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AERONAUTICAL REPORT

LR-412

A FLIGHT INVESTIGATION OF THE INFLUENCE
OF VARIOUS LEVELS OF DIHEDRAL EFFECT ON
V/STOL AIRCRAFT DIRECTIONAL HANDLING QUALITIES

BY

D. M. MCGREGOR

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 DIRECTIONAL HANDLING QUALITIES.

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SUMMARY

An investigation into the influence of dihedral effect on the directional angular rate dampings and control sensitivities required for both normal and emergency operation was undertaken, using an airborne V/STOL simulator. The visual flight task performed by the pilots during the evaluation included hovering turns and a complete circuit terminated by a low speed, steep angle approach to touch-down. Both a simulated steady wind and synthetic lateral turbulence were introduced into the simulation to represent realistic flight conditions. As the dihedral effect was raised the normal operation boundaries moved to higher levels of both directional angular rate damping and control sensitivity, while the emergency operation boundaries were found to be essentially insensitive to this parameter.

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LIST OF SYMBOLS

<u>Symbol</u>	<u>Definition</u>
L_{δ_a}	Rolling control sensitivity due to aileron input, $\frac{\text{rad./sec.}^2}{\text{in. of aileron control}}$
L_v	Dihedral effect or rolling acceleration per unit lateral velocity $\frac{\text{rad./sec.}^2}{\text{ft./sec.}}$ or $\frac{1}{\text{ft.-sec.}}$
L_p	Angular rate damping in roll, $\frac{1}{\text{sec.}}$
M_{δ_e}	Pitching control sensitivity due to elevator input, $\frac{\text{rad./sec.}^2}{\text{in. of elevator control}}$
M_q	Angular rate damping in pitch, $\frac{1}{\text{sec.}}$
N_{δ_r}	Yawing control sensitivity due to rudder input, $\frac{\text{rad./sec.}^2}{\text{in. of rudder control}}$
N_v	Weathercock stability parameter or yawing acceleration per unit lateral velocity, $\frac{1}{\text{ft.-sec.}}$
N_r	Angular rate damping in yaw, $\frac{1}{\text{sec.}}$
Y_v	Side force per unit lateral velocity \div mass of simulator, $\frac{1}{\text{sec.}}$
Y_p	Side force due to rolling velocity \div mass of simulator, $\frac{\text{ft.}}{\text{rad.-sec.}}$
Y_r	Side force due to yawing velocity \div mass of simulator, $\frac{\text{ft.}}{\text{rad.-sec.}}$
Y_{δ_r}	Side force due to rudder control input \div mass of simulator, $\frac{\text{ft./sec.}^2}{\text{in.}}$
Y_{δ_a}	Side force due to aileron control input \div mass of simulator, $\frac{\text{ft./sec.}^2}{\text{in.}}$
$p, \dot{\phi}$	Angular rate of roll, rad./sec.
$q, \dot{\theta}$	Angular rate of pitch, rad./sec.

LIST OF SYMBOLS (Cont'd)

<u>Symbol</u>	<u>Definition</u>
$r, \dot{\psi}$	Angular rate of yaw, rad./sec.
ψ	Angle out of simulated wind for hovering. Simulator heading for forward flight
g	Acceleration due to gravity, 32.2 ft./sec. ²
h_R	Height of rotor above the centre of gravity
ad	Average deviation relative to the best least squares linear correlation
db	Decibel
I_{xx}	Rolling moment of inertia of the simulator, slug-ft. ²
I_{zz}	Yawing moment of inertia of the simulator, slug-ft. ²
l_t	Tail rotor distance aft of the centre of gravity
m	Mass of simulator, slugs
n	Number of test points used in correlation of pilots' ratings
$r. m. s.$	Root mean square
\bar{R}	Average pilot rating
S	Laplace operator
U	Airspeed used in forward flight simulation, 30 knots
U_o	Simulated wind speed, 15 knots
v	Lateral component of velocity, ft./sec.
v_g	Lateral gust velocity, ft./sec.
δ_a	Aileron control deflection measured at the pilot's hand, in.
δ_e	Elevator control deflection measured at the pilot's hand, in.
δ_r	Rudder pedal deflection, in.

LIST OF SYMBOLS (Cont'd)

<u>Symbol</u>	<u>Definition</u>
ω	Frequency, rad./sec.
Λ	Indicates a function of the Laplace Operator
ω_{ϕ}	Undamped natural frequency of numerator quadratic in roll to aileron transfer function
ω_D	Dutch roll mode undamped natural frequency
$C_{\frac{1}{2}}$	Cycles to one-half amplitude

Subscripts

g	Gust
H	Helicopter
m	Model
o	Trimmed condition
e	Equivalent

A FLIGHT INVESTIGATION OF THE INFLUENCE OF VARIOUS LEVELS OF
DIHEDRAL EFFECT ON V/STOL AIRCRAFT DIRECTIONAL HANDLING QUALITIES

1.0 INTRODUCTION

This investigation of the influence of the dihedral effect, L_v , (rolling acceleration per unit lateral velocity) on directional handling qualities in hovering and low speed flight, was a continuation of the investigations of the effects of various parameters on directional characteristics previously reported in References 1 and 2. In Reference 1 it was found that the weathercock stability was extremely important in determining the directional angular rate dampings and control sensitivities necessary for both normal and emergency operations.

The deterioration of the pilots' ratings found therein was due mainly to the large gust response at high values of weathercock stability. Since the dihedral parameter has an effect on the normal modes of yawing motion, and on an aircraft's directional behaviour in turbulent conditions, albeit secondary to that of the weathercock stability, determination of its influence on the handling qualities was undertaken.

Four values of L_v , covering the range expected to be significant for V/STOL aircraft, were investigated, together with many combinations of directional damping and control sensitivity. The results are presented as contours of constant pilot opinion separating the important areas on the damping-control sensitivity planes, and indicate that the dihedral effect has a significant influence on the pilot's opinion.

The experimentation was conducted using the airborne "Model-Controlled" V/STOL simulator (Fig. 1) described in Reference 3. In this simulation method an

electrical analogue of the equations of motion of the simulated aircraft is inserted between the evaluation pilot's electric flying controls and a three-axis autopilot. The autopilot moves the helicopter controls to keep the angular rates of the simulator about its three mutually perpendicular axes the same as those calculated by the equations of motion and, hence, as the pilot moves his controls, the resulting angular motions are those to be expected from the simulated vehicle. Figure 2 is a schematic drawing showing the principles of operation of this system. The responses in the translational degrees of freedom are dependent, in general, on the basic helicopter characteristics, since no means is at present provided to produce the forces necessary to alter these motions. The lateral translational degree is modified significantly, however, by the roll and yaw moment derivatives set on the "model".

Turbulence was introduced synthetically to disturb the simulator, and provided the pilots with an indication of how aircraft with various levels of dihedral effect would react to lateral gusts.

The tasks undertaken by the four pilots participating in this programme while evaluating the various combinations of derivatives tested consisted of hovering turns, accelerating transitions, circuit flying, constant angle approaches at constant speed, decelerating transitions, and landings. Each "model" was assigned a number on the N. A. S. A. Pilot Opinion Rating System, (reproduced in Fig. 3 from Ref. 4), which was recorded, along with verbal comments, by the safety pilot who also acted as programme manager.

The following sections contain the derivation of the equations of motion of the "model", the test procedure, and a discussion of the results.

2.0 DESCRIPTION OF THE "MODEL" EQUATIONS OF MOTION

The electrical analogue comprising the "model" was located in the system, as described in the preceding Section, and was wired according to the equations of motion of the rotational degrees of freedom of the simulated aircraft. This Section describes these equations.

All the stability derivatives pertaining to moments are the dimensional derivatives divided by the moment of inertia about the appropriate axis. Then, for example, the pitching control sensitivity, M_{δ_e} , has dimensions of $\frac{\text{rad./sec.}^2}{\text{in.}}$ resulting from the actual pitching moment per in. of longitudinal control ($\frac{\text{lb. ft.}}{\text{in.}}$) divided by the pitching moment of inertia (slug. ft.^2).

A sign convention is used wherein nose-up pitching, right rolling, and right yawing displacements and moments, and the control movements causing these changes, are positive.

The longitudinal and lateral control maximum deflections were ± 4 in. and ± 3 in., as recommended in Reference 4, while the rudder control moved $\pm 3\frac{1}{2}$ in. The control force gradients were: longitudinal stick, 1 1/4 lb./in.; lateral stick, 0.6 lb./in.; and rudder, 10 lb./in.

The control sensitivities were maintained constant for the full travel of the controls; hence, the control powers were merely the product of control sensitivities and maximum control movements.

The evaluation pilot was responsible for control of all six degrees of freedom of the simulator, but, since the tests reported herein were concerned with the dihedral effect on directional characteristics only, the longitudinal and lateral derivatives, other than L_v , were set at desirable levels. It is felt that

this procedure is appropriate since most stability augmentation systems are designed in such a way that any single failure will affect one channel only, leaving all others with their original desirable characteristics.

2.1 Pitching Motion

The longitudinal, pitching equation of motion was made as simple as practicable, while still presenting a realistic situation to the pilot. Hence, only two stability derivatives were included: the longitudinal control sensitivity, M_{δ_e} , and the angular rate damping in pitch, M_q .

The equation of motion for this mode was then

$$\ddot{\theta} = M_{\delta_e} \cdot \delta_e + M_q \cdot \dot{\theta} \quad (1)$$

The particular values selected for the above derivatives were

$$M_{\delta_e} = 0.287 \frac{\text{rad./sec.}^2}{\text{in. of longitudinal control}} \quad \text{and} \quad M_q = -2.29 \frac{1}{\text{sec.}}$$

These values presented the pilot with a pleasant model that required relatively little of his attention and are identical with those used in References 1 and 2.

Figure 4 shows the "patching" of the analogue computer to achieve the above characteristics as well as those described in subsequent Sections.

2.2 Rolling Motion

Since this investigation strove to determine the influence of the dihedral effect on directional flying qualities, it was considered necessary to keep the lateral characteristics desirable. To ensure this, a high damping in roll, L_p , was necessary to prevent the roll response to turbulence from being the main

source of concern to the pilot as L_v was increased. A value of $-10 \frac{1}{\text{sec}}$ for the roll damping was found to give acceptable results. With this high damping level a large control sensitivity was necessary to maintain an acceptable response to control input, and a value of $L_{\delta_a} = 1.72 \frac{\text{rad./sec}^2}{\text{in.}}$ was used.

The dihedral effect, L_v , assumed values of -0.01, -0.02, -0.035, and -0.05, thus covering a large range of this parameter through which V/STOL aircraft of comparable size to this simulator will likely pass during transition.

Synthetic lateral turbulence, v_g , was constructed as described in Section 2.5, and was introduced into the rolling and yawing equations of motion to produce realistic flight conditions.

The rolling equation of motion was then

$$\ddot{\phi} = L_{\delta_a} \cdot \delta_a + L_p \cdot \dot{\phi} + L_v \cdot v + L_v v_g \quad (2)$$

The derivation of the lateral velocity, v , was obtained differently in hovering and during forward flight and is explained in Sections 2.6.1 and 2.6.2.

Figure 4 shows how gain-setting potentiometers C, D, and E, which were readily available to the safety pilot in the cockpit, controlled the level of the dihedral effect.

2.3 Yawing Motion

The investigation of the influence of the dihedral effect on the directional angular rate damping, N_r , and the directional control sensitivity, N_{δ_r} , necessary for normal and emergency operations, was the main purpose of this work. In addition to these two parameters, a representative level of weathercock stability, N_v , was

incorporated to produce a realistic effect and was held constant throughout the investigation at $0.02 \frac{1}{\text{ft.} \cdot \text{sec.}}$.

The yawing equation of motion was then

$$\ddot{\psi} = N_{\dot{\delta}_r} \cdot \dot{\delta}_r + N_r \cdot \dot{\psi} + N_v \cdot v + N_{v_g} \cdot v_g \quad (3)$$

The damping and control sensitivities were varied over different ranges for each value of L_v in an attempt to keep the number of data points reasonable while still allowing accurate definition of the important areas of the pilot opinion contours separating the significant regions on the $N_{\dot{\delta}_r} - N_r$ plane. Figures 7 and 8 show the combinations of the damping and control sensitivity tested for $L_v = -0.01$ and contain the averages of the pilots' opinions to illustrate the gradients found across the plane.

Gain-setting potentiometers A and B were available to the safety pilot in the cockpit, and set the directional damping and control sensitivity levels as indicated in Figure 4.

2.4 Derivation of the Lateral Velocity Effect

The task performed by the pilots while assessing the effects of the various combinations of the parameters investigated was basically the same as that used in the experiments reported in References 1 and 2. This included hovering turns, forward manoeuvring flight and low speed approaches, the details of which are found in Section 3.4. A meaningful simulation of the dihedral effect, L_v , could be obtained only if the effects of realistic lateral velocities, corresponding to hovering out of wind and to side-slips in forward flight, were included. This was

accomplished by including a simulated 15-knot wind for hovering flight and by measuring the actual helicopter side-slip angle during translation with a vane mounted well forward on the simulator. How these signals are utilized in the model may be seen in the circuit diagram of Figure 4, and a more detailed explanation of their derivation and use is contained in Reference 2.

2.5 Simulated Turbulence

A signal produced from the random counts of a Geiger tube, as suggested in Reference 5, was used to disturb the roll and yaw models with synthetic lateral gusts. The main portion of the experimentation was conducted utilizing the same turbulence spectral shape as that employed in Reference 1 and derived from the circuit presented therein. Curve "A" of Figure 5 shows the variation of the power spectral density signal initially used to represent the turbulence. All the data used in drawing the pilot opinion contours were obtained using this spectrum. It was subsequently felt, however, that a more realistic representation of low level turbulence should contain somewhat more power in the low frequency range, as shown by curve "B" of Figure 5. The shaping of the signal to obtain this spectral density variation was accomplished with analogue computer components. Twelve models, with a wide variety of dampings and control sensitivities at a constant L_V of 0.035, were flown to evaluate the effect of the alteration of turbulence shape, and indicated that the pilot was apparently insensitive to the change. The r. m. s. value of both gust intensity signals was set to be equivalent to approximately 8.9 ft./sec. using the entire frequency spectrum. It would appear that truncating the spectrum, as is normally done to derive this parameter from flight test data (see Ref. 6), would reduce the equivalent gust intensity to approximately 5 ft./sec.

2.6 Derivation of the Normal Modes of Directional Motion

Since the effective lateral velocity used in the simulation was obtained in different ways during hovering and forward flight, the resulting normal modes of directional motion were also different.

2.6.1 Hovering Flight

During hovering flight the effects of turning out of a 15-knot wind were incorporated in the simulation. This "wind" blew from the direction in which the simulator was heading at the time the evaluation pilot entered hovering flight: consequently, to hover over a given spot, it was necessary for him to apply the proper amount of rudder and lateral control to prevent drifting downwind during hovering turns.

The lateral velocity, v , of equation (3) was given by $v = -U_o \text{Sin}\psi$ where ψ is the angle out of the simulated wind. Equation (3) may then be written

$$\ddot{\psi} = N_{\delta_r} \cdot \delta_r + N_r \cdot \dot{\psi} - U_o N_v \text{Sin}\psi + N_v \cdot v_g \quad (4)$$

which, by the small perturbation analysis of Reference 1, yields a second order oscillatory mode of motion with natural frequency $\sqrt{U_o N_v \text{Cos}\psi_o}$ and damping ratio $\frac{-N_r}{2\sqrt{U_o N_v \text{Cos}\psi_o}}$. Thus, when trimmed into wind ($\psi_o = 0$), the frequency is simply

$\sqrt{U_o N_v}$; when trimmed cross-wind, the directional response to rudder input becomes that of a simple first-order system with a time constant of $-\frac{1}{N_r}$; and

when trimmed down wind, the mode is statically unstable, having a divergent root

$$\text{of } \frac{N_r}{2} \left(1 - \sqrt{1 + \frac{U_o N_v}{(N_r/2)^2}} \right) \text{ and a convergent root of } \frac{N_r}{2} \left(1 + \sqrt{1 + \frac{U_o N_v}{(N_r/2)^2}} \right).$$

It will be noted that nowhere in the above analysis does the dihedral effect, L_v , appear; hence, the yawing equation of motion in the hover was independent of this parameter.

2.6.2 Forward Flight

The lateral-directional equations of motion during forward flight must include the side force equation, since the lateral velocity was derived from a side-slip vane mounted on the helicopter. The three required equations, written using the Laplace Operator, are

$$\begin{aligned} \text{Helicopter Side Force: } (S-Y_v)\hat{v} - (Y_p S+g)\hat{\phi} + (U-Y_r)\hat{\psi} &= Y_{\delta_r} \cdot \hat{\delta}_r + Y_{\delta_a} \cdot \hat{\delta}_a + Y_v \cdot \hat{v}_g \\ \text{Model Rolling: } -L_v \cdot \hat{v} + S(S-L_p)\hat{\phi} &= L_{\delta_a} \cdot \hat{\delta}_a + L_v \cdot \hat{v}_g \\ \text{Model Yawing: } -N_v \cdot \hat{v} + (S-N_r)\hat{\psi} &= N_{\delta_r} \cdot \hat{\delta}_r + N_v \cdot \hat{v}_g \end{aligned}$$

The side force derivatives are the dimensional force derivatives divided by the helicopter mass and are functions of the simulated moment derivatives in the equations of motion as follows (assuming the fuselage forces are negligible):

$$\begin{aligned} Y_v &= \frac{1}{h_R} \frac{I_{XX}}{m} L_v - \frac{1}{l_t} \frac{I_{ZZ}}{m} N_v = 1.3 L_v - 0.8 N_v \\ Y_p &= \frac{1}{h_R} \frac{I_{XX}}{m} L_p = 1.3 L_p \\ Y_r &= -\frac{1}{l_t} \frac{I_{ZZ}}{m} N_r = -0.8 N_r \\ Y_{\delta_r} &= -\frac{1}{l_t} \frac{I_{ZZ}}{m} N_{\delta_r} = -0.8 N_{\delta_r} \\ Y_{\delta_a} &= \frac{1}{h_R} \frac{I_{XX}}{m} L_{\delta_a} = 1.3 L_{\delta_a} \end{aligned}$$

Using the above expressions for the lateral derivatives, the lateral-directional equations of motion are,

$$\begin{aligned}
 (S - 1.3 L_v + 0.8 N_v) \hat{v} - (1.3 L_p S + g) \hat{\phi} + (U + 0.8 N_r) \hat{\psi} \\
 &= - 0.8 N_{\delta_r} \cdot \hat{\delta}_r + 1.3 L_{\delta_a} \cdot \hat{\delta}_a + (1.3 L_v - 0.8 N_v) \hat{v}_g \\
 - L_v \cdot \hat{v} + S (S - L_p) \hat{\phi} &= L_{\delta_a} \cdot \hat{\delta}_a + L_v \cdot \hat{v}_g \\
 - N_v \cdot \hat{v} + (S - N_r) \hat{\psi} &= N_{\delta_r} \cdot \hat{\delta}_r + N_v \cdot \hat{v}_g
 \end{aligned}$$

The characteristic equation is

$$\begin{aligned}
 S^4 - (L_p + N_r + 1.3 L_v - 0.8 N_v) S^3 + \left((L_p + 1.3 L_v) N_r + (U - 0.8 L_p) N_v \right) S^2 \\
 - (g L_v + U L_p N_v) S + g L_v N_r = 0
 \end{aligned}$$

The derivatives N_v and L_p were constant throughout the investigation at values of 0.02 and -10 respectively, giving the following characteristic equation for $U = 50.6$ ft./sec. (30 knots),

$$\begin{aligned}
 S^4 + (10.016 - N_r - 1.3 L_v) S^3 + \left((1.3 L_v - 10) N_r + 1.172 \right) S^2 \\
 + (10.12 - 32.2 L_v) S + 32.2 L_v N_r = 0
 \end{aligned}$$

The lateral-directional modes of motion computed from the above characteristic equation consist of a roll subsidence mode having a time constant

of about 0.1 sec., essentially independent of L_v and N_r , and directly attributable to the roll damping, L_p ; a spiral mode having a large time constant at low N_r and decreasing to about 0.2 sec. at $N_r = -5$, again essentially independent of L_v ; and a Dutch roll mode. The Dutch roll mode has a period of about 6 sec. for moderate values of yaw damping ($-N_r < 1.5$) and is well damped for $-N_r > 0.5$. For values of $-N_r > 2$, the period increases (to 18 sec. for $-N_r = 6$) and the oscillation remains well damped. The period and damping are relatively insensitive, however, to the value of L_v . The roll-to-yaw ratio, on the other hand, increases in proportion to both $|L_v|$ and $|N_r|$, the oscillation being predominantly yaw at low values of $|L_v|$ and $|N_r|$ and mainly roll at the highest values of these parameters used in the investigation.

3.0 TEST PROCEDURES

3.1 Selection of Model Parameters

A great many combinations of the three variables, dihedral effect, L_v , yawing control sensitivity, N_{δ_r} , and angular rate damping in yaw, N_r , were investigated. L_v assumed values of -0.01, -0.02, -0.035, and -0.050, while a sufficient number of values of N_{δ_r} and N_r were tested to allow plotting of the limits of the significant areas on the $N_{\delta_r} - N_r$ plane for each value of L_v with a high degree of confidence.

For each flight the safety pilot was given a programme card containing six settings for each of the cockpit-mounted potentiometers (pots. A to E of Fig. 4) controlling these derivatives. These cards contained a random selection of all three variables chosen to ensure that the evaluation pilot did not have models of all the same type of characteristics in any given flight. In addition, a model with

pleasant characteristics (the "standard model" of Fig. 7) was flown on each trip from the hangar area to the test site (about three miles distance) to allow the pilot to "calibrate" himself and to ensure that the over-all system was operating correctly.

All models were assessed separately on their hovering and forward flight characteristics and were flown by at least two of the four pilots.

3.2 The Visual Approach Aid

A constant angle - constant speed approach was part of the flight task undertaken by the pilots during this investigation. To supply them with an indication of the glide path angle, a visual indicator was prepared as sketched in Figure 6. This device consists of two large boards of different colours, located to give the pilot an easily interpreted high or low indication of position relative to the desired 11-degree path throughout the entire approach. The sensitivity was such that the rear board was fully exposed above or below the front board when the glide path error was ± 4 degrees.

To allow the approaches to be made into the actual wind, the entire apparatus was rotated to align it with the surface wind. A similar apparatus was used successfully in Reference 1.

3.3 Pilots

Four pilots of widely varying backgrounds participated in this programme. Table I contains a resumé of their individual flying experience. Pilots A, B, and C were thoroughly familiar with the flying operation of the simulator and each flew a large number of test points. Pilot D, who had very little experience with the simulator, or with helicopters of the type used, but had flown 20 different types of helicopters as well as many fixed wing aircraft, flew a lesser number of models.

The varied experience of the pilots was not reflected significantly in their ratings of the characteristics tested, since the average deviation for each pilot from the others was quite low (e. g. see Fig. 11).

3.4 Flight Procedure

A visual flight task was performed by the pilots while assessing the characteristics of the various models. During the evaluation, the pilot had to control the motions in all six degrees of freedom as well as maintain a reasonably constant rotor speed, since no engine-governing system is installed in this aircraft.

Before take-off the safety pilot adjusted the gain-setting potentiometers to the proper levels for the model to be tested (potentiometers A to E of Fig. 4). He then lifted the helicopter into the hover, facing into the surface wind. After engaging and trimming the autopilot, the analogue computer, used to construct the model, was switched to its "Operate" mode and the evaluation pilot took complete control. He then carried out a series of hovering manoeuvres wherein the simulator was held into the simulated (15-knot) wind, turned across the wind to right and left, and turned tail to wind from both directions. The variation of the simulated wind with heading (following the sine law built into the computer) ensured that a realistic rudder application was necessary during these turns. In addition, the artificial turbulence allowed the pilot to experience disturbances representative of normal flight conditions in the presence of the selected characteristics.

After completing the above manoeuvres, the evaluation pilot related his assessment of the model up to that point to the safety pilot, and accelerated the simulator through transition to a climbing speed of 40 knots. At approximately 30 knots the "Hover-Forward Flight" switch (Fig. 4), controlling the modes of

interpreting side velocity in the model, was actuated by the safety pilot. A normal circuit was then accomplished at 500 ft. above ground until the helicopter was lined up on the approach to the visual glide path aid (Fig. 6) that had been aligned with the surface wind at the start of the flight. The airspeed was then reduced to 30 knots at constant altitude and was held throughout the approach. Upon intercepting the 11-degree glide path, a constant angle - constant speed approach was attempted down to the flare, when the ground speed was reduced to zero and the simulator was landed as soon as the pilot was able to do so safely. As the airspeed passed through 20 knots during the flare, the safety pilot returned the previously mentioned switch to its "Hover" position.

The evaluation pilot's assessments of the model in the hover and in the circuit were rated, using the N. A. S. A. Pilot Opinion Rating System (Fig. 3), and were recorded along with his verbal comments describing its outstandingly bad or good features.

The safety pilot then reset the cockpit-mounted potentiometers to the appropriate values for the next model and the above procedures were repeated.

4.0 RESULTS AND DISCUSSION

The results of this investigation are presented as contours of constant pilot opinion separating the regions of Normal Operation and Emergency Operation ($3\frac{1}{2}$ boundary), and Emergency Operation and No Operation ($6\frac{1}{2}$ boundary) on directional damping, control sensitivity planes. Four values of dihedral effect, $L_v = -0.01, -0.02, -0.035$ and -0.050 were tested, together with many combinations of directional damping and control sensitivity. In all, 119 test points were flown with each being evaluated by at least two of the four pilots.

Figures 7 and 8 present the handling qualities boundaries for the hovering and the circuit flying task determined for the lowest value of L_v tested (-0.01), and contain the points flown as well as the averages of the evaluations assigned by the pilots. The gradients across the plane illustrate that, although the contours are drawn as distinct lines, shaded areas would be more appropriate to represent the transition from one region to the next. The extent of these zones is very difficult to ascertain, however, and the boundaries shown are meant to represent their mid-paths.

Separate evaluations were made for the hovering and the circuit and landing phases of the task. The respective results call attention to the effect of airspeed on the pilot opinion boundaries and, therefore, may be used to predict the behaviour of an aircraft having a dihedral effect varying with airspeed.

Figures 9 and 10 show the handling qualities boundaries determined for all the values of dihedral effect tested for both the hovering and circuit flying phases of the task.

Initial flight testing to determine a single combination of roll rate damping and lateral control sensitivity acceptable over the entire range of dihedral effect showed a very distinct dependence of the former quantities on the latter, since only very large values of damping and control sensitivity were suitable in the presence of a large L_v , while much lower levels were satisfactory when L_v was numerically small. The details of the influence of dihedral effect on rolling characteristics require further investigation.

4.1 Hovering Results

Although the description of the equations of motion of Section 2.6.1 shows

that the dihedral effect, L_v , does not enter into the directional or yawing equation of motion for hovering flight, it was found that the $3\frac{1}{2}$ boundaries on the directional damping versus control sensitivity plane were sensitive to this parameter (Fig. 9). As L_v was increased from -0.01 to -0.05, the minimum damping required for normal operation increased from -2.3 to -4.9, with the major portion of this change occurring as L_v changed from -0.01 to -0.02, while the last step in L_v (from -0.035 to -0.05) caused only a minor increase in damping required. It would appear that the pilots insisted on these increased damping levels to make the control of the yaw degree of freedom increasingly more desirable as rolling motion demanded more attention, for, although the roll damping and control sensitivity had been set at desirable levels, this mode of motion became increasingly difficult to fly as L_v was increased. Retention of a reasonable yawing rate in the presence of these high damping levels required increased directional control sensitivities, that the pilots demanded before assigning a rating of three or less.

The results of Reference 1 for $N_v = 0.02$ (as used herein) and zero dihedral effect (i. e., $L_v = 0$) are included for comparison, and although the roll damping and control sensitivity were different for that investigation, it is seen that the positions of the curves agree well with the results reported here.

The $6\frac{1}{2}$ boundaries follow no consistent trend with changing dihedral effect and, in fact, seem to be insensitive to this parameter. This is probably due to the fact that the pilot does not insist on precise control when the characteristics are in this region on the rating scale, and even the rather severe variation in L_v investigated was not sufficient to result in changes in the $6\frac{1}{2}$ directional boundaries.

4.2 Forward Flight, Landing Results

The movements of the handling qualities boundaries (Fig. 10) for the circuit flying, landing phase of the task follow the same trends as those for the hovering portion. Somewhat more damping was required for normal operation and, at the higher values of dihedral effect, slightly lower control sensitivities were acceptable to the pilots in this mode of flight.

At low dampings, the pilots mainly objected to the disturbances caused by the turbulence and they insisted on dampings high enough to keep these motions small. As mentioned in Section 2.6.2, the amount of yawing motion associated with the Dutch roll mode decreased markedly with increased directional damping. This was especially true at the high values of L_V where, for damping levels in the region of the $3\frac{1}{2}$ boundaries, the motion was predominantly a rolling oscillation. This is one possible reason for the minor change detected in the $3\frac{1}{2}$ boundaries for the two largest values of dihedral effect tested.

On the other hand, the damping ratio of the Dutch roll mode is such that the oscillatory behaviour of this motion is well damped for values of N_r much less than the minimum levels needed for a $3\frac{1}{2}$ rating and, thus, could not be the bothersome feature to the pilots. (See discussion of modes in Section 2.6.2.) The required damping, then, appears to be determined by the response of the spiral mode to turbulence rather than by the character of the Dutch roll mode.

As for the hovering assessments, the boundaries of the emergency operation regions were found to vary little with dihedral effect and, in fact, the differences between the curve for the lowest value of L_V tested are insignificantly different from that for the highest value investigated.

As in the previous Section, the applicable curves from Reference 1 have been included in Figure 10. The $3\frac{1}{2}$ boundary from that report indicates a higher level of damping required than suggested by an extrapolation of the results determined here. The $6\frac{1}{2}$ boundary is essentially similar to the results of this investigation.

4.3 Correlation of Pilots' Ratings

The method outlined in the Appendix of Reference 1 was used to obtain the correlation of each pilot with all the rest, and for pilot A yielded the relation shown in Figure 11. It can be seen that the agreement found was excellent in that the slope of the line relating his ratings with the others was very nearly unity and the average deviation of the ratings was quite low. This was also the case for the other three pilots, where the average deviations were 0.53, 0.43 and 0.68 for pilots B, C, and D, respectively. Pilot D did the least flying on the programme, was relatively unfamiliar with the helicopter used as the simulator, and was introduced to the N. A. S. A. pilot rating system during this programme. However, even an average deviation of 0.63 is considered quite acceptable.

4.4 Comparison of Dutch Roll Characteristics with Specifications

The results of this investigation were compared with the lateral-directional requirements of References 4 and 7 and with the $\frac{\omega_{\phi}}{\omega_D}$ ratio of Reference 8.

As was found in Reference 1, the damping ratios suggested as being adequate for lateral-directional modes of oscillatory motion in the AGARD recommendations (Ref. 4) were much too low for both normal and emergency operations.

A comparison of several combinations of the damping parameter, $\frac{1}{C_{1/2}}$, and the $\left| \frac{\phi}{v_c} \right|$ ratio with the requirements of Reference 7 indicates a large disagreement with the curves published therein. Figure 12 contains several points tested for $L_v = -0.05$ and shows the pilot ratings at the directional control sensitivity that gave the best correspondence between these results and the curves A and B. It can be seen that, even though all the points shown are in the acceptable region of the requirements, all but one received a rating greater than 3.

Reference 8 suggests that the $\frac{\omega_\phi}{\omega_D}$ ratio (see list of symbols) is an important parameter in determining lateral-directional handling qualities, with an optimum rating occurring when this ratio is close to unity and degrading very rapidly as it changes on either side of this value. This result was not verified during these tests, where optimum pilot ratings were assigned in the presence of large values of $\frac{\omega_\phi}{\omega_D}$ (greater than 3).

The above discussion is not meant to imply that the references cited are in error, but rather than the characteristics of the Dutch roll mode were not the dominant factors in this investigation.

It would appear that the spiral mode was decisive in determining the damping levels found necessary for normal operation during these tests, and these, in turn, were dictated mainly by the response of this mode of motion to turbulence.

5.0 CONCLUSIONS

From a flight investigation of the influence of various levels of dihedral effect on desirable and minimum acceptable directional handling qualities, the

following conclusion may be drawn:

(1) The boundaries ($6\frac{1}{2}$ contours) defining the minimum acceptable region on the directional control sensitivity, directional rate damping plane do not appear to be influenced by the level of dihedral effect, even over a very wide range of this parameter.

(2) The minimum satisfactory boundaries ($3\frac{1}{2}$ contours) moved to significantly higher levels of both damping and control sensitivity as the dihedral effect increased at low values, but at higher values a rather small shift was detected. This would imply that, if a V/STOL aircraft possesses a large dihedral effect and poor directional characteristics, then a large decrease in dihedral effect would be needed to improve the directional handling qualities significantly.

(3) From preliminary indications obtained during this programme it would appear useful to investigate the influence of dihedral effect on lateral (or rolling) control sensitivity and damping.

(4) The influence of turbulence appeared to be more important than the characteristics of the oscillatory normal mode of motion of the simulator in determining desirable handling qualities boundaries.

6.0 ACKNOWLEDGEMENT

The assistance afforded by Canadair Limited in providing one of the pilots for this programme is gratefully acknowledged.

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/LES

TABLE I

PILOT	FIXED WING, PROPELLER	FIXED WING, JET	ROTARY WING
A	250	250	690
B	1900	6	400
C	3700	400	1000
D	2200	100	2050

SUMMARY OF PILOTS' FLYING EXPERIENCE, (HOURS).



VIEW OF SIMULATOR

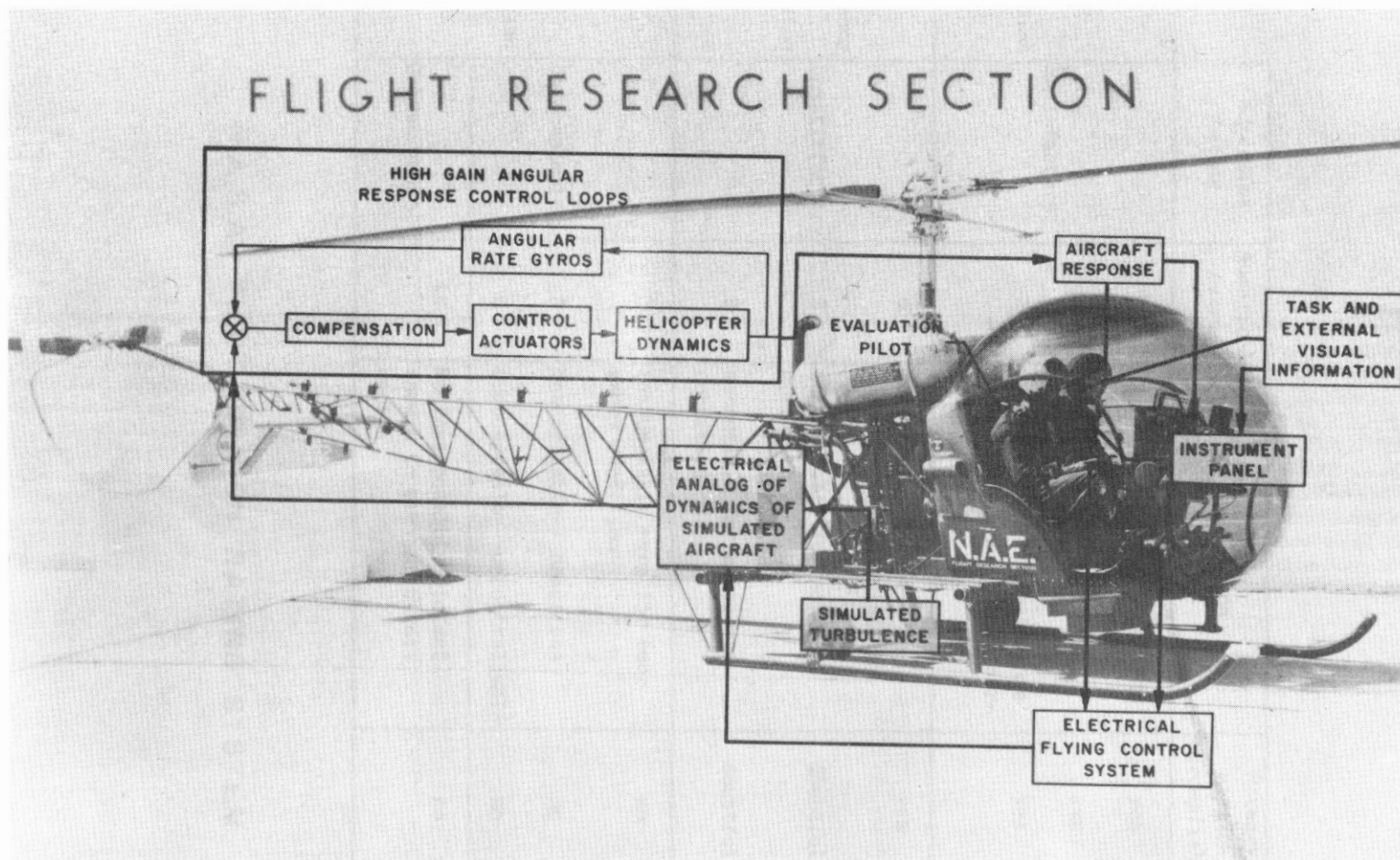
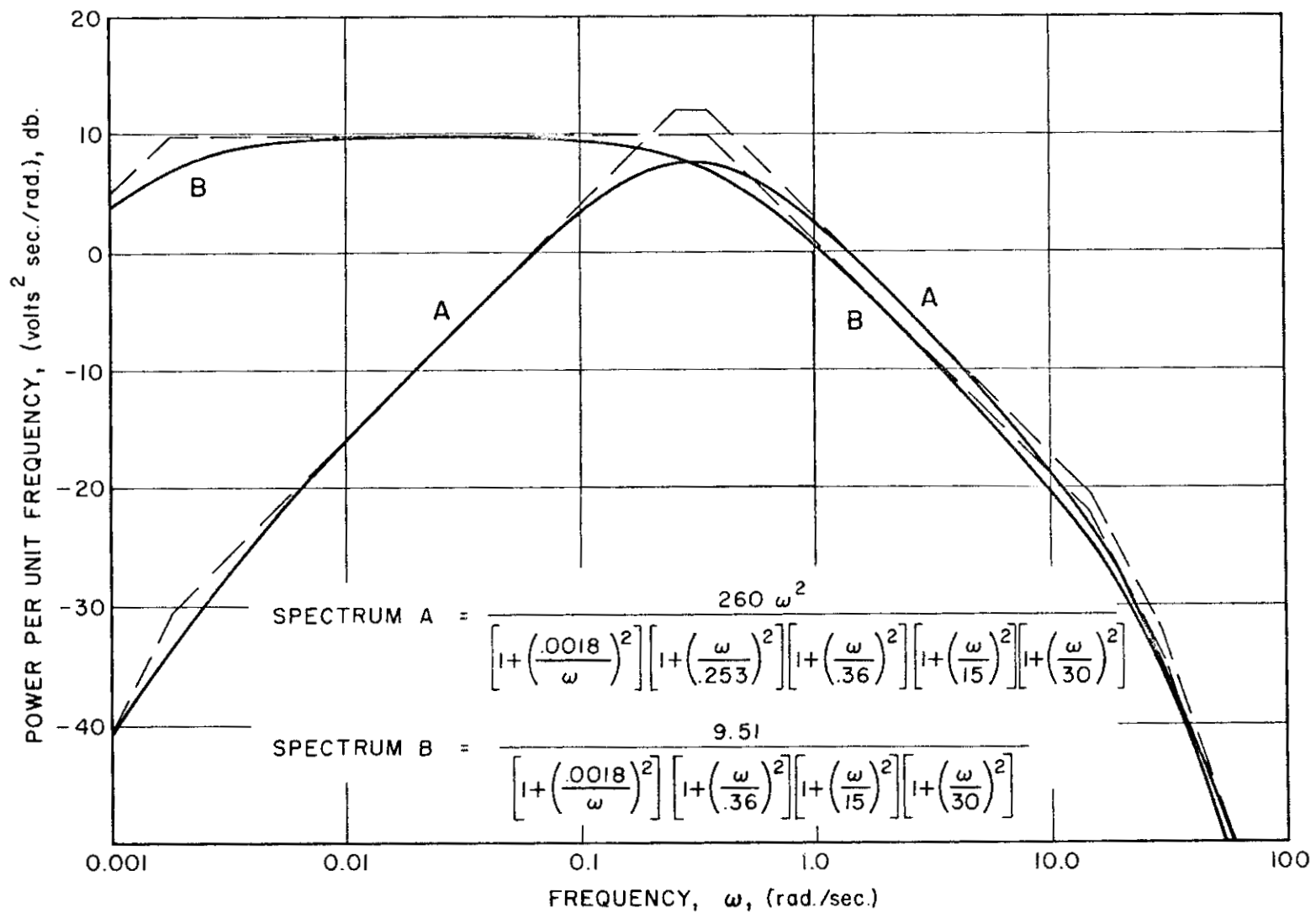


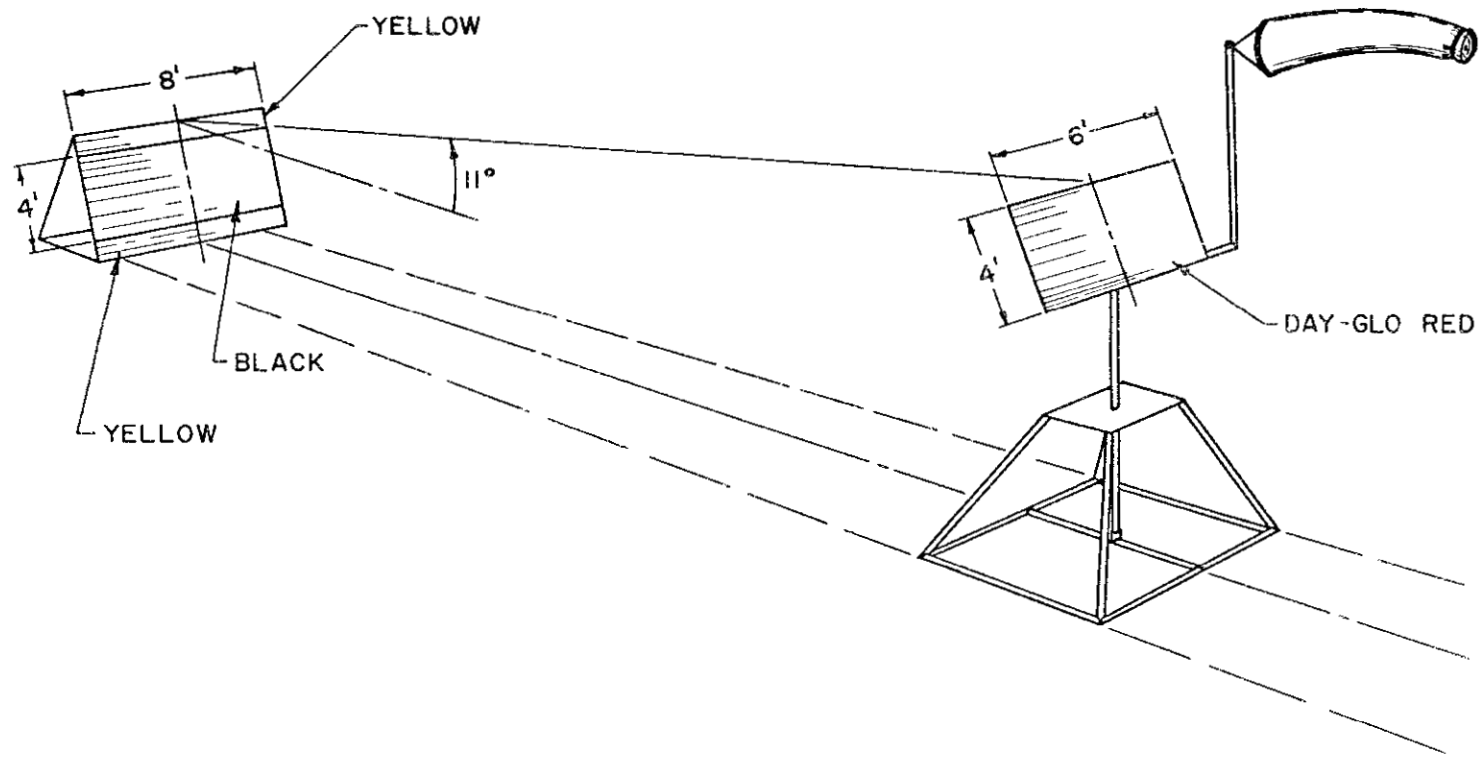
DIAGRAM OF SIMULATOR SYSTEM

	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	yes	yes
		2	Good, pleasant to fly	yes	yes
		3	Satisfactory, but with some mildly unpleasant characteristics	yes	yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	yes	yes
		5	Unacceptable for normal operation	doubtful	yes
		6	Acceptable for emergency condition only	doubtful	yes
No operation	Unacceptable	7	Unacceptable even for emergency condition	no	doubtful
		8	Unacceptable - dangerous	no	no
		9	Unacceptable - uncontrollable	no	no
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	no	no

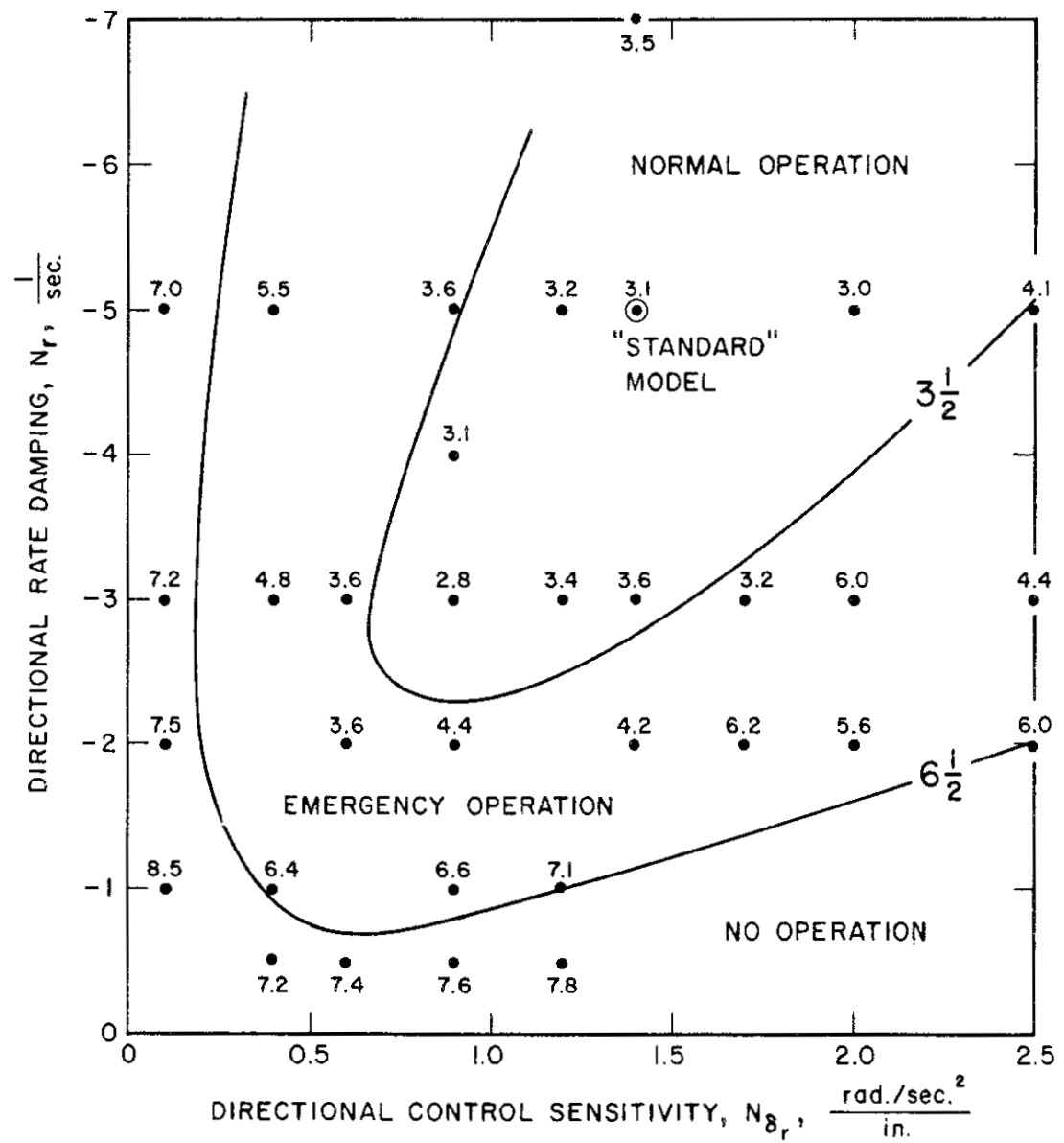
N.A.S.A. PILOT OPINION RATING SYSTEM



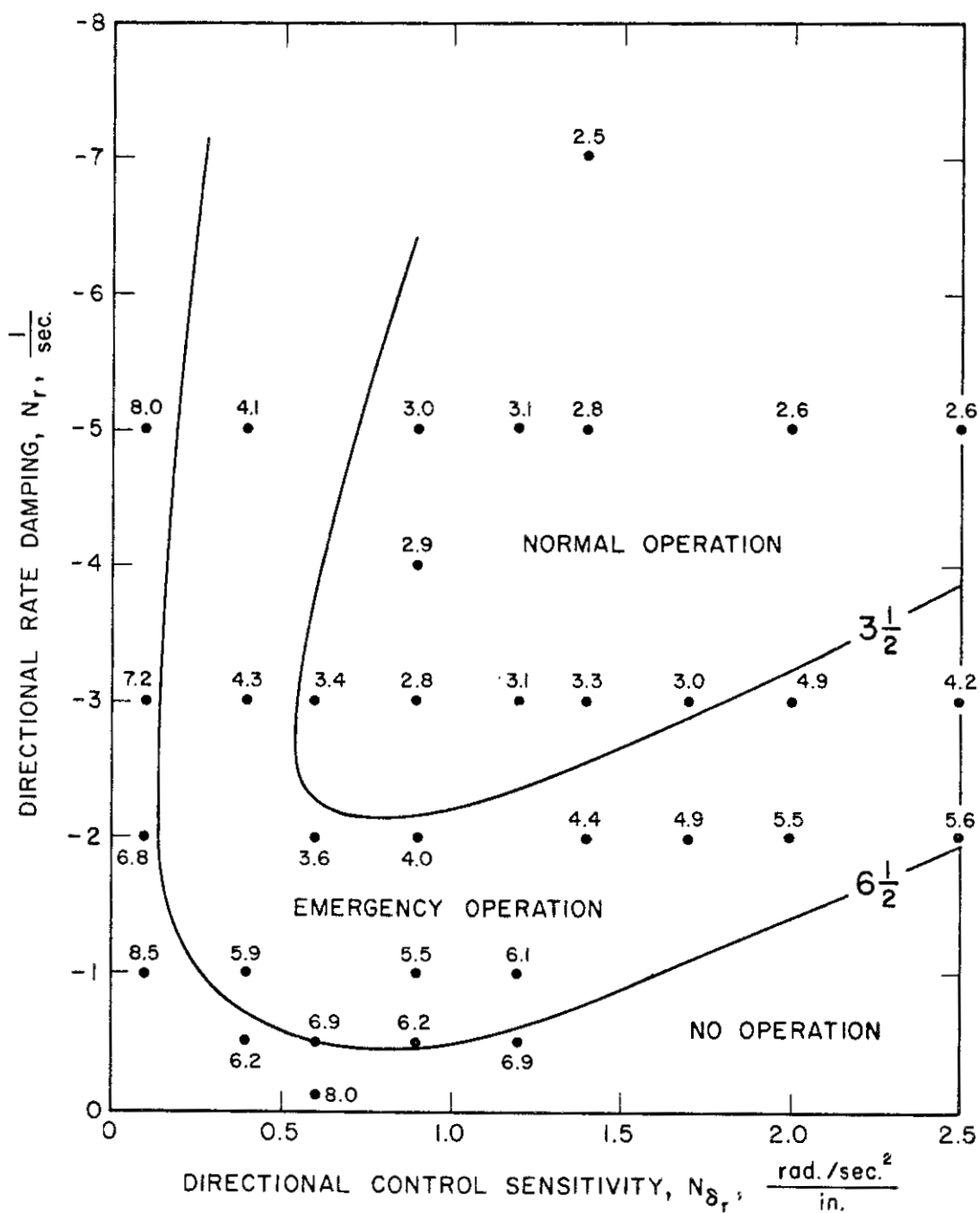
POWER SPECTRAL DENSITY CURVES FOR RANDOM NOISE GENERATOR



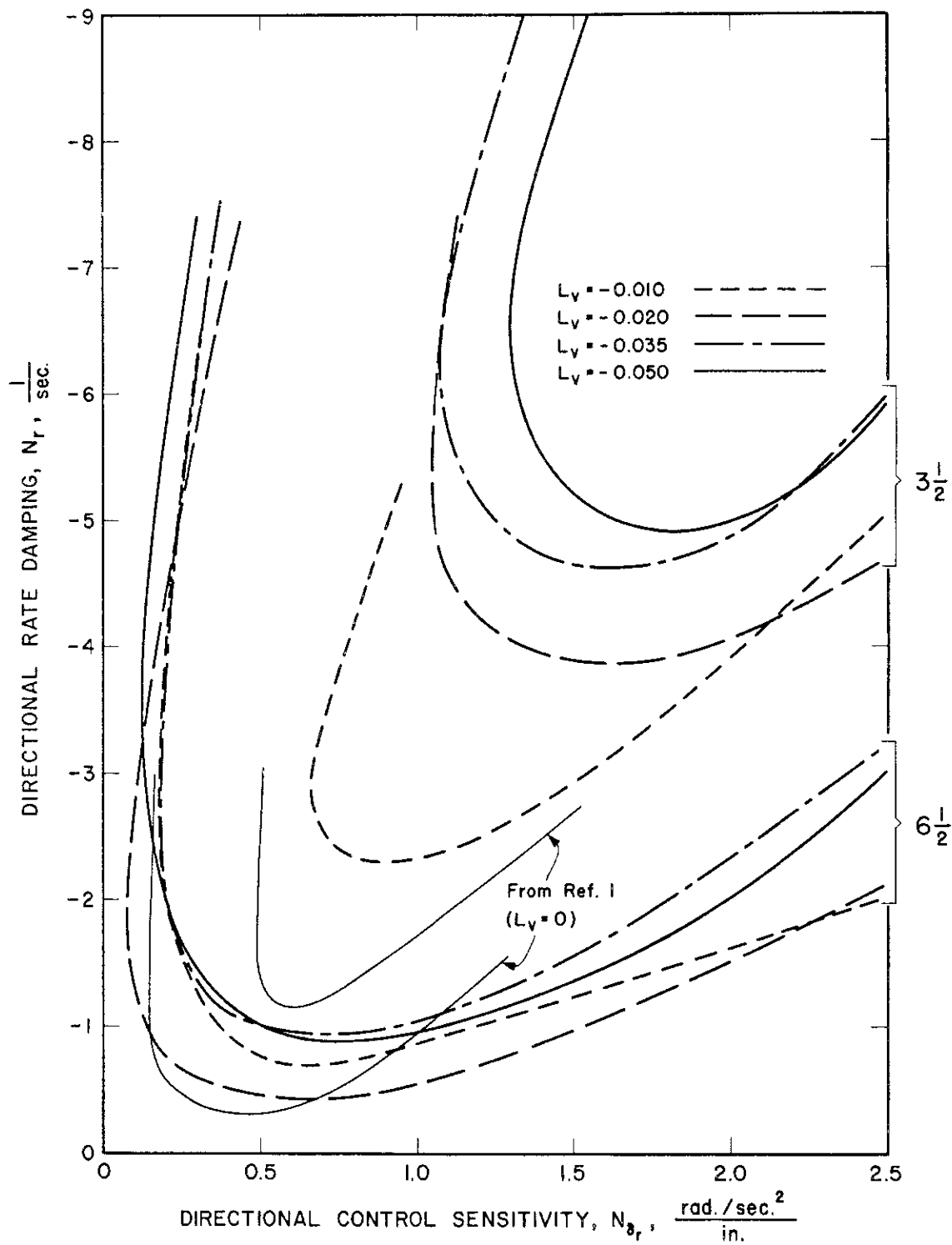
VISUAL GLIDE PATH INDICATOR



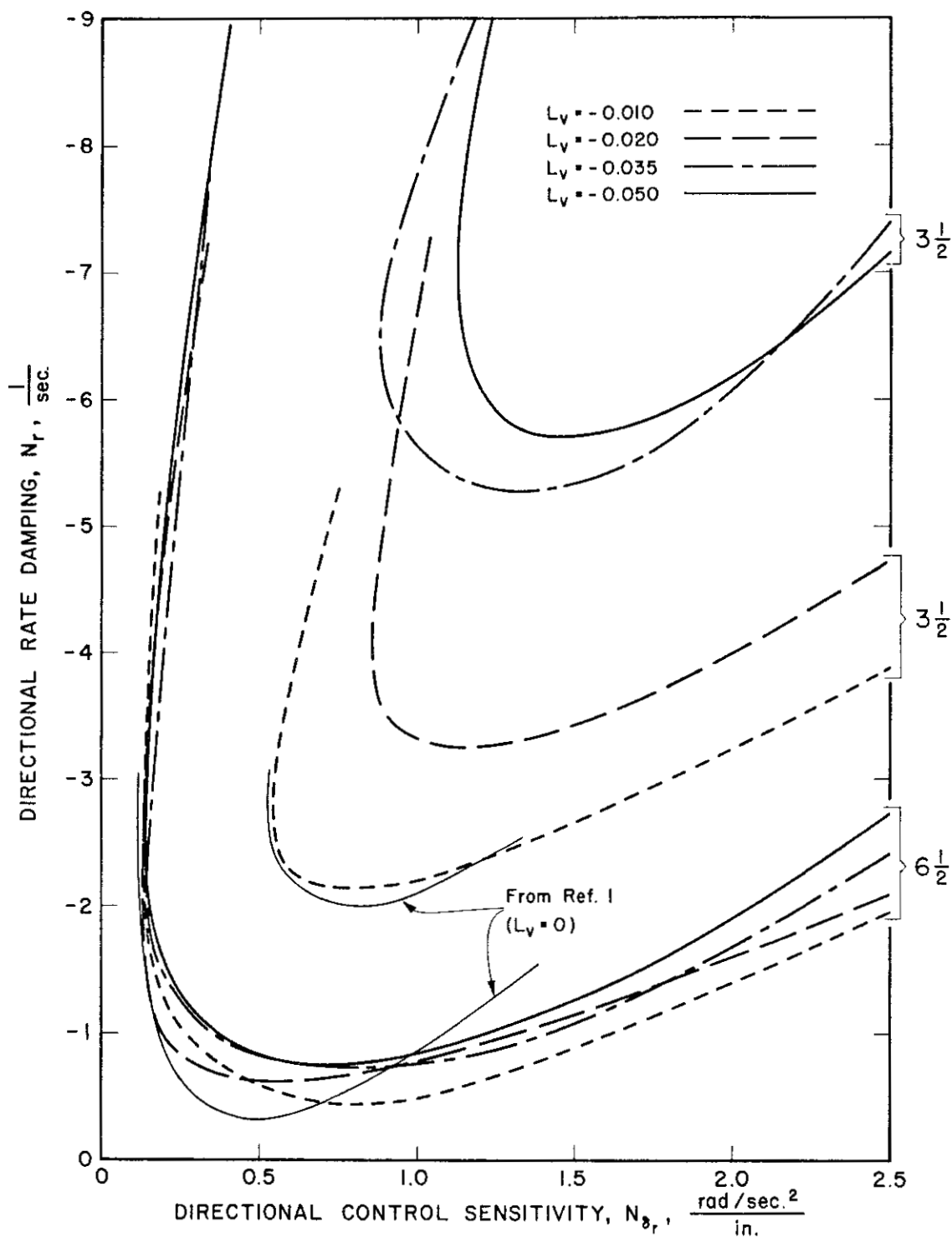
HANDLING QUALITIES BOUNDARIES,
HOVERING TASK, $L_v = -0.010$



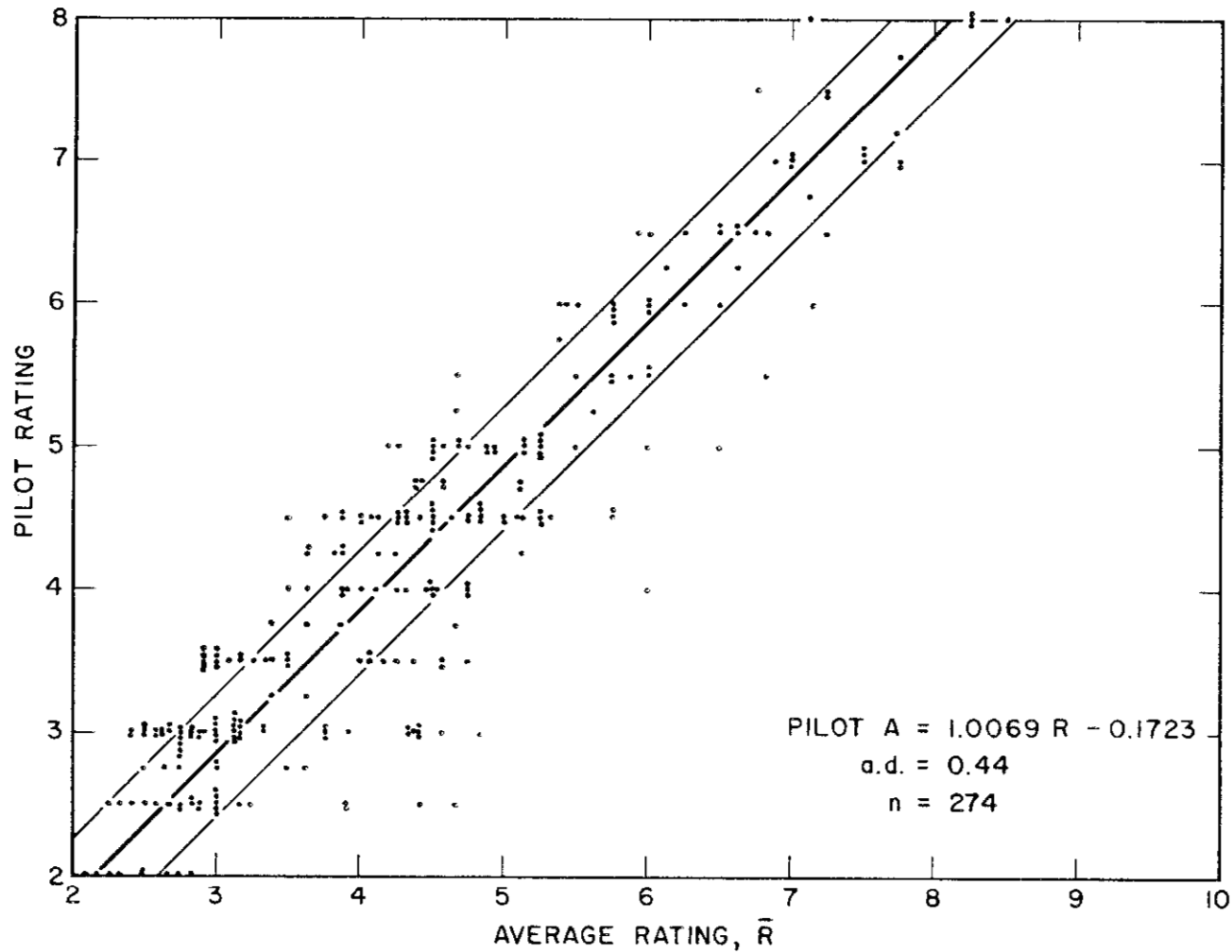
HANDLING QUALITIES BOUNDARIES,
CIRCUIT FLYING TASK, $L_v = -0.010$



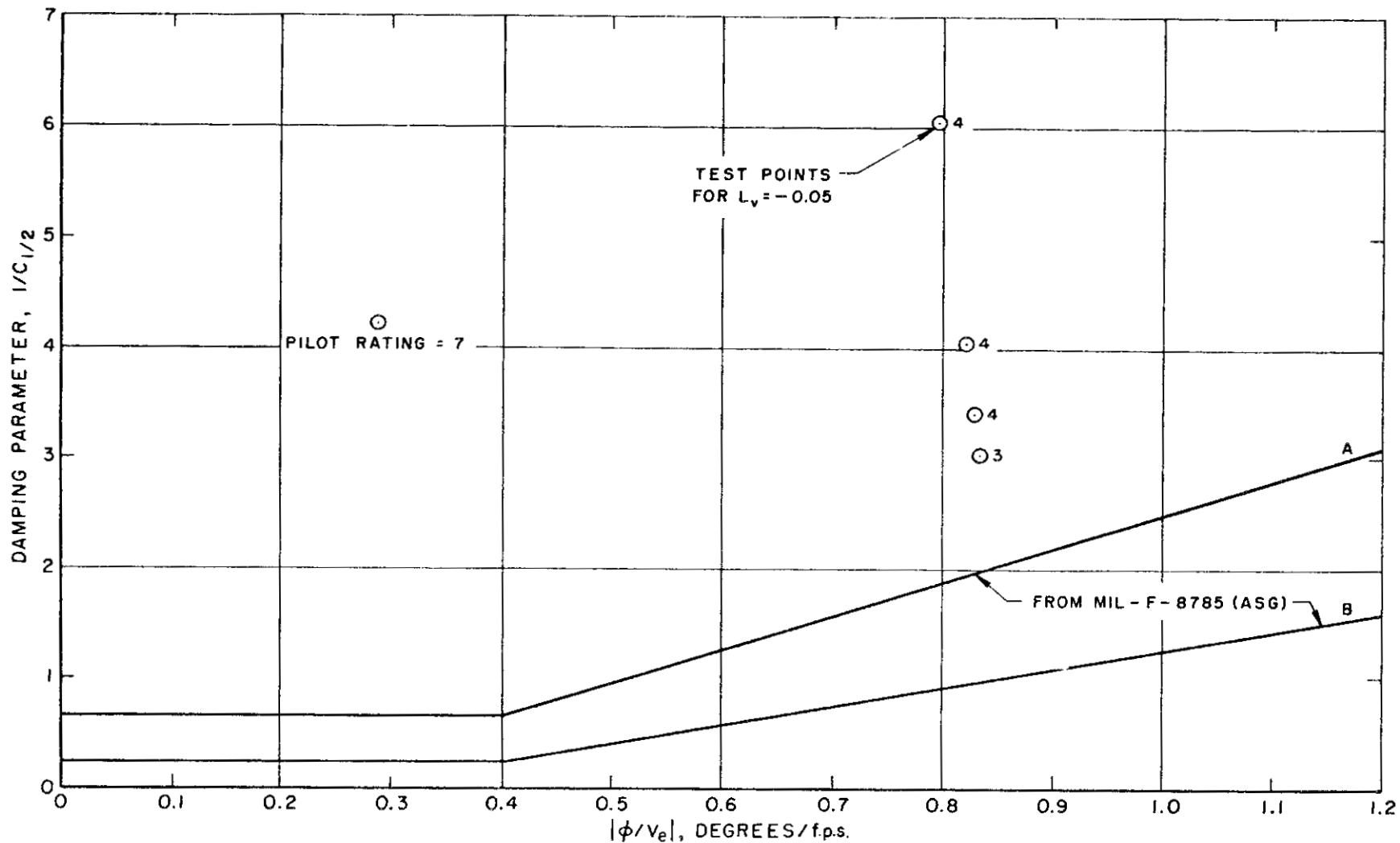
COMPARISON OF HANDLING QUALITIES BOUNDARIES
FOR VARIOUS VALUES OF DIHEDRAL EFFECT,
HOVERING TASK



COMPARISON OF HANDLING QUALITIES BOUNDARIES
FOR VARIOUS VALUES OF DIHEDRAL EFFECT,
CIRCUIT FLYING TASK



CORRELATION OF RATINGS OF PILOT A WITH THE AVERAGE RATING



COMPARISON WITH AIRCRAFT LATERAL-DIRECTIONAL DAMPING REQUIREMENTS [MIL-F-8785 (ASG)]