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FINAL REPORT

Contract FA 67 WA-1752

FLYING QUALITIES OF SMALL GENERAL AVIATION AIRPLANES

Part I. The Influence of Dutch-roll Frequency, Dutch-roll Damping, and Dihedral Effect

JUNE 1969

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Part 1. The Influence of Dutch-roll Frequency, Dutch-roll Damping, and Dihedral Effect

June 1969

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ABSTRACT

As the first phase of a study of flight characteristics criteria for small general aviation aircraft, experiments were conducted with a variable-stability flying simulator to determine the influence of Dutch-roll frequency, Dutch-roll damping ratio, and dihedral effect. Other lateral-directional parameters were held fixed at favorable levels. An ILS approach flown at 105 knots in simulated moderate turbulence was the piloting task. The results are presented in a generalized quantitative form useful to designers. High Dutch-roll frequency (or high directional stability) and large dihedral were found undesirable because of excessive yawing and rolling due to turbulence. Low Dutch-roll frequency led to poor heading control, large sideslip excursions, and difficulty in trimming the airplane, but low, even zero, dihedral did not interfere with the approach task. Flying qualities were found to deteriorate rapidly for Dutch-roll damping ratio lower than one-tenth, but relatively little was gained by increasing it beyond that value.

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SYMBOLS AND NOTATION

I_x	moment of inertia about the roll axis (slug-ft^2)
I_y	moment of inertia about the pitch axis (slug-ft^2)
I_z	moment of inertia about the yaw axis (slug-ft^2)
I_{xz}	product of inertia (slug-ft^2)
ILS	instrument landing system
K_d / K_{ss}	Dutch-roll excitation parameter
L	rolling moment (ft-lb)
L_p	roll damping $\frac{1}{I_x} \frac{\partial L}{\partial p}$ (rad/sec^2 per rad/sec)
L_r	roll due to yaw rate $\frac{1}{I_x} \frac{\partial L}{\partial r}$ (rad/sec^2 per rad/sec)
L_β	dihedral effect $\frac{1}{I_x} \frac{\partial L}{\partial \beta}$ (rad/sec^2 per rad)
$L_{\delta a}$	aileron effectiveness $\frac{1}{I_x} \frac{\partial L}{\partial \delta a}$ (rad/sec^2 per in)
N	yawing moment (ft-lb)
N_p	yaw due to roll rate $\frac{1}{I_z} \frac{\partial N}{\partial p}$ (rad/sec^2 per rad/sec)
N_r	yaw damping $\frac{1}{I_z} \frac{\partial N}{\partial r}$ (rad/sec^2 per rad/sec)
N_β	directional stability $\frac{1}{I_z} \frac{\partial N}{\partial \beta}$ (rad/sec^2 per rad)
$N_{\delta a}$	aileron yaw $\frac{1}{I_z} \frac{\partial N}{\partial \delta a}$ (rad/sec^2 per in)
$N_{\delta r}$	rudder effectiveness $\frac{1}{I_z} \frac{\partial N}{\partial \delta r}$ (rad/sec^2 per in)

V	true airspeed (ft/sec)
j	$\sqrt{-1}$
p	roll rate (rad/sec)
r	yaw rate (rad/sec)
rms	root-mean-square
s	Laplace transform operator $s = \sigma \pm j\omega$
β	sideslip angle (rad)
δa	aileron stick deflection (in)
δr	rudder pedal deflection (in)
ζ_d	Dutch-roll damping ratio
$\left\lvert\frac{\varphi}{\beta}\right\rvert_d$	ratio of roll-to-sideslip
σ	real part of Laplace operator
σ_L	rms rolling moment disturbance per unit moment of inertia (I_x) due to gusts (rad/sec^2)
σ_N	rms yawing moment disturbance per unit moment of inertia (I_z) due to gusts (rad/sec^2)
τ_{rm}	roll mode time constant (sec)
τ_{sp}	spiral mode time constant (sec)
φ	bank angle (rad or deg)
ω	undamped natural frequency (rad/sec)
ω_d	undamped natural Dutch-roll frequency (rad/sec)
ω_φ	undamped natural frequency of $\frac{\varphi}{\delta a}$ transfer function numerator
$(\zeta\omega)_d$	Dutch-roll real damping parameter

INTRODUCTION

This report presents the results of the first phase of a systematic study of the flying qualities of small general aviation aircraft. The program was inspired in part by the successful development, over recent years, of quantitative flying qualities criteria for piloted military airplanes, and it employs many of the methods and tools, especially the variable stability in-flight simulator, which proved to be useful in the research leading to those results. The unique capabilities of the variable stability airplane make it possible to design experiments in which certain characteristics are varied while all others remain fixed. The effects of these variations can then be examined in the context of a particular piloting task.

This phase of the study is focused upon Dutch-roll mode frequency and damping, and effective dihedral, characteristics which heavily influence the airplane designer's choice of tail size, tail length, and wing dihedral angle. Roll response and spiral mode characteristics are held fixed at favorable levels. The piloting task is an ILS approach in moderate turbulence.

It should be noted that no attempt is made to simulate particular existing airplanes; rather, the range of each parameter is selected to be broad enough to encompass both present design practice and possible variations due to unconventional aerodynamics or artificial stability augmentation (yaw damping, for example). The variables in the experiments are handled in a manner which accounts for inertia and speed effects as well as dimensions and geometry, and the results are thus generally applicable to all reasonably small airplanes. Very large airplanes or those with special mission requirements (such as STOL operations) are not within the scope of this study.

Later phases of the program will consider variations in roll mode characteristics, Dutch-roll excitation parameters, and longitudinal flying qualities.

LATERAL-DIRECTIONAL DYNAMICS AND FLYING QUALITIES - A REVIEW

Conventional subsonic airplanes normally exhibit three distinct natural modes of motion involving the flight variables sideslip angle, heading (or yaw angle), and bank angle. These lateral-directional motions, which differ from each other in character and in time scale, are termed the roll mode, the Dutch-roll mode, and the spiral mode.

The Roll Mode

The roll mode appears to the pilot as a rapid increase in roll rate to a steady value following a lateral control deflection, or conversely, as the almost immediate reduction of roll rate to zero when the lateral control is neutralized; it is the mode which he deliberately induces to control bank angle. The characteristic time involved is termed the roll mode time constant, τ_{rm}, and physically it represents the time required for the airplane to reach 63% of the ultimate steady-state roll rate following an abrupt step-like lateral control surface deflection (or a step-like rolling moment from turbulence). Large roll damping leads to small time constants, a quarter or even a tenth of a second being typical values for general aviation aircraft. In fact, experiments show that the time constant must be small (less than a second) if the airplane is to be precisely controlled. It is thus an important flying qualities parameter; the roll mode characteristics selected for the present experiments are discussed in the section on experimental procedure.

The Dutch-roll Mode

The lateral-directional motion known as the Dutch-roll is the oscillation involving simultaneous rolling, yawing, and sideslipping which may be observed following a gust encounter, or following any control application which results in sideslipping (such as "uncoordinated" use of aileron and rudder in a turn entry). It is not deliberately used by the pilot in the sense that he uses the roll mode for banking and the longitudinal short-period mode for pitching, but nonetheless it must be considered by the designer because the typical lightly damped Dutch-roll motions can, under some circumstances, seriously interfere with precise control of the flight path.

The oscillatory character and time scale of the mode are closely associated with the yawing moments which arise due to sideslip - the directional stability of the airplane. The frequency of the oscillation is, in fact, given approximately by the square root of the static directional stability parameter, N_β.[1] Small inertia about the yaw axis and/ or large aerodynamic restoring moments due to sideslip lead to large values for N_β, and hence to high frequency (or, alternatively, short period) motions, and vice versa. The aerodynamic portion involves air density and airspeed - low altitude and higher speeds result in higher frequency - and airplane geometry. This last factor is the one over which the designer has a measure of control, since it includes tail size and tail length; higher frequency results if either is increased.

The damping of the oscillation - the characteristic decrease of amplitude with time - is due primarily to the yawing deceleration resulting from yaw rate, N_r. Aerodynamic moments which resist yawing are provided mainly by the vertical tail, a rotary motion about the yaw axis resulting in an increment of angle of attack of the vertical tail proportional to yaw rate. The resultant

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[1] N_β is an example of a "dimensional" stability derivative. Physically, these derivatives represent acceleration per unit of the variable involved, in this case yawing acceleration per unit of sideslip angle. They are the coefficients in the equations of motion presented in the Appendix. It should be noted that they involve the mass or moment of inertia, flight condition, and airplane size and geometry. A textbook such as Reference 1 should be consulted for details on estimation of these derivatives.

moment is a function of tail area and shape and the square of tail length, so the designer has a measure of control over yaw damping. The effect of inertia about the yaw axis works against the aerodynamic damping moments, since once the motion is started the inertia tends to make it persist. Secondary influences on damping arise from lateral resistance to sideslip (Y_β / V), roll due to sideslip (L_β), yaw due to roll rate (N_p), roll damping (L_p), and roll due to yaw rate (L_r); but generally the effects of these derivatives are small compared to the influence of N_r.

In this report the level of damping is measured in terms of a damping ratio, ζ, which compares the actual damping available to that just sufficient to prevent an oscillation from occurring. Thus no damping is signified by $\zeta = 0$, and negative ζ indicates an unstable motion; $\zeta = 1$ indicates no oscillatory character and a system with $\zeta = 0.7$ is considered heavily damped since it exhibits virtually no overshoot of the steady-state value in its response to a step input. By comparison, the Dutch-roll mode is almost always lightly damped in small general aviation aircraft, $\zeta = 0.1$ being not unusual.

Dutch-roll Excitation

In general, whenever yawing or rolling moments or side forces are applied to the airplane the Dutch-roll will be excited. The two sources of such forces and moments are turbulence and control deflections; the factors influencing the size and nature of the excitation are discussed in this section.

(A) Excitation from Turbulence. An airplane flying in random turbulence is subjected to a gust field which may be resolved into side gust, vertical gust, and fore-and-aft gust components. It is useful to think of these gusts as causing small increments in the flight variables: a side gust, for example, produces a sideslip, a vertical gust a change in angle of attack. These changes in the flow field produce incremental aerodynamic loads on the airplane and the resultant forces and moments cause rolling, yawing, and pitching accelerations.

The point to be emphasized is that the response of the airplane, that is, the size of the acceleration caused by a gust, is indicated by the size of the corresponding stability derivative. A large value for the dihedral effect, L_β, for example, will lead to large roll accelerations due to side gusts; and large directional stability, indicated by a large value for N_β (or high Dutch-roll frequency), will lead to large yawing accelerations. Since the dimensional derivatives are ratios between aerodynamic force (or moment) and mass (or moment of inertia), it is apparent that the gust response of the airplane is affected by both its aerodynamic characteristics and its inertia.

Thus the stability derivatives that determine the basic dynamic response characteristics of the airplane also determine the manner and extent to which the airplane will be disturbed by turbulence. In general, the designer is faced with the need to compromise, because aerodynamic characteristics which seem desirable for flight in smooth air, such as very large directional stability, may lead to undesirable characteristics for flight in turbulence.

(B) <u>Excitation from Lateral Control Deflection.</u> Yawing moments which arise from use of the lateral control are an important, and particularly undesirable, source of Dutch-roll excitation - undesirable because the pilot depends so heavily upon precise control of bank angle for turning, and any significant yawing and rolling oscillations will interfere with accurate control of the flight path. At best, some pilot compensation in terms of conscious attempts to stop the oscillations or careful aileron-rudder coordination to prevent them from starting will be required; at worst, the pilot's attempts to stop the oscillations with his roll control may only aggravate them, resulting in an unstable pilot-airframe system.

The important factors here are yaw due to lateral control deflection $N_{\delta a}$, and yaw due to roll rate, N_p. The first makes its effect felt at the instant of control deflection, while the second comes into play as soon as the roll rate becomes significant. Both are usually in the "adverse" sense, a roll to the right resulting in yaw to the left. It is important to note that simply providing ailerons (or some other lateral control device) which give zero adverse yaw will not completely remove the Dutch-roll excitation effects of lateral control use, because the yawing from roll rate (N_p) factor remains.[1] Since N_p is influenced mainly by wing geometry it is not much under the control of the stability and control engineer.

The parameters which serve as measures of this lateral-control excitation of the Dutch-roll mode are the ratios $\omega_\varphi / \omega_d$ and K_d / K_{ss}. Although these are not treated as variables in this phase of the program, they play an important role in the design of the experiments and in the interpretation of the results. They are discussed in the section entitled "Parameters Related to Flying Qualities."

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[1] There will also be a small residual Dutch-roll even if both N_p and $N_{\delta a}$ are zero. It is caused by sideslip due to bank, and is usually small enough to be ignored.

(C) Excitation from Rudder Deflection. Rudder deflections can, of course, excite the Dutch-roll by producing yawing accelerations, and in fact a vigorous right-left-neutral (or vice versa) rudder input is an excellent way of obtaining a Dutch-roll oscillation for purposes of observation. Once the rudder has produced yaw and sideslip, the restoring tendency of the directional stability (N_β) and the coupling effects of dihedral (L_β) and roll due to yaw (L_r) come into play to start the motion. This sort of excitation can and does occur when the pilot attempts to make heading corrections with rudder alone - there will be some transient yawing oscillations before the airplane settles down on the new heading.

The Spiral Mode

In contrast to the roll mode, the spiral mode is (usually) a slow-acting motion which is often unstable. The pilot recognizes it as a tendency for bank angle and yaw rate to increase for the unstable case (or decrease for the stable case) if the airplane is left unattended in a wing-down attitude. The characteristic times are long - the time required for the bank angle or yaw rate to double or halve is usually more than ten seconds - and the mode will go unnoticed if the pilot is actively controlling bank angle. However, the spiral has a history of association with accidents involving noninstrument-rated pilots flying in bad weather, and unusually quick divergence might add materially to the workload of even the experienced instrument pilot, so the mode is not a trivial one. Detailed consideration of the stability derivatives involved will be deferred to a later phase of the program, but a discussion of the treatment of the spiral in the present Dutch-roll research is included in the section on experimental procedure.

Parameters Related to Flying Qualities

The previous sections have dealt with the character of lateral-directional dynamics, especially the Dutch-roll oscillation, and the means by which these dynamic modes are excited. The purpose of this section is to discuss factors which are recognized as being related to the study of flying qualities as contrasted with airframe-only dynamics.

(A) Dutch-roll Mode. As previously indicated, the Dutch-roll mode can, under some circumstances, seriously interfere with precise control of the airplane. The pilot can directly sense the frequency (ω_d) of the motion and the damping (ζ_d or $\zeta_d\omega_d$), and since they determine the time scale and the persistence of the oscillation they are important flying qualities parameters. They have a bearing upon whether the motion will be so objectionable as to require pilot attention to suppress it (perhaps because of low damping, or very low frequency associated with low directional stability) and whether he can indeed do so (very high frequencies, for example, might require very fast and precise action with the rudder). As noted previously, the Dutch-roll frequency is closely related to the yawing disturbances from turbulence through the derivative N_β, a higher frequency leading to larger turbulence response. This is obviously an important factor to the pilot.

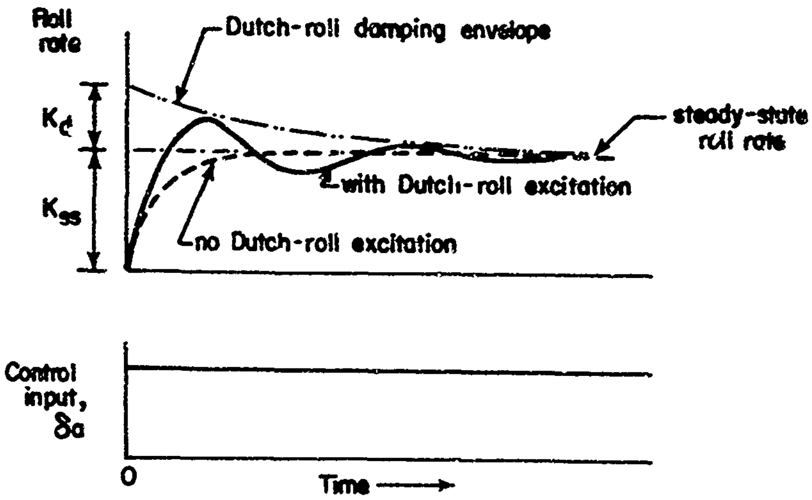
Other features of the basic Dutch-roll dynamics may be important to the flying qualities, the most prominent probably being the ratio known as $|\varphi/\beta|_d$, the ratio of bank angle to sideslip in the natural Dutch-roll oscillation. Large values of $|\varphi/\beta|_d$ represent Dutch-roll modes which have predominantly rolling motions; small $|\varphi/\beta|_d$ represents a yawing-type motion. For typical light airplanes the ratio is about unity, but very high performance airplanes, especially those with swept wings, may have values of ten or more. Large values of $|\varphi/\beta|_d$, usually associated with large dihedral, have long been held to be undesirable and to require more favorable values of other parameters such as damping ratio. Again, this reflects the need for precise control over bank angle in order to accurately control the flight path.

The phasing of the bank and sideslip in the Dutch-roll is sometimes important. This is the matter of whether or not the motion is positive bank with positive sideslip (right-wing down with nose-left, the normal case), and it is a factor in situations where Dutch-roll excitation from the lateral control tends to lead to pilot-induced instability.

(B) Roll Response to Lateral Control. The response of the airplane to lateral control inputs is of primary importance in the study of lateral-directional flying qualities because of the pilot's great dependence on precise bank angle control. He must be able to achieve a desired bank without overshooting and without having to cope with excessive interference from Dutch-roll excitation if he is to accurately control the flight path.

The roll mode is central to this matter. As mentioned previously, this is the primary mode involved in banking and turning, and the relevant flying qualities parameter is the time constant, τ_{rm}. If this time constant is long, say much over one second, the pilot tends to have trouble reaching a desired bank angle without overshooting and needing to make several small corrective inputs.

The Dutch-roll component in the roll response needs to be considered in some detail. Use of lateral control will excite the Dutch-roll mode due to the presence of yaw from the control itself ($N_{\delta a}$) and from roll rate (N_p), and the total roll response will be the sum of the roll mode and the roll component of the Dutch-roll. A convenient parameter used to indicate the degree of excitation is the ratio K_d / K_{ss}, which expresses the magnitude of the roll-rate due to the Dutch-roll mode at the instant of an abrupt step-like lateral control input compared to the steady-state roll rate. This is illustrated on the following page:



It is apparent that K_d / K_{ss} equal to zero will signify that the Dutch-roll mode is not excited by use of the lateral control, which is a desirable feature. This is not to imply that the Dutch-roll no longer exists, but rather that a lateral control input does not give rise to moments which excite it. If K_d / K_{ss} is about unity the roll rate will reach almost zero on the first downswing, and the bank-angle response will have a stair-step nature. Large values of the ratio - greater than unity - are indicative of roll-rate reversal, clearly an undesirable response to a step input.

Another parameter discussed widely in the literature and associated with Dutch-roll excitation in the roll response is the ratio $\omega_\varphi / \omega_d$. Here ω_d is the true Dutch-roll natural frequency and ω_φ is a constant occurring in the transfer function of roll response to lateral control. It is physically identifiable as the frequency of a special Dutch-roll which would result if the wings could be held exactly level with the lateral control so that the oscillation would have only yawing and sideslipping motions. In general, this particular kind of Dutch-roll would differ in both damping and frequency from the real motion because of the yawing moments from the lateral control ($N_{\delta a}$) and because of the lack of rolling. At any rate, the frequency ratio $\omega_\varphi / \omega_d$ is indicative of whether the frequency of the pilot-airframe system in a roll-tracking situation will be higher or lower than the basic airplane Dutch-roll frequency. It turns out that if $\omega_\varphi / \omega_d$ is unity or less, the pilot-airframe system will be stable, but if the ratio is greater than one and the basic airplane damping is low, the system may exhibit poor stability, or may even be unstable. In this case the pilot, attempting to control bank angle, actually drives the system into unstable oscillations.

(C) Individual Stability Derivatives. The static stabilities N_β and L_β are important in their own right aside from the ways in which they influence the dynamic response and other parameters mentioned above. The association of N_β with the yawing response to turbulence was made in part (A) of this section and the dihedral, L_β, is similarly important. Large dihedral leads to large rolling disturbances from side gusts and these are certainly of concern to the pilot. (It might be noted here that the disturbance effects associated with other derivatives such as L_p, N_r, N_p, Y_β are generally much smaller than N_β and L_β effects, and unless the former happen to be very large compared to N_β and L_β the pilot doesn't usually single them out as important turbulence response factors.)

The pilot also senses N_β and L_β directly when performing steady sideslips. Large N_β gives a "stiff" airplane, one resistant to sideslipping, while small N_β results in an airplane which is "weak" directionally and which sideslips readily. The normal sense of the dihedral, L_β, requires that the pilot cross control - right aileron and left rudder for a slip to the right, for example - in order to hold a steady sideslip. It also figures largely in the ability of the pilot to roll the airplane with the rudder only, a matter of some importance if lateral control is poor at angles of attack near or beyond the stalling angle.

(D) Control Effectiveness. Control effectiveness, measured by roll acceleration per unit of lateral control, $L_{\delta a}$, and yaw acceleration per unit of yaw control, $N_{\delta r}$, are important flying qualities parameters, although they do not alter the characteristic frequencies, damping, or time constants of the lateral-directional modes. From the pilot's standpoint the control must seem neither too sensitive nor too sluggish. However, this cannot be studied independently of the basic dynamic characteristics of the airplane; the optimum roll sensitivity ($L_{\delta a}$), for example, is closely related to the value of the roll mode time constant. Likewise, rudder effectiveness must be appropriate for the existing levels of static directional stability and yaw damping.

EXPERIMENTAL PROCEDURE

An experimental approach to flying qualities research almost always involves the use of some form of simulator as a substitute for the actual airplane. Cost considerations aside, the researcher often needs to explore a wide range of parameters or change one characteristic without altering others at the same time. This obviously would be difficult, if not impossible, to do even if he were allowed to build a fleet of specially-configured airplanes - hence the research simulator. The form depends upon the importance and complexity of the problem, and ranges from comparatively primitive fixed chair-stick-and-pedals with voltmeters for instruments, to moving-base devices with several degrees of freedom and sophisticated visual displays, and finally to the variable stability airplane, a true flying simulator. This last-mentioned device offers the least compromise with reality, since the pilot is in an actual flight environment. Such a machine was used for the experiments in this program.

The Variable Stability Navion

Variable stability (or better, variable response) airplanes come in several sizes and degrees of system complexity, but in general they all provide for in-flight variation of the static and dynamic stability parameters over a wide range and thus have "variable flying qualities." The variable response airplane used for this program was derived from a North American Navion airframe and is pictured in Figures 1 and 2. The machine and its control system are described in detail in References 2 and 3, but a short review of the principle of operation may be helpful in understanding the experiments.

The most basic modification of the airplane is the provision for power-actuated control surfaces. Electro-mechanical servos drive the ailerons, rudder, and elevator, with a fast-acting hydraulic servo moving the flap. The operating signal for each servo is a sum of the signals from the evaluation pilot's controls (which are not connected mechanically to the surfaces and which produce only electrical signals proportional to deflection) and sensors which measure the flight variables. For example, the aileron servos may receive a signal summed from a roll control command, plus signals proportional to sideslip angle from a yaw vane, and roll rate and yaw rate from gyros. The last three signals are the ones which change the airplane's basic roll response characteristics by causing it to accelerate in roll more (or less) than the basic Navion does for the same roll rate, the same sideslip angle, or the same yaw rate. Similar "feedbacks" are applied to the rudder to change the yawing response to sideslip, yaw rate, and roll rate; to the elevator to change the angle of attack and pitch-rate response; and to the flap to alter the lift response to changes in angle of attack. Thus the dynamic response characteristics of the basic Navion are changed by augmenting or diminishing the individual static and dynamic stability factors - the stability derivatives mentioned in the previous section. The size of each feedback signal is controllable from the cockpit so that the simulator may be adjusted in flight.

In addition to the signals from the control stick, rudder pedals, and the sensors, tape-recorded signals representing turbulence are sent to the servos and produce the disturbances of flight in rough air, which are appropriate to the airplane being simulated. An airplane with large dihedral effect, for example, will be simulated with appropriately large rolling disturbances due to side gusts. The overall level of the artificial turbulence can be adjusted to produce severity ranging from zero, or no disturbance, through "heavy moderate," a level which might be experienced in the vicinity of a squall line or in the lee of a mountain range. The turbulence signals have frequency characteristics which are like those of the turbulent atmosphere: strong gusts have relatively low frequency of occurrence compared to smaller gusts and as the frequency increases beyond a certain level the gust intensity diminishes until, at very high frequencies, the amplitude is very small. The influence of turbulence on flying qualities is of such fundamental importance that it just cannot be avoided or treated casually, and thus the capability for simulating the effects is one of the more important features of the variable stability Navion.

It is imperative to know exactly what is being simulated, and unfortunately the desired configurations can be set only approximately by ground calibration. For this reason an in-flight calibration called "configuration matching" is carried out to determine the exact variable stability system control settings needed to produce the desired response characteristics. The process involves setting up an analog computer representation of the desired airplane and then adjusting the flying simulator until its response matches that of the ground-based computer. In practice, the control deflections of the simulator are sent to the computer via telemetry and thus the pilot flies the computer airplane and the real airplane simultaneously; the motions of the airplane likewise are telemetered to the ground and compared with the computer output. Special matching maneuvers are performed and the variable stability system is adjusted until the responses agree closely.

The Variables in the Phase I Experiment

The variables selected for the first phase of this study of general aviation airplane flying qualities were Dutch-roll frequency (ω_d), Dutch-roll damping ratio (ζ_d), and dihedral effect (L_β). As indicated in the previous section, these are all important lateral-directional flying qualities parameters and are to a large degree within the control of the designer. It was felt that knowledge of the effects of these three quantities would be a useful framework within which to study Dutch-roll excitation and roll-damping requirements in a later phase. The range of each of the variables is indicated below:

(A) Dutch-roll Frequency. This variable ranged from 1.3 radians per second to 3.0 radians per second, corresponding to Dutch-roll periods of 4.8 seconds and 2.1 seconds respectively. Most light airplanes fall within these extremes. Intermediate configurations with ω_d = 1.8 radians per second and 2.3 radians per second were also tested. For reference, the basic Navion frequency is 2.2 radians per second at normal weight and a speed of 105 knots.

(B) Dutch-roll Damping Ratio. The tests were conducted at three discrete damping ratios: $\zeta_d = 0.05$, $\zeta_d = 0.10$, and $\zeta_d = 0.40$. The first is definitely "light damping," but $\zeta_d = 0.10$ is fairly typical of small airplanes without artificial yaw damping ($\zeta_d \doteq 0.15$ for basic Navion). The high damping ratio, $\zeta_d = 0.40$, is larger than normal aerodynamic configurations are likely to provide. It was selected in order to explore the possible benefits of additional yaw damping, either aerodynamic or artificial in nature. Most of the testing was carried out with $\zeta_d = 0.10$.

(C) Dihedral Effect. Dihedral effect ranging from zero to moderately high (L_β = -32) was tested. (An unfortunate sign convention may be noted here: normal, or "positive," dihedral effect, signifying a roll to the left for a sideslip to the right, is associated with negative values of the derivative L_β.

All configurations tested had dihedral in the normal sense.) For reference, the basic Navion dihedral effect is about L_β =-16 at a speed of 105 knots and normal weight.

It should be noted that the roll control sensitivity ($L_{\delta a}$) and rudder sensitivity ($N_{\delta r}$) were not considered to be variables in the experiments, but neither were they fixed. The evaluation pilots were asked to use the levels which they considered optimum for each configuration. This was done to prevent the results from being influenced by the use of controls which were too sensitive or too sluggish for the dynamics being tested.

For reference purposes, a list of the configurations and their parameters is included as Table 1. Time histories of the roll rate and yaw rate responses of each configuration to a step lateral control deflection and a step rudder deflection are shown in Figures 3 and 4 respectively.

Characteristics Held Constant

The variable response capabilities of the flying simulator were used to hold other lateral-directional characteristics fixed while the effects of the specific test variables were investigated. These fixed characteristics were the following:

(A) Roll Mode. The roll mode was given a time constant (time to reach 63% of the steady roll rate following a lateral control step input) equal to one-quarter of a second. This is a value which permits very satisfactory control of bank angle without overshooting, and selection of a compatible control sensitivity is not difficult or critical.

(B) Dutch-roll Mode Excitation. This was held to a low, noninterfering level as measured by the parameters K_d / K_{ss} and $\omega_\varphi / \omega_d$. Referring to Table 1, it is seen that K_d / K_{ss} for most cases is less than 0.2, and $\omega_\varphi / \omega_d$ is unity or less, both conditions leading to a good pilot-airframe system as far as roll control is concerned. The notable exceptions are Configuration 14

($\omega_d = 1.8$, $\zeta = 0.1$, $L_\beta = -32$, $\omega_\varphi/\omega_d = .78$, $K_d/K_{ss} = .33$) and Configuration 29 ($\omega_d = 1.3$, $\zeta_d = 0.4$, $L_\beta = -16$, $\omega_\varphi/\omega_d = .87$, $K_d/K_{ss} = .8$): Dutch-roll excitation is clearly evident in the roll-response time histories shown in Figure 3. Configuration 14 has been studied previously (References 2 and 3) and it has been shown that pilots are concerned with its excessive turbulence response due to dihedral and not with excessive Dutch-roll excitation. Configuration 29 has a damping ratio sufficiently large to preclude piloting problems in roll due to K_d/K_{ss}. They were included in order to retain a complete set of configurations which had been used in a previous study, and with which it was desired to compare results.

Except for the two configurations noted above the time histories indicate good roll response to step aileron inputs, a requirement for proper interpretation of the effects of Dutch-roll excitation arising from L_β and ω_d (or N_β).

(C) Spiral Mode. The spiral mode was adjusted to be neutral - that is, neither convergent nor divergent - for all configurations. This was done to prevent the mode from possibly interfering with the evaluation of the test variables, since not controlling it would have resulted in extremely quick convergence for the high dihedral, low frequency airplanes and extreme divergence for the zero-dihedral, high frequency machines.

This adjustment of the spiral was done largely with the derivative L_r, the roll due to yaw rate, or "overbanking tendency," because other derivatives which are important to the mode, L_β, N_β, and N_r, are either independent variables themselves (L_β) or are closely associated with the independent variables (N_β with ω_d and N_r with ζ_d). This leads to unrealistically large values of L_r for some configurations (for example, $L_r = 18.94$ for Configuration 29 which has $L_\beta = -16$, $\omega_d = 1.3$, $\zeta_d = 0.4$, compared to the basic Navion $L_r \doteq 2$). On the other hand, it leads to the requirement that L_r be zero for the zero-dihedral configurations, and this is not physically possible for finite wing-span, normally-configured airplanes.

Fortunately, the effect of these unrealistic values of L_r on the roll mode is nil, and the effect on the Dutch-roll is small. With $L_r = 0$ the Dutch-roll oscillation for the zero dihedral-effect airplane is one of yaw and sideslip only - there is no rolling whatsoever; with $L_r = 2$ there would be a small roll component, and the roll-to-sideslip ratio would be about four-tenths instead of zero as tested. Moderate frequency, moderate dihedral configurations would change hardly at all with $L_r = 2$, while reducing L_r from 18.94 to $L_r = 2$ on Configuration 29 would change the roll-to-sideslip ratio from $|\varphi/\beta|_d = 3.6$ to $|\varphi/\beta|_d = 2.7$.

(D) Other Constants. Other constants are the side-acceleration derivative Y_β/V and the factor g/V. The side-force characteristics of the Navion cannot be varied, but they are typical of this class of airplane. The experiments were flown at trim airspeed of 105 knots.

Roll due to rudder deflection, $L_{\delta r}$, was made equal to zero. It is hard to assign a "typical" nonzero value to this derivative, and the effects are likely to be small.

Yaw due to lateral control, $N_{\delta a}$, was made zero for all configurations in order to keep Dutch-roll excitation to a low level. This derivative enters into both ω_φ/ω_d and K_d/K_{ss}, and will be treated as a variable in a later phase of the program.

Finally, the longitudinal characteristics were held fixed at basic Navion levels.

The Turbulence Level

The disturbances produced by a turbulent atmosphere with rms linear velocity components of about 6 ft/sec were simulated. Traversing this field of turbulence at 105 knots produced equivalent rms sideslip (β) of about 2 degrees, roll rate (p) about 3 degrees per second, and yaw rate (r) about 3-1/2 degrees per second. This is a moderate level which probably would not be encountered every day, but certainly more often than once a year.

The Piloting Task

An ILS approach in turbulence was selected as the piloting task for the flight experiments. The factors involved in such a selection are many in number, often involving operational considerations or problems in evaluating results. The ILS approach was picked on its merits as a realistic, demanding task from which measures of performance could be obtained.

The matter of realism involved the questions of whether or not the task was one that an airplane of this class might be expected to perform, and whether or not the flying qualities of the airplane were important to task performance. To enlarge upon this point, all airplanes spend a large proportion of their total time in cruising flight, but if the pilot is not engaged in tight control of heading or bank angle, one cannot make much of a case for needing good Dutch-roll damping, good roll response or good behavior in turbulence (except perhaps from the standpoint of riding comfort); the task is one of keeping the airplane generally right side up and pointed in the desired general direction and is essentially "open-loop" as far as piloting is concerned. Small perturbations on top of the gross flight path are not of much consequence.

As the pilot is required to control the machine more and more precisely - to hold the wings level, fly a particular heading, track a VOR radial, then do all of these things by reference only to instruments - he must not only be more proficient, but such things as adequate damping, good control response, and good behavior in turbulence become more important.

This reasoning led to the selection of the instrument approach in turbulence as a demanding task which primarily involves the flying qualities of the airplane. It requires precise control of the airplane and presents an inherently high workload, so that any need for the pilot to compensate for poor flying qualities is particularly undesirable. From an experimental standpoint, each approach is of sufficient length to permit a good evaluation of a configuration, and it is possible to measure and record task performance in terms of localizer and glide slope deviations. To summarize: for the ILS approach, task performance was measurable, the highest level of tracking and precise control of the airplane were required, and the workload was inherently high enough so that any requirement for the pilot to compensate for poor flying qualities was undesirable.

Standard gyro horizon, directional gyro, and ILS cross-pointer information without flight director or horizontal situation displays were used. This was felt to be typical of equipment used in general aviation instrument flying, and at least representative of back-up equipment for aircraft with more sophisticated instrumentation.

The foregoing should not be taken to imply that other tasks might not be important or informative. The visual portion of the final approach and the flare and touchdown, perhaps in the presence of wind-shear and/or crosswinds, represents a total task with its own high demands on control response and control power and behavior in turbulence; this is indeed worthy of investigation but it presents problems of performance measurement and evaluation and simulation which are beyond existing capabilities. Simpler tasks, such as precision heading tracking which is an important part of the overall ILS approach, are indeed often informative (and in fact such tests are referred to later in the report), but lack the validity which comes from having the pilot perform the whole task. Maneuvers involving flight director tracking also are potentially useful in examining certain aspects of the overall piloting problem.

Data Acquisition

(A) Pilot Ratings. The primary data in a flying qualities study such as this one consist of numerical ratings and comments supplied by pilots who are trained and experienced in the art of evaluating flight characteristics. The revised rating scale shown in Table 2 (the so-called Cooper-Harper scale from Reference 3) was used, and it represents a useful conversion of verbal descriptions to numbers. It may be noted that the pilot is being asked to rate the airplane on the basis of how much he must compensate for undesirable characteristics - characteristics, for example, which require him to anticipate or lead motions, or produce intentional lags, or which require too much control activity. Even if the actual level of task performance stays uniformly high as the flying qualities get worse (a situation which is not unusual up to the point where the pilot's capabilities are saturated), the pilot can sense that he is working harder. He is being asked, in other words, to measure and report his own workload, and a trained test pilot can do this very effectively.

The comments which accompany the ratings are extremely important, because with them the pilot indicates just what it is about a configuration that is bothering him, and it is necessary to know this for proper interpretation of the results. In this program the pilots were asked to comment specifically on control response, control techniques, turbulence response, and airplane dynamic characteristics.

It must be emphasized that results in terms of ratings and comments should be viewed in the context of the task flown; they may or may not be directly applicable to other situations. In this regard, it is usual to attempt to pick a "critical task" so that flying qualities criteria established for that situation will result in airplane flight characteristics which are also satisfactory in other flight regimes. If that is not possible, then testing must be carried out for at least the more important flight regimes.

Four evaluation pilots were used in this program, three of whom were ATR-rated, the other Commercial-Instrument rated. Two had engineering flight testing backgrounds and prior experience in flying qualities evaluation; the other two were relatively inexperienced in this respect but were given special briefings and training in the variable-stability airplane. All had extensive experience in instrument flying and in the class of airplane considered in this program.

Before each flight the pilot was briefed on the task, the rating scale, and the type of comments needed. In the air, ratings and comments were given and recorded immediately following each approach.

(B) Other Data. Measurements of airplane motions, pilot activity, and task performance were relayed to the ground via telemetry and recorded on magnetic tape. Angular rates in yaw and roll were the most important items in the first category; the second category, pilot activity, involved stick and rudder pedal movements; localizer and glide slope deviations were the measures of task performance.

Conduct of the Experiment

The ILS approaches were flown at Mercer County Airport, Trenton, New Jersey. The system there is standard with a 3.0° glideslope and 4.5 nautical mile separation between outer and middle marker beacons, giving about 2.5 minutes between markers at the test speed of 105 knots. A race-course pattern involving an outbound track parallel to the final-approach course and a turn to intercept the localizer about one mile beyond the outer marker was substituted for the standard procedure turn to expedite testing.

The airplane with its simulated stability and response characteristics, but without artificial turbulence, was handed over to the evaluation pilot abeam the outer marker, outbound, for familiarization and selection of optimum $L_{\delta a}$ and $N_{\delta r}$. After the turn-around and upon intercepting the localizer the turbulence was turned on; data recording was begun at the outer marker and continued down to the middle marker, where the telemetry signal usually became unreliable. At a point past the middle marker the evaluation pilot was instructed to raise the hood and continue the approach down to the runway threshold, where control was taken back by the safety pilot (left seat, standard mechanical controls) for the pull-up and climbing turn back to the outbound course.

During the climb back to the outer marker the evaluation pilot communicated his ratings and comments to the safety pilot who recorded them and then set up the next configuration. It should be noted that only the lateral-directional characteristics were being changed; the pilot was required to track the glideslope and hold airspeed in the interests of task realism, but the longitudinal characteristics were held fixed at favorable values and he was not asked to rate them separately.

RESULTS AND DISCUSSION

Basic Results

The results of the flight experiments define, in a quantitative way, what levels of dihedral and Dutch-roll frequency are best for the instrument approach task; they also indicate the gains and penalties associated with changes in Dutch-roll damping. If used properly, they can assist the designer in the choice of dihedral angle, tail length, and tail size. These results are presented in Figures 5 and 6 and are discussed in detail in the following paragraphs. As noted previously, only dihedral effect, Dutch-roll damping ratio, and Dutch-roll frequency were treated as variables; all other characteristics were fixed at favorable values so as not to interfere. Thus, regardless of the level of dihedral or the Dutch-roll mode characteristics, the pilot was evaluating an airplane with good roll response, a neutral spiral mode, low levels of Dutch-roll excitation from the lateral control, optimum rudder sensitivity, and good longitudinal characteristics. He was asked only to evaluate changes in Dutch-roll dynamics and the response of the machine to turbulence, in the context of the ILS approach.

The combined effects of varying dihedral effect and Dutch-roll frequency with the Dutch-roll damping fixed at $\zeta_d = 0.1$ are shown in Figure 5. In this figure the darkened circles represent the particular configurations used in the flight experiments, with the average pilot rating shown adjacent to each test point. Each configuration was flown an average of six times; three of the four evaluation pilots did the bulk of the flying, and flew each airplane at least twice. The pilot rating contours were obtained by fairing curves through the averaged pilot opinion data, first plotting pilot rating vs. dihedral effect at constant frequency, and then pilot rating vs. Dutch-roll frequency at constant dihedral effect. These then served as a basis for picking points on the ω_d vs. L_β plot through which the numerical rating contours could be expected to pass. The dashed segments represent the trends of the present data; these should be considered provisional pending further testing.

Figure 5 indicates that the best airplane will have moderate normal dihedral effect and an intermediate level of static directional stability. Quantitatively, this means the dihedral effect stability derivative is best at a value of about $L_\beta = -12$ rad/ sec^2/ rad and the directional stability should be large enough to give a Dutch-roll frequency of about two radians per second (a period of slightly more than three seconds). These are not unusual numbers, being slightly smaller than those for the basic Navion at 105 knots. In the neighborhood of this optimum the ratings change gradually, and acceptable, satisfactory machines are indicated for frequencies from about 1.5 rad/ sec to 2.8 rad/ sec provided the dihedral is between $L_\beta = 0$ and $L_\beta = -24$.

At frequencies below $\omega_d = 1.5$ rad/ sec the pilot must begin to compensate for lower-than-desirable directional stability; excessive rolling due to side gusts starts to require compensation at about the $L_\beta = -24$ level. Frequencies greater than about $\omega_d = 2.8$ rad/ sec mark the beginning of tendencies toward excess directional stability which results in undesirable yawing motions due to side gusts. It may be noted that the "optimum" airplane is one which strikes a compromise by having enough stability for good dynamic response and controllability, but not so much that it is disturbed excessively in turbulence.

The results indicate that, provided the frequency of the yawing-type Dutch-roll motion is favorable, low or even zero dihedral effect in itself does not make an airplane unacceptable for instrument approach flying. Although no configurations with abnormal or reverse dihedral effect are shown on Figure 5, some preliminary testing was done which indicated that there is no sharp change in rating as the sign of L_β changes, and that the constant-rating contours can be expected to close smoothly on the left-hand side of the axis. Even if this is confirmed for the ILS approach by further testing, however, it must be pointed out that significant levels of reverse dihedral may prove undesirable for other reasons - for example: flight near the stall, if rudder must be used for lateral control; unnatural control in cross-wind landings; and excessive spiral divergence in situations where heading or bank angle is not closely monitored.

The low-frequency, low-dihedral case is of special importance because most straight-wing airplanes tend to have this combination of characteristics at low speeds (airplanes with swept-back wings tend toward low frequency, high-dihedral under the same conditions) and in landing configuration. Figure 5 indicates that even with $\omega_d = 1.3$ rad/sec the pilots were beginning to compensate for some undesirable characteristics, and pilot commentary indicated that the problems involved difficulty in trimming the airplane in roll and yaw, poor heading control, and sideslipping due to lack of directional stability. Preliminary tests with an even lower frequency configuration ($\omega_d \doteq$ 0.8 rad/sec) indicated that the ratings degrade very rapidly at frequencies lower than one radian per second. All in all, the results of Figure 5 suggest that for the ILS approach there is virtually no penalty associated with low (but still normal sense) dihedral effect. The designer might well choose a dihedral angle giving a value of L_β for the approach which is lower than the optimum and thus avoid having too much sensitivity to turbulence in cruise.

The configurations of Figure 5 all had the same Dutch-roll damping ratio, $\zeta_d = 0.1$. The effect of changing the damping ratio both to higher and lower values is shown in Figure 6. It is seen that a sharp degradation of pilot rating occurs if the damping ratio is reduced to $\zeta_d = 0.05$, while an increase to $\zeta_d = 0.4$, which might be accomplished with artificial yaw damping, results in only very modest improvement. The fairing of the data indicates that the basic requirement is for a damping ratio of about one-tenth, a level which can usually be attained aerodynamically. This value is in agreement with the findings of Reference 4.

It must be emphasized again that the above results were obtained with all parameters other than the specific test variables held at favorable levels. The presence of significant Dutch-roll excitation from the lateral control will be especially detrimental; even if the rating contours are not changed in general shape, the numerical levels almost certainly will be. A shrinking effect on the individual boundaries might be expected. To maintain the rating level associated with a particular configuration in Figure 5 in the presence of Dutch-roll excitation, a higher damping ratio than that indicated in Figure 6 will probably be required - at least for high $\omega_\varphi / \omega_d$. These matters will be investigated in detail in the next phase of the program.

Interpretation of the Results from a Flying Qualities Research Viewpoint

The previous section dealt with the general features of the results and their significance to designers; this section will present in more detail the reasons for certain configurations being rated as they were.

(A) The Role of Turbulence. All of the configurations tested were reasonably pleasant and well-behaved (Cooper-Harper rating of 2) when flown in smooth air. In simulated continuous turbulence, on the other hand, the differences between configurations began to stand out, and in some cases the turbulence response was the outstanding feature of the airplane. The configurations for which this was true were those with high frequency Dutch-roll motions (associated with large directional stability, N_β) and/or large dihedral effect. Pilot commentary indicated that the airplanes of Figure 5 with $\omega_d = 3.0$ rad/sec and $L_\beta = -24$ or $L_\beta = -32$ were downgraded primarily for the yaw and/or roll disturbances associated with turbulence. Figure 7 presents this result graphically; in place of frequency and dihedral coordinates, the axes are labeled with root-mean-square angular acceleration due to turbulence (also listed in Table 1 for each configuration), σ_L for roll, and σ_N for yaw. Pilot rating contours of the same general shape as the contours of Figure 5 serve to fair the average ratings, thus lending support to the finding that turbulence is a major factor in the ratings for airplanes with large static stabilities. (It should be noted that a low level of roll disturbance, due to L_p, exists even with zero dihedral. Also note that levels of turbulence excitation in yaw lower than $\sigma_N = .04$ are associated with configurations with such small directional stability that undesirable dynamic response, rather than turbulence, is the problem.)

The 3.0 boundary in Figure 7 would become an approximate 4.0 line if the damping were decreased to $\zeta_d = 0.05$. The pilot comments for these configurations indicated that the airplanes were in almost constant motion due to the tendency for the lightly-damped Dutch-roll to persist, and heading control was difficult.

The roll-to-sideslip ratio, $|\varphi/\beta|_d$ has in the past been considered an indicator of turbulence problems in roll, but Figure 8 indicates that the effects are better correlated by dihedral effect, L_β, itself. In this figure it is apparent that the contours of constant pilot rating from Figure 5 do not agree with the superimposed lines of constant $|\varphi/\beta|_d$; in general, for any given moderate $|\varphi/\beta|_d$ level it is possible to have both good and poor airplanes, depending on the level of directional stability available.

The absolute values of pilot rating obtained are admittedly dependent upon the level of turbulence used in the simulation, in this case rms linear velocity components of about 6 ft/sec. As noted in the section on experimental procedure, traversing this field of turbulence at 105 knots produces equivalent rms sideslip (β) of about 2 degrees, roll rate (p) of about 3 deg/sec, and yaw rate (r) of about 3-1/2 deg/sec. Qualitatively, the disturbance level for configurations with small stability is very low; for those with large stability derivatives it is high; for the airplane in the middle of Figure 5, the "optimum" airplane, it simply presents a continuous piloting task and causes a degradation of perhaps one-half of one rating unit compared to an approach in smooth air. The pilot ratings would improve, of course, if the turbulence intensity were lower, but the level used is felt to be representative of "moderate" disturbances encountered operationally.

Finally, it should be noted that these findings with respect to turbulence are neither new nor unique; they correspond quite closely, in fact, with those of References 2 and 3, and serve to further emphasize the important role of turbulence in flying qualities.

(B) The Effects of Dynamics. The character of the Dutch-roll changed considerably over the range of configurations tested: the period went from slightly more than two seconds to nearly five seconds; the mode changed from a pure yawing-and-sideslipping motion at zero dihedral to an oscillation with a very large roll component at the highest dihedral tested; and the damping ratio varied from very light to relatively heavy. In the last section it was pointed out that the ratings in the high-frequency, high-dihedral areas of Figure 5 were downgraded because of their poor behavior in turbulence. To amplify this point, the period was neither too short nor the rolling too violent to prevent the pilots from controlling the motions; their comments indicated that it was mainly the relatively large size and continuous nature of the disturbances that caused them to downgrade these configurations. The dynamics of the Dutch-roll, in other words, were not being criticized, but rather the high levels of static stability which accompanied those particular dynamics.

On the other hand, the pilot ratings for the low frequency ($\omega_d = 1.3$ rad/sec) configurations are *primarily* due to poor dynamics and the associated controllability problems. It should be recalled that these airplanes had good roll response characteristics, and indeed poor roll control itself was never listed as a factor in the ratings. According to the pilot comments, the problems are generally poor control over heading and large sideslip excursions. In these cases the turbulence disturbances in yaw are small due to the low level of directional stability, N_β, but roll disturbances are present and become large at high levels of dihedral. Three important sources of excitation of the characteristically slow (4.8 second period) Dutch-roll are thus present: the roll turbulence, which leads to banking and hence to sideslipping and the complete Dutch-roll; rolling and yawing originating in the airplane being out of trim (these low frequency configurations are generally difficult to trim accurately because of the "weak" directional stability that allows the airplane to sideslip easily; on instruments, in turbulence, re-trimming is a virtual impossibility); and the pilot himself, who will be trying to suppress the roll turbulence excursions and control the flight path simultaneously.

It is conceivable that the pilot can fly these configurations with precision only under VFR conditions, wherein the "visual display" seen through the window is perfectly integrated and all of the physical cues to the pilot are in perfect harmony. Under the hood, in IFR conditions, there are difficulties associated with priorities in the instrument scan, sampling rates, integration of the information, and adequacy of the information itself. For example, it is by no means certain that the yaw rate information available from the instruments - from rate of movement of the directional gyro or from the turn-and-bank indicator - can be either sensed adequately or monitored closely enough by the pilot to permit his working effectively on yaw-rate with the rudder. Or, bank angle information sampled from a gyro horizon may not give the rather precise control over bank angle needed to pin down a certain heading, or to avoid unintentional sideslips. It is pertinent to mention here that a series of runs were made in which the pilot was asked to remove the blind-flight hood late in the approach and then rate the configuration separately for the instrument and visual portions. In no case was the airplane rated worse for the visual task, and generally one-half to one unit better.

The matter of piloting technique is important here. Sometimes pilots indicated that they were controlling heading with the rudder; at other times, or for other configurations, they claimed to be "coordinated," that is, they were moving stick and pedals together while banking and unbanking the airplane to achieve heading changes. But for the latter case the roll control was the primary one. Analysis of several of the approaches indicates that typically the pilots moved the stick and rudder in the same direction (to give right roll and right yaw, for example) about 80% of the time, in opposite directions about 5% of the time, and didn't move the rudder at all 15% of the time. This is not conclusive, of course, but such results so far, for the ILS approach, differ little from pilot to pilot, or between configurations. As a matter of interest, a sample approach record is shown in Figure 9.

This pattern of commentary and ratings concerning airplanes with different combinations of L_β and N_β should fit a rationale of pilot-vehicle closed-loop system analysis, but this is complicated by the presence of two controls, aileron and rudder, and the multiple-loop nature of the ILS task itself. Before the structure of this system can be defined, specialized data are needed, such as that from experiments in which the pilot is asked to track only heading. The response of the airplane to rudder inputs takes on new importance here, since civilian pilots (as contrasted with the military jet pilots of References 2 and 3) are inclined by training and experience to use it heavily; most previous lateral-directional flying qualities work has been concerned with roll response to lateral control and thus is of little assistance.

Measures of Pilot Activity and Task Performance

Records of the approaches such as Figure 9 - mentioned previously in connection with piloting technique - were examined in an effort to find correlations between control activity (control position zero-crossings, control reversals), task performance (localizer and glide slope deviations), configuration parameters, and pilot rating. No significant correlations were evident in the control activity data. The tracking data showed as much pilot-to-pilot variation (and even day-to-day variation with the same pilot) as it showed between configurations, evidence of the fact that a proficient pilot can maintain a high level of performance in a complex task even while flying a poor-handling airplane.

CONCLUSIONS

The following conclusions, based upon experiments carried out with a variable stability flying simulator, apply to small general aviation airplanes with good roll mode characteristics, low Dutch-roll excitation from the lateral control, and near-neutral spiral mode, flown on an ILS approach:

1. The best level of Dutch roll frequency is ω_d between 1.8 and 2.3 rad/sec (Dutch-roll period between 2.7 and 3.5 seconds). This represents a compromise wherein the level of directional stability is large enough to give good dynamics, but not so large as to cause excessive yawing in turbulence.

2. Directional stability large enough to produce a Dutch-roll frequency in the neighborhood of 3 rad/sec (2.1 second period) leads to excessive turbulence response in yaw.

3. Dutch-roll frequencies lower than about 1.4 rad/sec (4.5 second period) associated with low directional stability are undesirable because they require the pilot to compensate for poor heading control, large sideslip excursions, and difficulty in trimming the airplane in roll and yaw.

4. Flying qualities for the instrument approach task deteriorate rapidly for Dutch-roll damping ratios less than $\zeta_d = 0.10$, but relatively little is gained by increasing ζ_d beyond this value - at least for low Dutch-roll excitation in the roll response. For some cases of high Dutch-roll excitation higher damping would undoubtedly be beneficial.

5. The best range for dihedral effect is $L_\beta = -8$ to $L_\beta = -16$ rad/sec^2/rad, but there is little penalty in terms of flying qualities for lower values. Even zero dihedral effect does not interfere with the task of flying an ILS approach.

6. Large dihedral effect ($L_\beta = -24$ or more negative) is undesirable because it produces excessive rolling due to turbulence.

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TABLE 1

CONFIGURATION PARAMETER AND DERIVATIVE VALUES

Config. No.	τ_{rm}	ζ_d	ω_d	$\frac{\omega_\varphi}{\omega_d}$	$\frac{K_d}{K_{ss}}$	$\left\|\frac{\varphi}{\beta}\right\|_d$	L_p	L_β	L_r	N_p	N_β	N_r	σ_L	σ_N
1 (201)	.25	.1	1.3	1.0	0	0	-4	0	0	0	1.69	-.006	.209	.027
2 (128)	.25	.1	1.8	1.0	0	0	-4	0	0	0	3.213	-.106	.209	.051
3 (230)	.25	.1	2.3	1.0	0	0	-4	0	0	.01	5.24	-.206	.209	.083
4 (234)	.25	.1	3.0	1.0	0	0	-4	0	0	.01	8.91	-.346	.209	.140
5 (202)	.25	.1	1.3	.97	.073	1.9	-3.96	-10.04	.294	.13	1.57	-.046	.261	.026
6 (2)	.25	.1	1.8	.957	.108	1.1	-3.92	- 8.0	.52	0	2.9	-.19	.242	.047
7 (231)	.25	.1	2.3	.98	.06	1.1	-3.92	-10.66	.613	.05	4.97	-.286	.268	.079
8 (237)	.25	.1	3.0	.987	.034	.6	-3.94	- 8.51	.4	.03	8.71	-.406	.247	.138
9 (203)	.25	.1	1.3	.948	.137	3.1	-3.92	-16.37	.94	.13	1.50	-.086	.339	.026
10 (6)	.25	.1	1.8	.903	.261	2.2	-3.83	-16.0	1.75	0	2.56	-.281	.327	.042
11 (232)	.25	.1	2.3	.95	.13	1.7	-3.84	-16.82	1.32	.01	4.67	-.366	.338	.074
12 (235)	.25	.1	3.0	.983	.046	1.3	-3.9	-17.6	.91	.07	8.62	-.446	.348	.136
13	.25	.1	1.3	.918	.20	4.5	-3.92	-24	3.73	.13	1.41	-.206	.430	.026
14 (10)	.25	.1	1.8	.782	.73	4.6	-3.61	-32	8.56	0	1.85	-.494	.540	.032
15 (236)	.25	.1	3.0	.985	.052	2.3	-3.86	-32.4	1.82	.11	8.62	-.486	.551	.136

TABLE 1 (continued)

Config. No.	τ_{rm}	ξ_d	ω_d	$\frac{\omega_\varphi}{\omega_d}$	$\frac{K_d}{K_{ss}}$	$\left\|\frac{\varphi}{\beta}\right\|_d$	L_p	L_β	L_r	N_p	N_β	N_r	σ_L	σ_N
22 (204)	.25	.4	1.3	1.0	0	0	-4.0	0	0	0	1.49	-.786	.209	.027
23 (109)	.25	.4	1.8	1.0	0	0	-4.0	0	0	0	2.94	-1.19	.209	.048
24 (240)	.25	.4	2.3	1.0	0	0	-4.0	0	0	.01	4.89	-1.586	.209	.078
29 (206)	.25	.4	1.3	.87	.804	3.6	-3.38	-16.28	18.94	.07	1.21	-1.406	.317	.024
30 (242)	.25	.4	2.3	1.02	.107	1.9	-3.72	-16.02	6.04	.11	4.95	-1.866	.324	.079
32	.25	.05	1.3	1.0	0	0	-4.00	0	0	.006	1.72	- .124	.210	.027
34	.25	.05	2.3	1.0	0	0	-4.00	0	0	.005	5.30	- .024	.210	.083
36	.25	.05	1.3	.88	.21	3.0	-3.91	-16	+.391	.08	1.32	- .032	.330	.021
38	.25	.05	2.3	.955	.10	1.6	-3.865	-16.05	.373	.02	4.78	- .111	.320	.076

(   ) Configuration numbers from Reference 3

Note: $Y_\beta / V = -.254$
$g / V = +.181$
$N_{\delta a} = L_{\delta r} = 0$ for all configurations
$L_{\delta a}$, $N_{\delta r}$ optimum

TABLE 2

PILOT OPINION RATING SCALE

CONTROLLABLE Capable of being controlled or managed in context of mission with available pilot attention.	ACCEPTABLE May have deficiencies which warrant improvement, but adequate for mission. Pilot compensation, if required to achieve acceptable performance, is feasible.	SATISFACTORY Meets all requirements and expectations, good enough without improvement. Clearly adequate for mission.	Excellent, highly desirable.	A1
			Good, pleasant, well behaved.	A2
			Fair. Some mildly unpleasant characteristics. Good enough for mission without improvement.	A3
		UNSATISFACTORY Reluctantly acceptable. Deficiencies which warrant improvement. Performance adequate for mission with feasible pilot compensation.	Some minor but annoying deficiencies. Improvement is requested. Effect on performance is easily compensated for by pilot.	A4
			Moderately objectionable deficiencies. Improvement is needed. Reasonable performance requires considerable pilot compensation.	A5
			Very objectionable deficiencies. Major improvements are needed. Requires best available pilot compensation to achieve acceptable performance.	A6
	UNACCEPTABLE Deficiencies which require mandatory improvement. Inadequate performance for mission even with maximum feasible pilot compensation.		Major deficiencies which require mandatory improvement for acceptance. Controllable. Performance inadequate for mission, or pilot compensation required for minimum acceptable performance in mission is too high.	U7
			Controllable with difficulty. Requires substantial pilot skill and attention to retain control and continue mission.	U8
			Marginally controllable in mission. Requires maximum available pilot skill and attention to retain control.	U9
UNCONTROLLABLE Control will be lost during some portion of the mission.			Uncontrollable in mission.	10

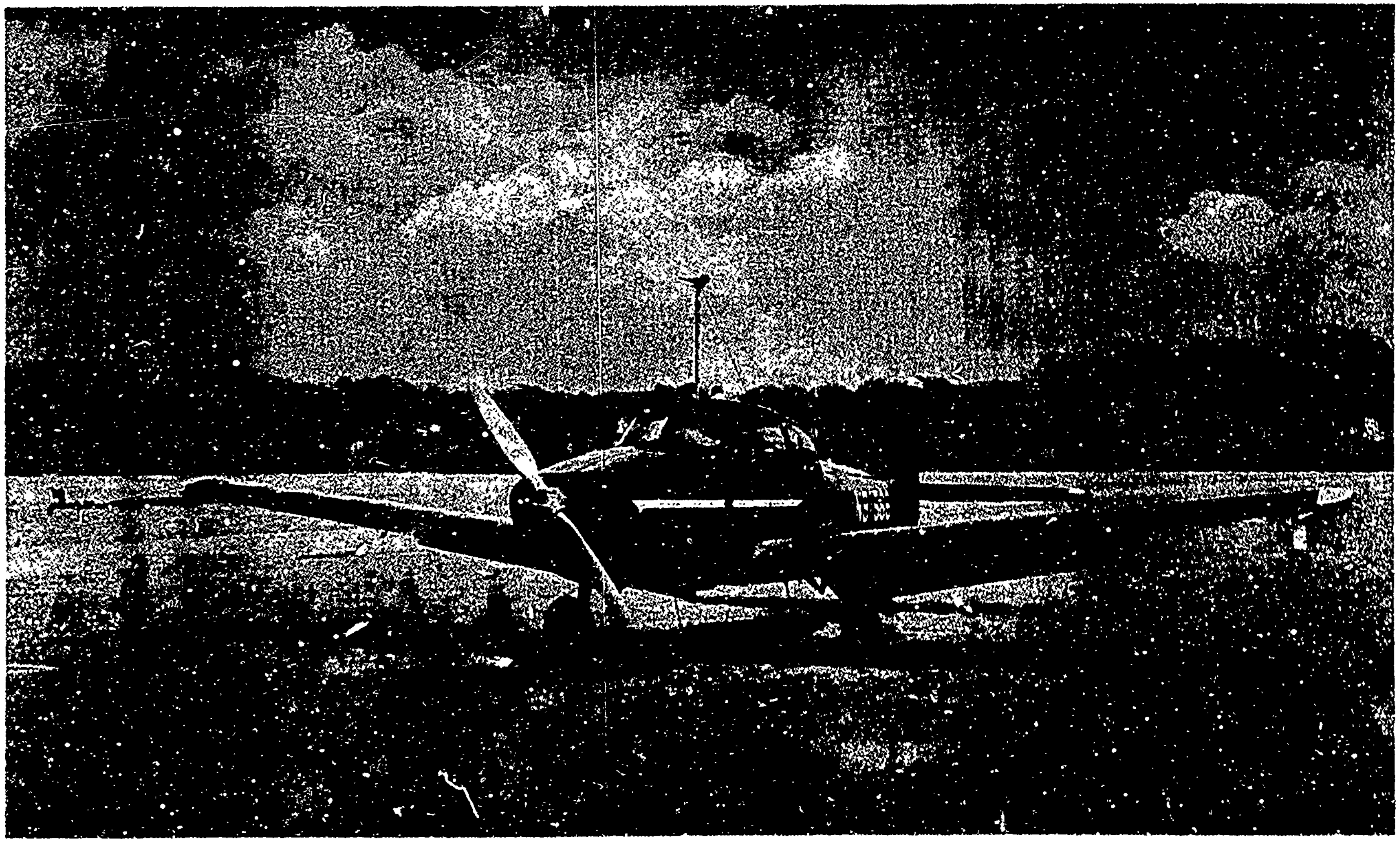

FIGURE 1 [illegible] NAVION FLYING SIMULATOR
([illegible] CONFIGURATION)

Note: ILS meter replaced angle-of-attack indicator on evaluation pilot's panel

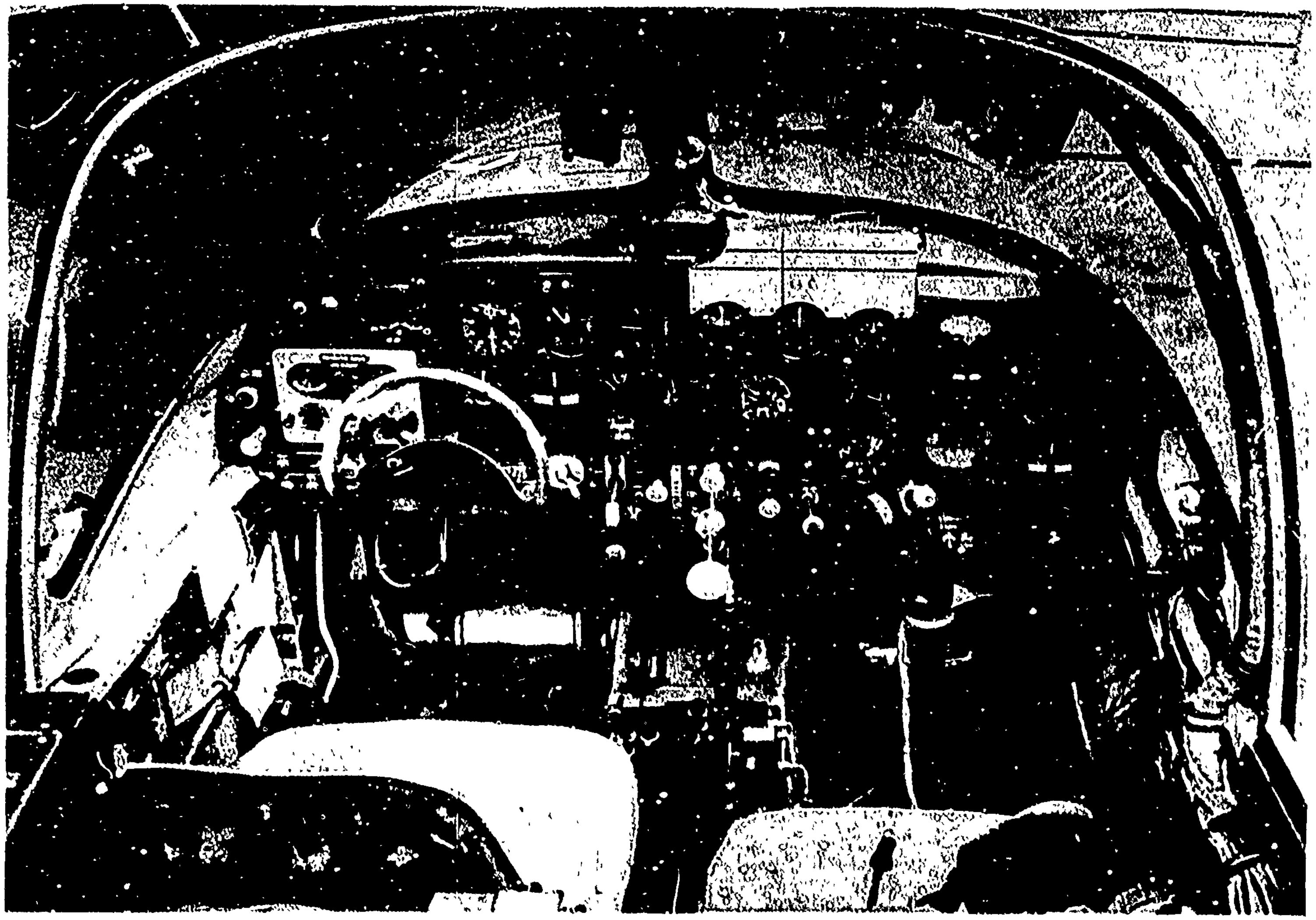

FIGURE 2 COCKPIT LAYOUT

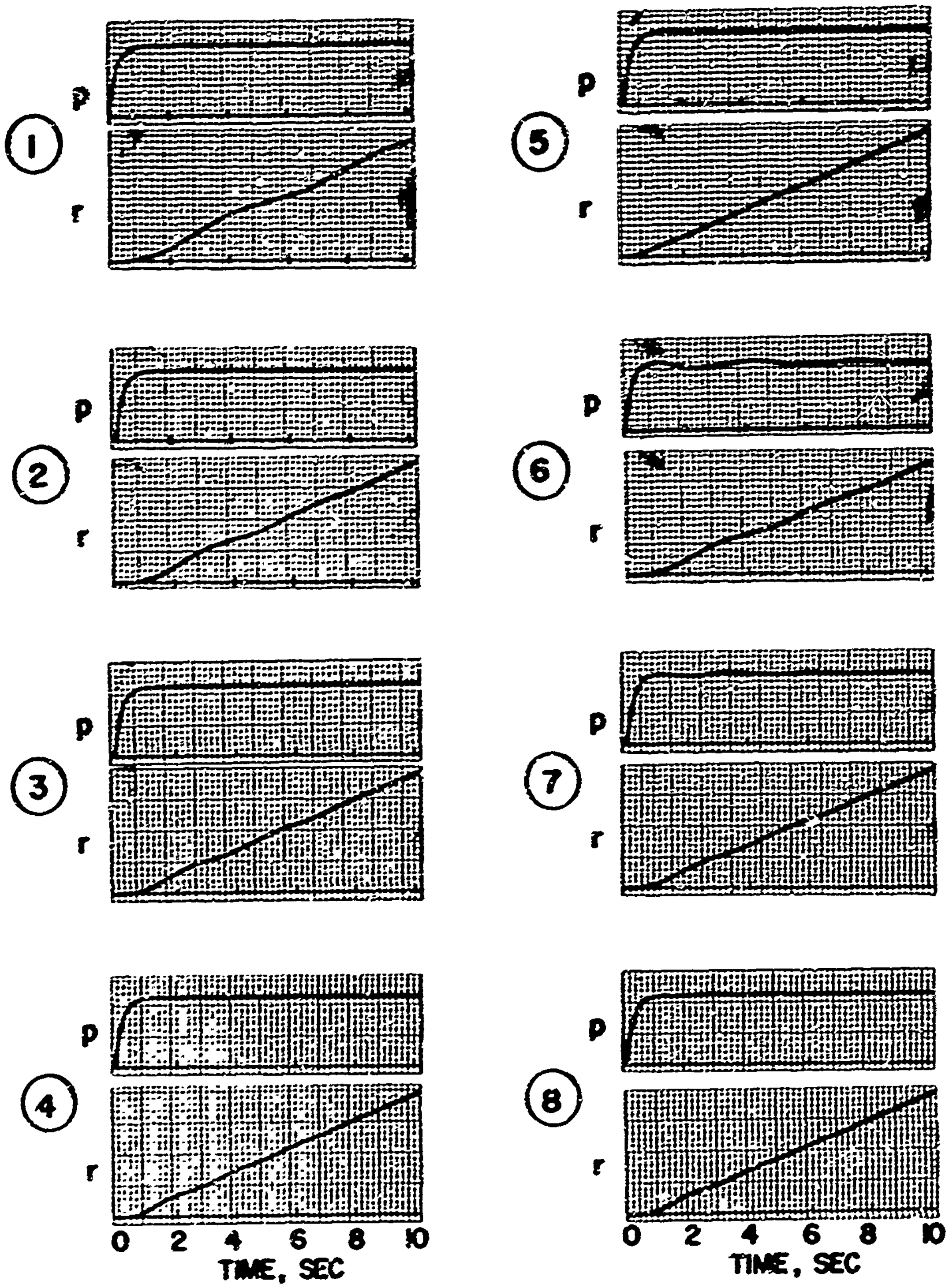

FIGURE 3 ANALOG COMPUTER ROLL RATE AND YAW RATE RESPONSES TO AILERON STEP INPUTS

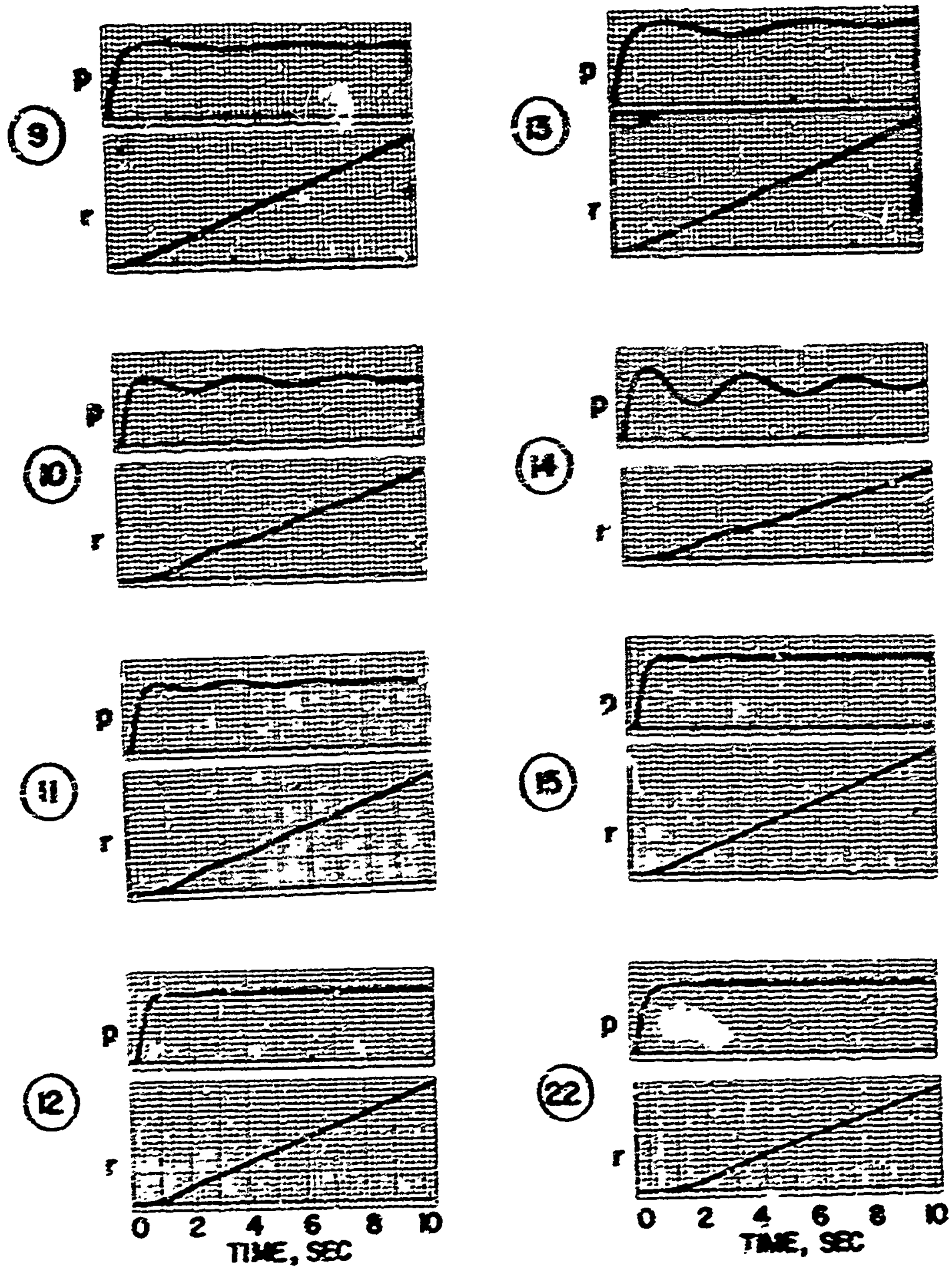

FIGURE 3 ANALOG COMPUTER ROLL RATE AND YAW RATE RESPONSES TO AILERON STEP INPUTS

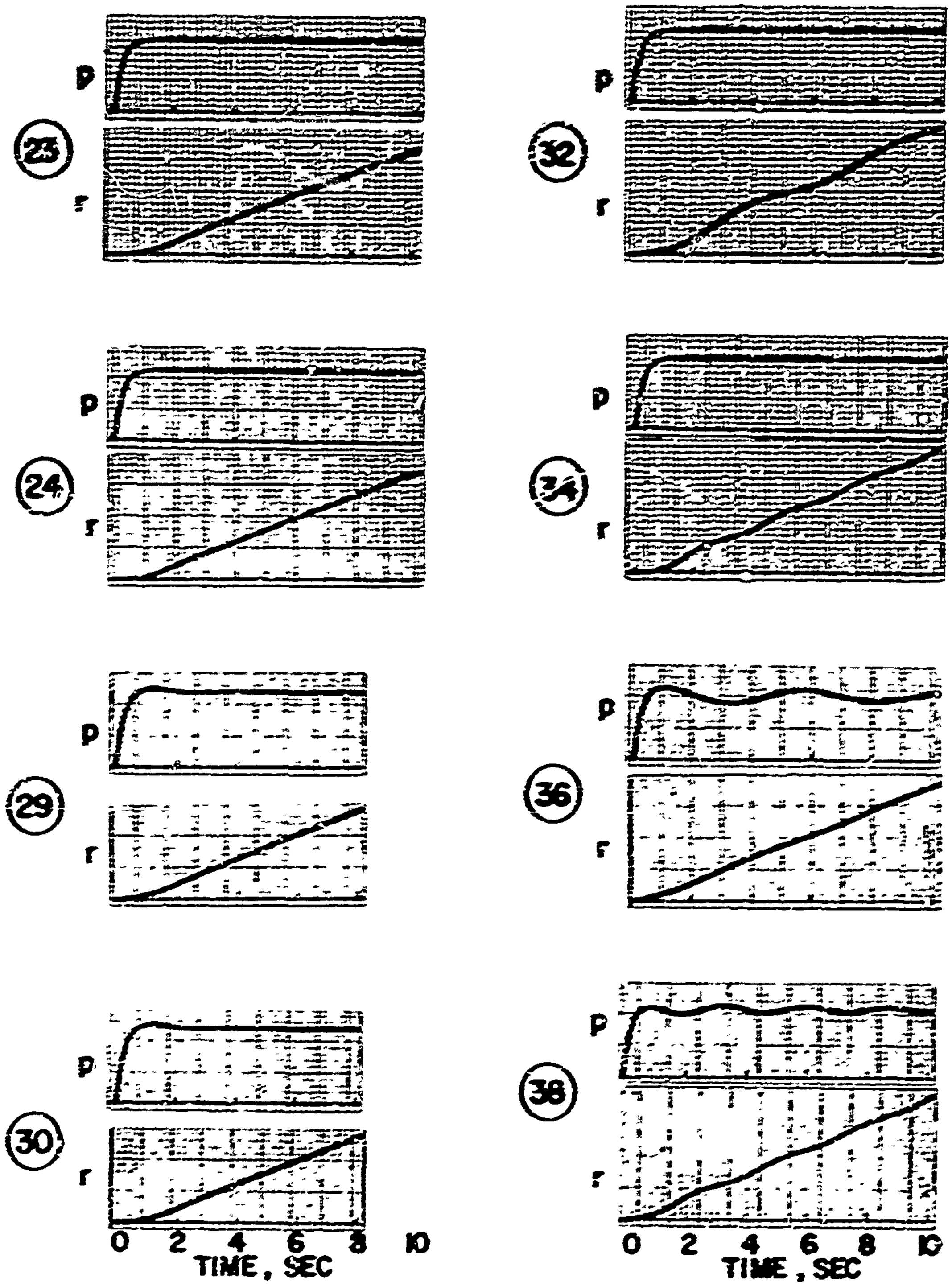

FIGURE 3 ANALOG COMPUTER ROLL RATE AND YAW RATE RESPONSES TO AILERON STEP INPUTS

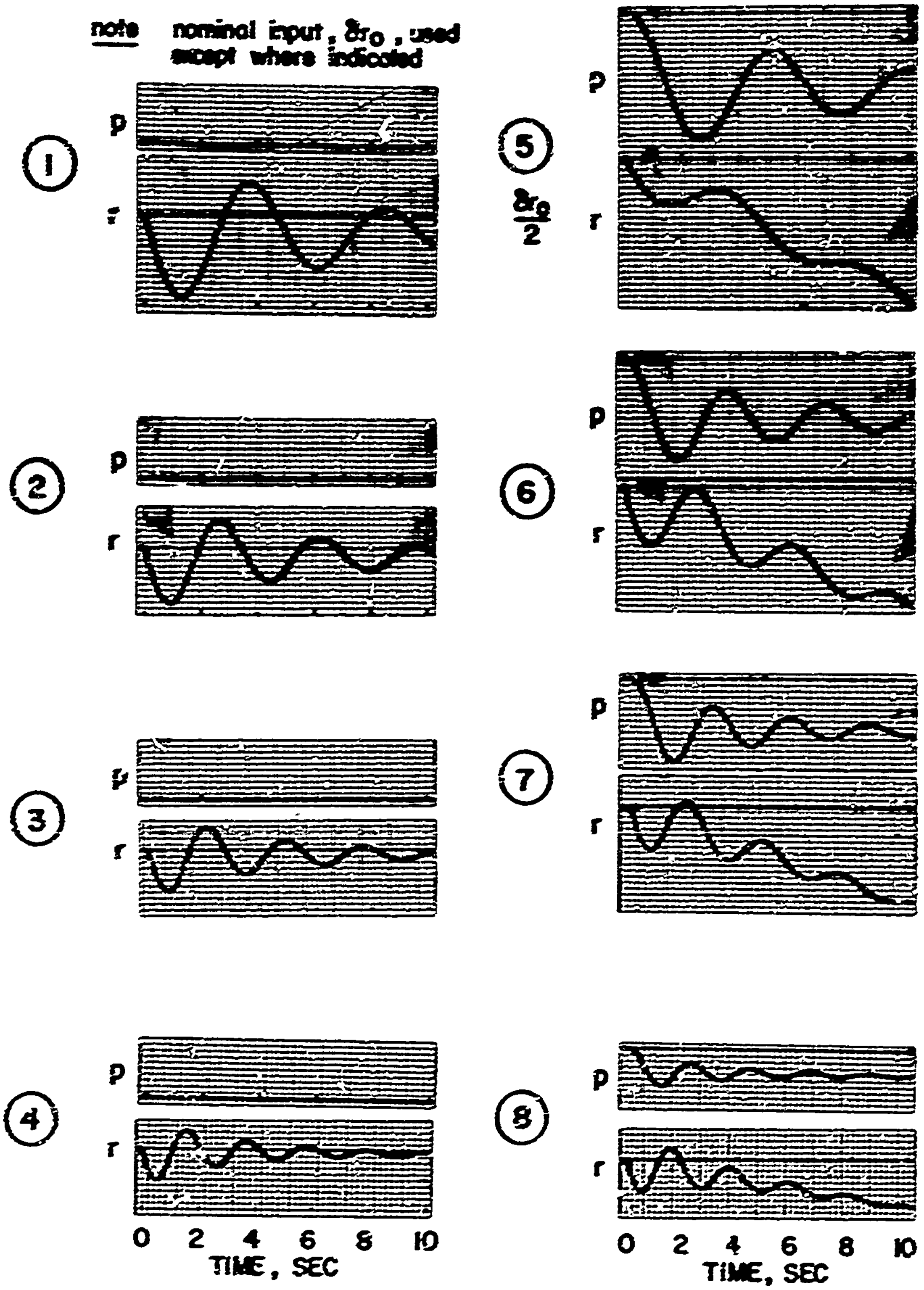

FIGURE 4 ANALOG COMPUTER ROLL RATE AND YAW RATE RESPONSES TO RUDDER STEP INPUTS

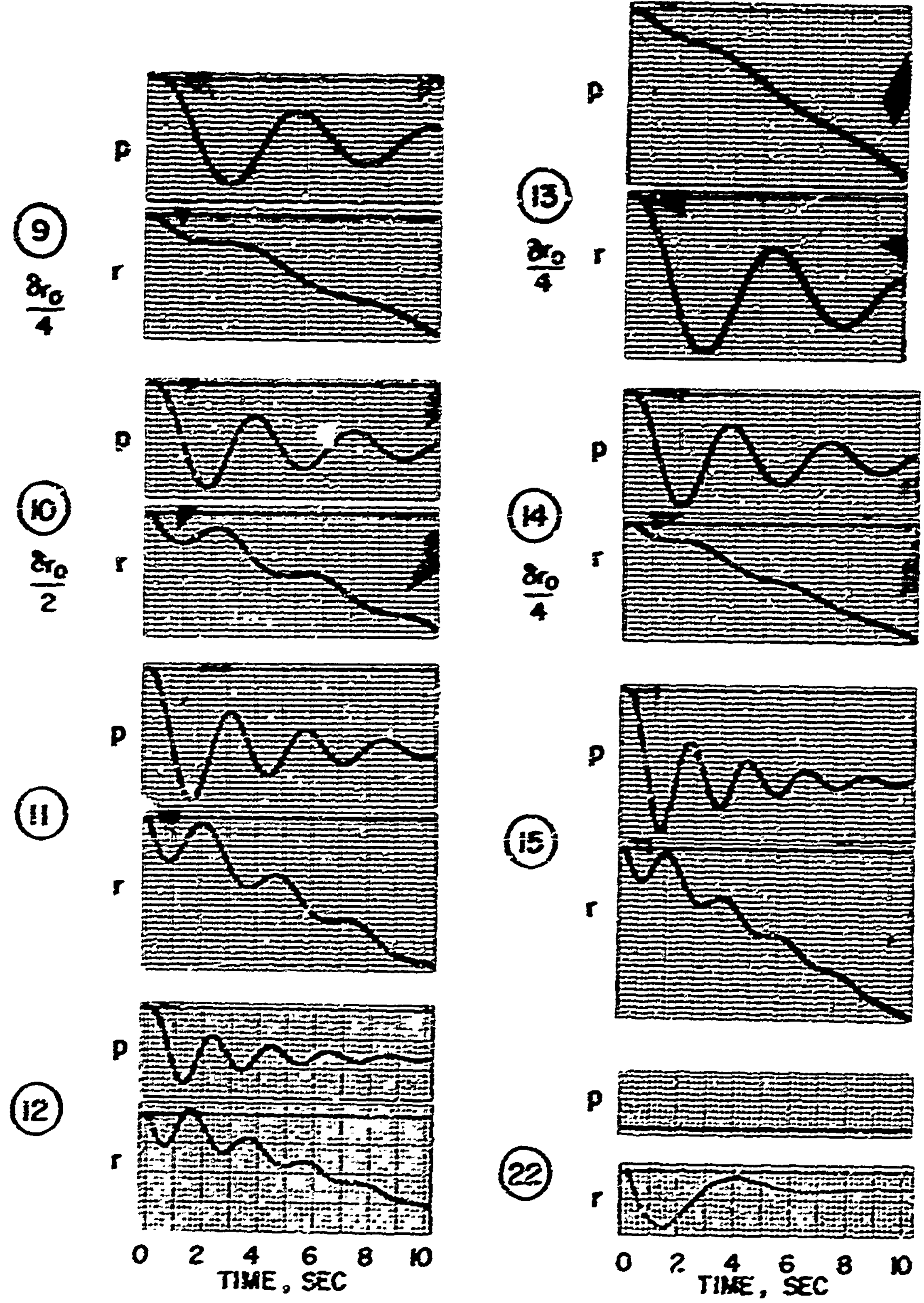

FIGURE 4 ANALOG COMPUTER ROLL RATE AND YAW RATE RESPONSES TO RUDDER STEP INPUTS

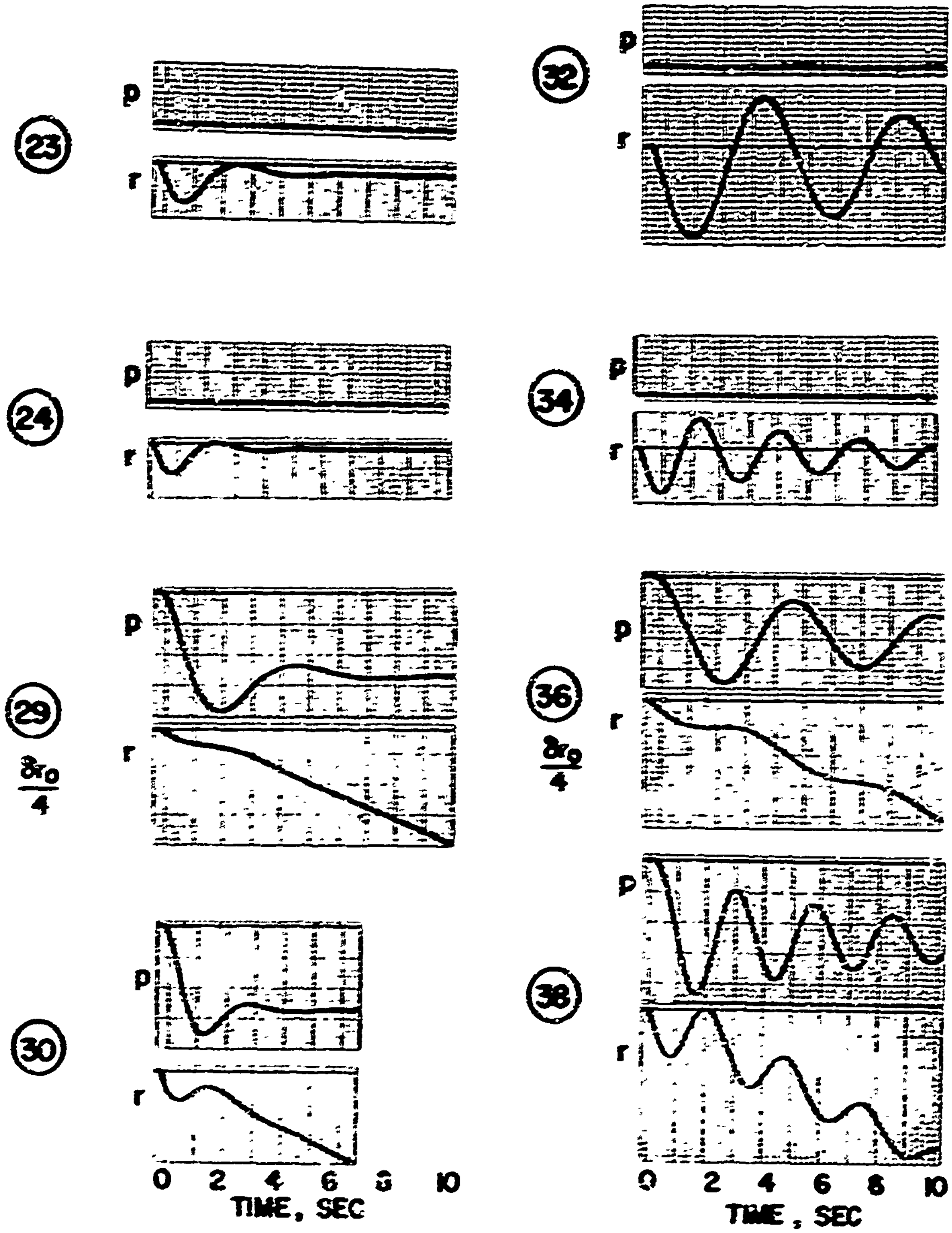

FIGURE 4 ANALOG COMPUTER ROLL RATE AND YAW RATE RESPONSES TO RUDDER STEP INPUTS

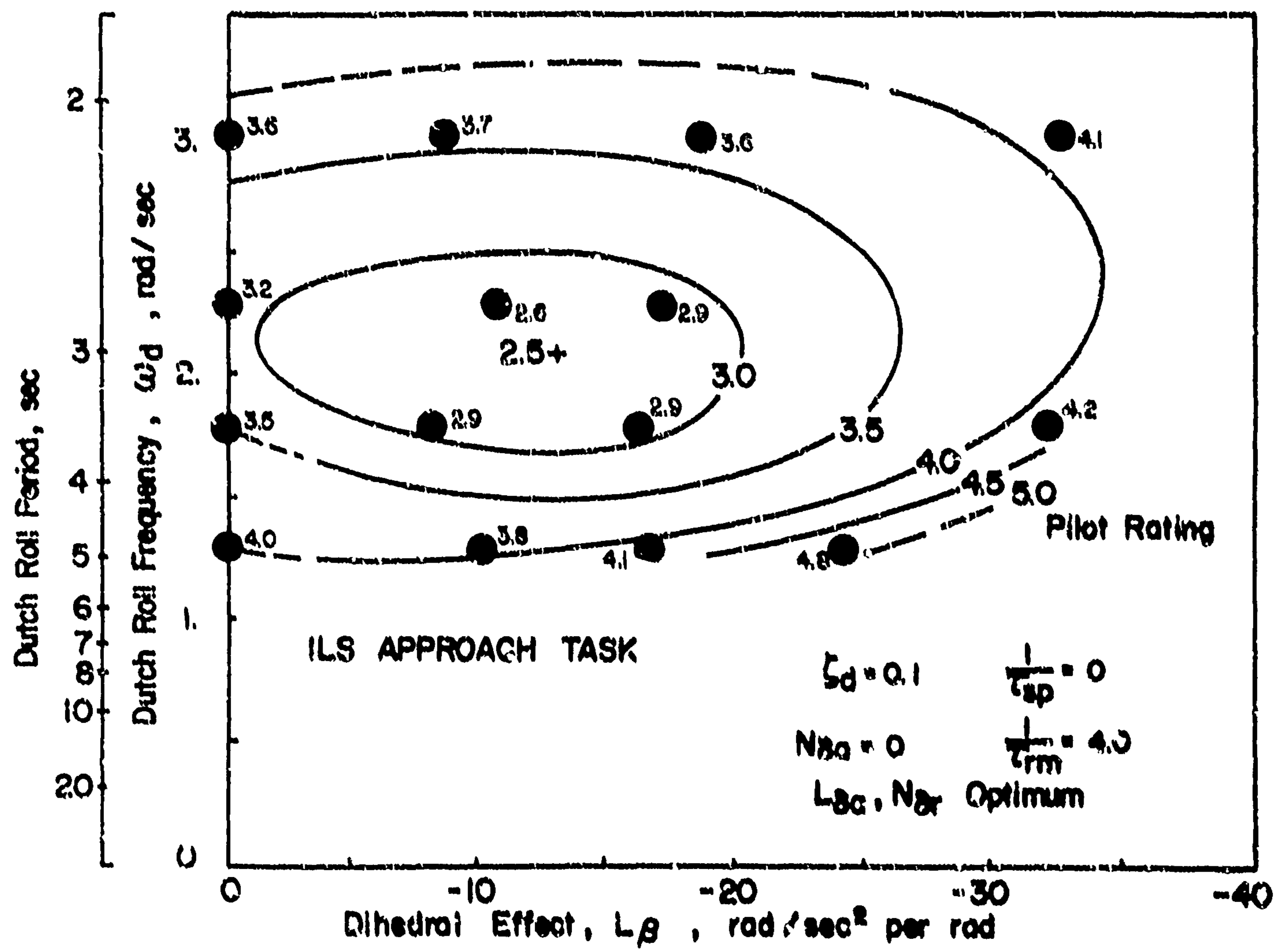

FIGURE 5 PILOT RATING CONTOURS, ω_d vs L_β, $\zeta_d = 0.1$

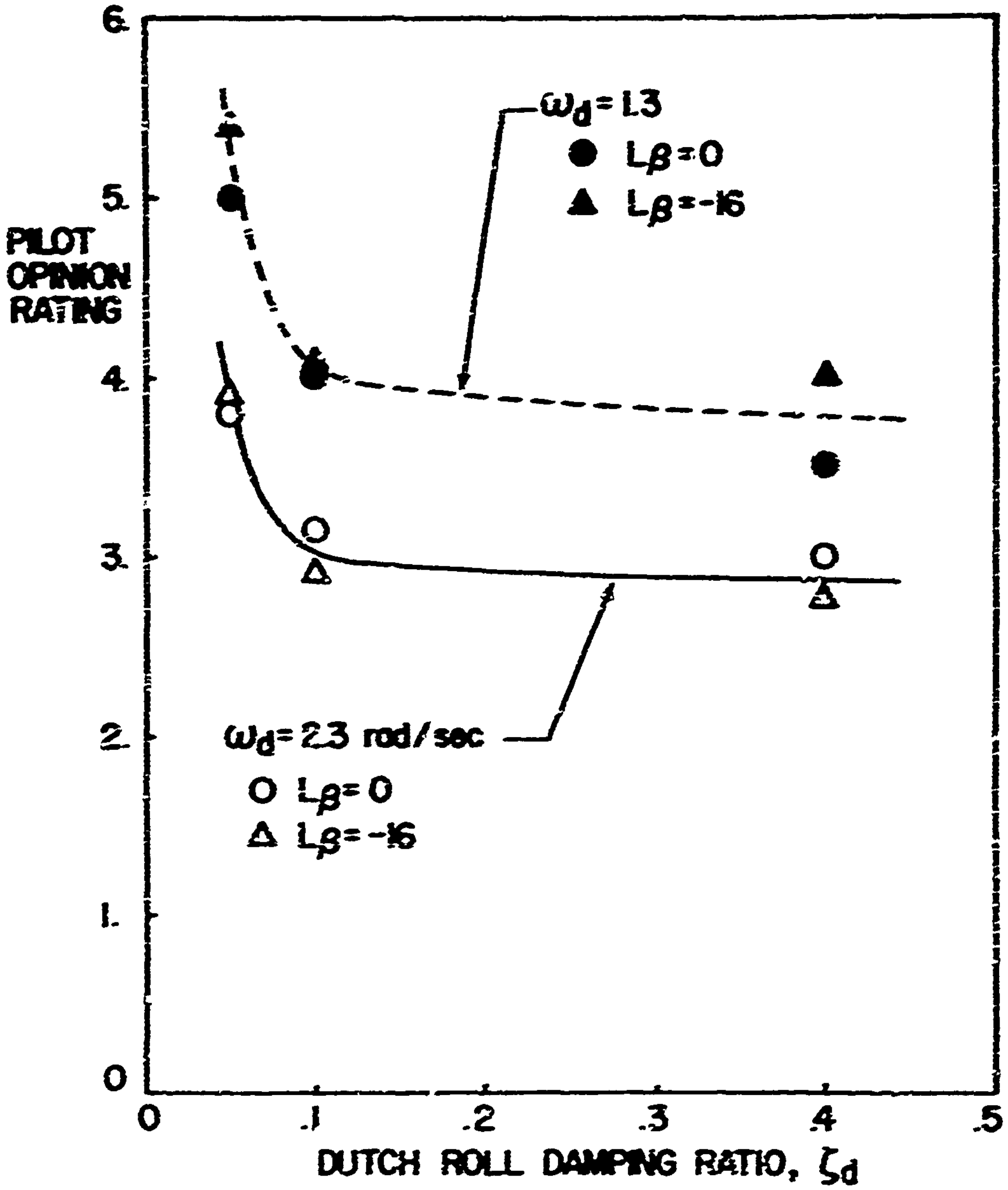

FIGURE 6 PILOT RATING AS A FUNCTION OF DUTCH ROLL DAMPING RATIO, ω_d CONSTANT

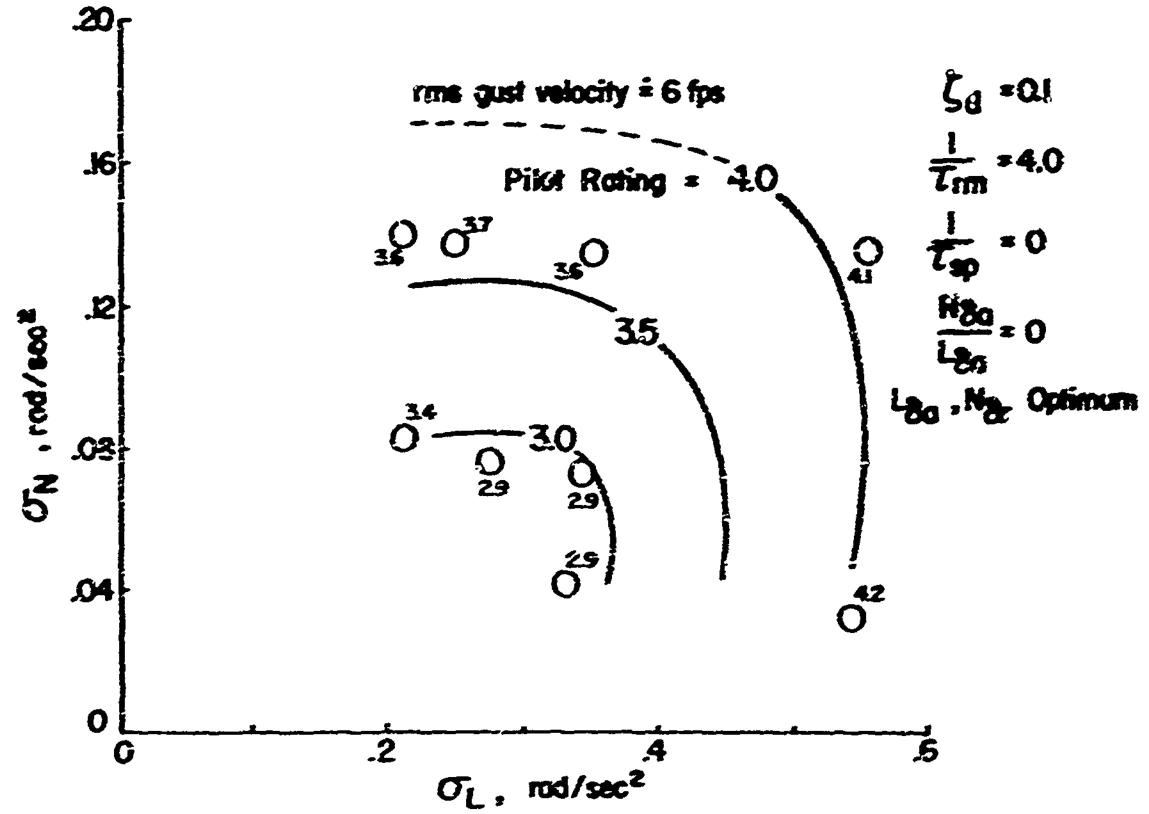

FIGURE 7 PILOT RATING CONTOURS, σ_N vs σ_L

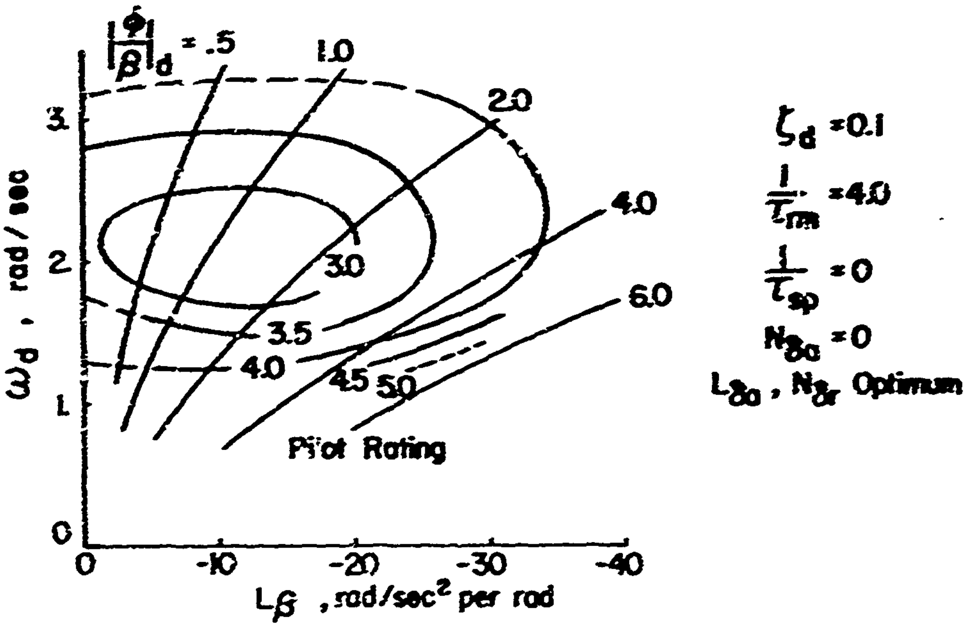

FIGURE 8 CONSTANT $\left|\frac{\phi}{\beta}\right|_d$ SUPERIMPOSED ON PILOT RATING CONTOURS, ω_d vs L_β

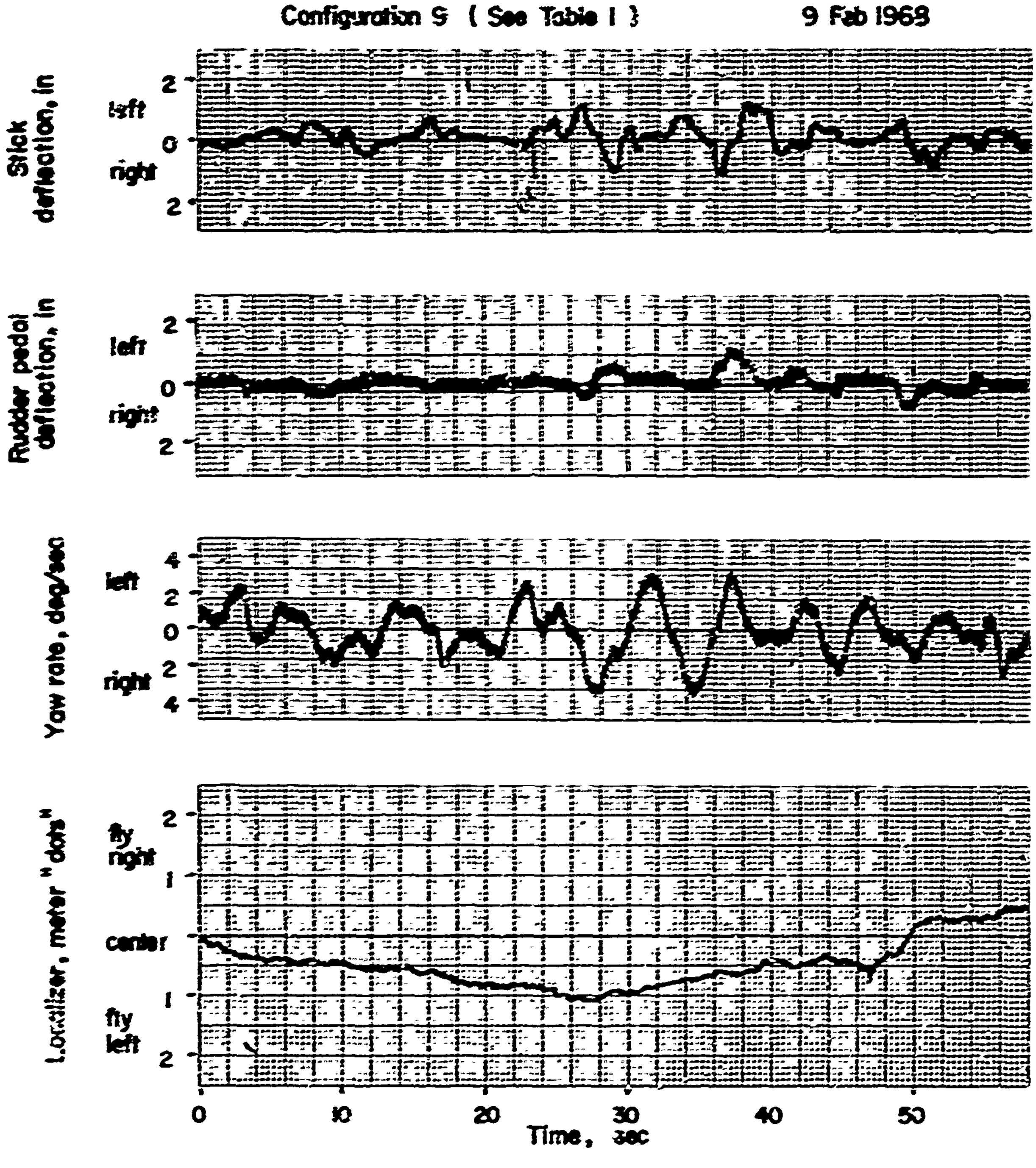

FIGURE 9 SAMPLE TEST DATA : LATERAL CONTROL AND RUDDER CONTROL DEFLECTIONS, YAW RATE AND LOCALIZER DEVIATIONS. SIMULATED TURBULENCE

APPENDIX

Lateral-Directional Equations and Approximate Response Factors

The following lateral-directional equations of motion and approximate response factors are included for reference purposes:

$$\left(s - \frac{Y_\beta}{V}\right)\Delta\beta + \Delta r - \frac{g}{V}\Delta\varphi = \frac{Y_{\delta r}}{V}\Delta\delta r$$

$$-L'_\beta\,\Delta\beta - L'_r\,\Delta r + (s^2 - L'_p s)\,\Delta\delta = L'_{\delta a}\,\Delta\delta a + L'_{\delta r}\,\Delta\delta r$$

$$-N'_\beta\,\Delta\beta + (s - N'_r)\,\Delta r - N'_p\,s\,\Delta\varphi = N'_{\delta r}\,\Delta\delta r + N'_{\delta a}\,\Delta\delta a$$

The "primed derivatives" in the roll and yaw equations incorporate the effects of product of inertia, I_{xz}, according to the definitions

$$L'_i \equiv \frac{L_i + \frac{I_{xz}}{I_x} N_i}{1 - \frac{I_{xz}^2}{I_x I_z}} \qquad N'_i = \frac{N_i + \frac{I_{xz}}{I_z} L_i}{1 - \frac{I_{xz}^2}{I_x I_z}}$$

For conventional, subsonic airplanes the characteristic equation is factored into roll mode, spiral mode, and Dutch-roll roots:

$$\left(s + \frac{1}{\tau_{rm}}\right)\left(s + \frac{1}{\tau_{sp}}\right)\left(s^2 + 2\zeta_d\omega_d + \omega_d^2\right) = 0$$

The following approximate factors are often useful:

$$\frac{1}{\tau_{rm}} \doteq -L'_p + \frac{L'_\beta}{N'_\beta}\left(N'_p - \frac{g}{V}\right)$$

$$\frac{1}{\tau_{sp}} \doteq \tau_{rm}\frac{g}{V}\left(\frac{L'_\beta}{N'_\beta}N'_r - L'_r\right)$$

$$2\zeta_d\omega_d \doteq -\left(\frac{Y_\beta}{V} + N'_r\right) - \frac{L'_\beta}{N'_\beta}\left(N'_p - \frac{g}{V}\right)$$

$$\omega_d \doteq (N'_\beta)^{\frac{1}{2}}$$

provided that

1. ζ_d is small
2. $\left|L'_p\left(\frac{Y_\beta}{V} + N'_r\right)\right| << \left|N'_\beta\right|$
3. $\left|\frac{L'_\beta}{N'_\beta}\left(N'_p - \frac{g}{V}\right)\right| << \left|L'_p\right|$