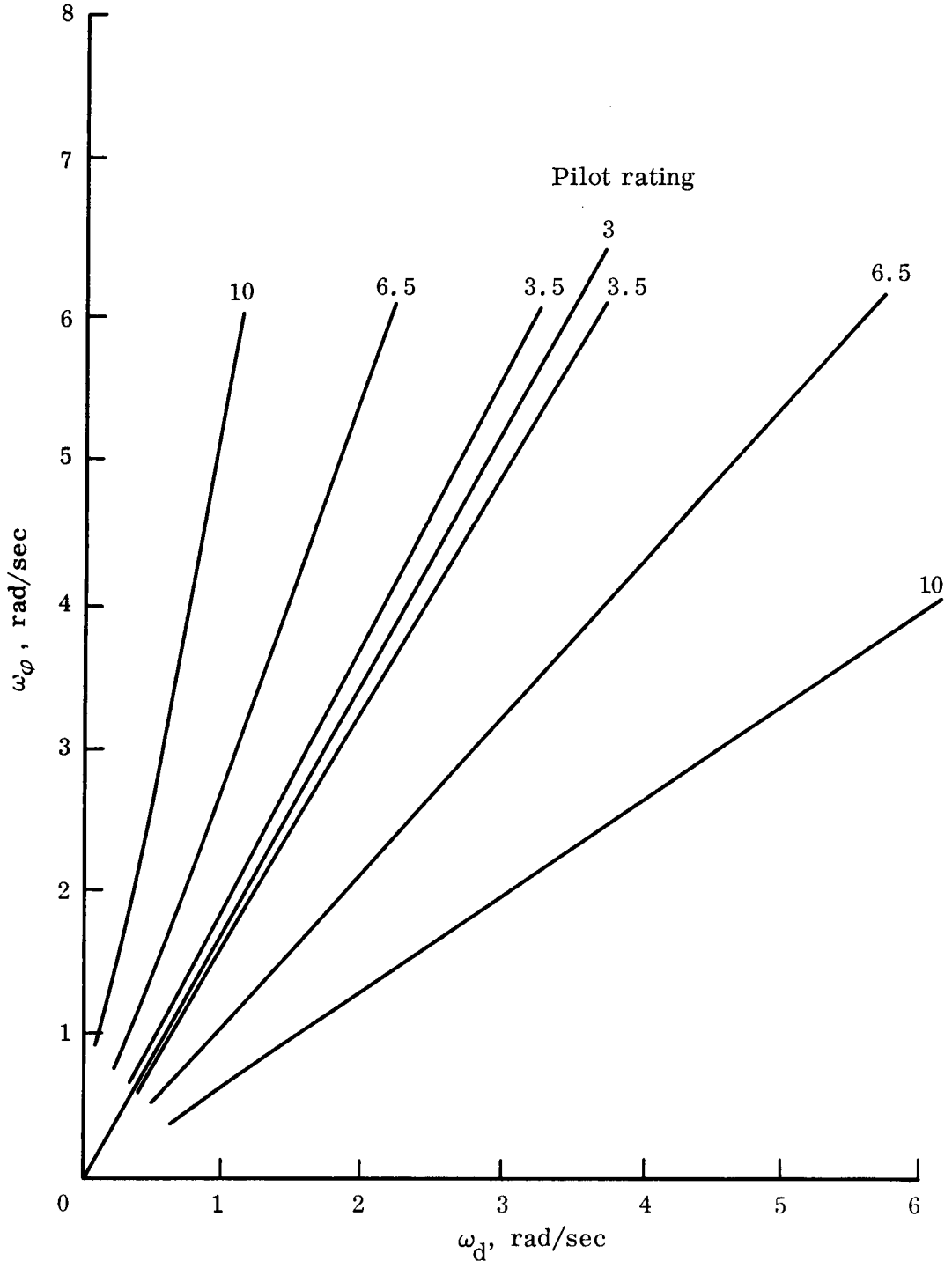
(hh) $L_{\delta_a}\delta a_{max} = 30.0$, $2\zeta_d\omega_d = 0.025$, $\frac{1}{\tau_r} = 0.1$, $\left|L^*_\beta\right| = 100.$

Figure 3.– Continued.



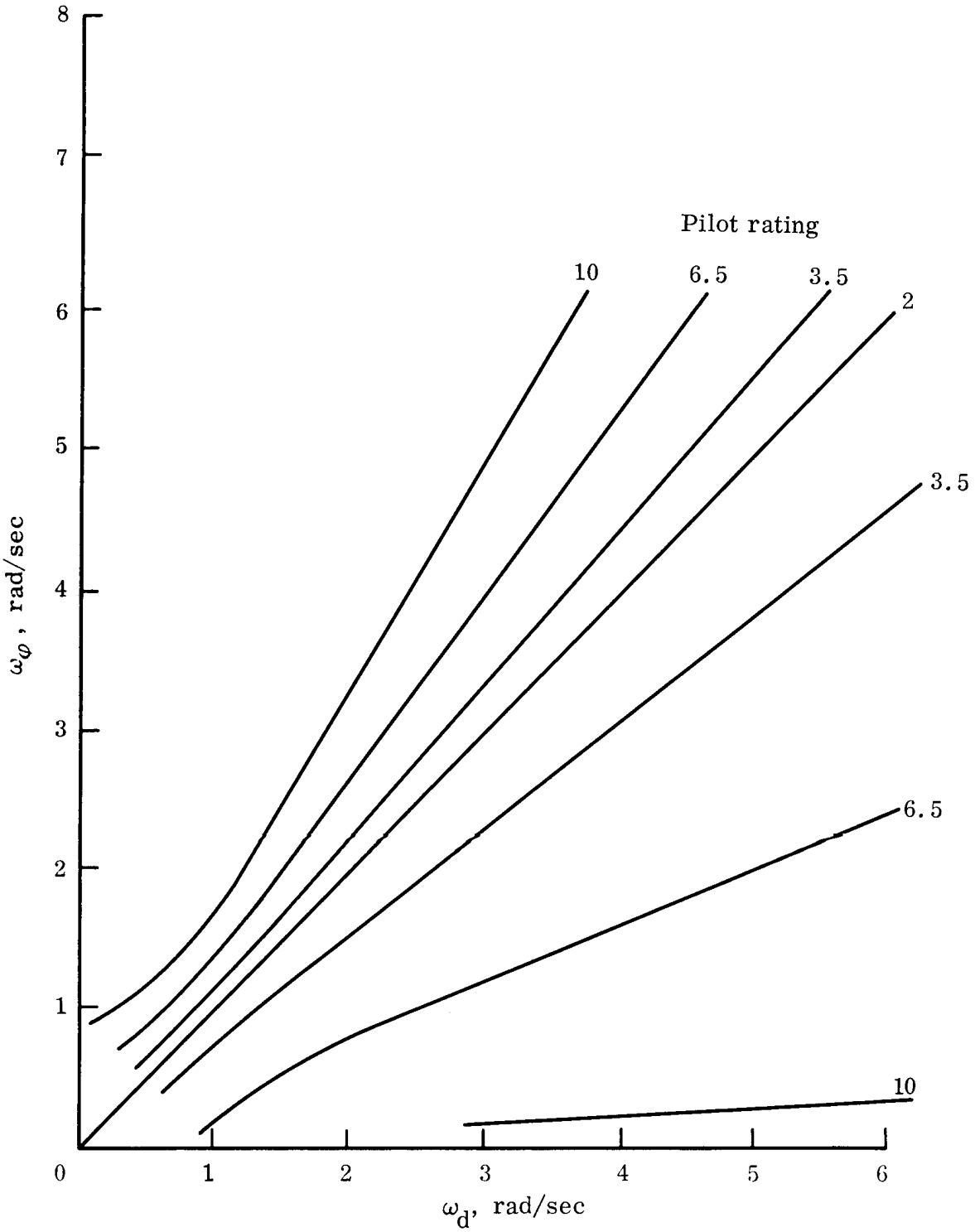
(ii) $L_{\delta_a}\delta_{a_{max}} = 100.0$, $2\zeta_d\omega_d = 0.025$, $\frac{1}{\tau_r} = 0.1$, $\left|L^*_\beta\right| = 100.$

Figure 3.– Continued.



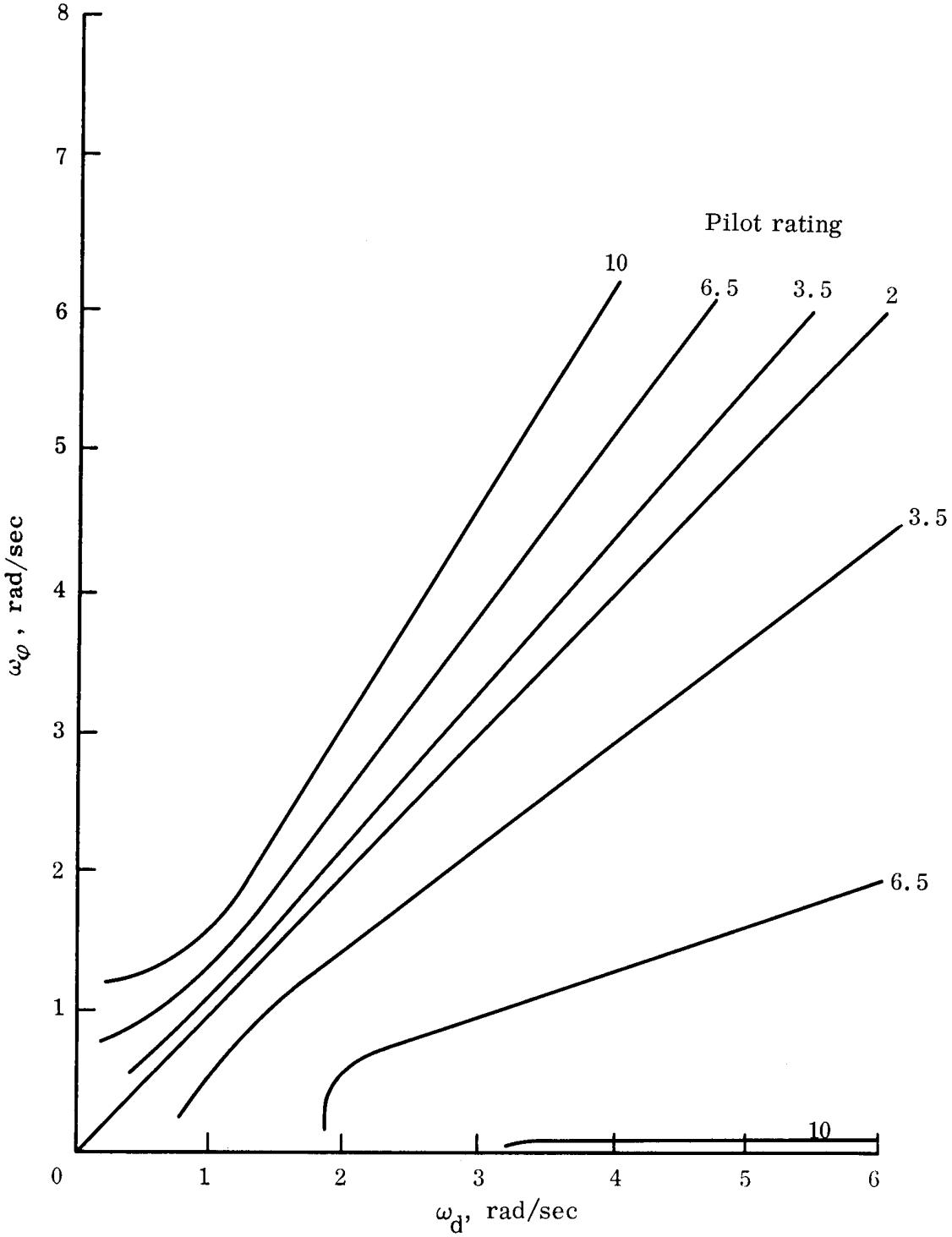
(jj) $L_{\delta_a}\delta_{a_{max}} = 0.1,\ 2\zeta_d\omega_d = 0.25,\ \frac{1}{\tau_r} = 1.0,\ \left|L^*_\beta\right| = 100.$

Figure 3.– Continued.



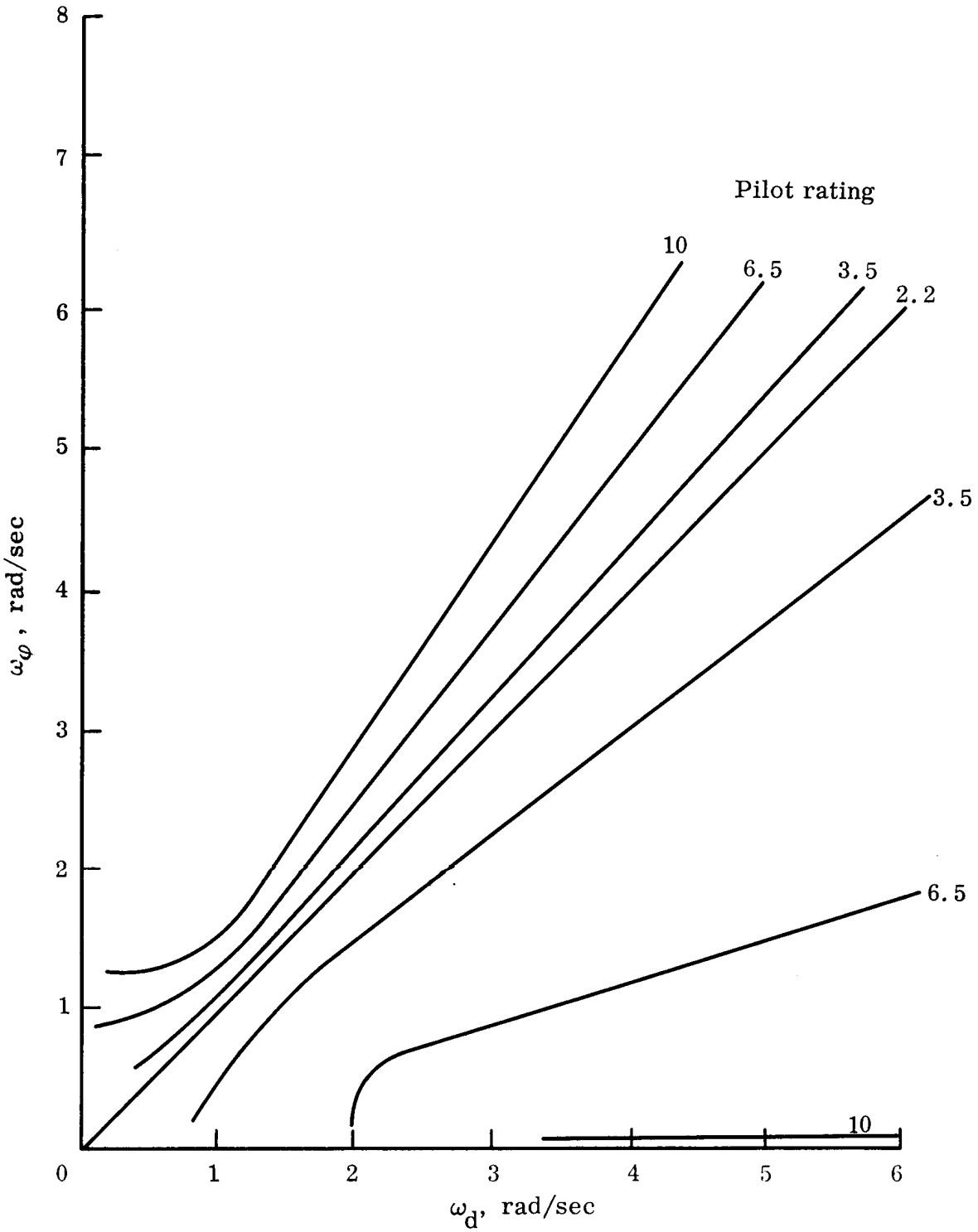
(kk) $L_{\delta_a}\delta_{a_{max}} = 3.0,\ 2\zeta_d\omega_d = 0.25,\ \frac{1}{\tau_r} = 1.0,\ \left|L^*_\beta\right| = 100.$

Figure 3.– Continued.



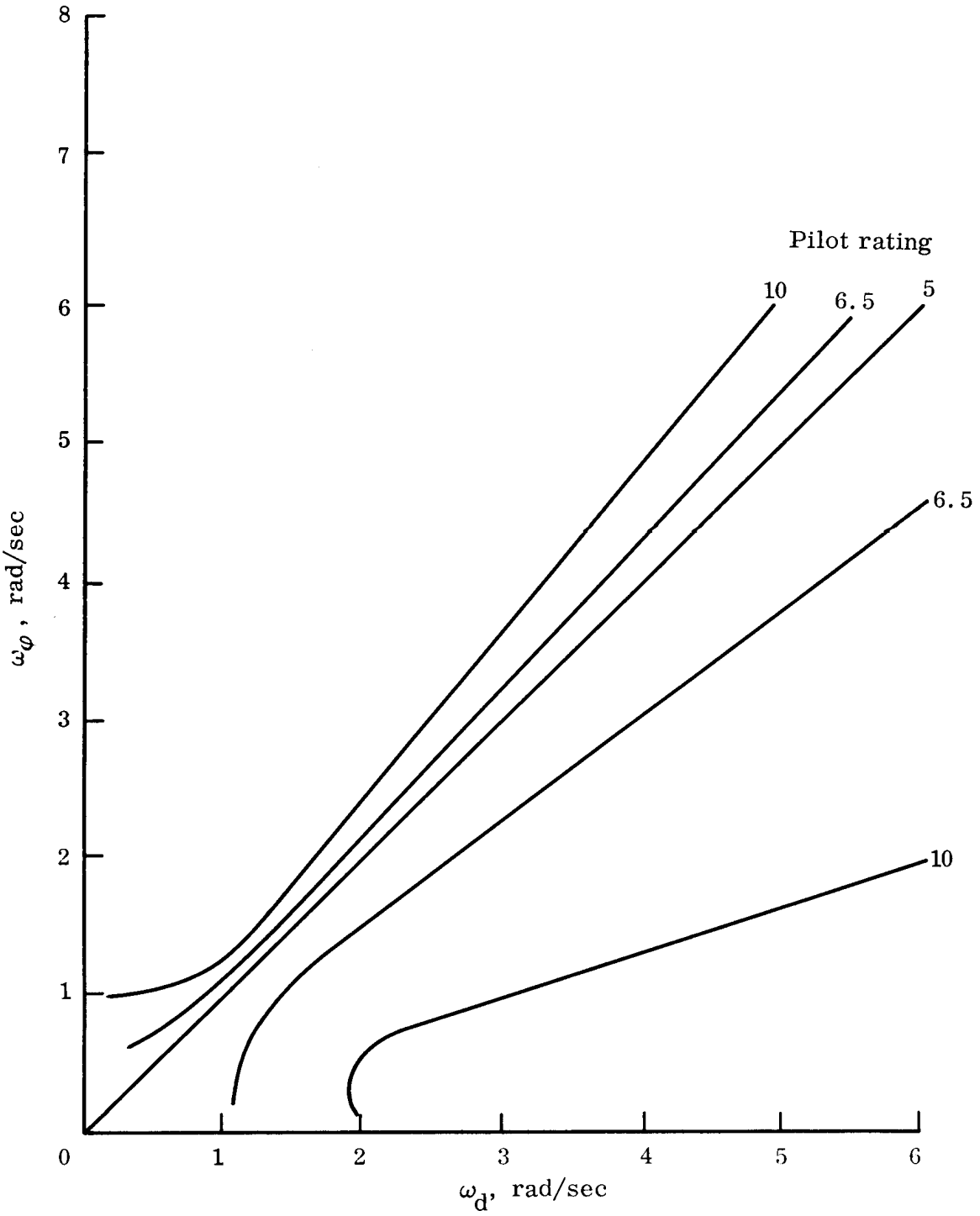
(*ll*) $L_{\delta_a}\delta_{a_{max}} = 10.0$, $2\zeta_d\omega_d = 0.25$, $\frac{1}{\tau_r} = 1.0$, $\left|L^*_\beta\right| = 100.$

Figure 3.– Continued.



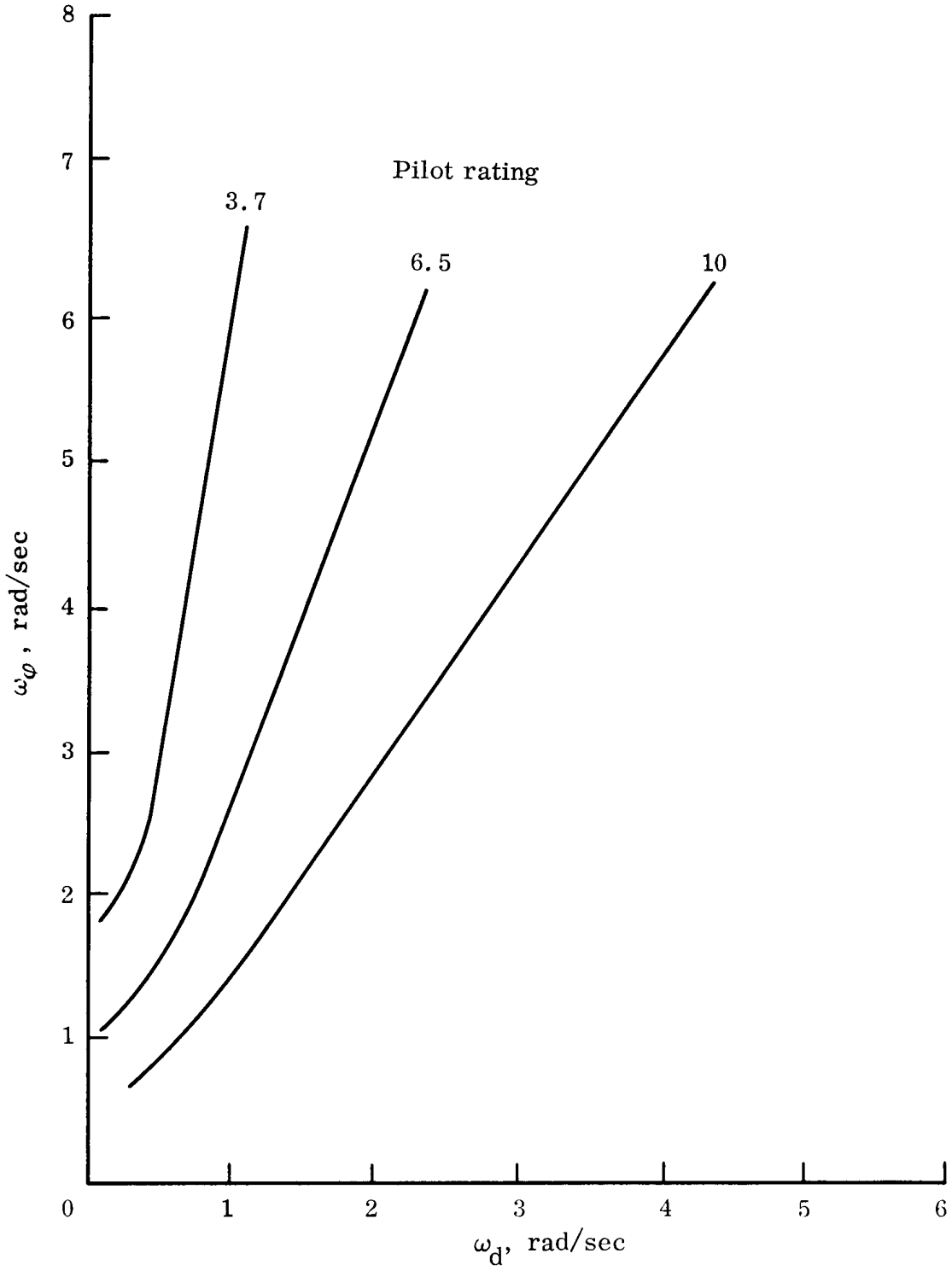
(mm) $L_{\delta_a}\delta_{a_{max}} = 30.0$, $2\zeta_d\omega_d = 0.25$, $\frac{1}{\tau_r} = 1.0$, $\left|L^*_\beta\right| = 100.$

Figure 3. – Continued.



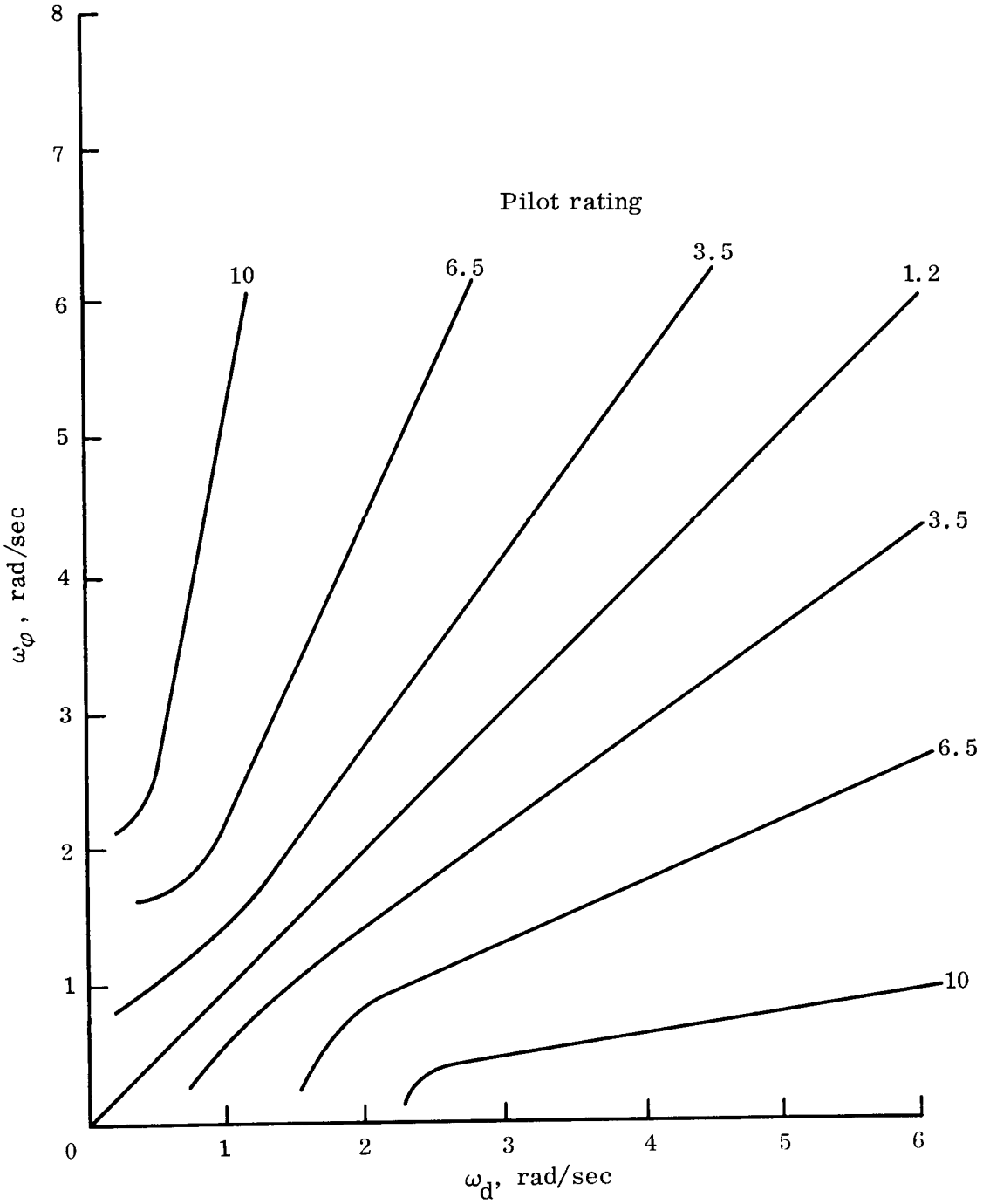
(nn) $L_{\delta_a}\delta_{a_{max}} = 100.0$, $2\zeta_d\omega_d = 0.25$, $\frac{1}{\tau_r} = 1.0$, $\left|L^*_\beta\right| = 100.$

Figure 3.– Continued.



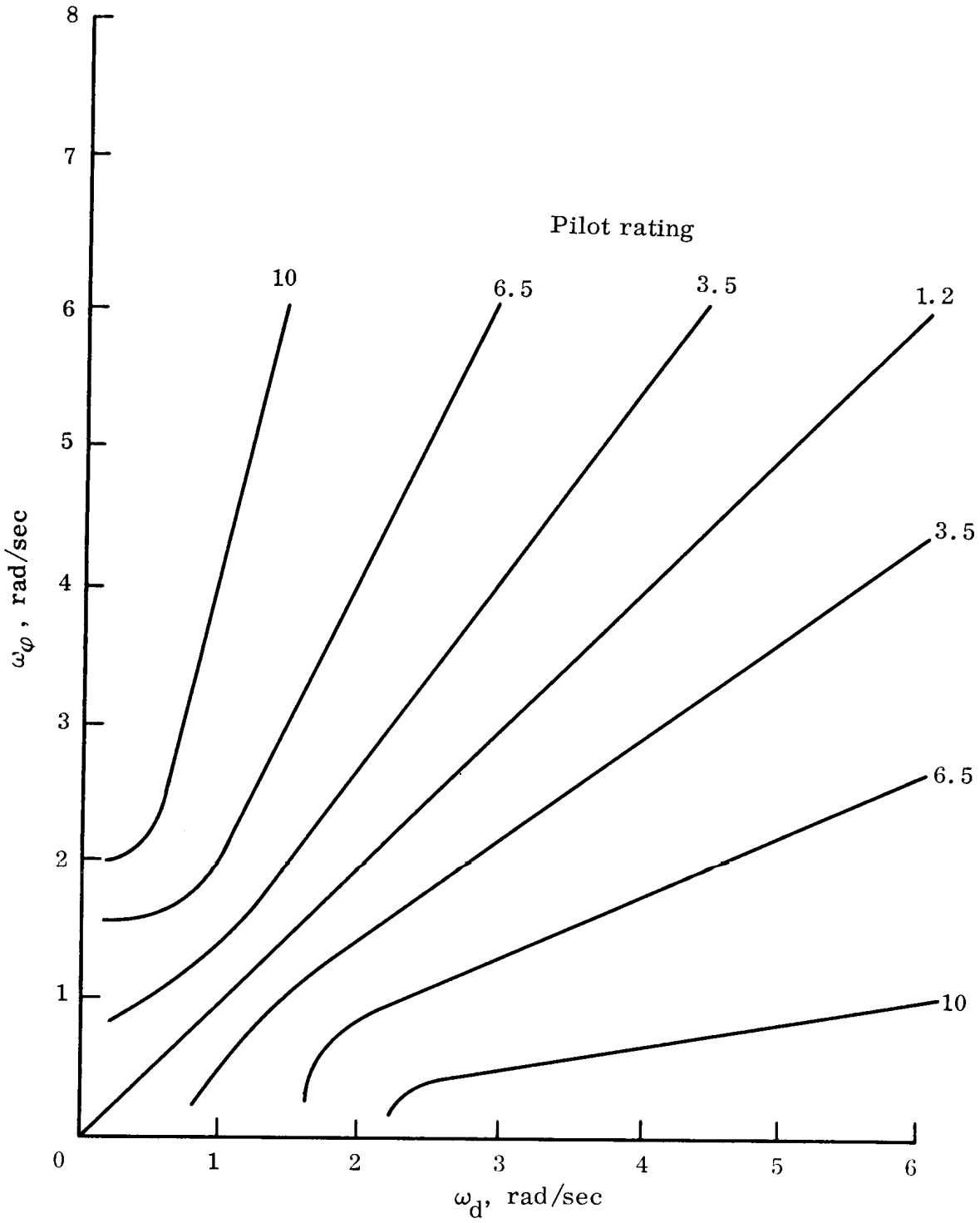
(oo) $L_{\delta_a}\delta_{a_{max}} = 0.1,\ 2\zeta_d\omega_d = 1.0,\ \frac{1}{\tau_r} = 4.0,\ \left|L^*_\beta\right| = 100.$

Figure 3. – Continued.



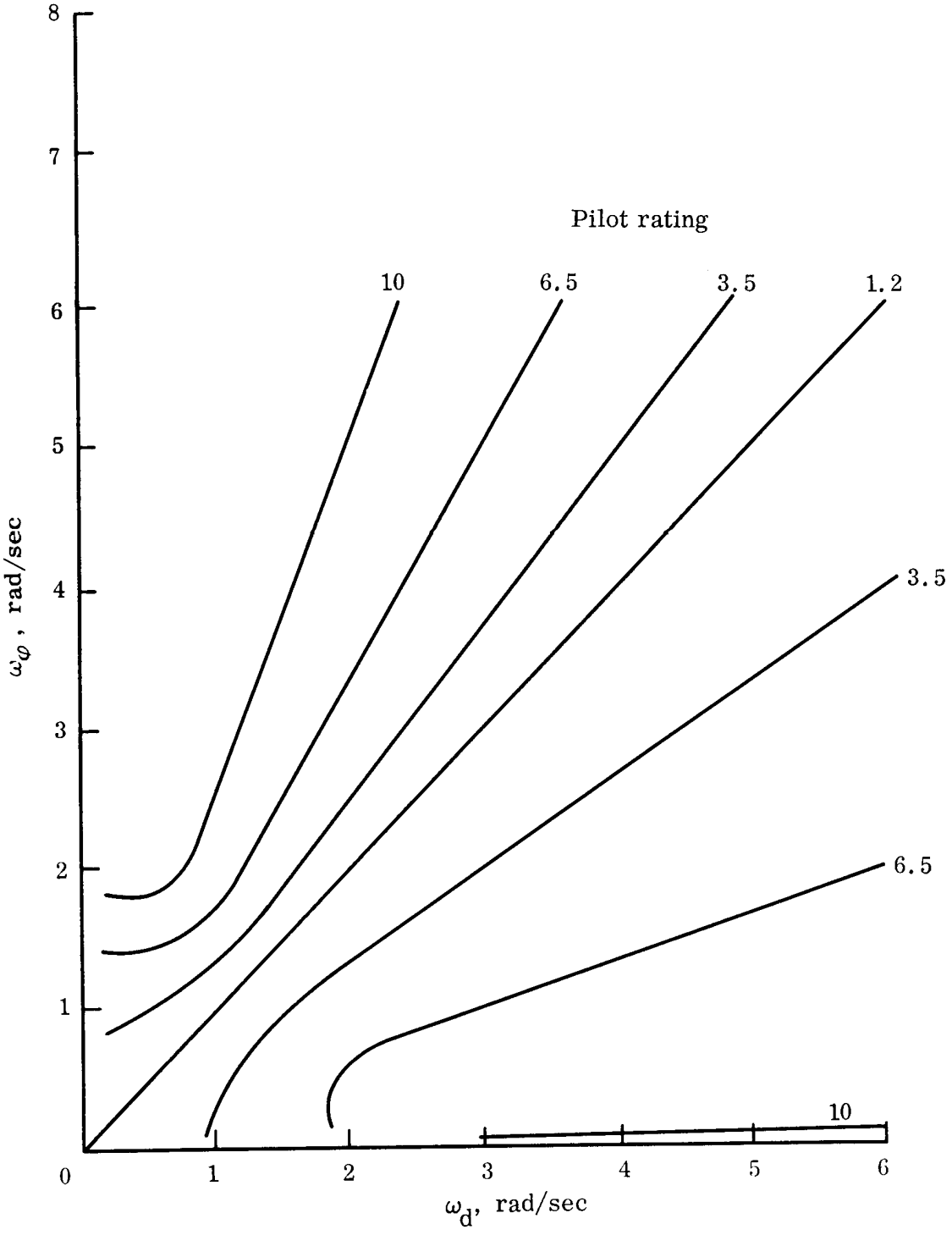
(pp) $L_{\delta_a}\delta_{a_{max}} = 3.0$, $2\zeta_d\omega_d = 1.0$, $\frac{1}{\tau_r} = 4.0$, $\left|L^*_\beta\right| = 100.$

Figure 3.– Continued.



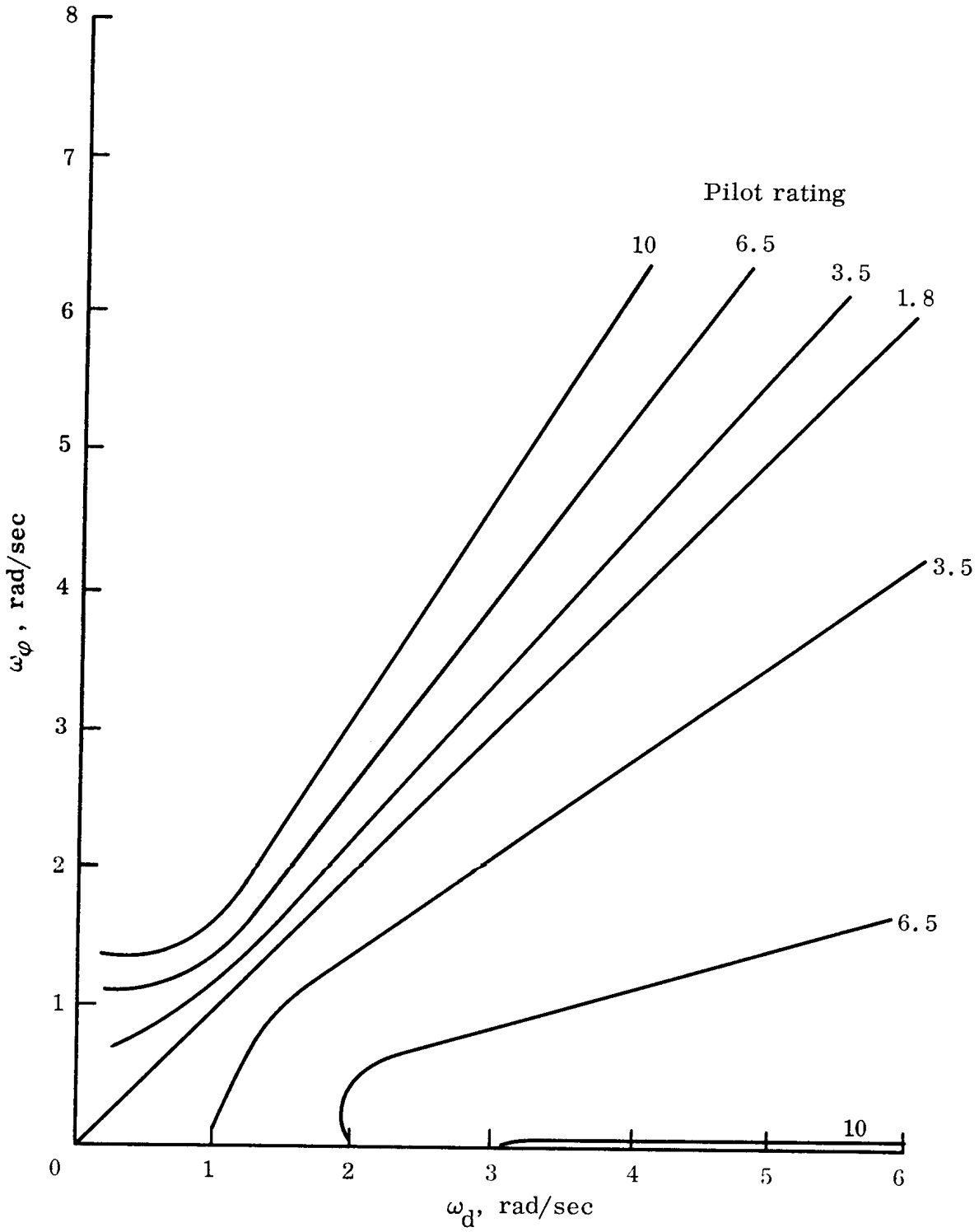
(qq) $L_{\delta_a}\delta_{a_{max}} = 10.0$, $2\zeta_d\omega_d = 1.0$, $\frac{1}{\tau_r} = 4.0$, $\left|L_\beta^*\right| = 100.$

Figure 3.– Continued.



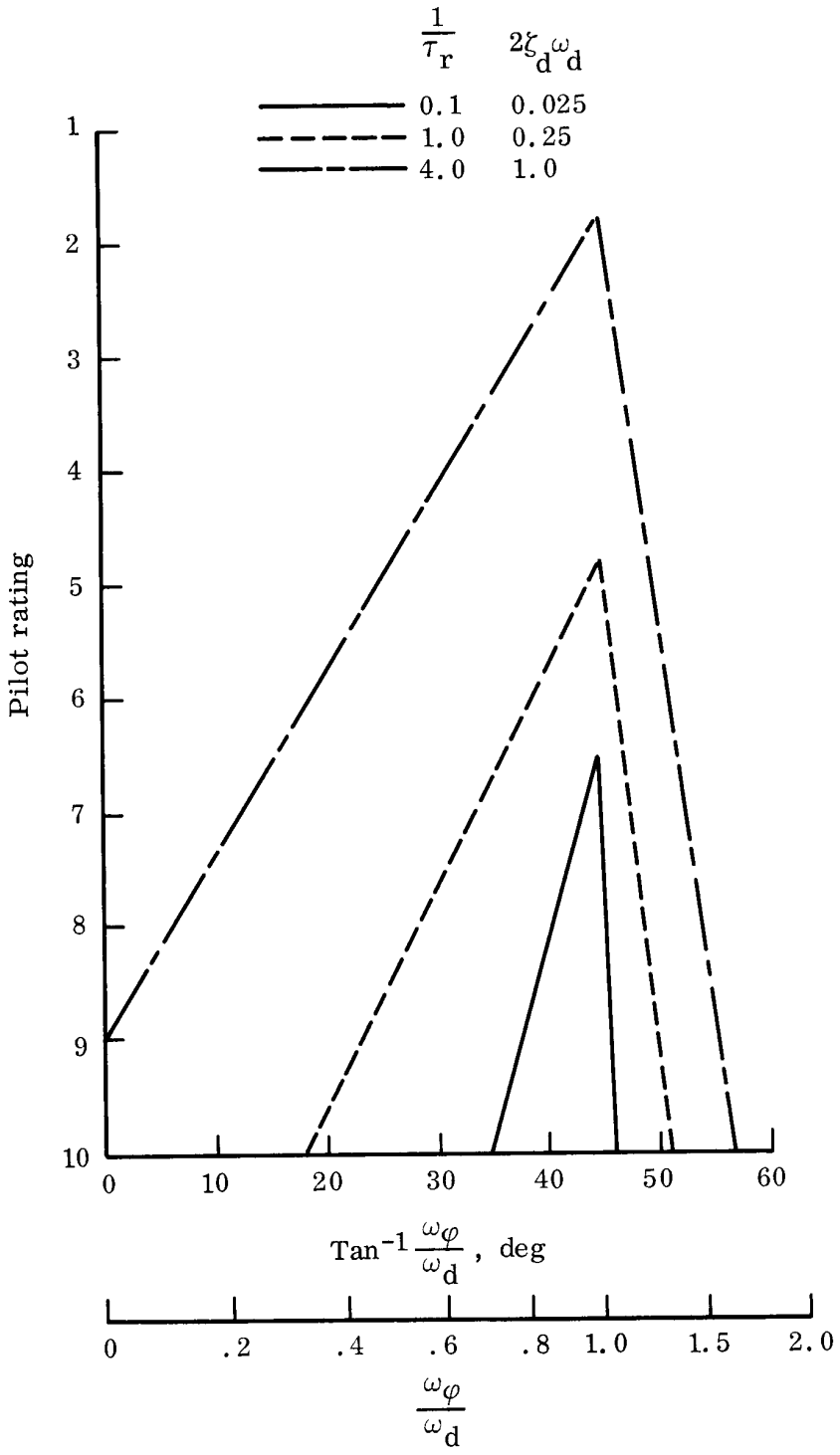
(rr) $L_{\delta_a}\delta_{a_{max}} = 30.0$, $2\zeta_d\omega_d = 1.0$, $\frac{1}{\tau_r} = 4.0$, $\left|L_\beta^*\right| = 100.$

Figure 3. – Continued.



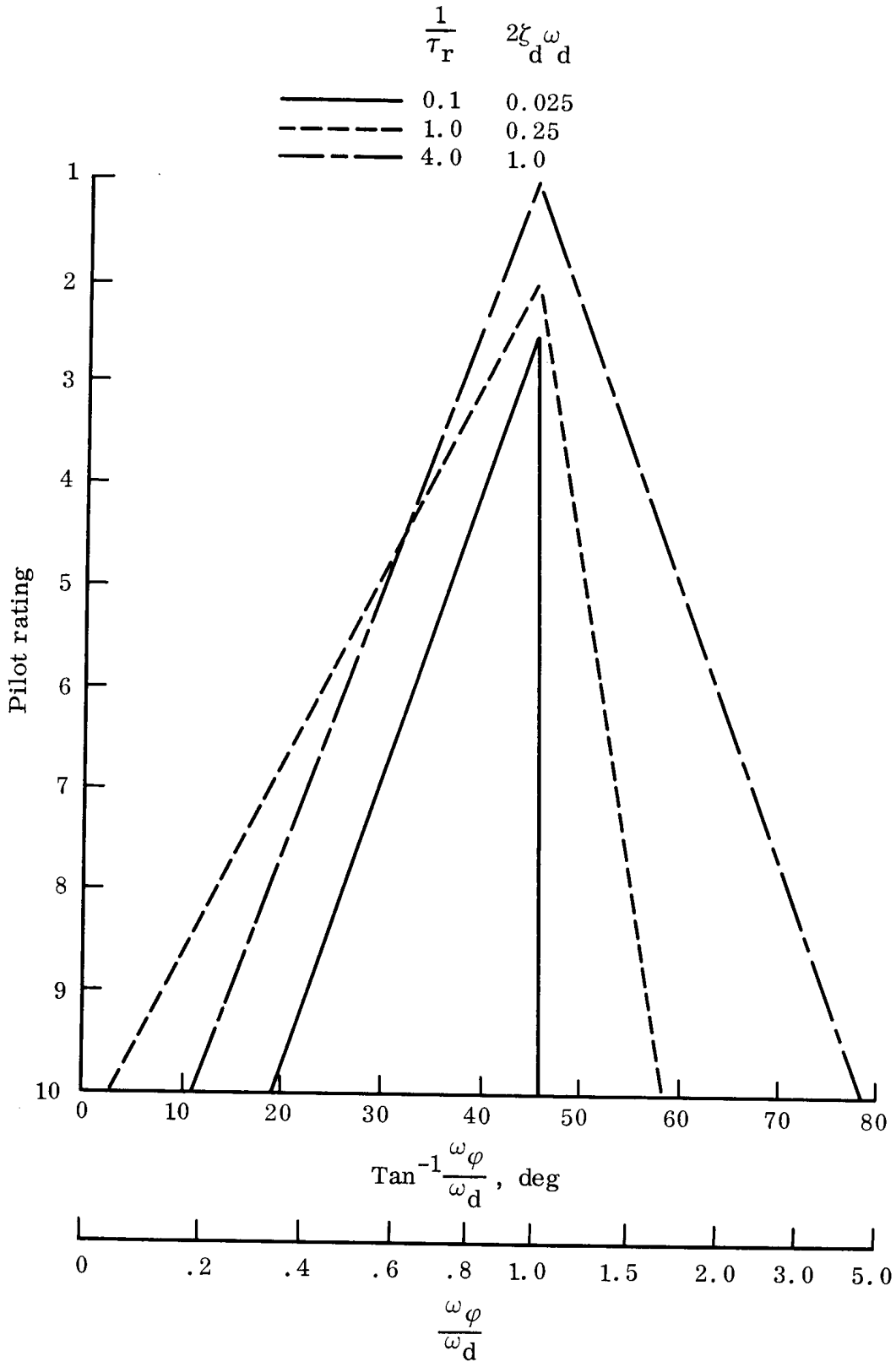
(ss) $L_{\delta_a}\delta_{a_{max}} = 100.0$, $2\zeta_d\omega_d = 1.0$, $\frac{1}{\tau_r} = 4.0$, $\left|L^*_\beta\right| = 100.$

Figure 3.—Concluded.



(a) $\left|L^*_\beta\right| = 30$, $L_{\delta_a}\delta_{a_{max}} = 100$, $\omega_\varphi + \omega_d > 3.0$.

Figure 4.– Effect of damping on pilot ratings.



(b) $\left|L_\beta^*\right| = 10$, $L_{\delta_a}\delta_{a_{max}} = 3$, $\omega_\varphi + \omega_d > 3.0$.

Figure 4.—Concluded.

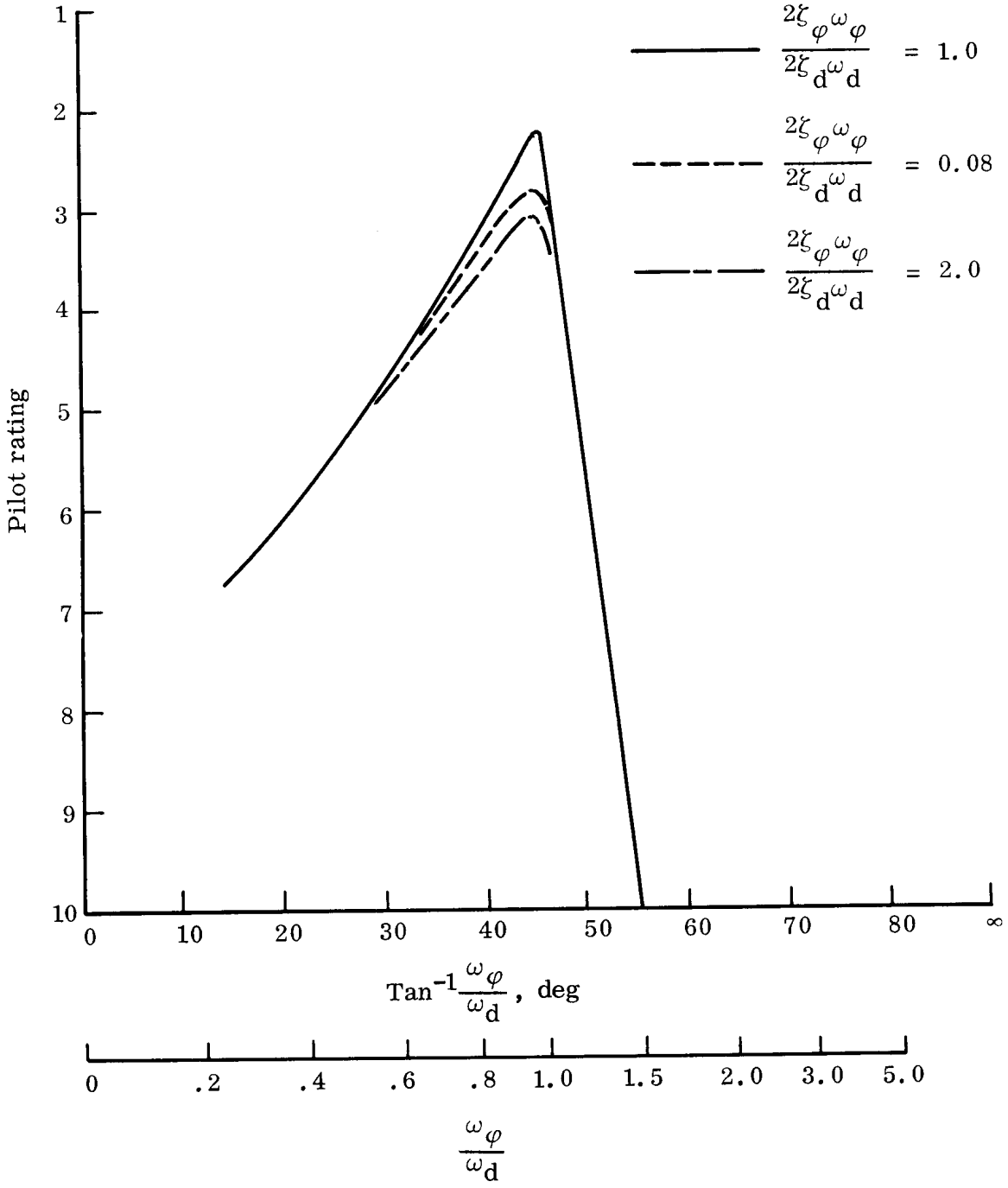


Figure 5.– Effect of $\frac{2\zeta_\varphi\omega_\varphi}{2\zeta_d\omega_d}$ on pilot ratings. $\left|L^*_\beta\right| = 30$; $\frac{1}{\tau_r} = 1.0$; $L_{\delta_a}\delta_{a_{max}} = 10$; $\omega_\varphi + \omega_d = 3.0$; $2\zeta_d\omega_d = 0.25$.

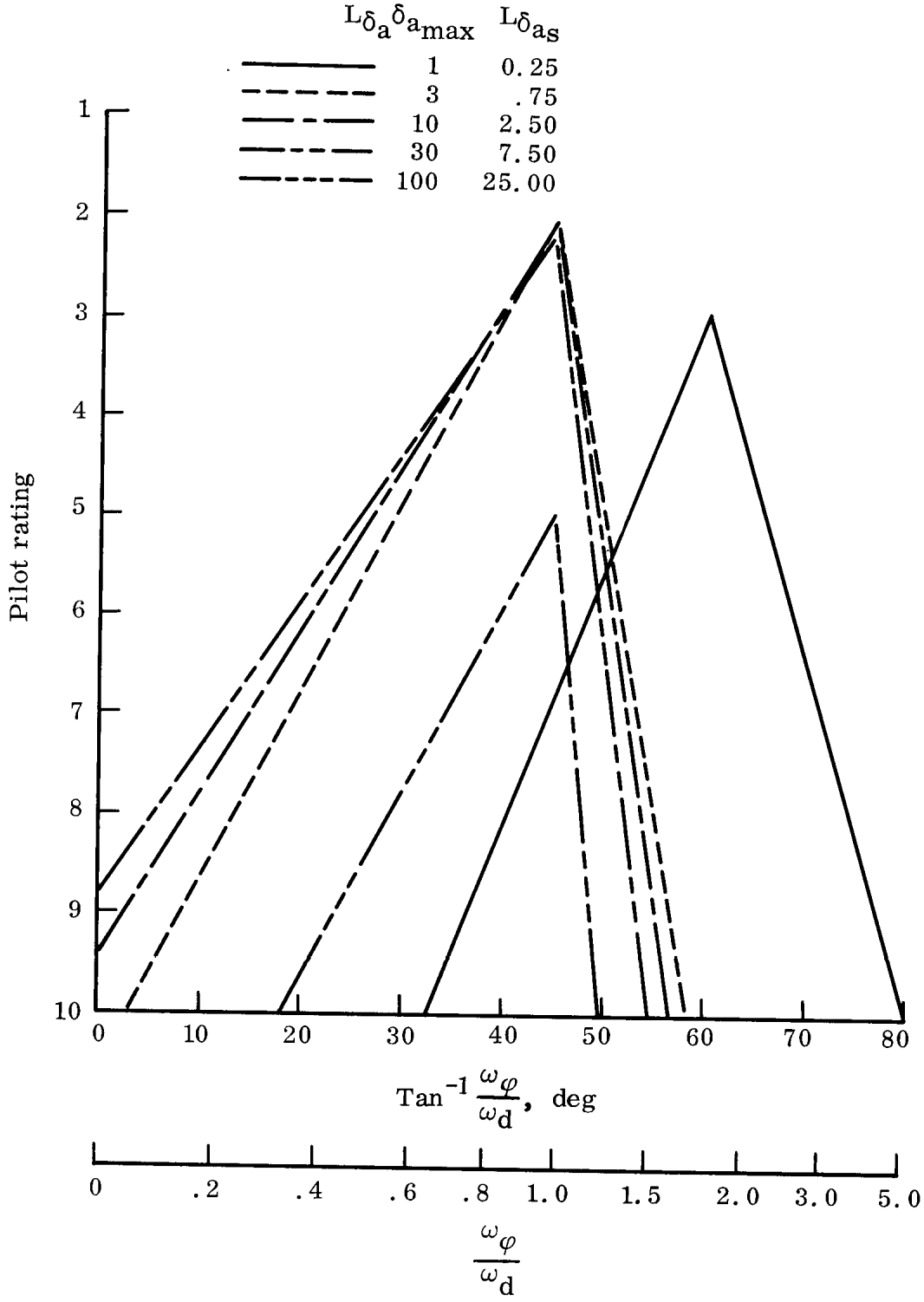


Figure 6.– Effect of aileron control power or sensitivity on pilot ratings.

$$\left|L_\beta^*\right| = 30;\ 2\zeta_d\omega_d = 0.25;\ \frac{1}{\tau_r} = 1.0;$$

$$\omega_\varphi + \omega_d = 3.0.$$

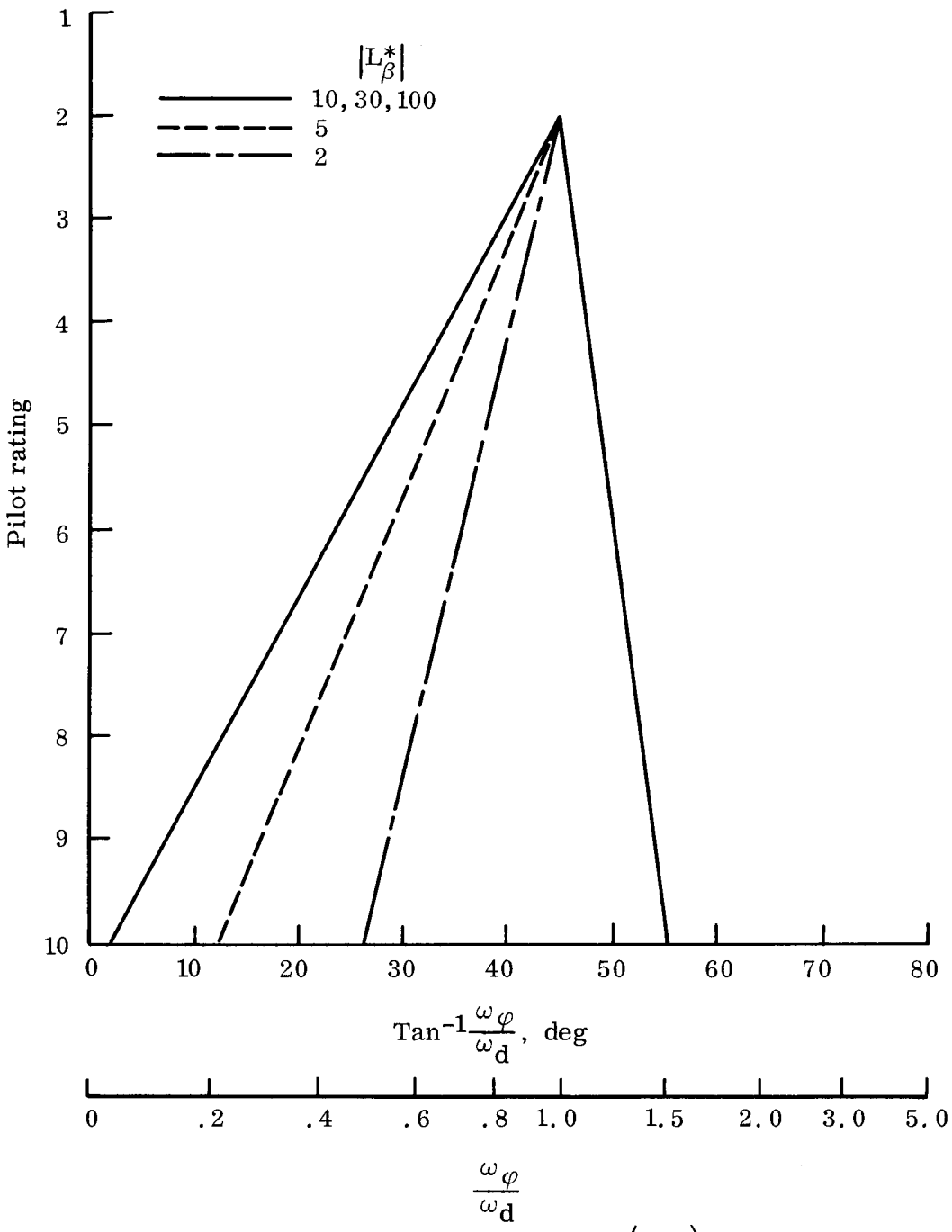
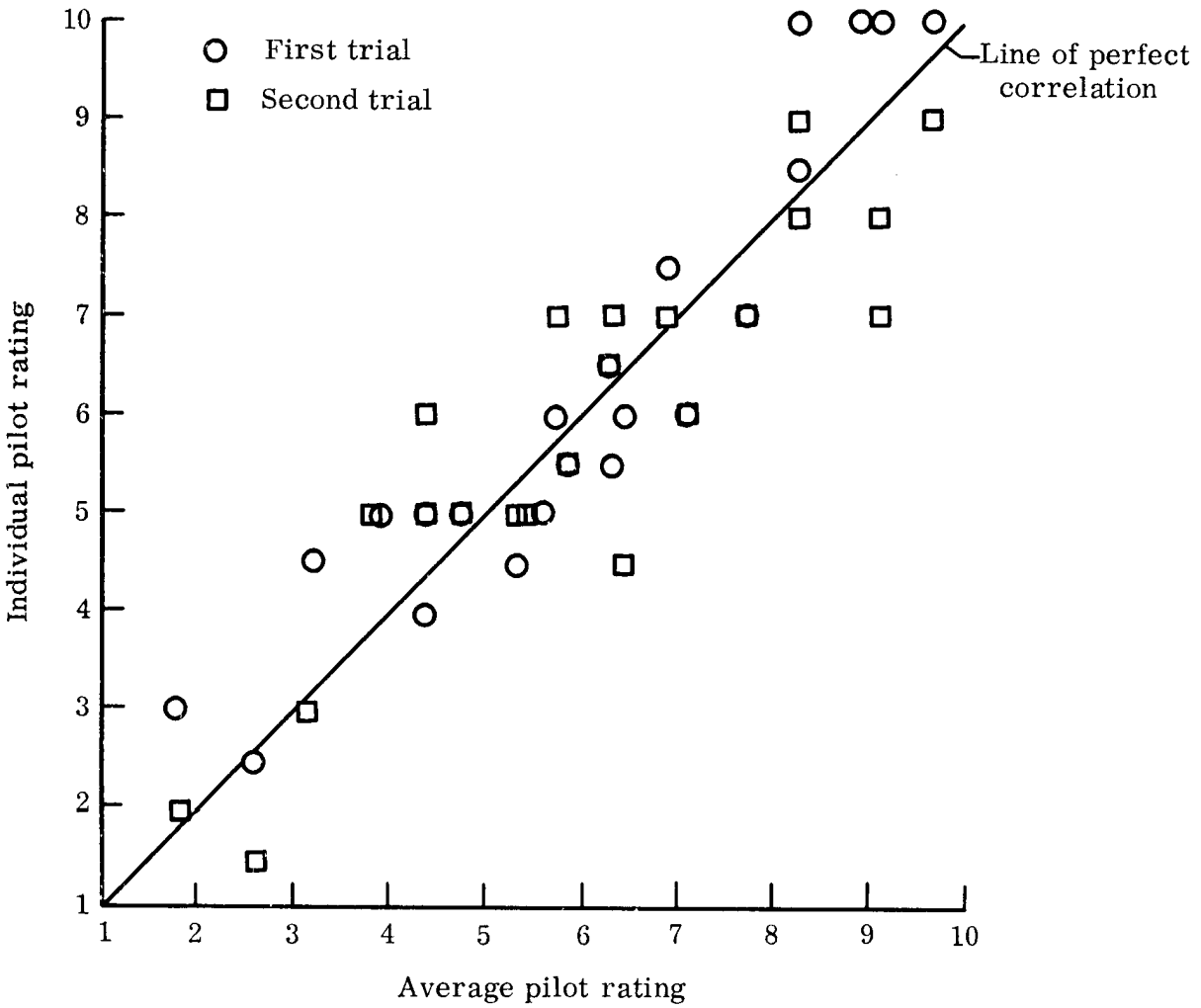


Figure 7.– Effect of aileron-induced sideslip $\left(\frac{1}{|L^*_\beta|}\right)$ on pilot ratings.

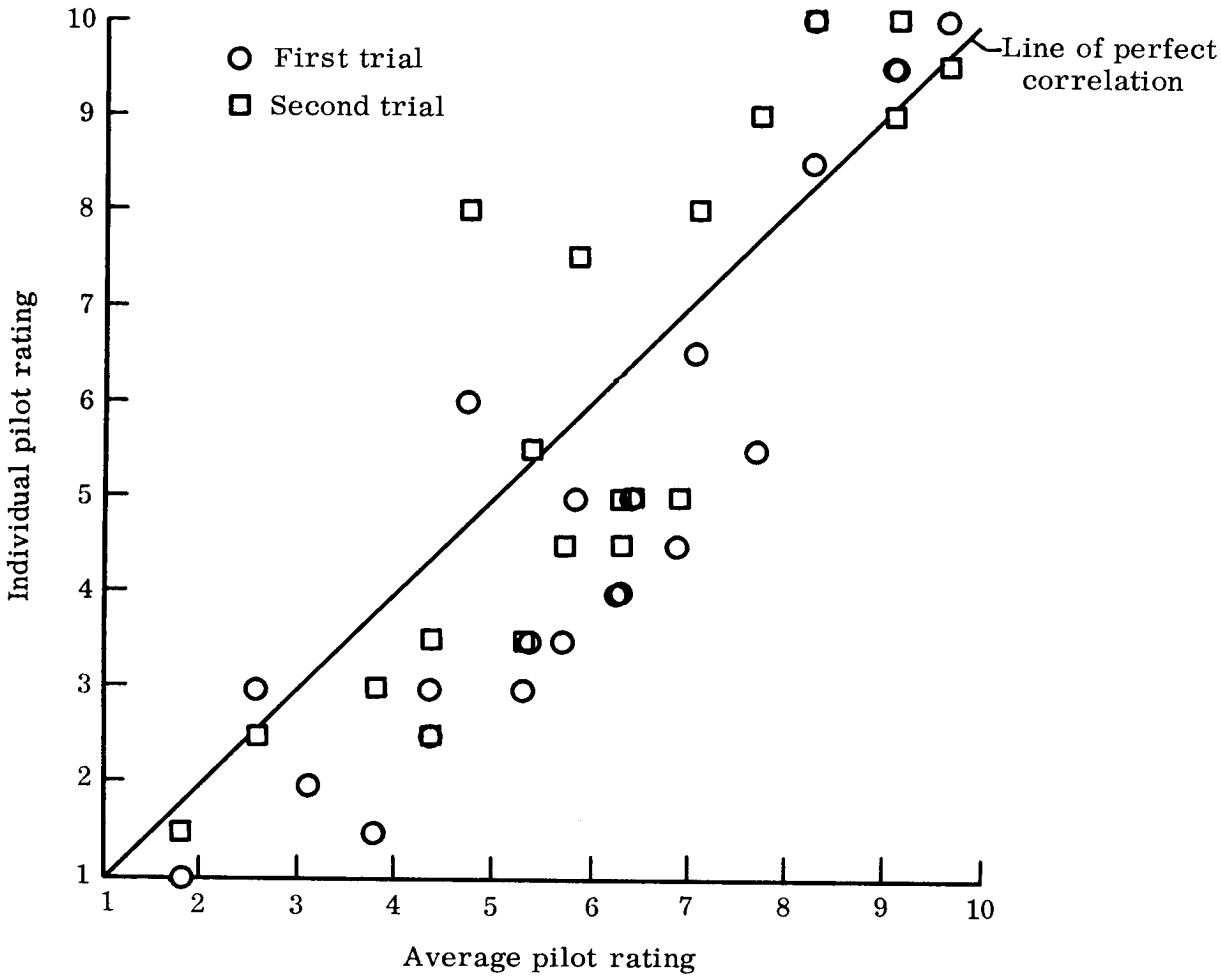
$L_{\delta_a}\delta a_{max} = 10$, $2\zeta_d\omega_d = 0.25$, $\frac{1}{\tau_r} = 1.0$,

$\omega_\varphi + \omega_d = 3.0$.



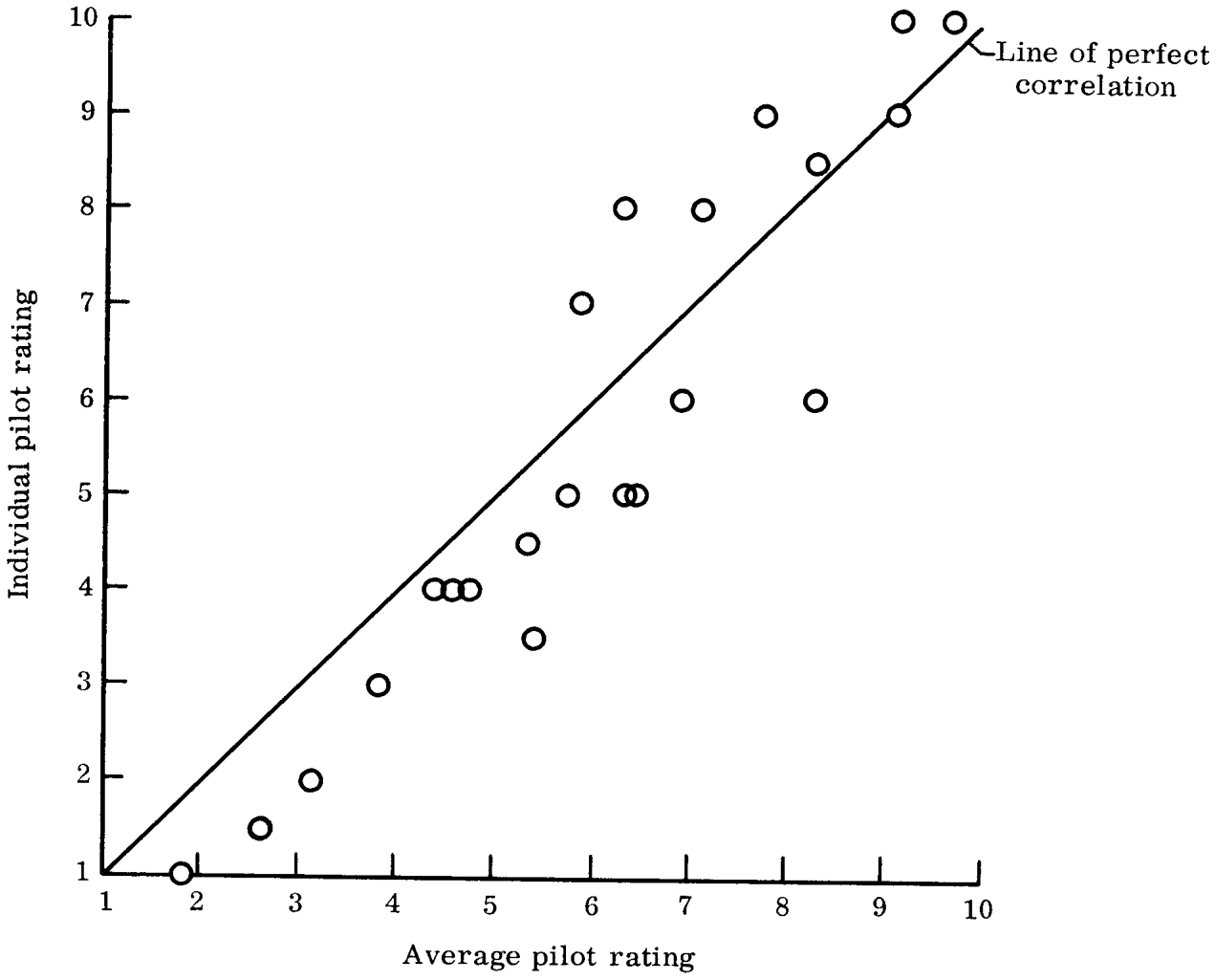
(a) Pilot A, $\sigma = 0.88$.

Figure 8. – Correlation of individual pilot ratings with actual pilot average ratings for the general mission.



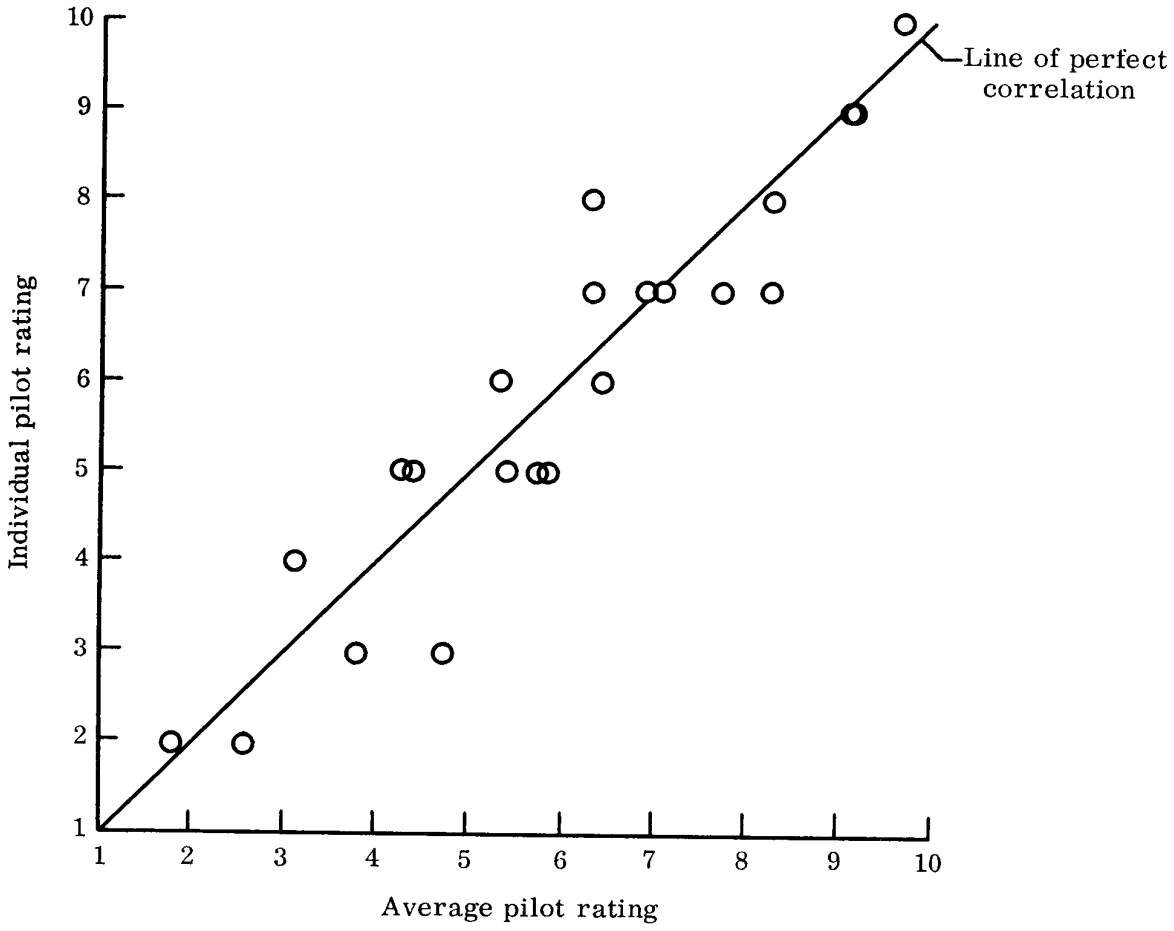
(b) Pilot B, $\sigma = 1.51$.

Figure 8.– Continued.



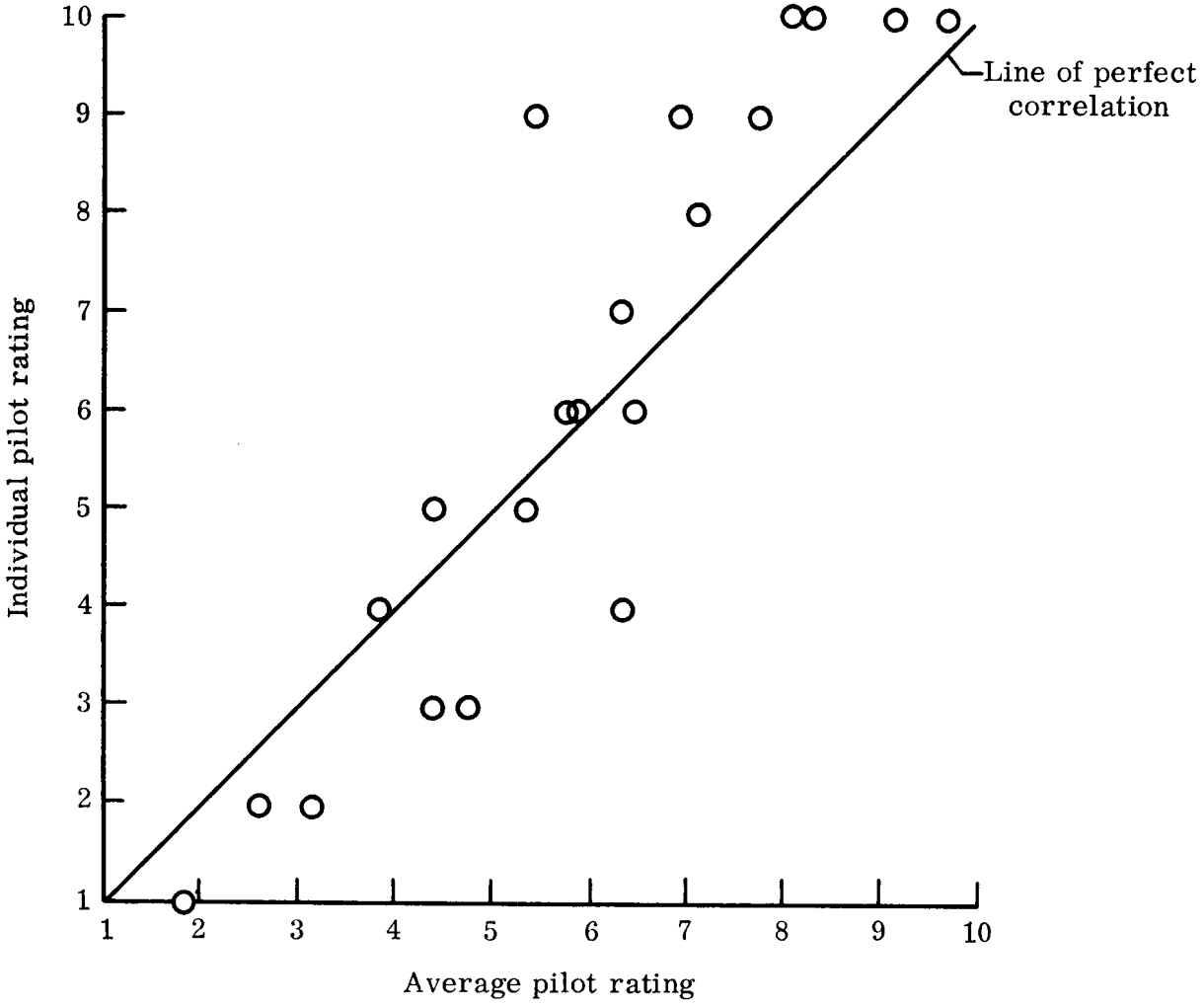
(c) Pilot C, σ = 1.10.

Figure 8.– Continued.



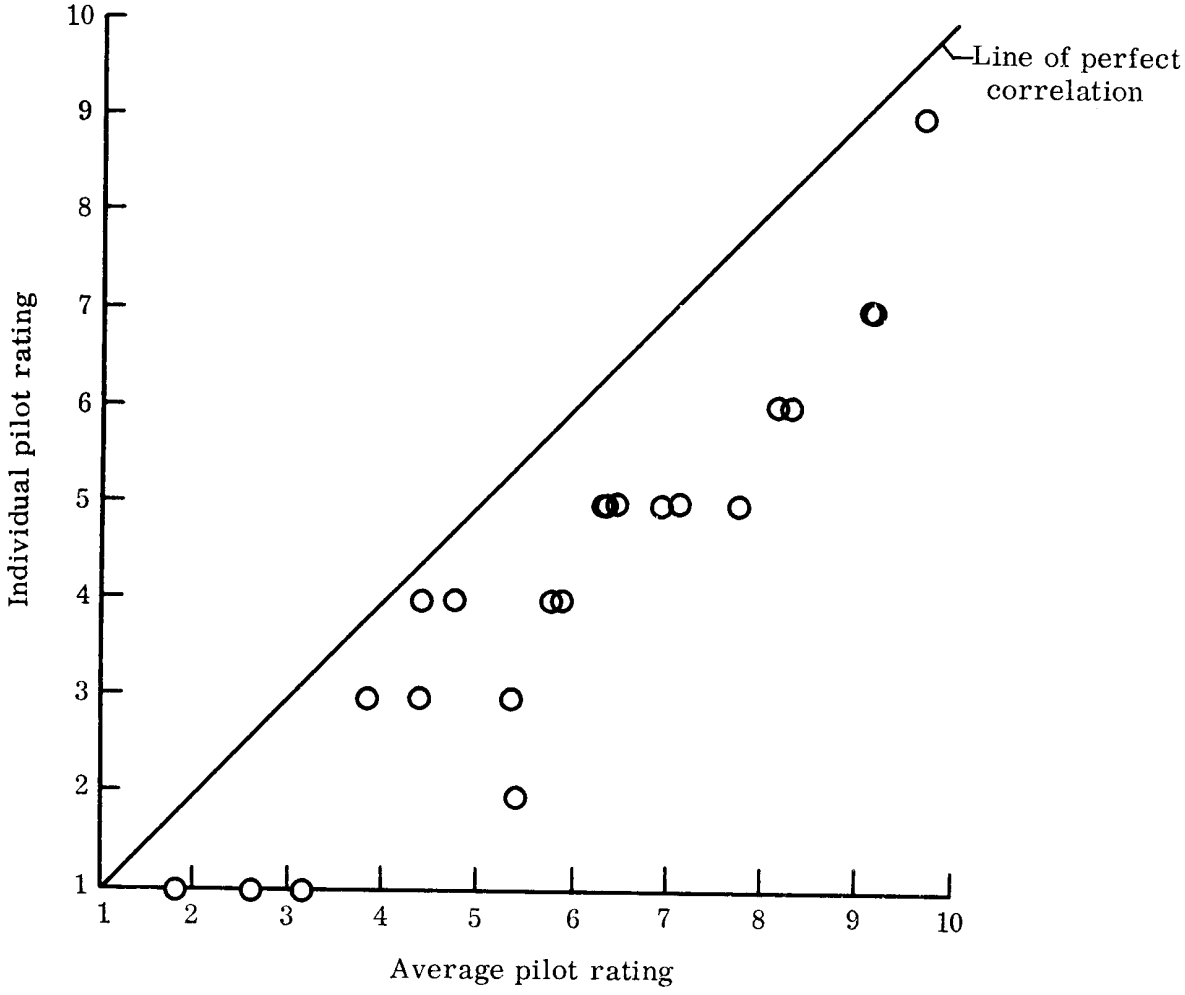
(d) Pilot D, $\sigma = 0.78$.

Figure 8.– Continued.



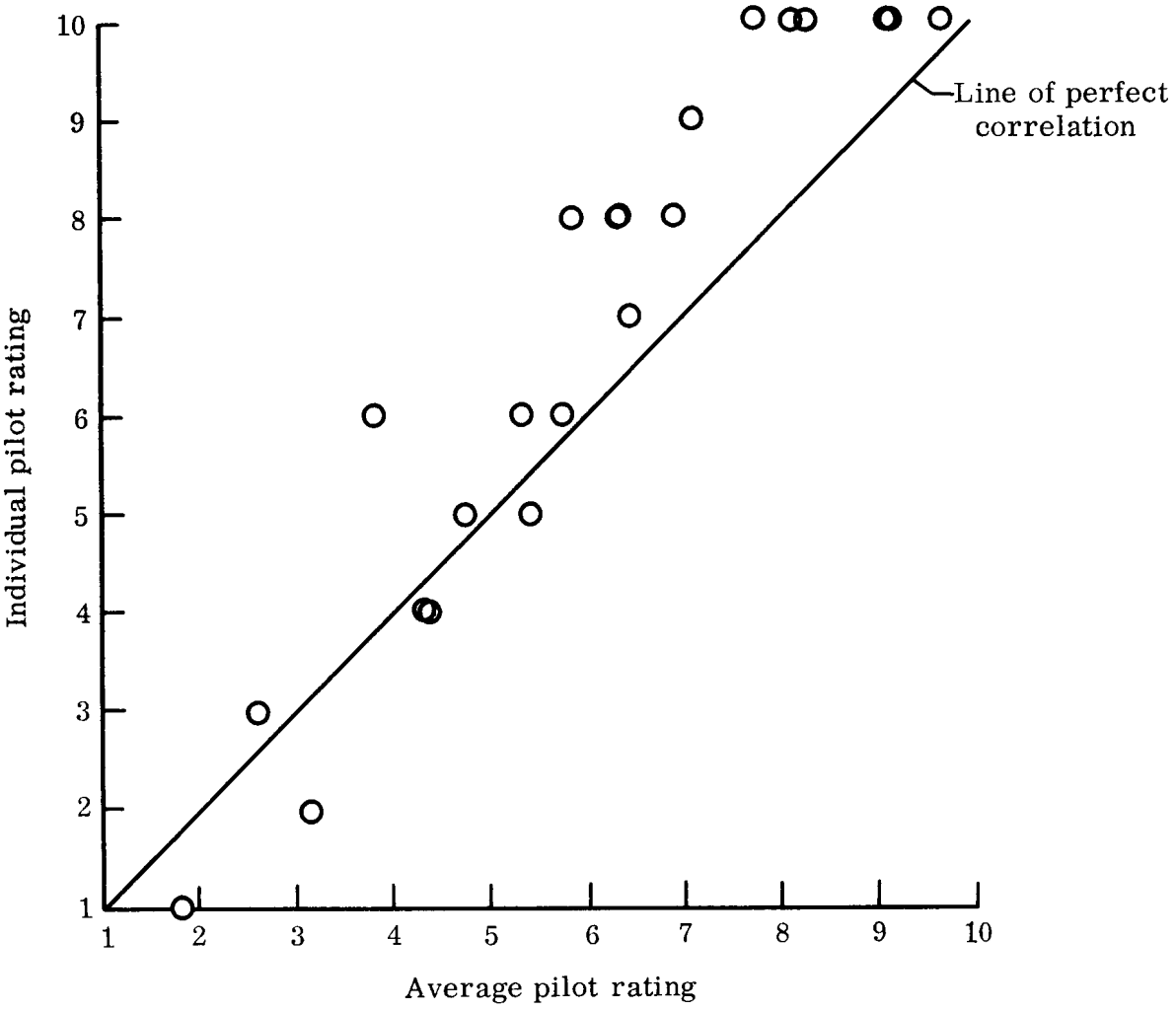
(e) Pilot E, $\sigma = 1.38$.

Figure 8.– Continued.



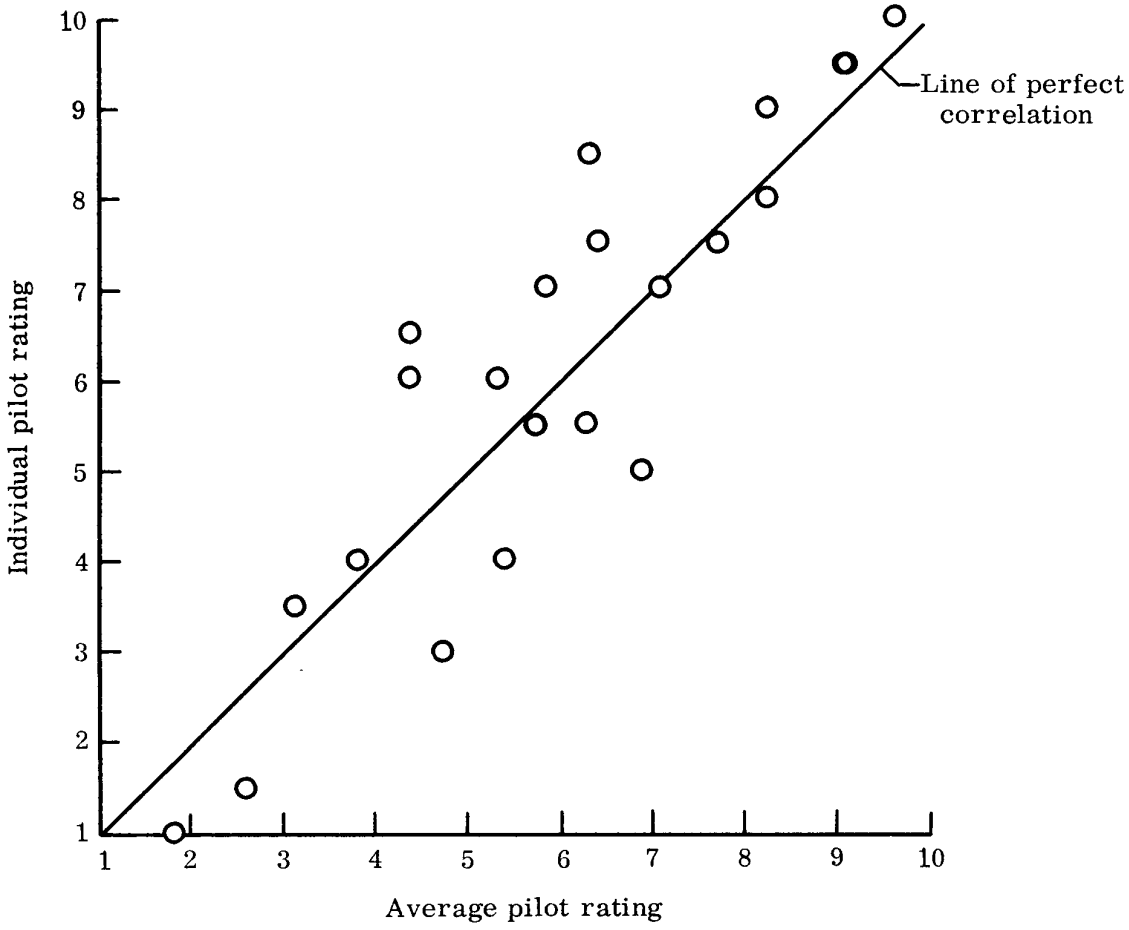
(f) Pilot F, $\sigma = 1.83$.

Figure 8. – Continued.



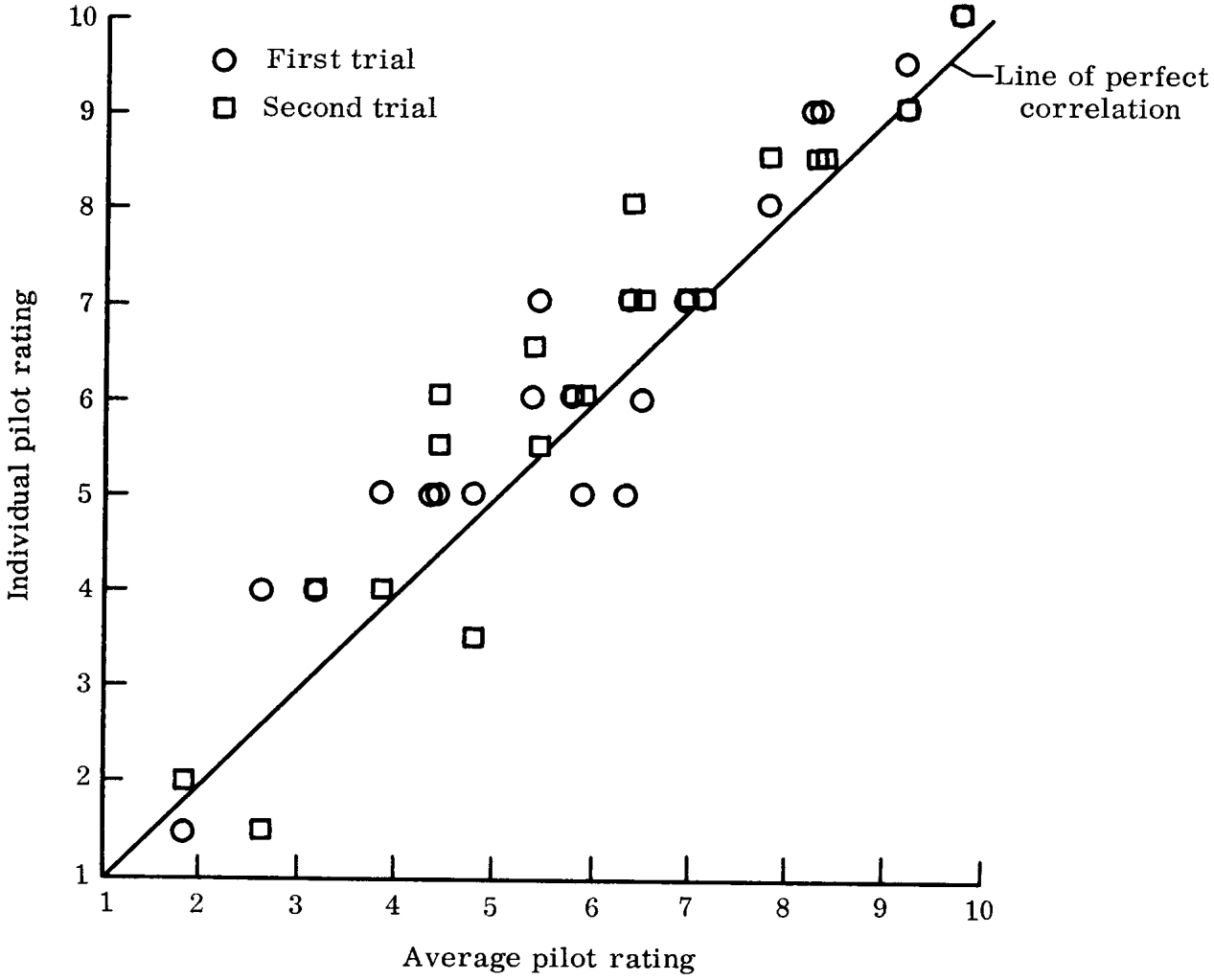
(g) Pilot G, $\sigma = 1.30$.

Figure 8. – Continued.



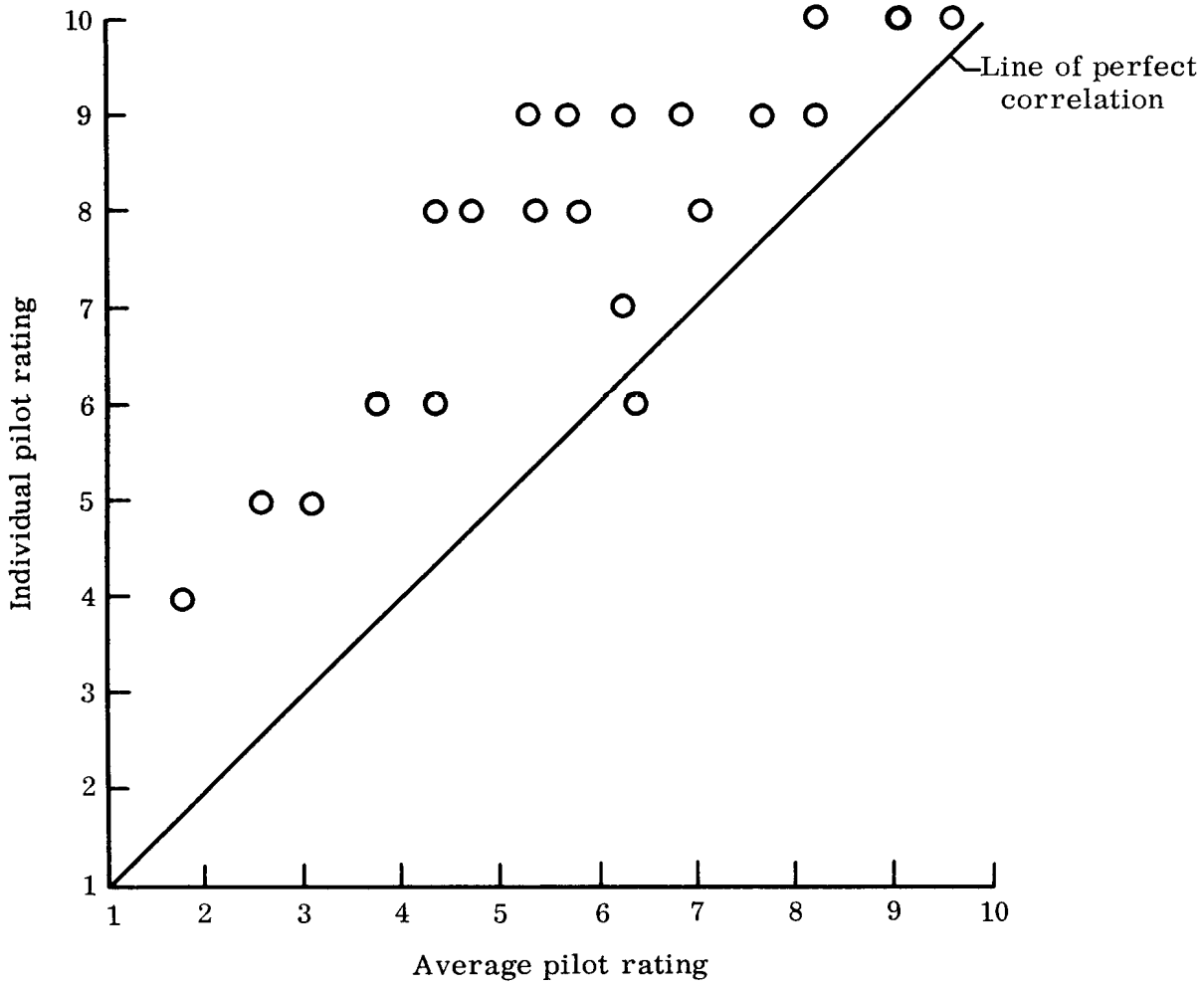
(h) Pilot H, $\sigma = 1.12$.

Figure 8. – Continued.



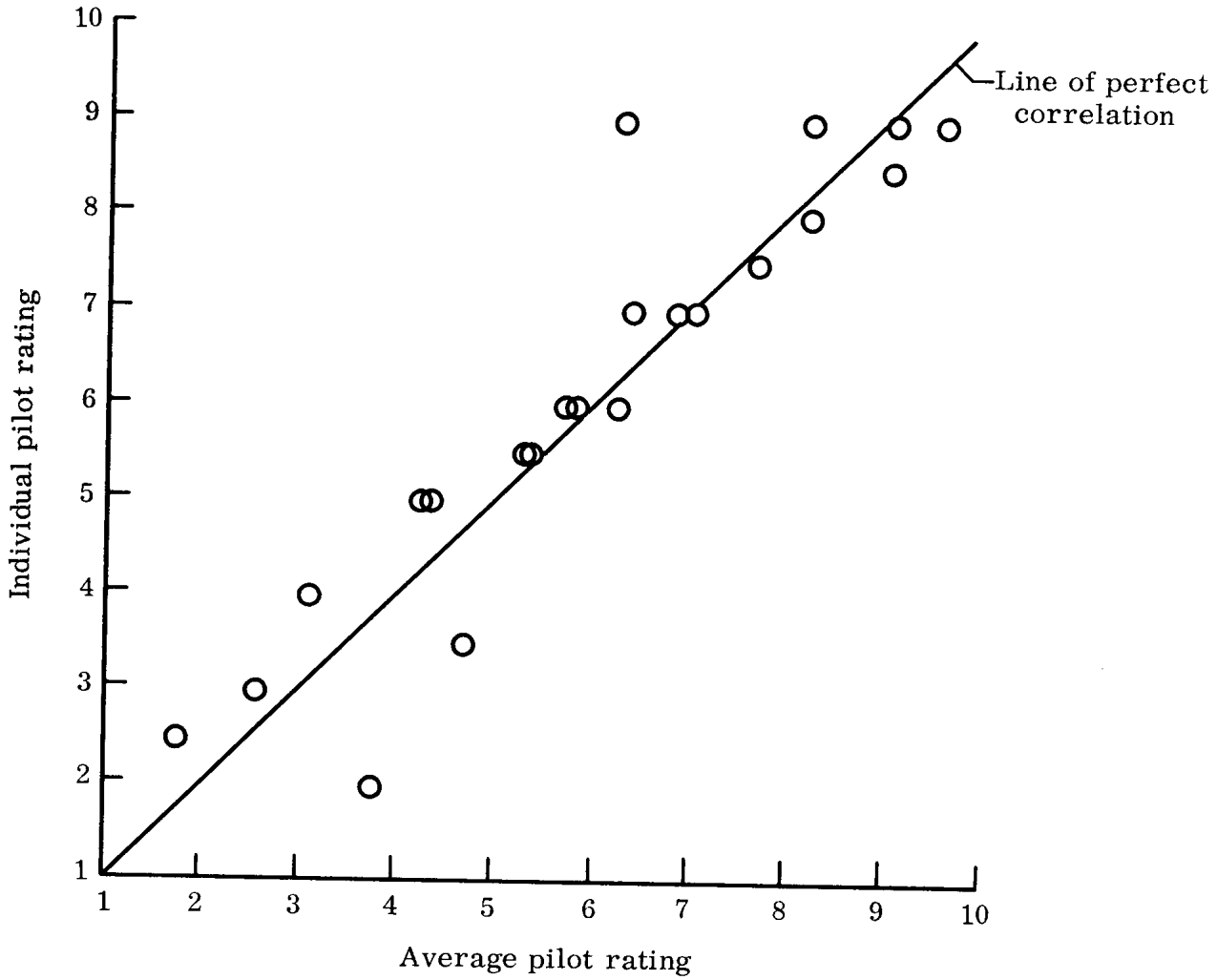
(i) Pilot I, $\sigma = 0.78$.

Figure 8.– Continued.



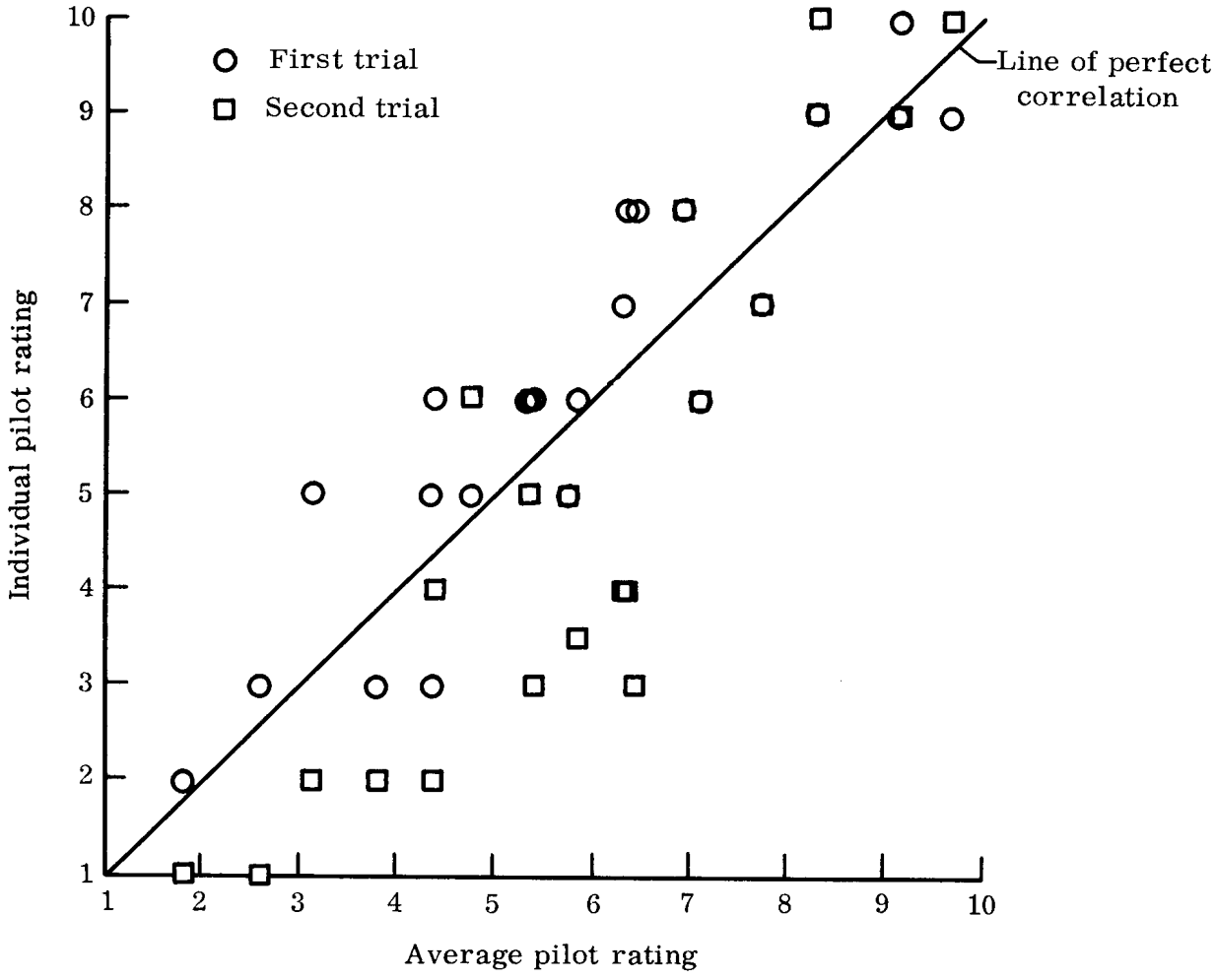
(j) Pilot J, $\sigma = 2.15$.

Figure 8. – Continued.



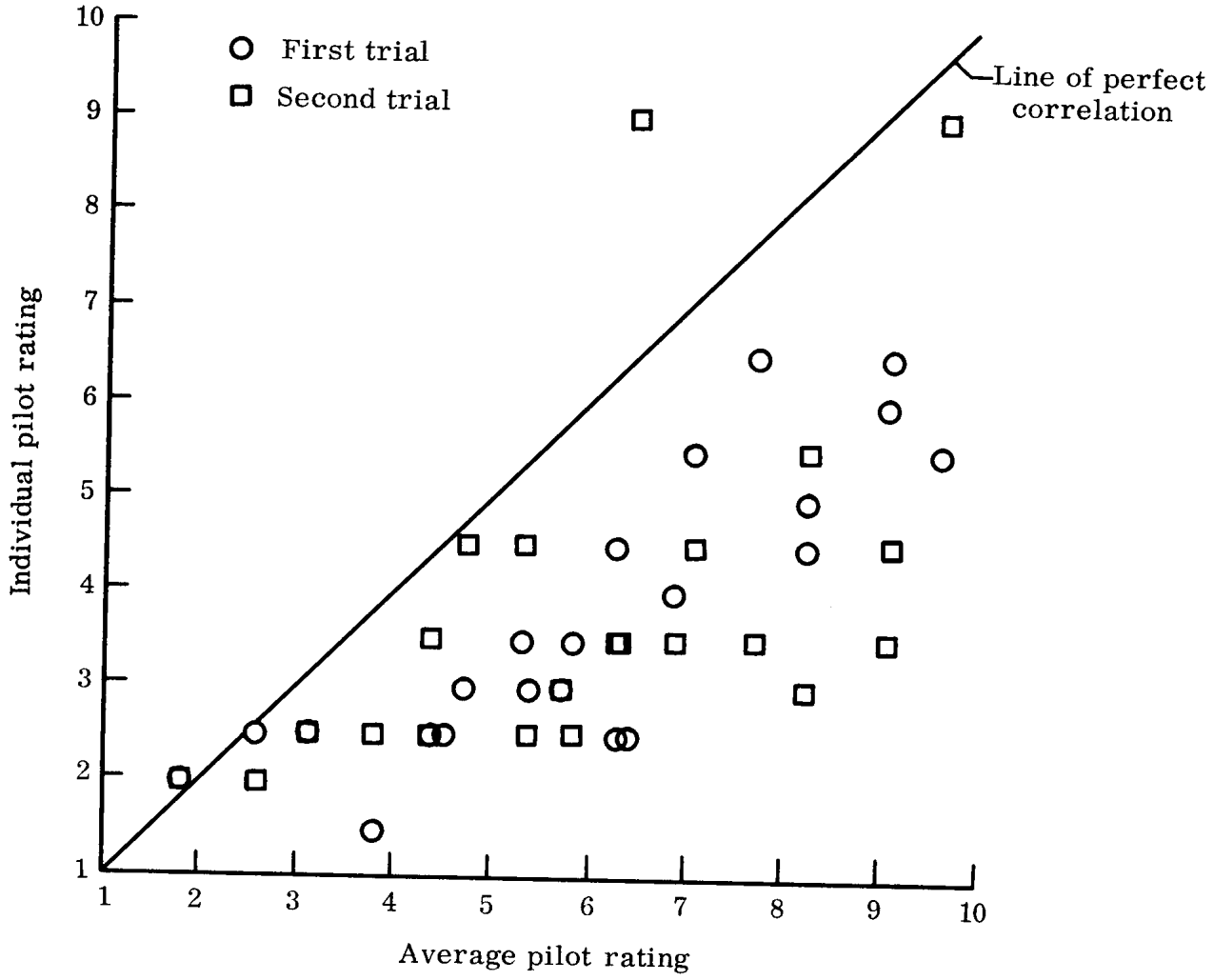
(k) Pilot K, $\sigma = 0.85$.

Figure 8.– Continued.



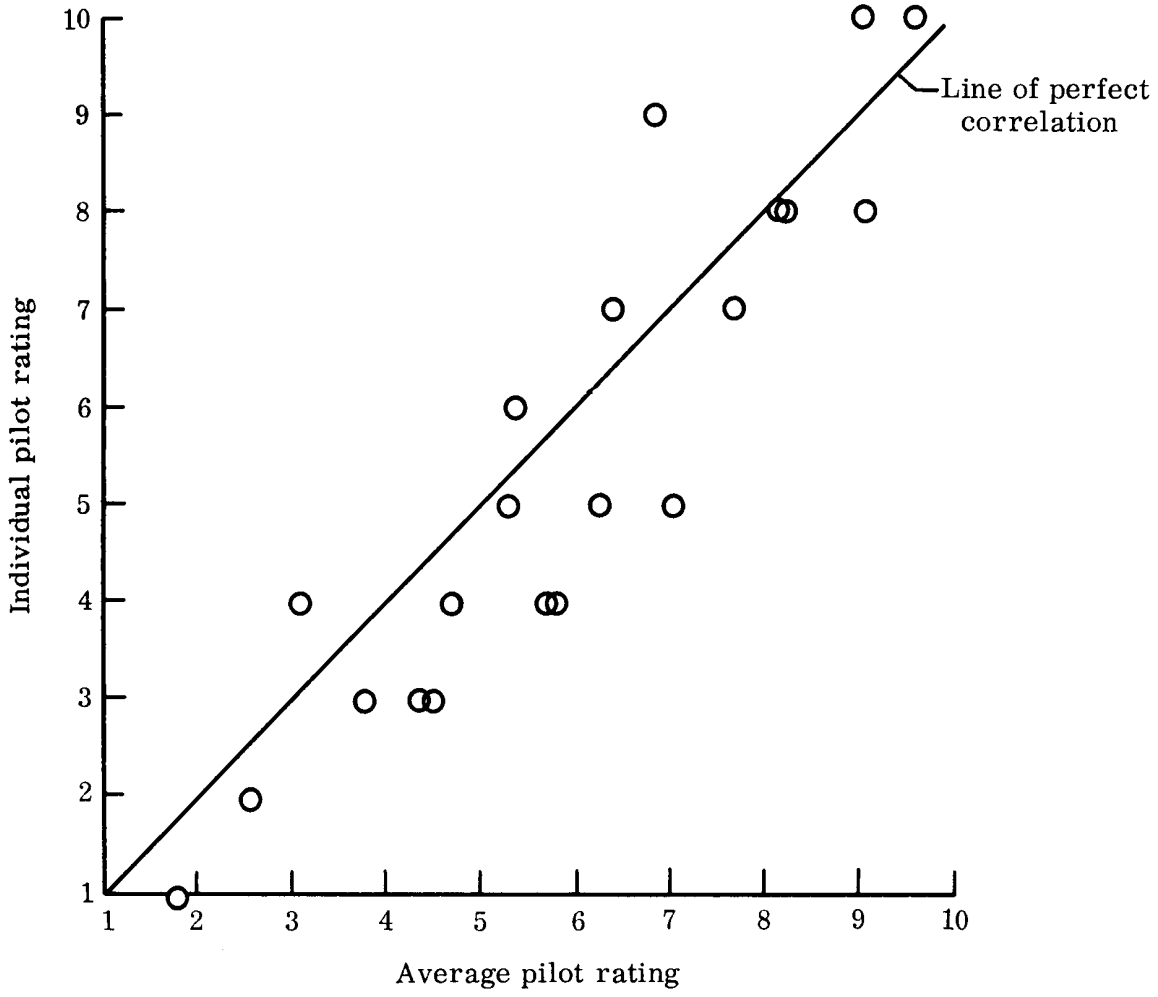
(*l*) Pilot L, $\sigma = 1.32$.

Figure 8.– Continued.



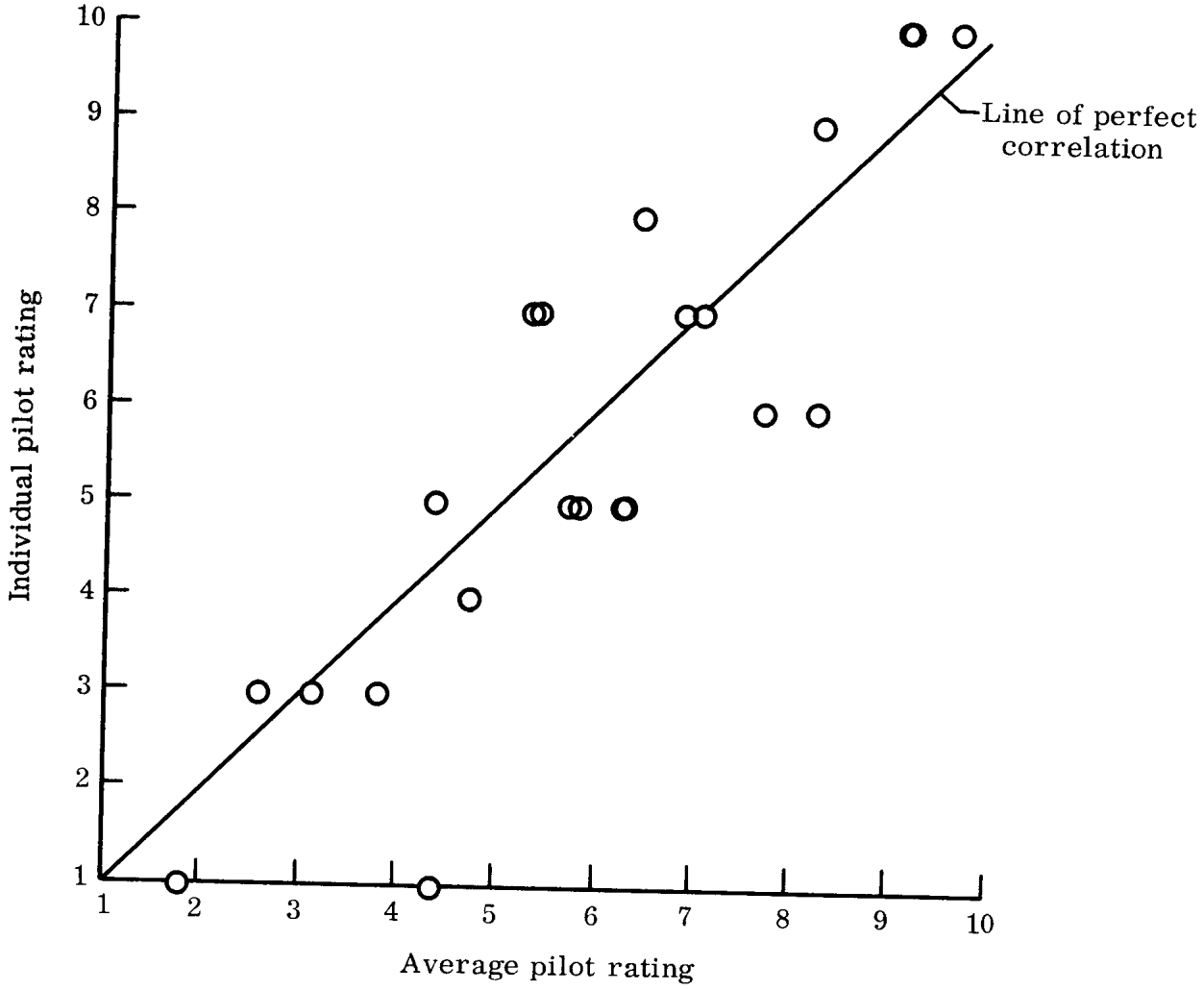
(m) Pilot M, $\sigma = 2.69$.

Figure 8.– Continued.



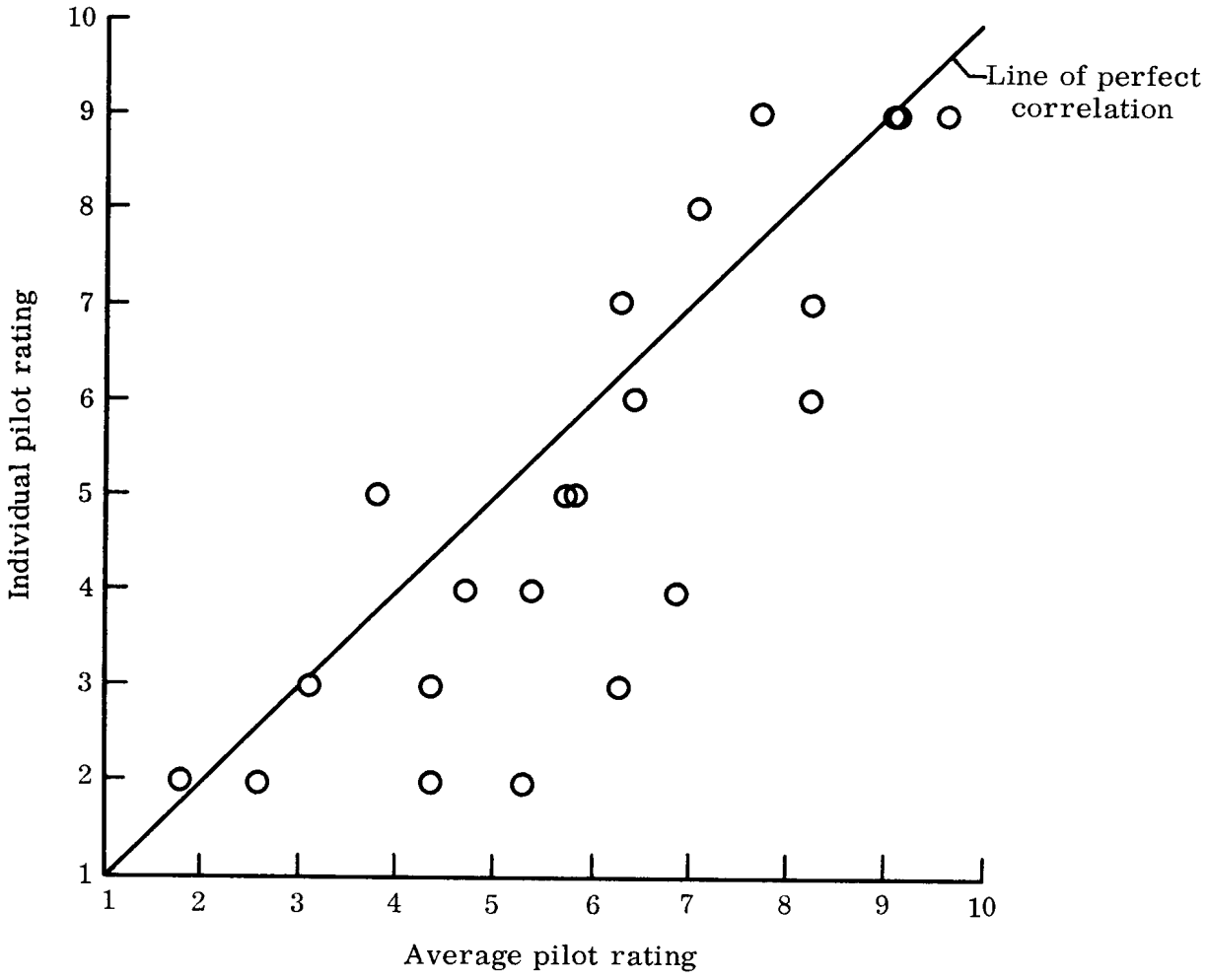
(n) Pilot N, σ = 1.14.

Figure 8.– Continued.



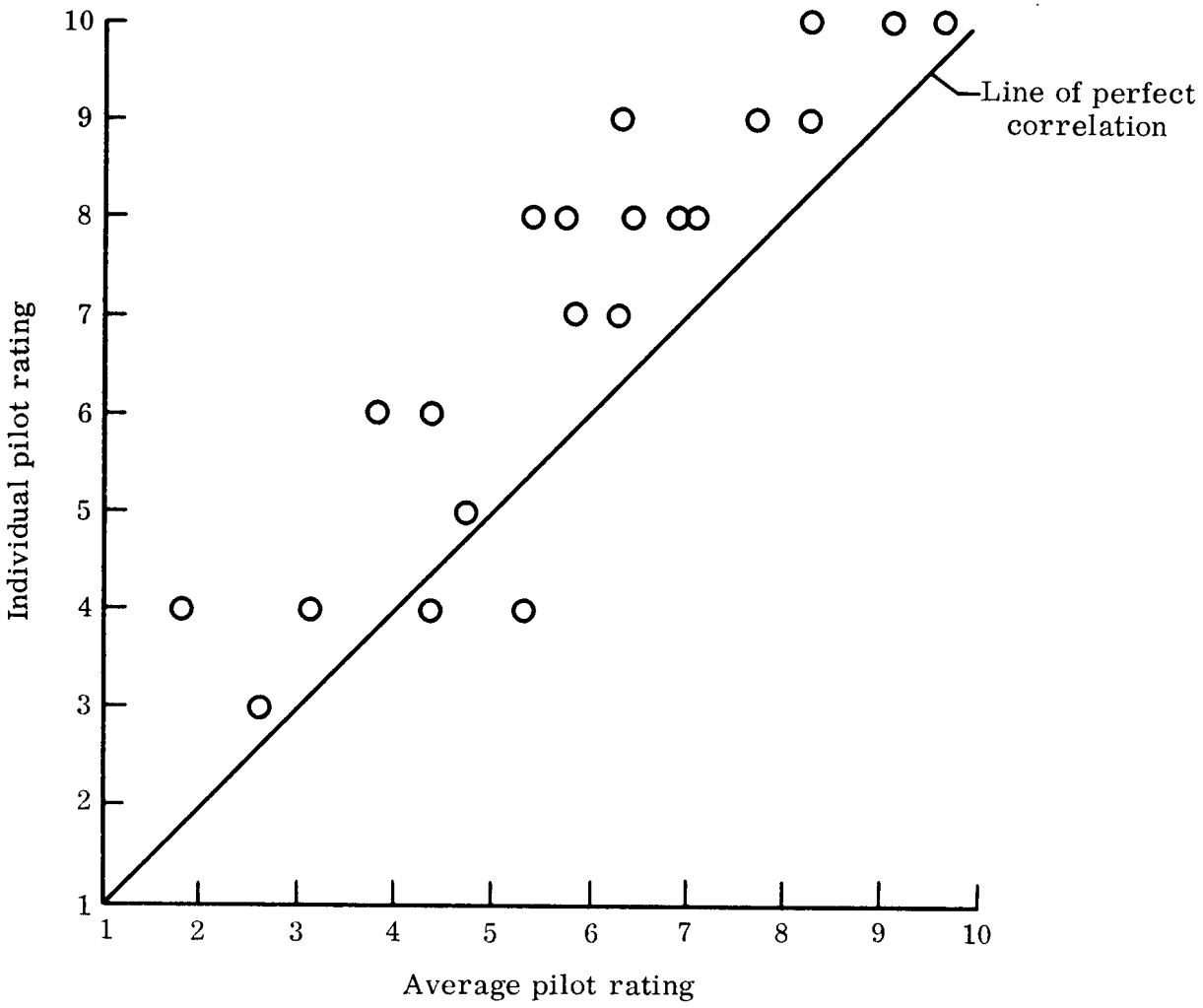
(o) Pilot O, σ = 1.29.

Figure 8.– Continued.



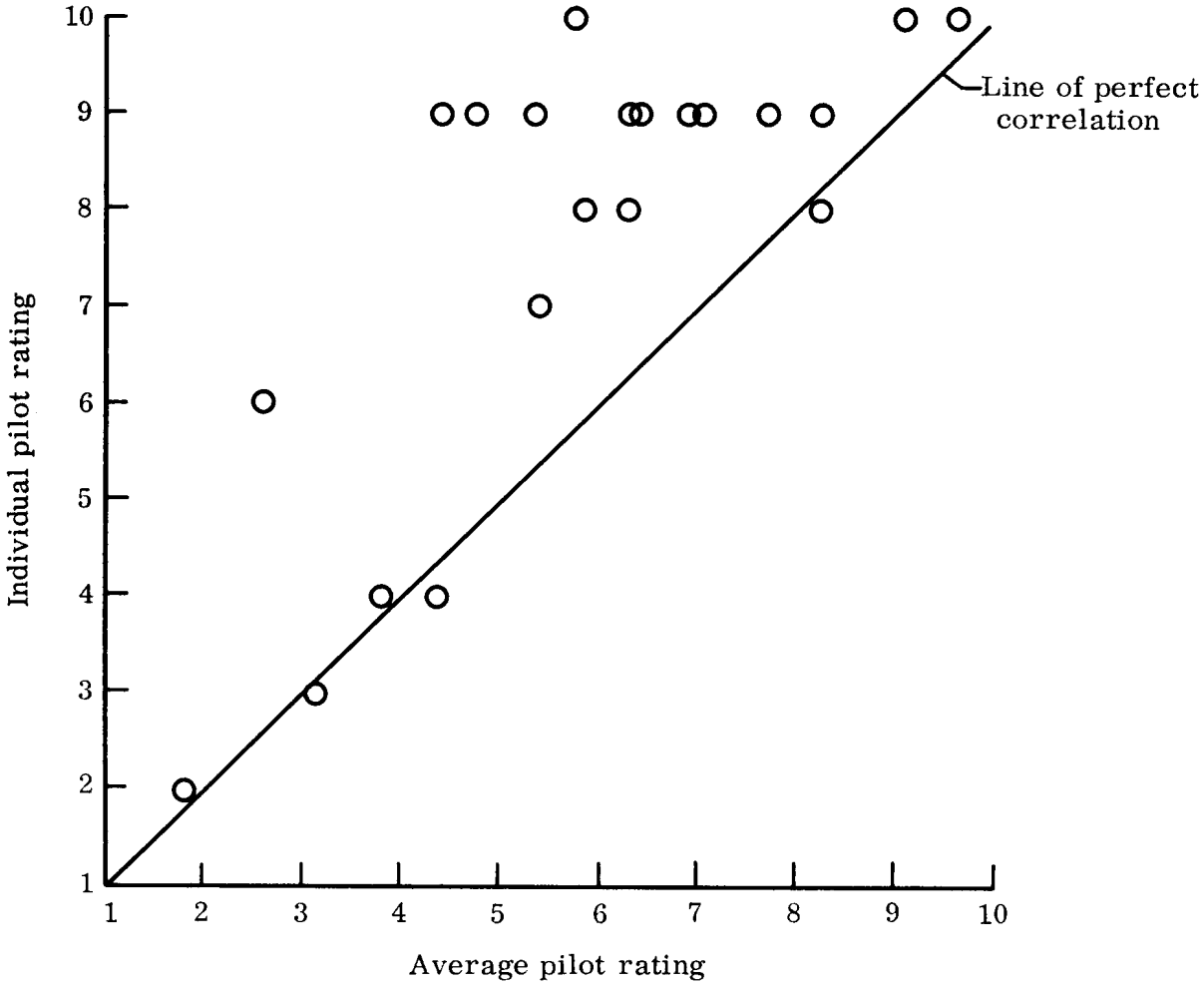
(p) Pilot P, $\sigma = 1.56$.

Figure 8.– Continued.



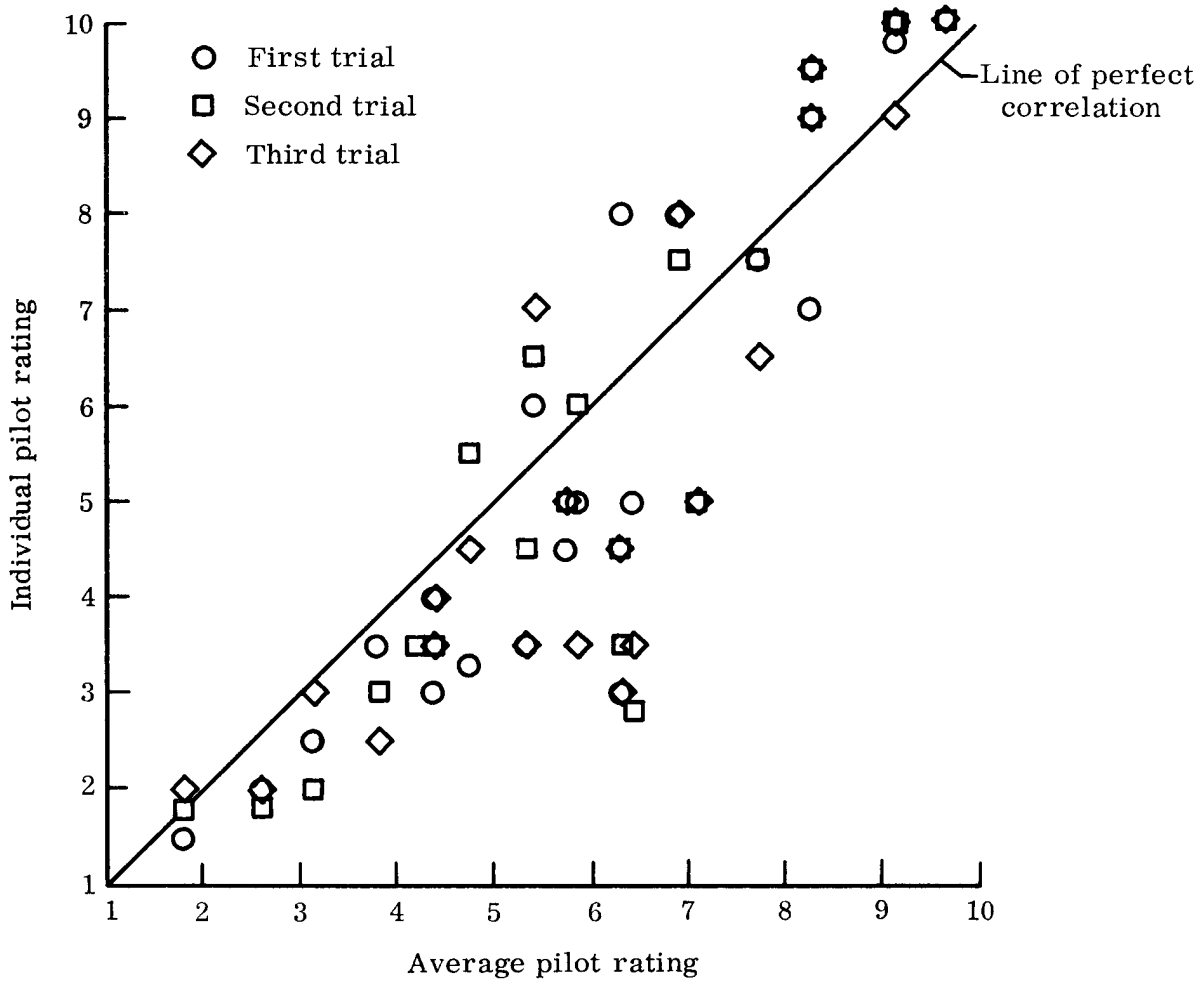
(q) Pilot Q, $\sigma = 1.48$.

Figure 8.– Continued.



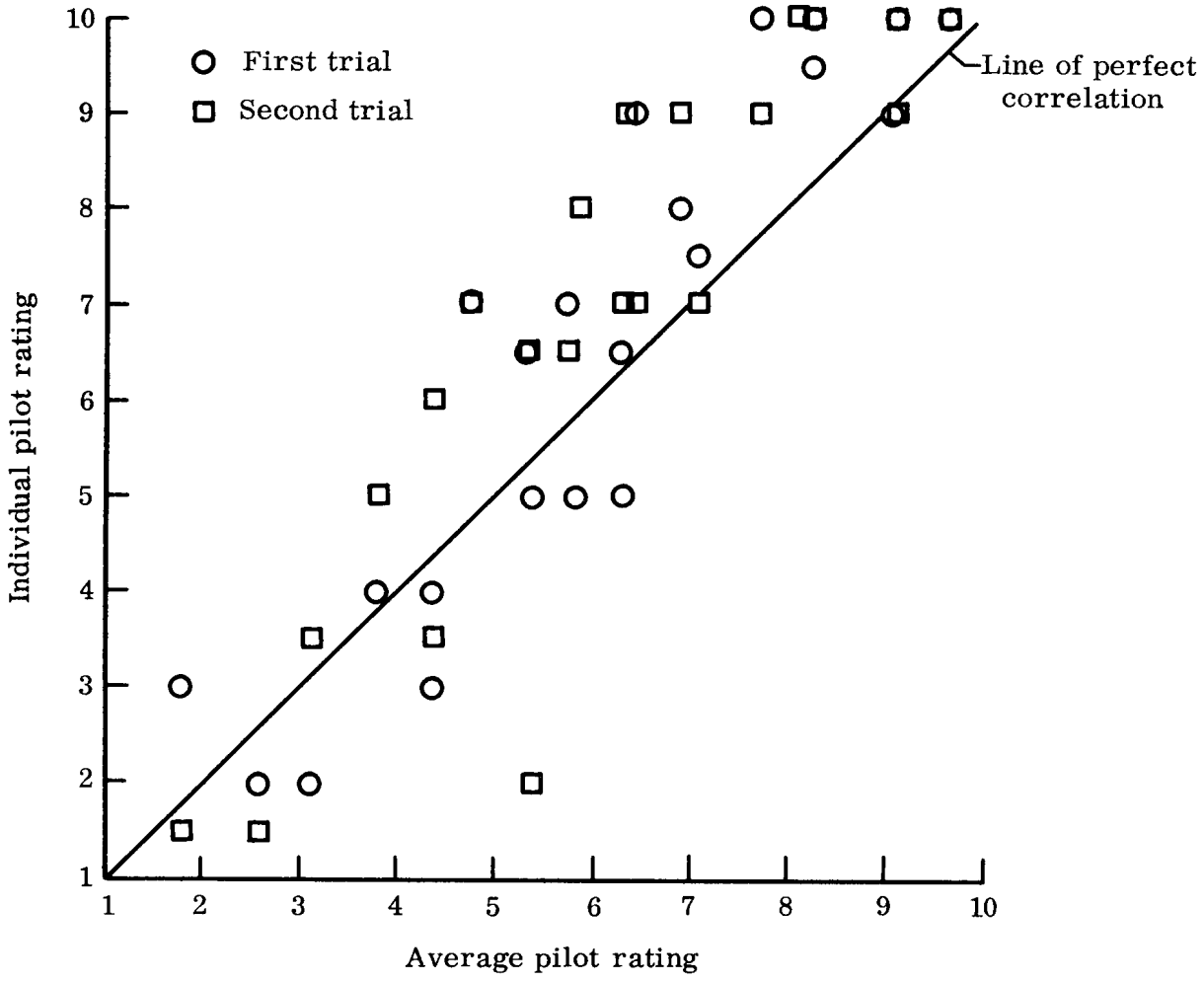
(r) Pilot R, $\sigma = 2.34$.

Figure 8.– Continued.



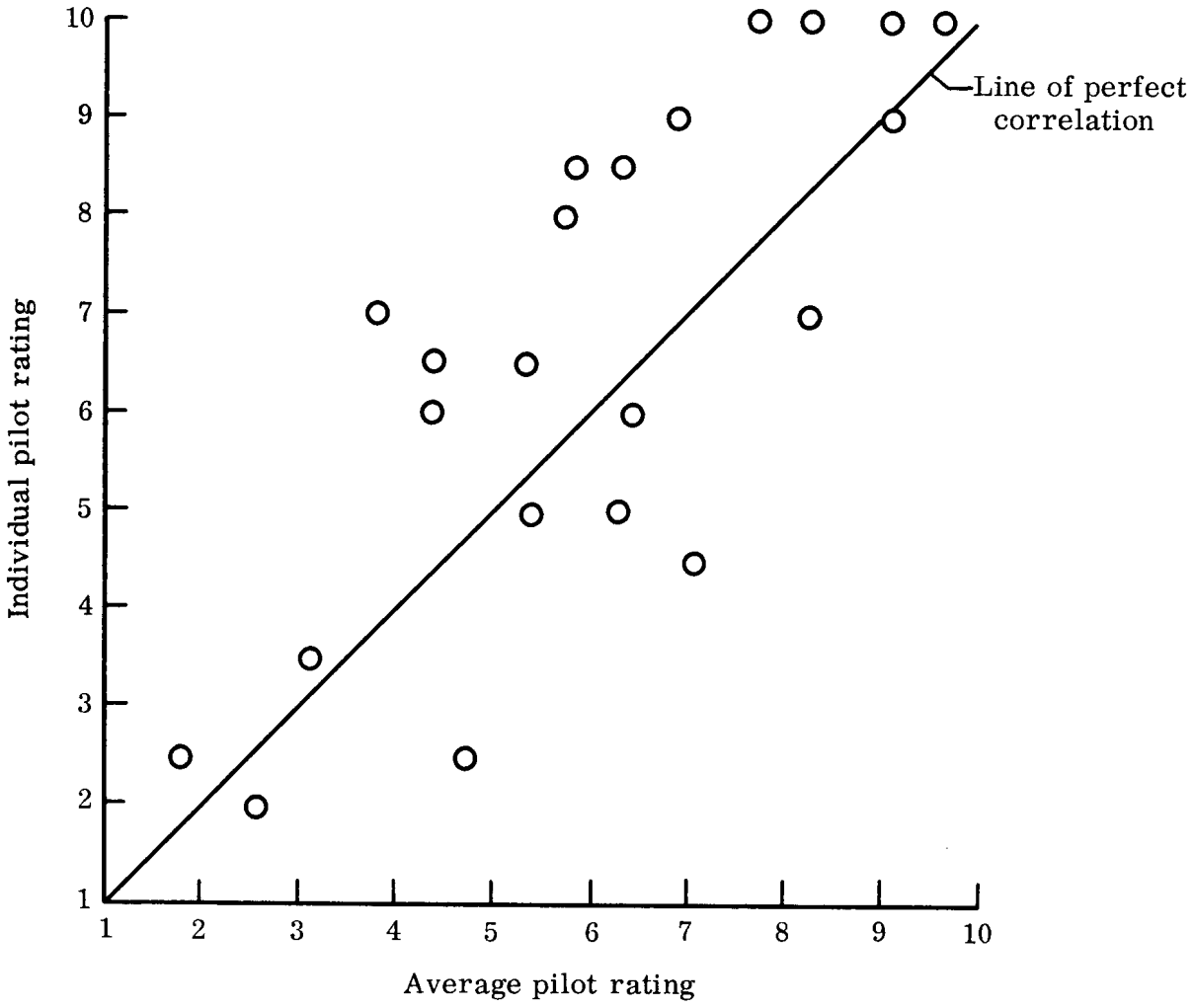
(s) Pilot S (engineer), σ = 1.37.

Figure 8.– Continued.



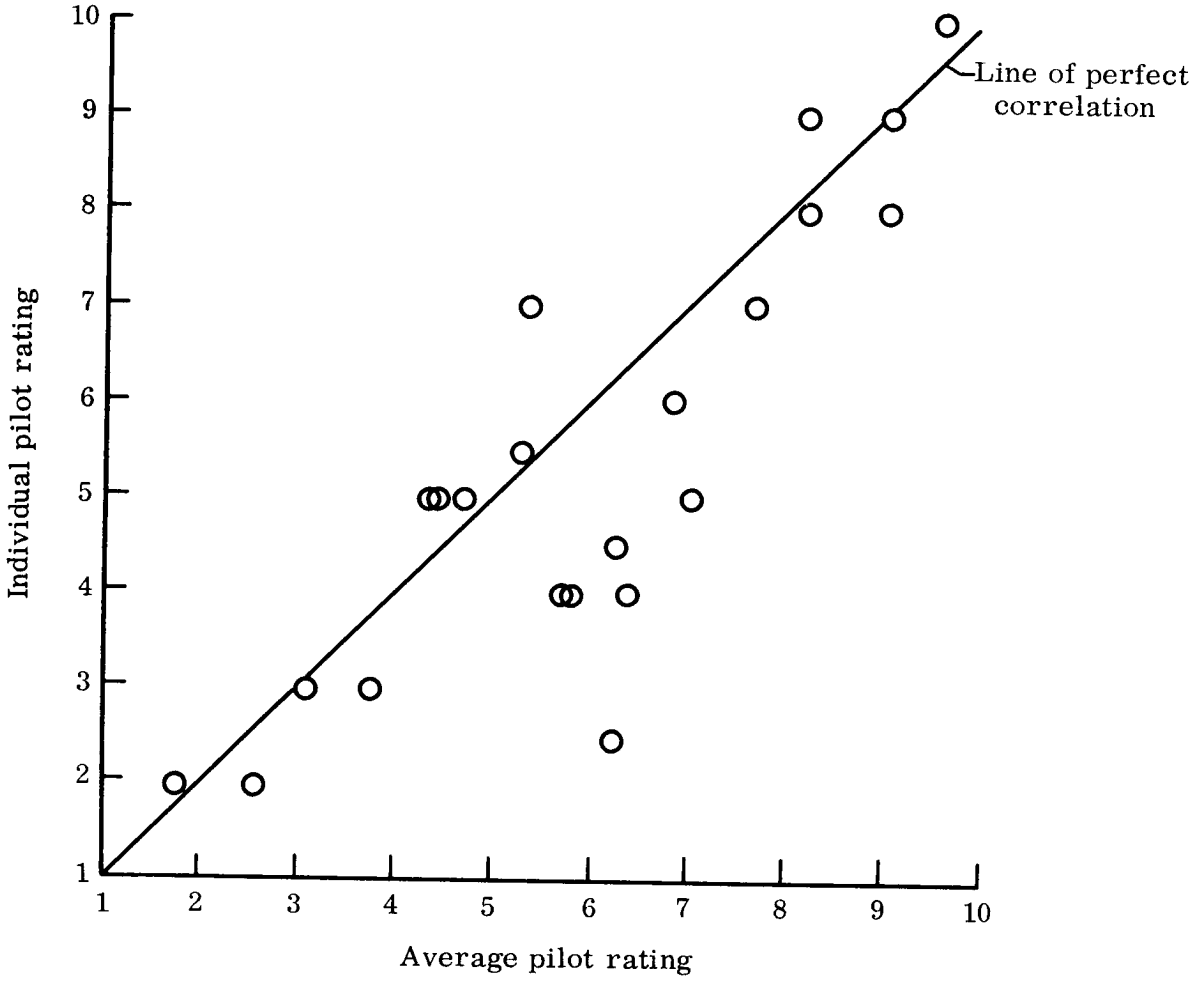
(t) Pilot T (engineer), $\sigma = 1.40$.

Figure 8.– Continued.



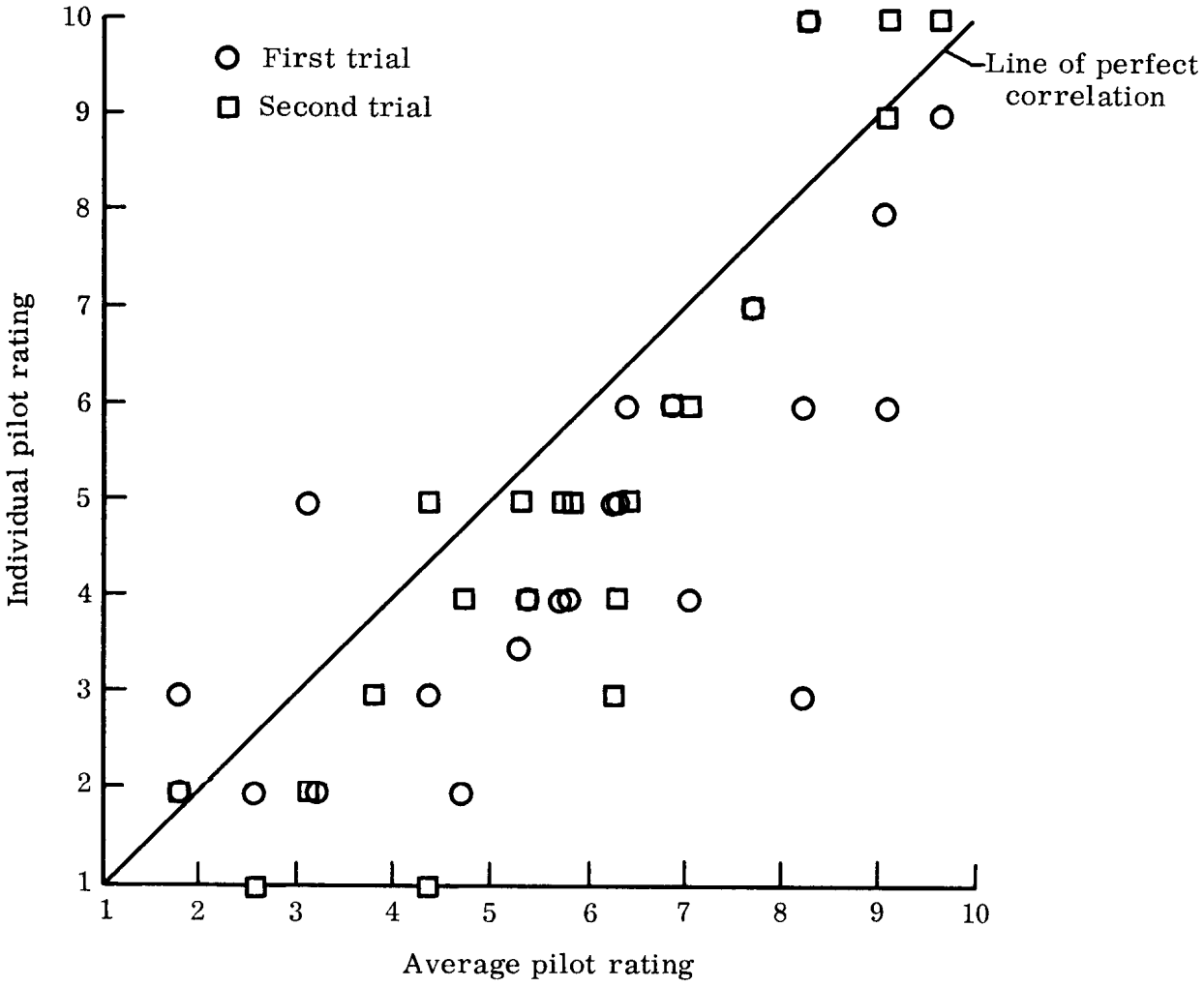
(u) Pilot U (engineer), $\sigma = 1.73$

Figure 8.– Continued.



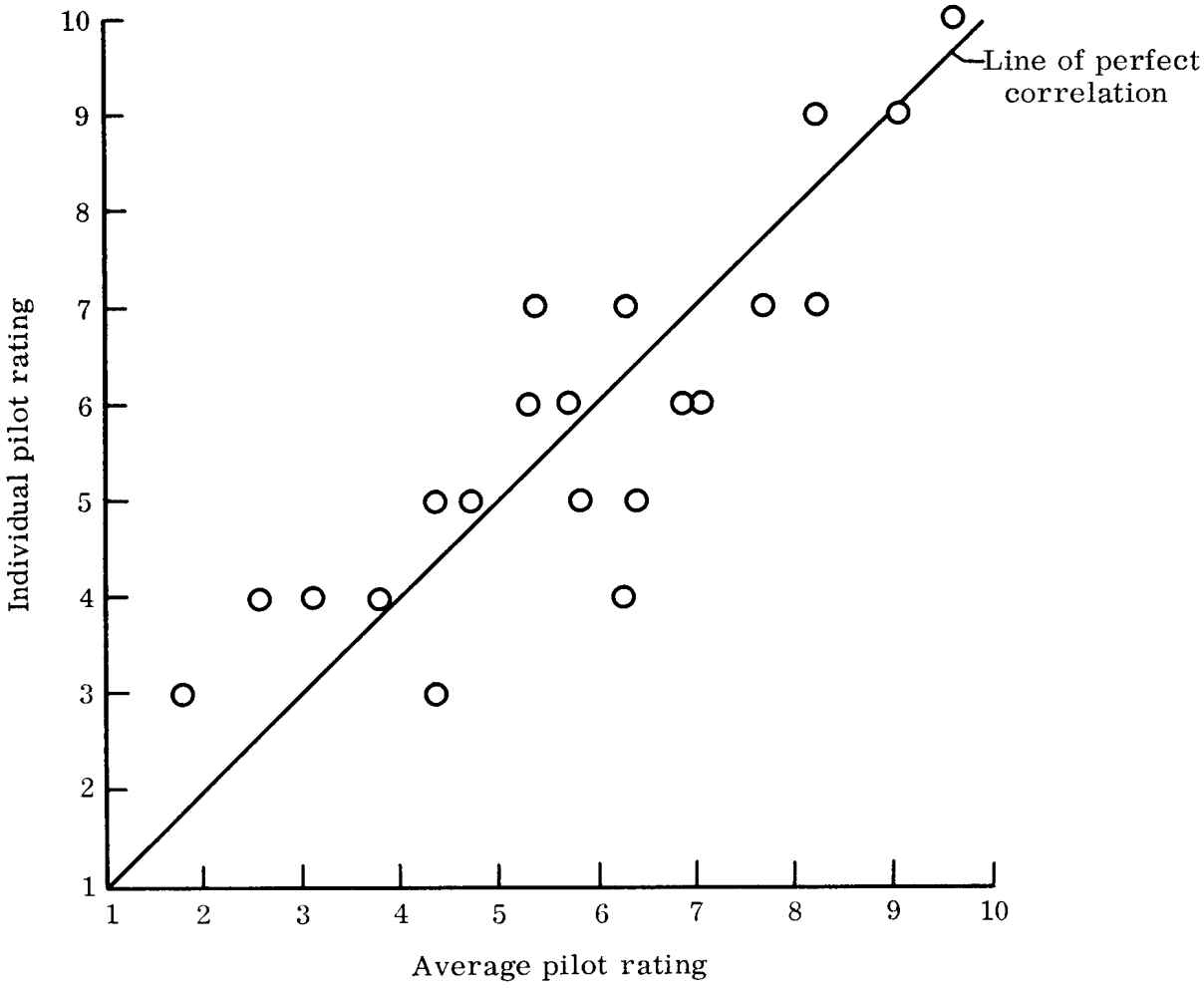
(v) Pilot V (engineer), $\sigma = 1.38$.

Figure 8.– Continued.



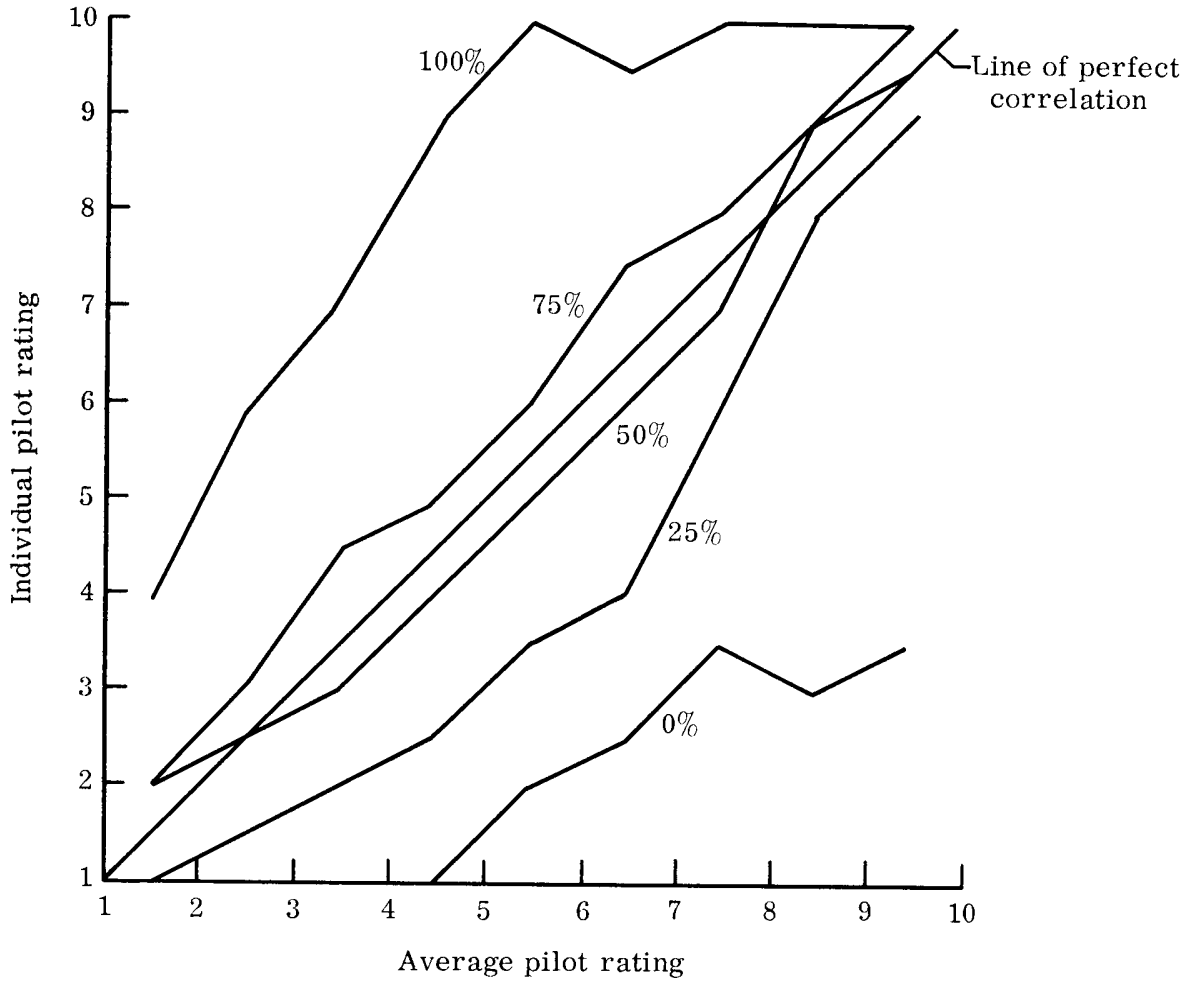
(w) Pilot W (engineer), $\sigma = 1.79$.

Figure 8. – Continued.



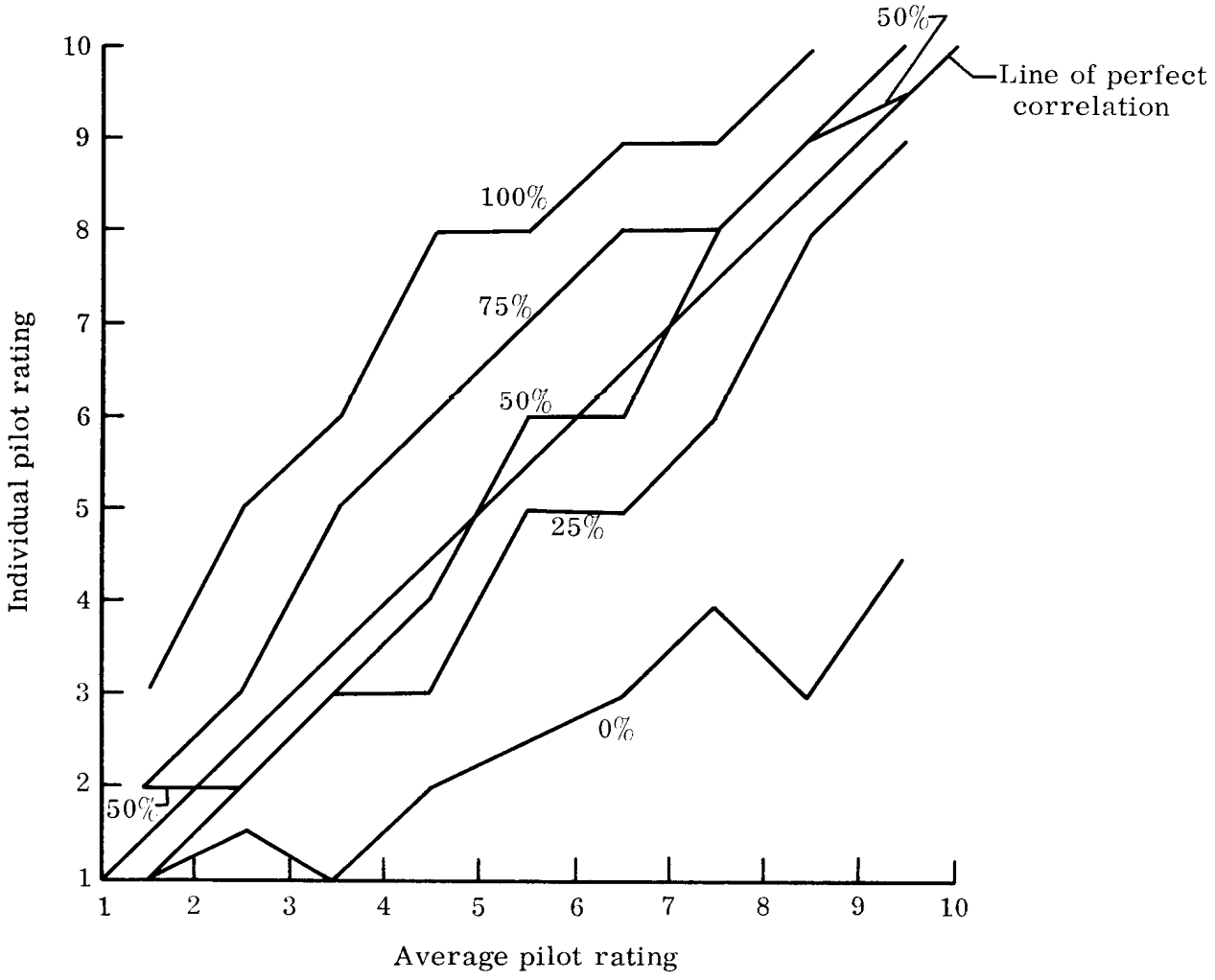
(x) Pilot X (engineer), $\sigma = 1.02$.

Figure 8.– Concluded.



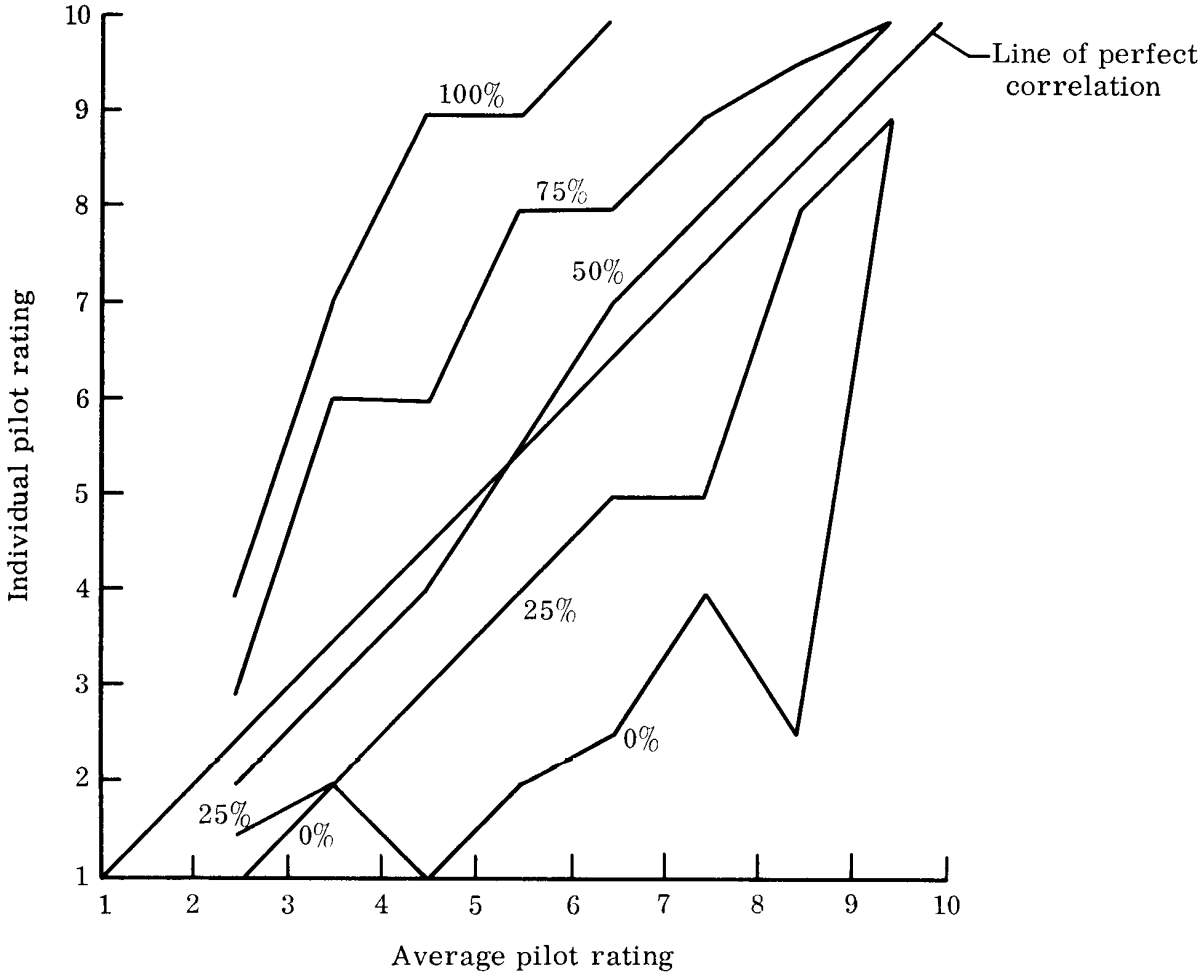
(a) General mission.

Figure 9.– Variability of pilot ratings for the various missions considered.



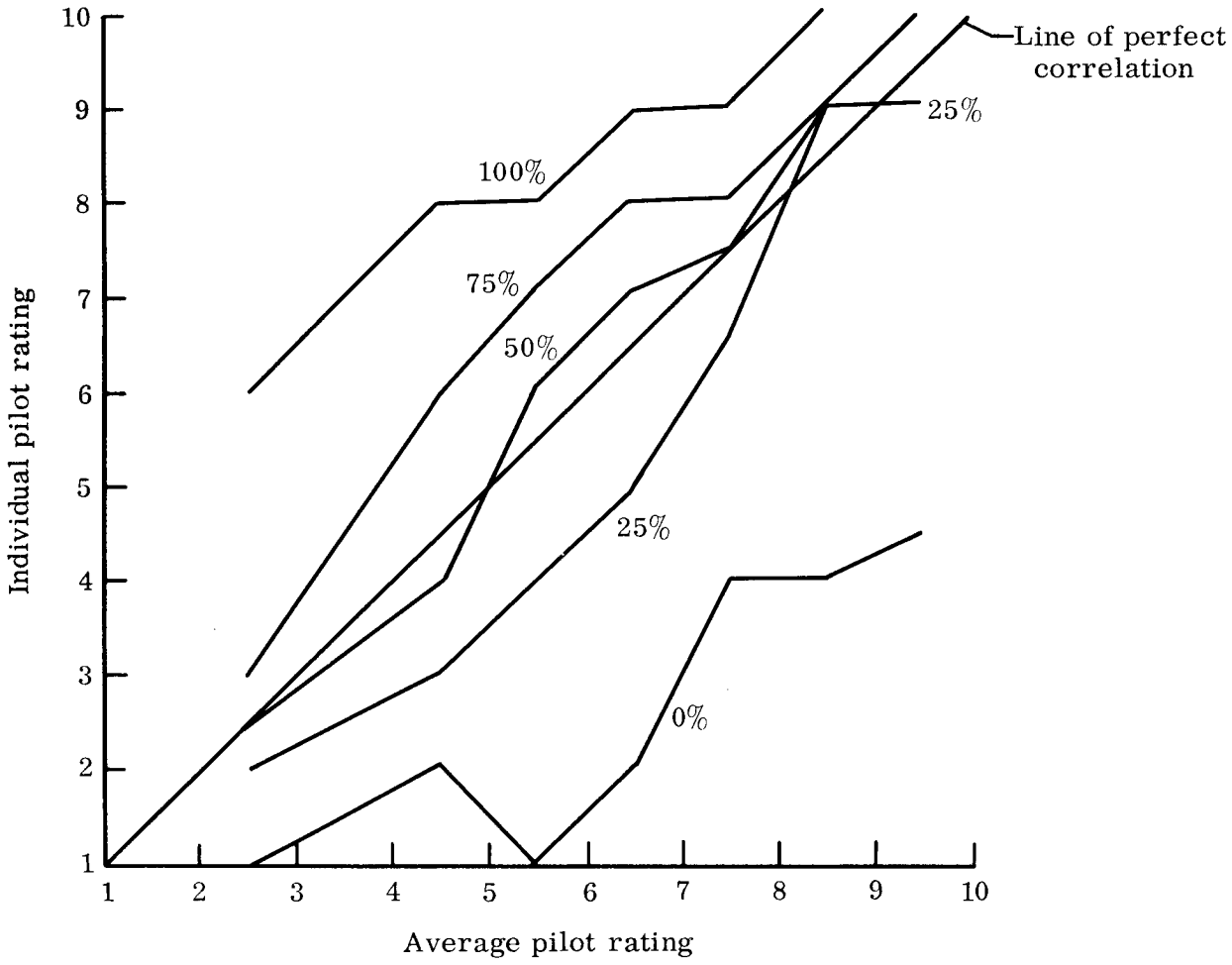
(b) Fighter mission.

Figure 9.– Continued.



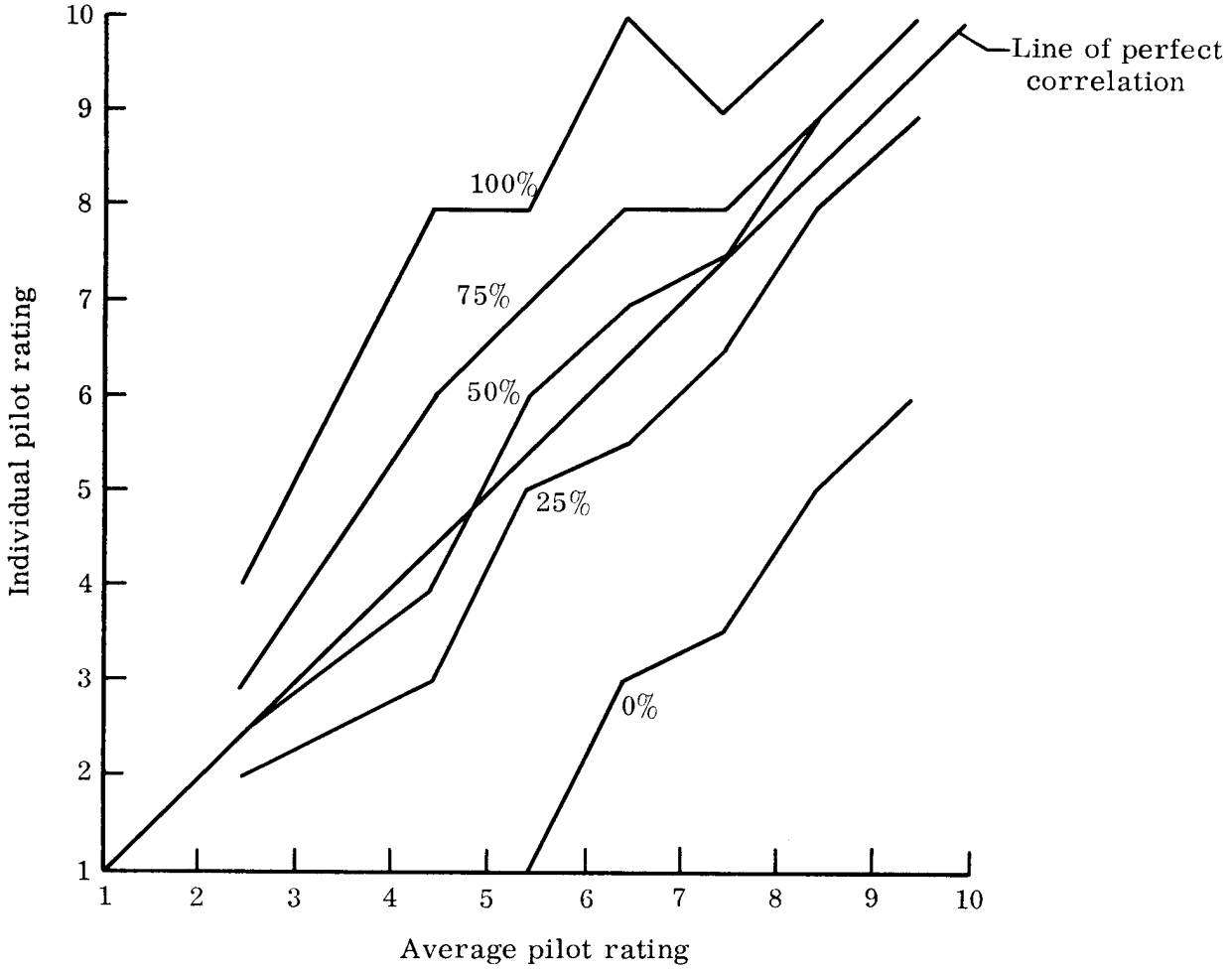
(c) Reentry-vehicle mission.

Figure 9.– Continued.



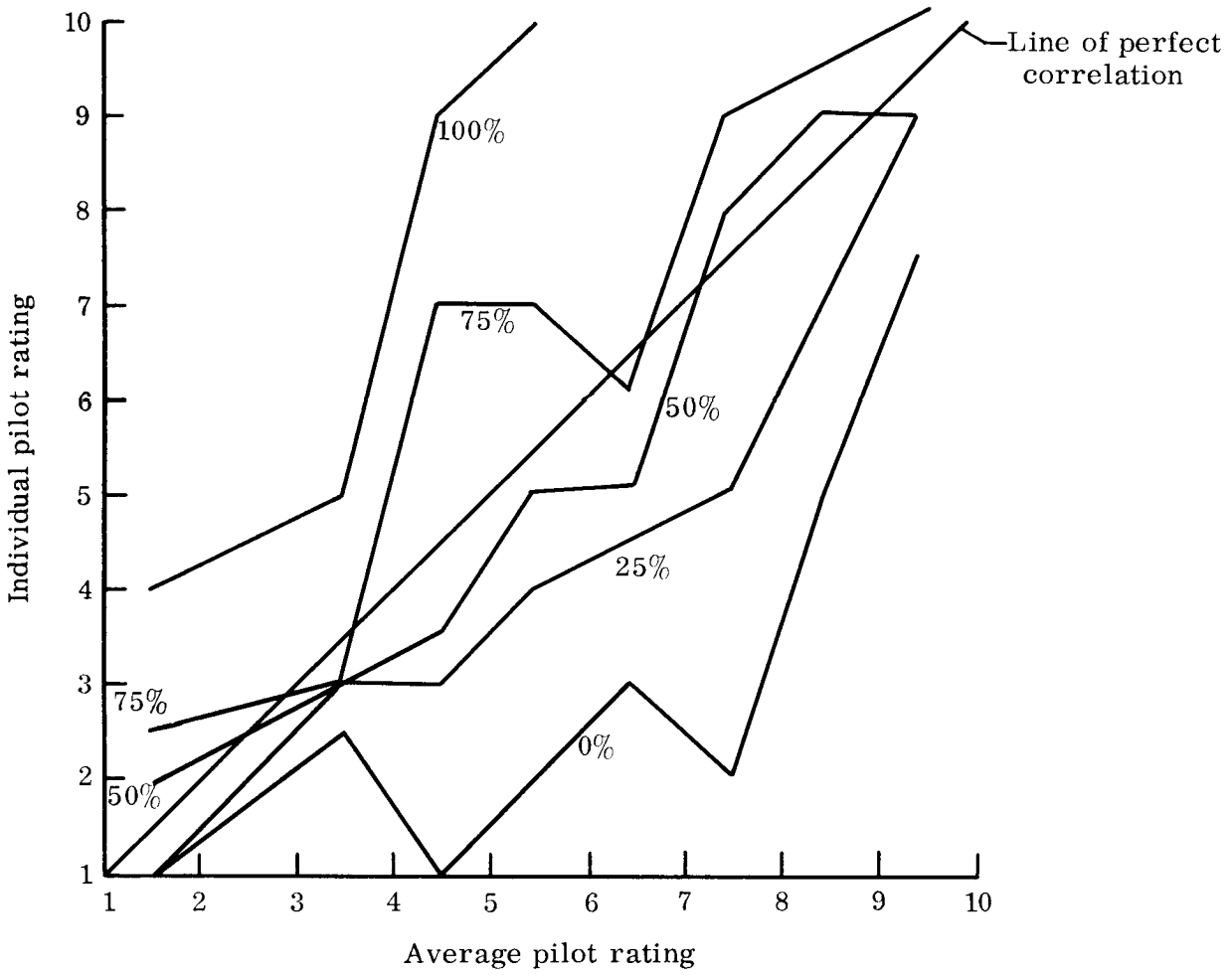
(d) Bomber mission.

Figure 9.– Continued.



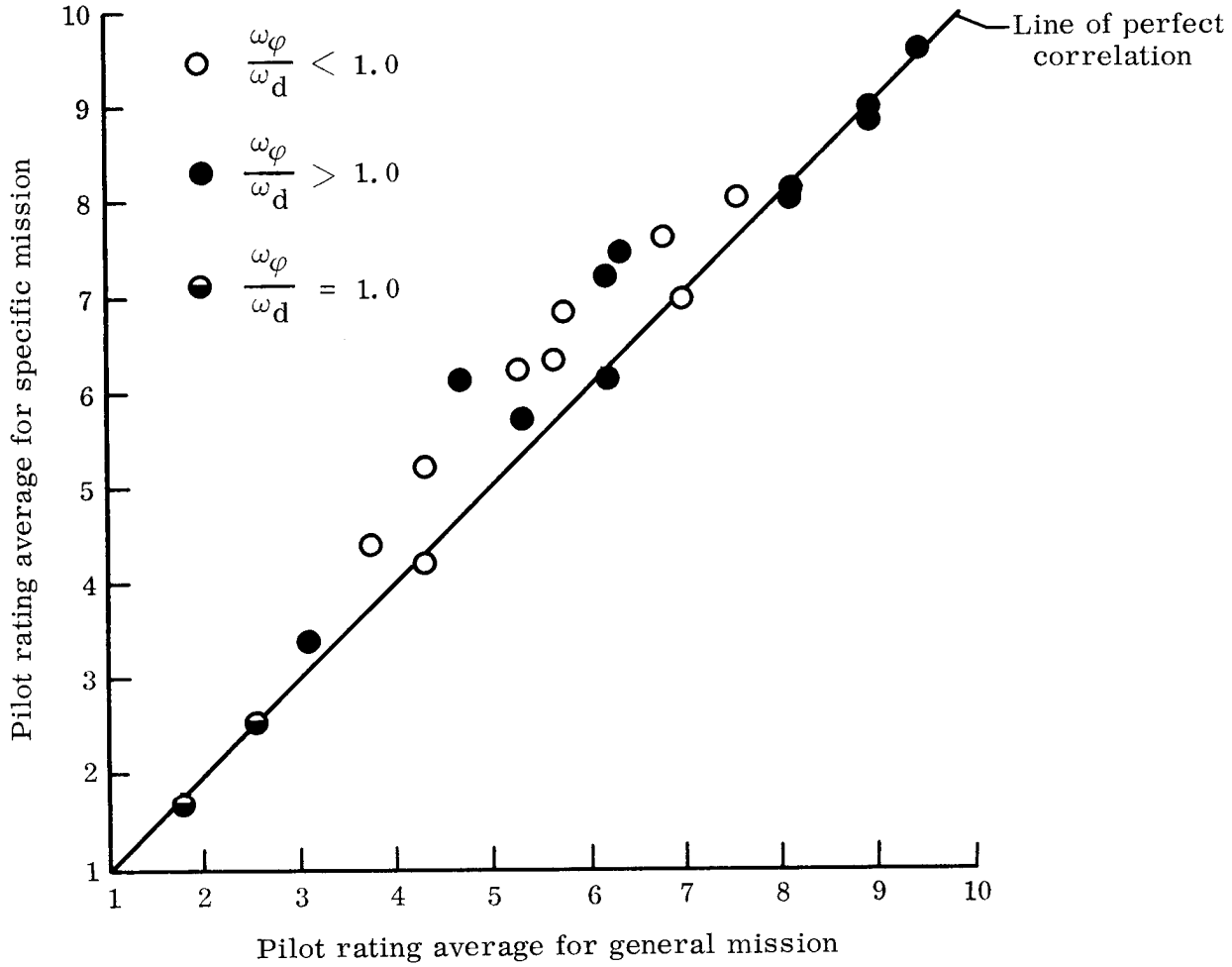
(e) Supersonic-transport mission.

Figure 9.– Continued.



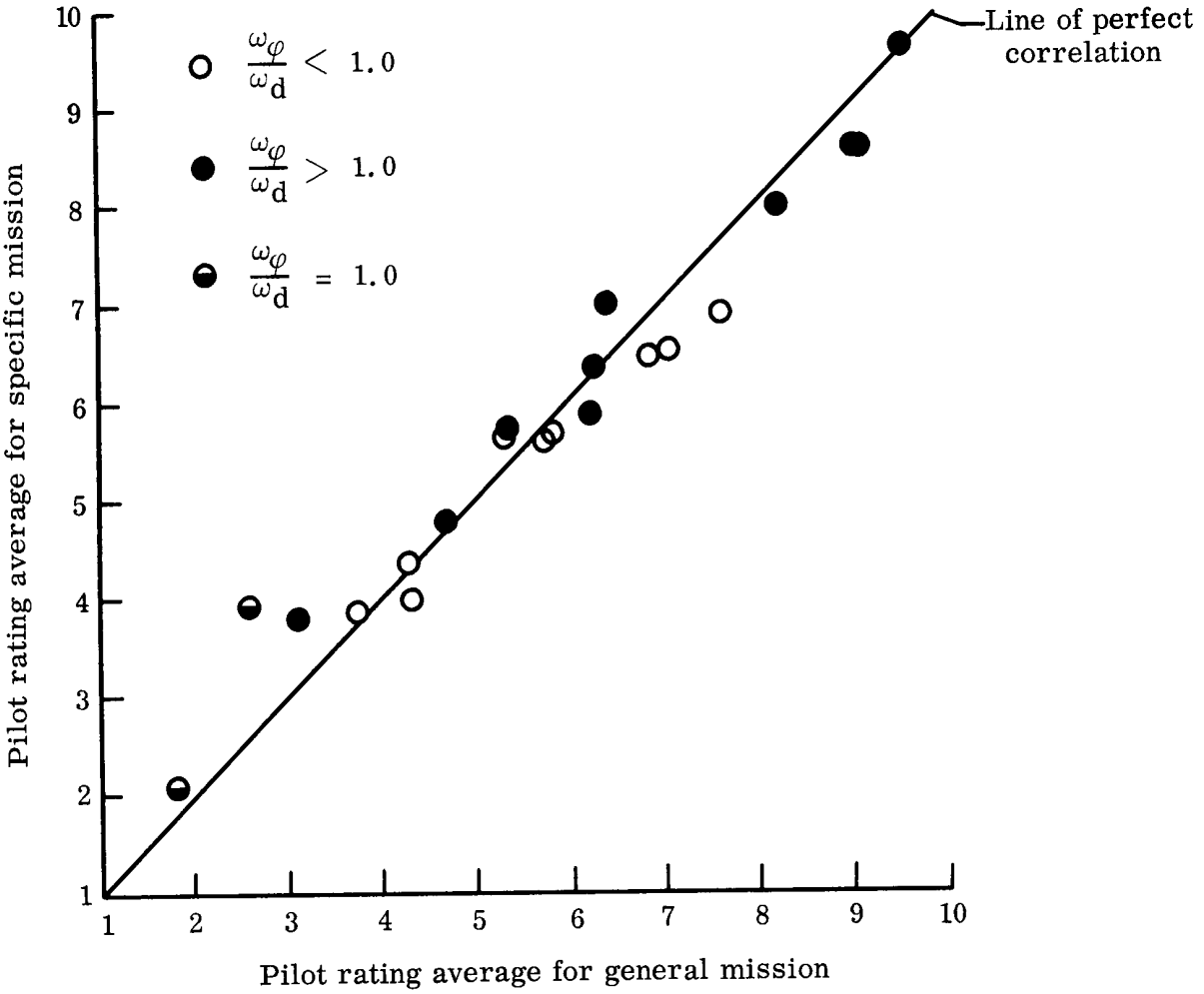
(f) Light-airplane mission.

Figure 9.– Concluded.



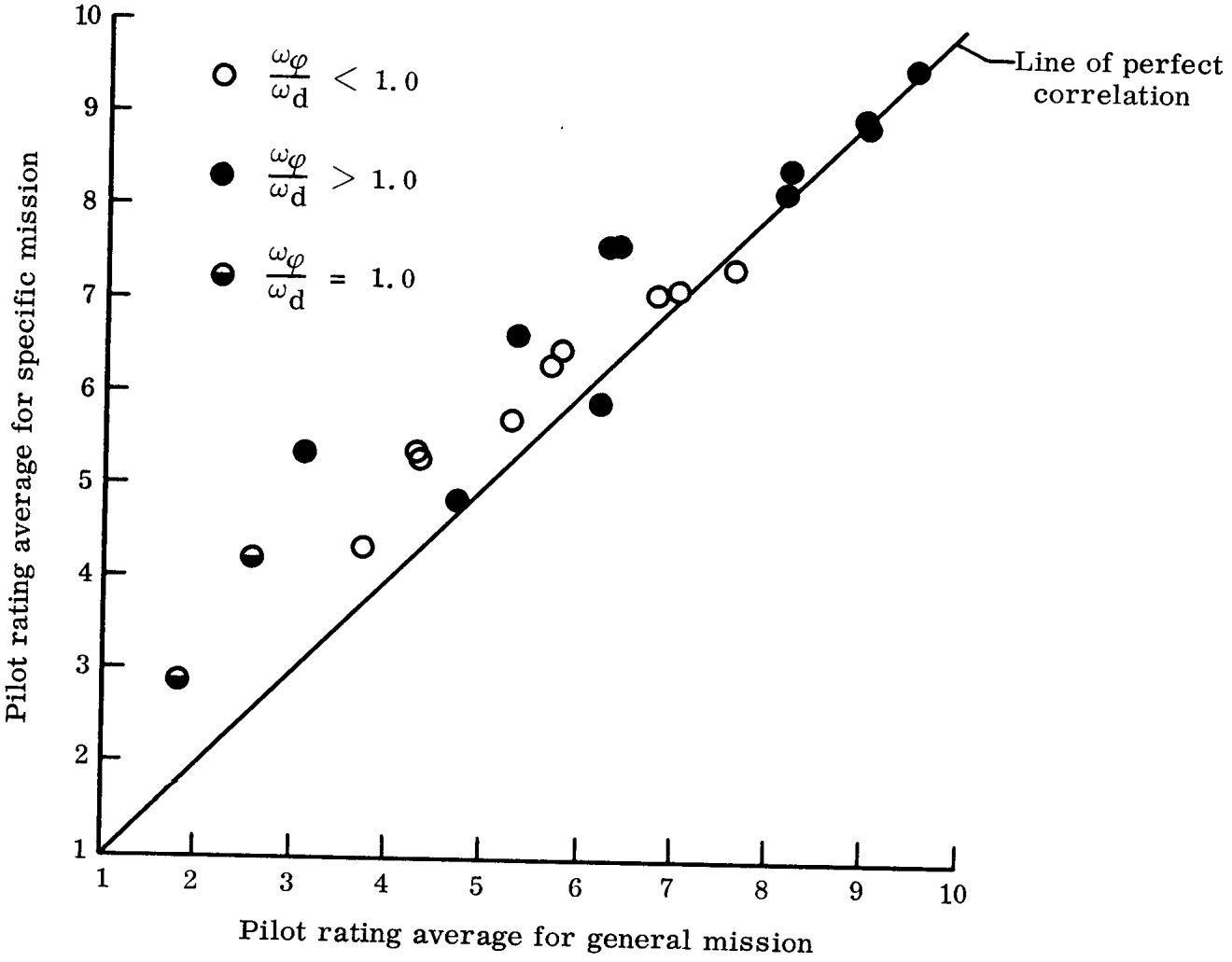
(a) Fighter mission. $\sigma = 0.64$.

Figure 10.– Correlation of pilot ratings for the general mission and ratings for specific missions.



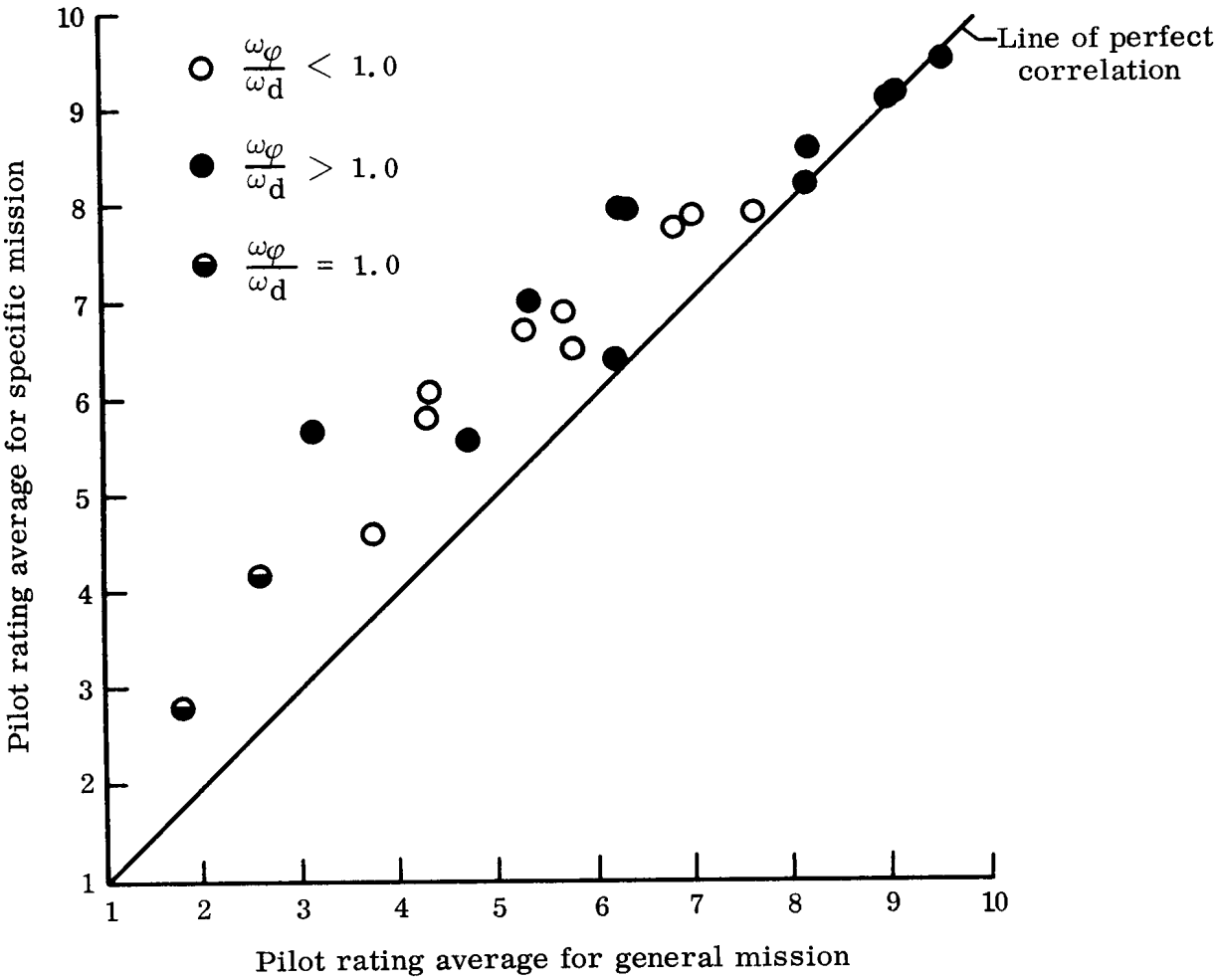
(b) Reentry vehicle mission. $\sigma = 0.48$.

Figure 10. – Continued.



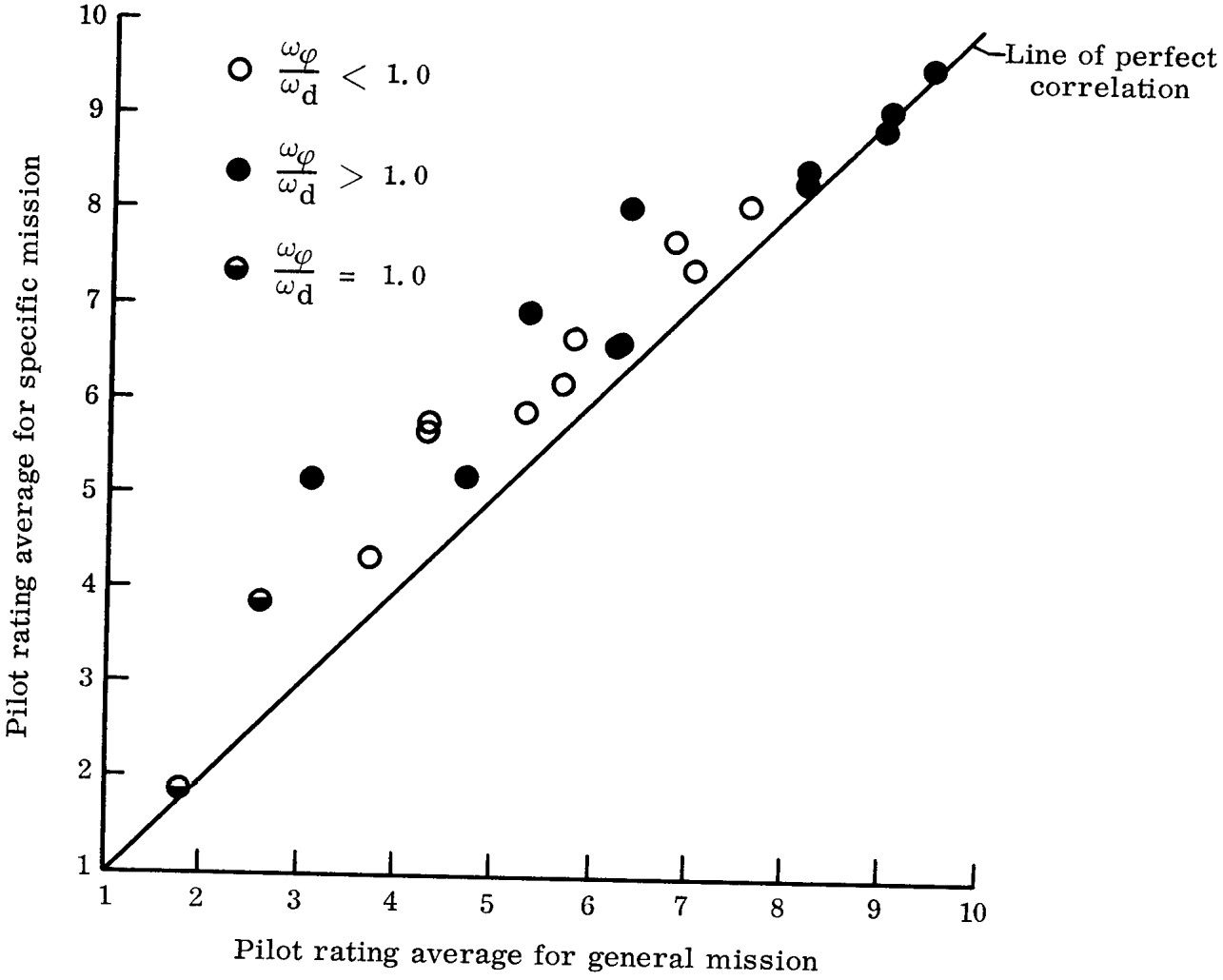
(c) Bomber mission. $\sigma = 0.90$.

Figure 10. – Continued.



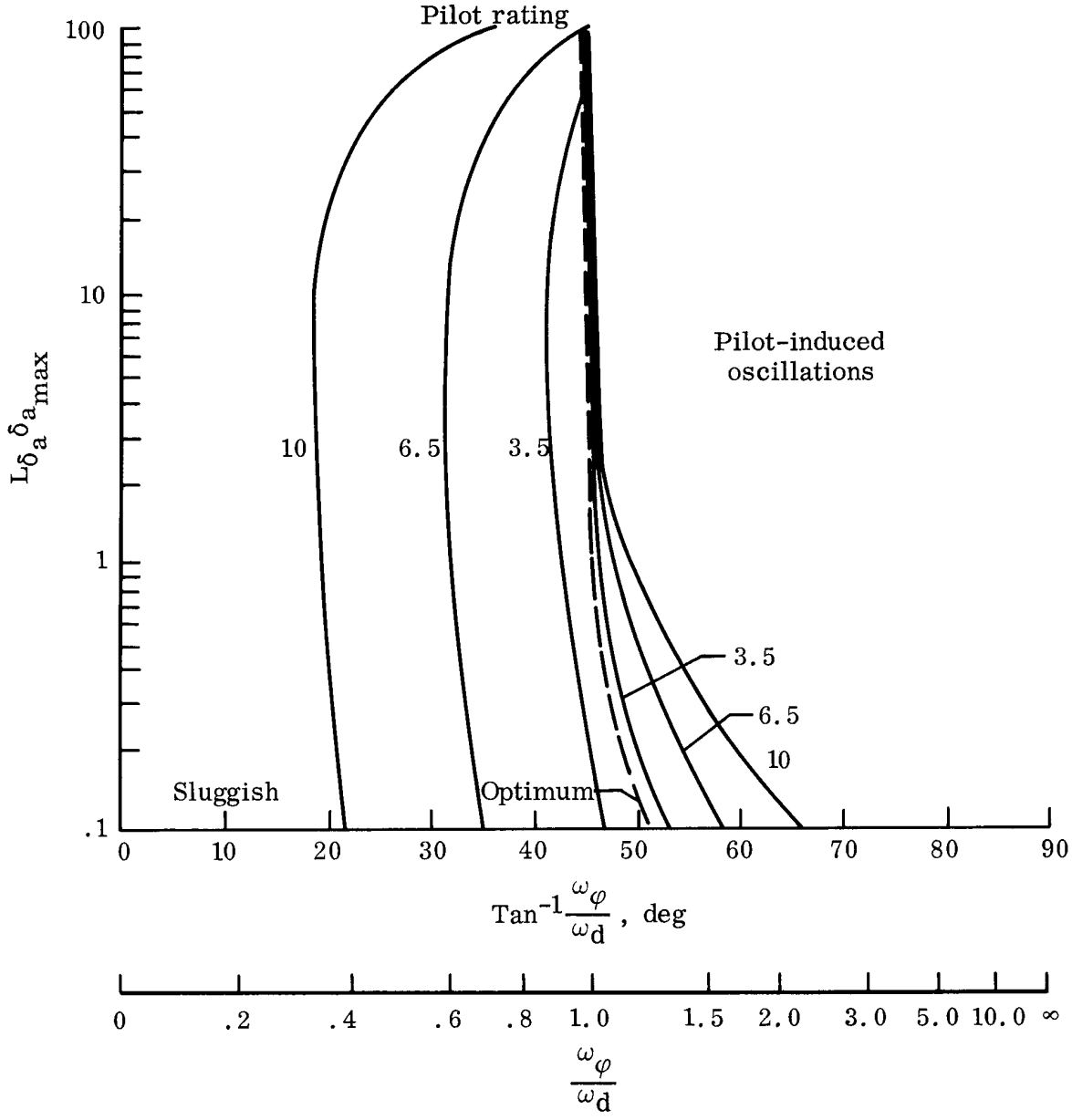
(d) Supersonic-transport mission. $\sigma = 1.20$.

Figure 10. – Continued.



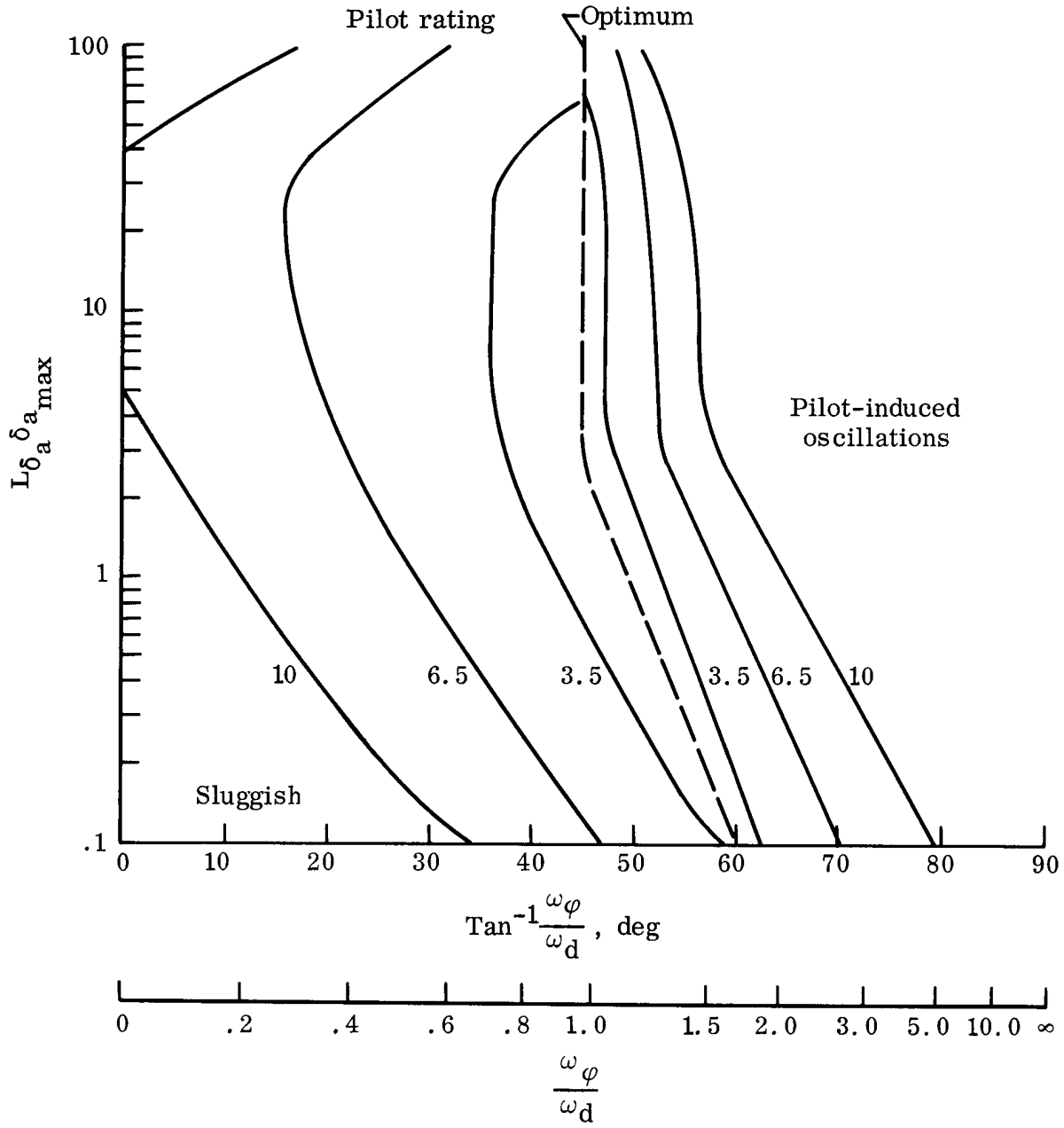
(e) Light-airplane mission. $\sigma = 0.90$.

Figure 10. – Concluded.



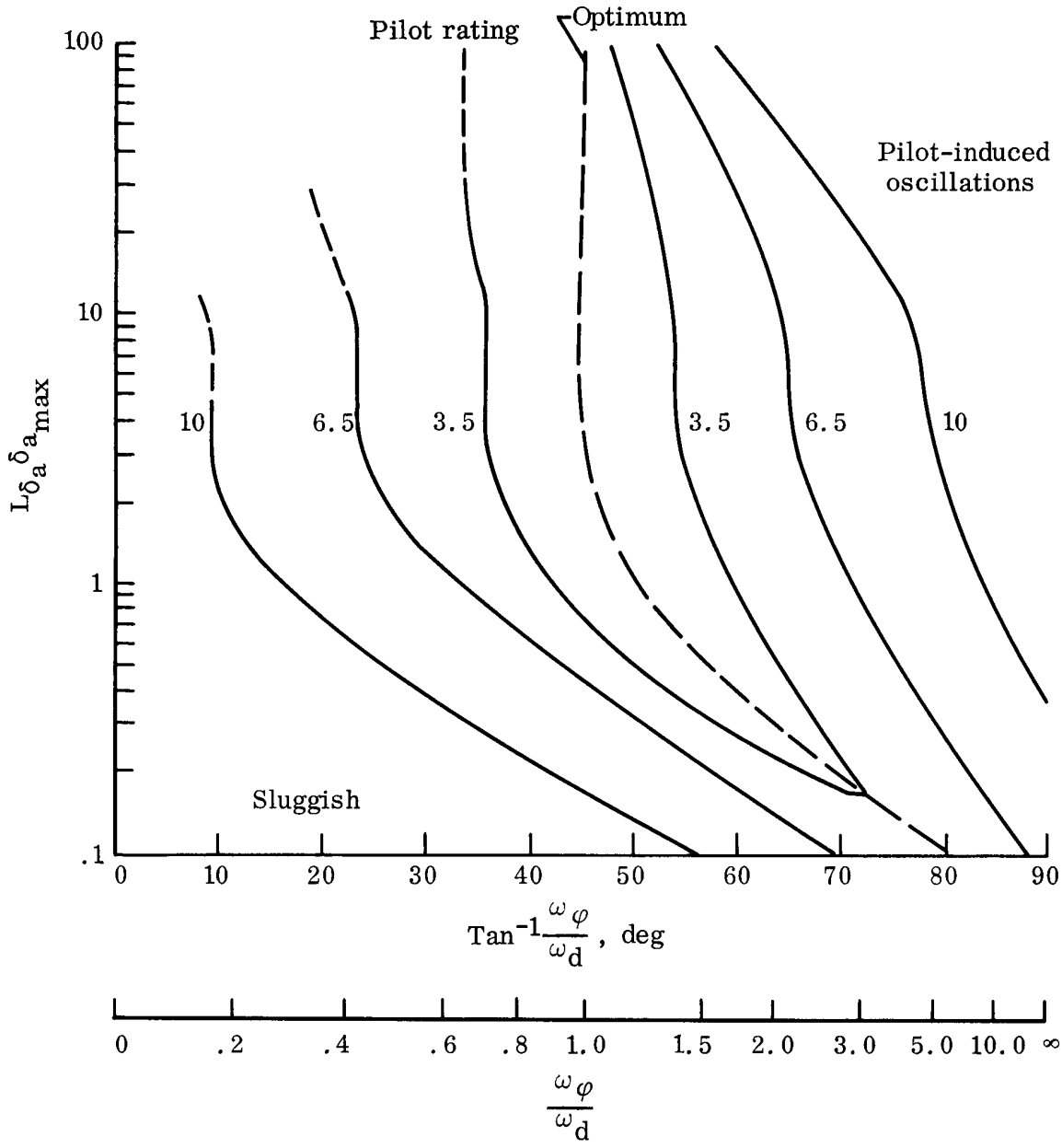
(a) Very low damping. $2\zeta_d\omega_d = 0.025$, $\frac{1}{\tau_r} = 0.1$.

Figure 11.– Pilot rating survey summary plots. $\omega_\varphi + \omega_d \geq 3.0$; $\left|L^*_\beta\right| > 10$.



(b) Low damping. $2\zeta_d\omega_d = 0.25$, $\frac{1}{\tau_r} = 1.0$.

Figure 11.– Continued.



(c) Moderate damping. $2\zeta_d\omega_d = 1.0$, $\frac{1}{\tau_r} = 4.0$.

Figure 11.– Concluded.

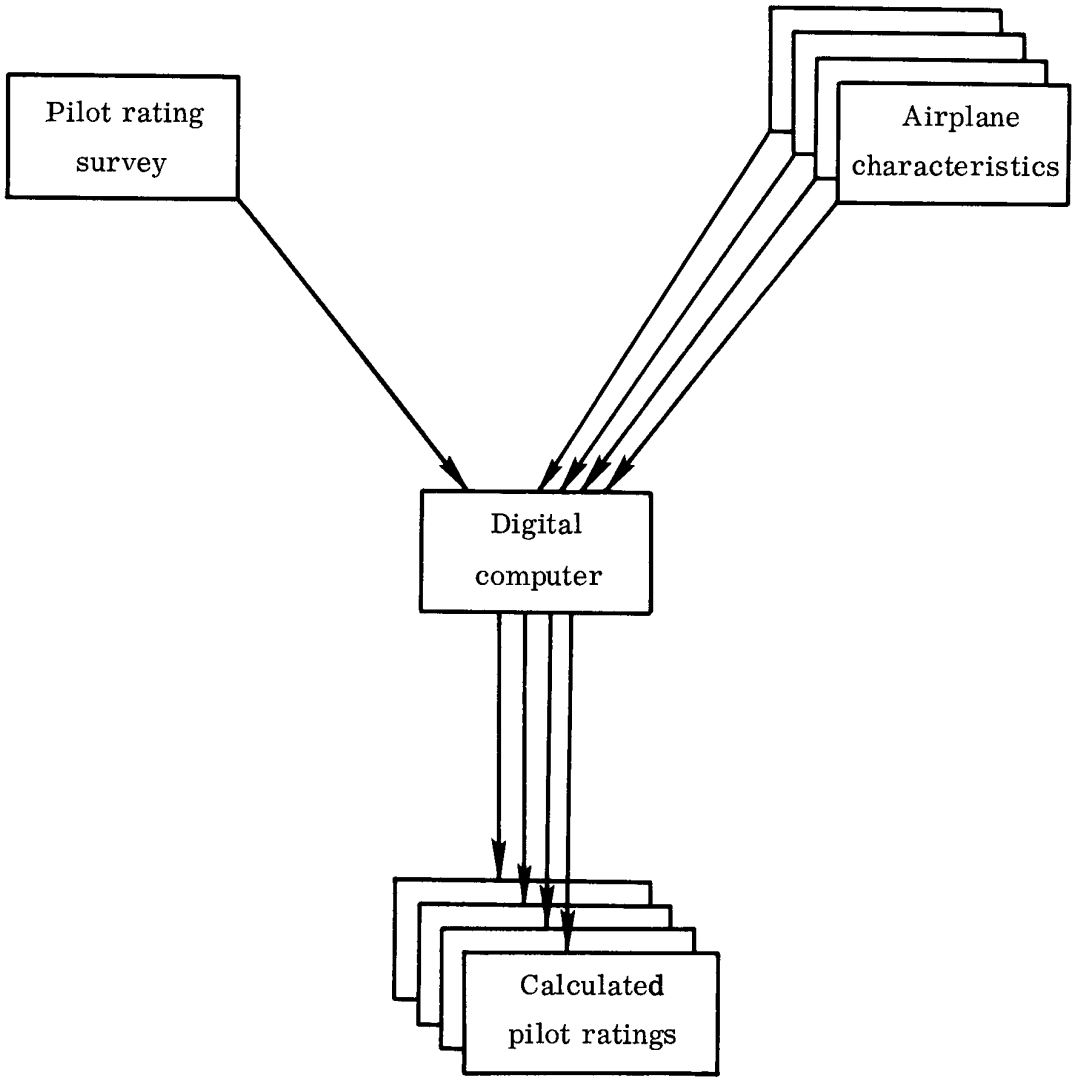


Figure 12.– Mechanization of prediction method.

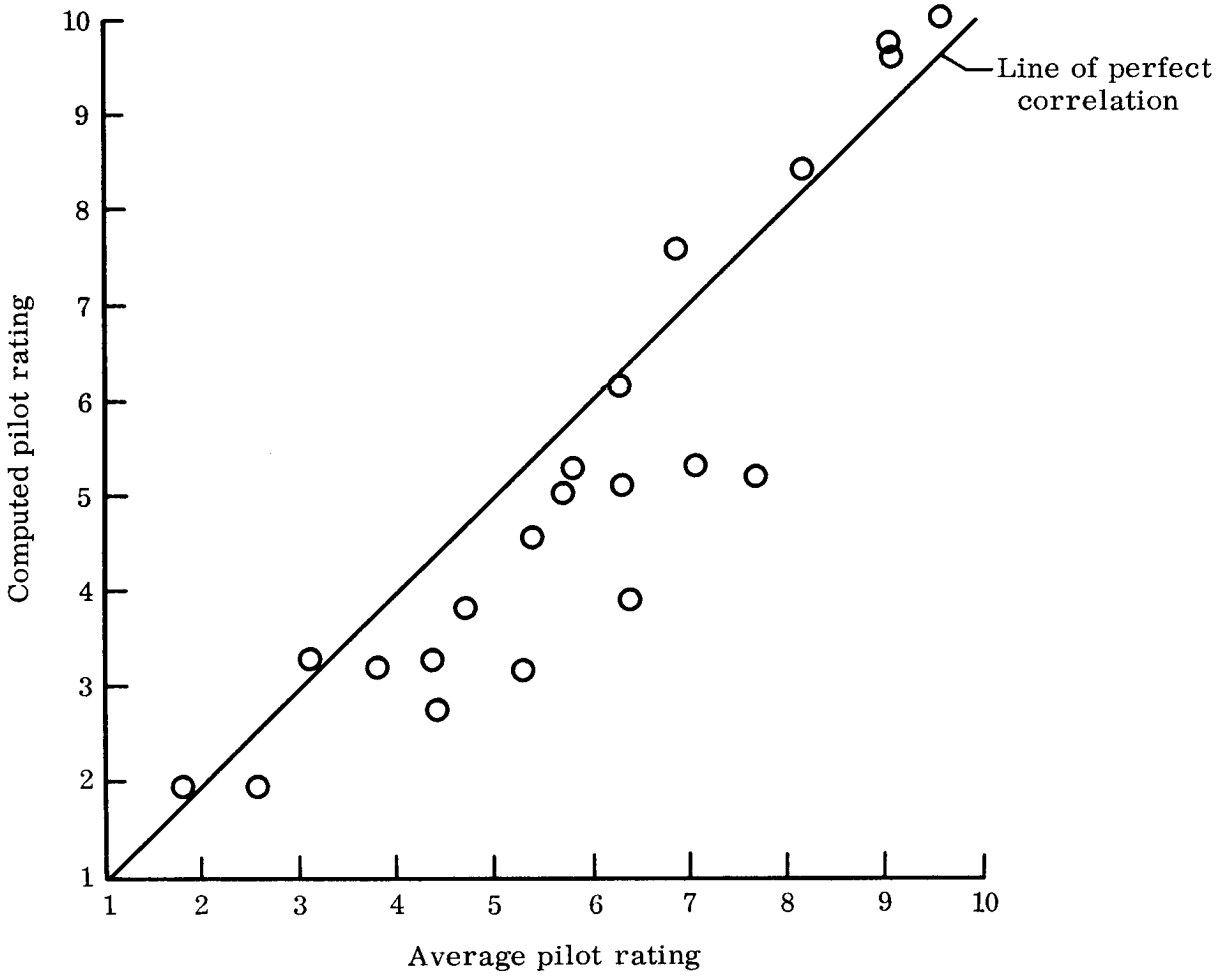


Figure 13. – Correlation of computed pilot ratings with the actual pilot average ratings. $\sigma = 1.00$.

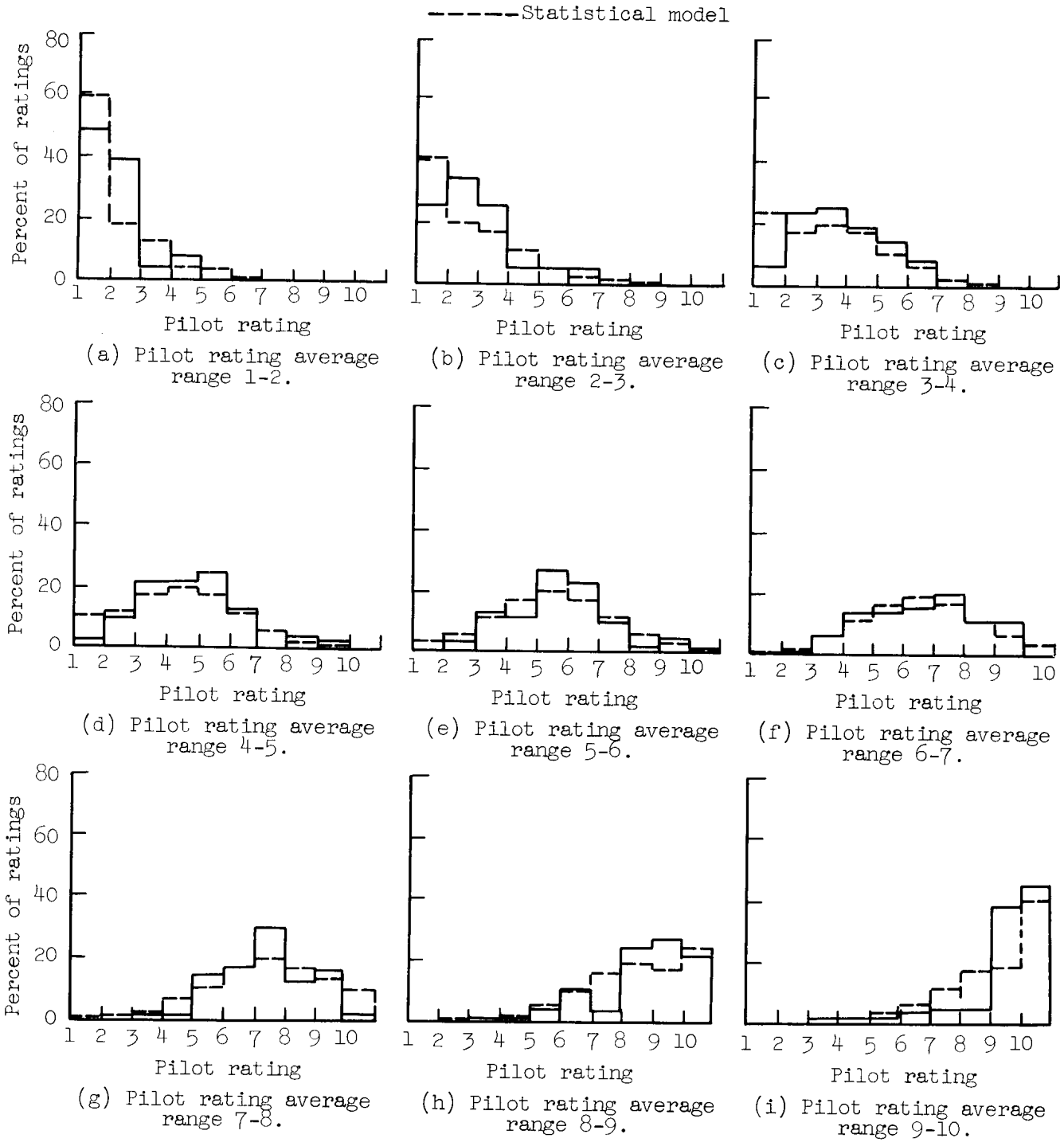


Figure 14. – Histograms for the variation in actual pilot ratings and the statistical model for various ranges of average pilot ratings.

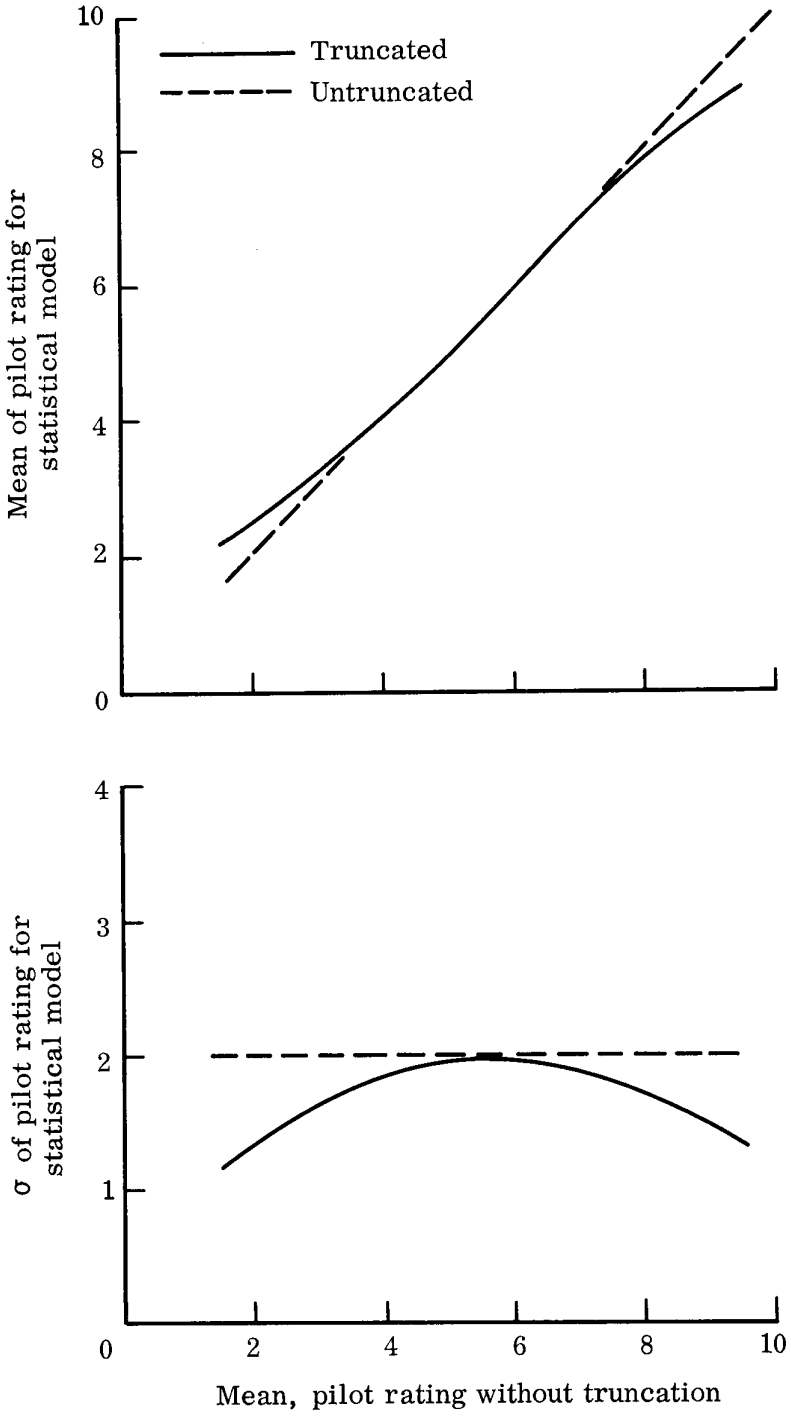


Figure 15. – Bias in measures of mean and variance of pilot ratings.