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EFFECTS OF AIRCRAFT DESIGN ON STOL RIDE QUALITY-- A SIMULATOR STUDY

Annual Status Report
Grant No. NGR 47-005-208

Submitted to:

National Aeronautics and Space Administration
Scientific and Technical Information Facility
P.O. Box 33
College Park, Maryland 20740

Submitted by:

Ira D. Jacobson

and

Craig R. Jones

RESEARCH LABORATORIES FOR THE ENGINEERING SCIENCES

SCHOOL OF ENGINEERING AND APPLIED SCIENCE

UNIVERSITY OF VIRGINIA

CHARLOTTESVILLE

Report No. ESS-4035-102-74
July 1974

#1

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Short-Haul Air Transportation Program
Memorandum Report 403502

DEPARTMENT OF ENGINEERING SCIENCE AND SYSTEMS
RESEARCH LABORATORIES FOR THE ENGINEERING SCIENCES
SCHOOL OF ENGINEERING AND APPLIED SCIENCE
UNIVERSITY OF VIRGINIA
CHARLOTTESVILLE, VIRGINIA

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INTRODUCTION AND PROGRAM DESCRIPTION

For many years, a considerable amount of work, resources, and time have been spent by military and civil groups in the aeronautical field to determine what qualities or characteristics an aircraft should have for it to be most easily and effectively flown. As a result, certain basic criteria have been formulated as guidelines for satisfactory aircraft handling qualities (1),(2),(3). However, even though much attention has been given in the past to developing aircraft with good handling qualities, very little attention has been devoted to developing aircraft with good ride qualities, i.e., aircraft in which the traveling public find flying pleasant (4). In the past, this has not presented serious problems since passengers on commercial flights, as a whole, were not especially annoyed by the experience of flying. However, with the increasing use of short take-off and landing aircraft (STOL) in commercial operation, the question of acceptable levels of ride quality has arisen due to the often unpleasant nature of motion encountered on such aircraft (5).

To improve the ride quality in these aircraft, several means have been investigated. In general, these methods consist of placing sensors in the aircraft which sense aircraft motion, usually linear accelerations and angular rates. These signals are then used to deflect control surfaces which generate aerodynamic forces and moments which tend to minimize the motion which the passenger feels. One of the disadvantages of some of these systems is that they may tend to degrade the handling qualities or controllability of the airplane, making it more difficult or annoying for the pilot to fly.

Rather than using active control systems to control ride quality, one might possibly design aircraft so that they are inherently pleasant to ride. Thus, the purpose of this study is to determine the relationship between characteristic aircraft motions and aircraft ride quality.

Most aircraft have five distinct characteristic motions, 2 longitudinal and 3 lateral. These motions are determined by aircraft geometry, mass distribution, and flight conditions such as velocity, and air density. The phugoid longitudinal mode and spiral lateral mode are normally of such long period that these pure motions would normally not be sensed by flying passengers. In fact, they are rarely seen in typical flight because these motions are readily damped out (usually unconsciously) by the pilot. Likewise, the rolling mode is not deemed important to aircraft ride quality because of the pilots tendency to keep the wings level in cruise, and when maneuvering, to keep rolling rates small. The two remaining aircraft modes, the Dutch Roll and the short-period modes, are of particular interest in ride quality studies since their associated periods and amplitudes fall into the spectrum of motions found uncomfortable by human beings. The quantities which usually define the handling qualities of these two modes are the undamped natural frequency, and the damping ratio of the short-period mode, and the number of cycles to half amplitude, time to half amplitude and a roll-to-sideslip parameter for the Dutch Roll mode. Using the parameters established for defining satisfactory handling qualities for these two aircraft motions, the limits which satisfactory ride quality place on these parameters will be determined by subjecting human subjects to such motion in aircraft simulators and eliciting their subjective comfort responses.

The test program is divided into two distinct phases. The first phase investigated the feasibility and the effects of varying certain parameters on ride and handling qualities. The range of parameter variation and the effects of these variations on ride quality were studied in the University of Virginia's Analog Flight Simulator.

Once these studies were completed, the second phase was initiated at NASA's Langley Research Center. Here tests were begun on the Visual Motion Simulator (VMS) using aircraft parameters determined in the first phase. Simultaneous measurements of both ride and handling qualities will be made for various aircraft configurations and finally, the tradeoffs between ride and handling qualities will be defined.

SIMULATOR EXPERIMENTS AT THE UNIVERSITY OF VIRGINIA

The University of Virginia's fixed-base analog flight simulator was programmed with the six degree-of-freedom equations of motion given in Figure 1. The aircraft used in the simulation was a 11,500 pound deHavilland Canada DHC-6 Twin Otter. This particular aircraft was chosen because it is a typical STOL aircraft and has been in service since 1966 in many roles. Also, its flying characteristics are well known, and there are many pilots available with flying experience in the Twin Otter to validate the ground-based simulations. Flight conditions of level flight at 3000 feet and an equilibrium flight speed of 175 mph were chosen as the typical environment in which this aircraft is operated. Based on these flight conditions, stability derivatives were obtained from an unpublished NASA document containing a mathematical model for the Twin Otter used in a fixed-base simulation at the Langley Research Center to study STOL air traffic control procedures. These stability derivatives agree well with ones contained in NASA Contractor Report 2276 for a Twin Otter in approximately the same flight conditions. The stability derivatives for this flight condition may be found in Table 1. This condition and its corresponding set of stability derivatives will be referred to as the "nominal" conditions.

In addition to the nominal configuration, other stability conditions were run. These conditions were produced by varying C_{m_α} and C_{m_q} in the longitudinal mode, and C_{y_β} and C_{n_β} in the lateral mode. The longitudinal parameters were varied holding the lateral derivatives at the nominal conditions and the lateral derivatives were varied holding the longitudinal derivatives at their nominal values.

For each set of stability derivatives, the quantities which determine the handling qualities of the short period and Dutch Roll modes were computed by a computer program which solves the longitudinal and lateral 4th degree equations for the characteristic modes. From these characteristic values, the short period undamped natural frequency, ω_n and the damping

$$-{}'\dot{u} = -\dot{\psi}\beta + \dot{\theta}\,{}'\alpha + \left[-\frac{C_{x_u} Sq}{mU}\right] {}'u - \left[\frac{Sqc}{2mU^2} C_{x_{\dot{\alpha}}}\right] {}'\dot{\alpha} + \left[\frac{C_{x_\alpha} Sq}{mU}\right] {}'\alpha$$

$$+ \left[\frac{Sqc}{2mU^2} C_{x_q}\right] \dot{\theta} + \left[\frac{g}{U}\right] \theta - \left[\frac{Sq\, C_{x_{\delta_T}}}{mU}\right] \delta_T$$

$$-{}'\dot{\alpha} = -\left[\frac{\frac{mU}{Sq} + \frac{c}{2U} C_{z_q}}{\frac{mU}{Sq} - \frac{c}{2U} C_{z_{\dot{\alpha}}}}\right] \dot{\theta} - \left[\frac{\frac{mU}{Sq}}{\frac{mU}{Sq} - \frac{c}{2U} C_{z_{\dot{\alpha}}}}\right] \dot{\theta}\,{}'u + \left[\frac{\frac{mU}{Sq}}{\frac{mU}{Sq} - \frac{c}{2U} C_{z_{\dot{\alpha}}}}\right] \dot{\phi}\beta$$

$$+ \left[\frac{C_{z_u}}{-\frac{mU}{Sq} + \frac{c}{2U} C_{z_{\dot{\alpha}}}}\right] {}'u + \left[\frac{C_{z_\alpha}}{-\frac{mU}{Sq} + \frac{c}{2U} C_{z_{\dot{\alpha}}}}\right] {}'\alpha - \left[\frac{c}{\ell_t}\right]\left[\frac{C_{m_{\delta_e}}}{\frac{mU}{Sq} - \frac{c}{2U} C_{z_{\dot{\alpha}}}}\right] \delta_e$$

$$-\ddot{\theta} = -\left[\frac{Sqc\, C_{m_u}}{I_y}\right] {}'u + \left[-\frac{Sqc^2\, C_{m_{\dot{\alpha}}}}{2UI_y}\right] {}'\dot{\alpha} + \left[-\frac{Sqc}{I_y} C_{m_\alpha}\right] {}'\alpha$$

$$+ \left[-\frac{Sqc^2}{2UI_y} C_{m_q}\right] \dot{\theta} - \left[\frac{C_{m_{\delta_e}}\, Sqc}{I_y}\right] \delta_e$$

$$-\dot{\beta} = -\dot{\phi}\,{}'\alpha + \dot{\psi} + \dot{\psi}\,{}'u - \left[\frac{Sq}{mU} C_{y_\phi}\right] \phi - \left[\frac{Sqb}{2mU^2} C_{y_r}\right] \dot{\psi} + \left[-\frac{Sq\, C_{y_\beta}}{mU}\right] \beta$$

$$- \left[\frac{Sq}{mU} C_{y_{\delta_r}}\right] \delta_r - \left[\frac{Sqb}{2mU^2} C_{y_p}\right] \dot{\phi}$$

$$-\ddot{\phi} = + \left[-\frac{Sqb^2}{2UI_x}\right] C_{\ell_p}] \dot{\phi} - \left[\frac{Sqb^2}{2UI_x} C_{\ell_r}\right] \dot{\psi} + \left[-\frac{Sqb}{I_x} C_{\ell_\beta}\right] \beta$$

$$- \left[\frac{Sqb}{I_x} C_{\ell_{\delta_a}}\right] \delta_a - \left[\frac{Sqb}{I_x} C_{\ell_{\delta_r}}\right] \delta_r$$

$$-\ddot{\psi} = + \left[-\frac{Sqb^2}{2UI_z} C_{n_p}\right] \dot{\phi} + \left[-\frac{Sqb^2}{2UI_z} C_{n_r}\right] \dot{\psi} - \left[\frac{Sqb}{I_z} C_{n_\beta}\right] \beta$$

$$+ \left[-\frac{Sqb}{I_z} C_{n_{\delta_a}}\right] \delta_a + \left[-\frac{Sqb}{I_z} C_{n_{\delta_r}}\right] \delta_r$$

FIGURE 1. EQUATIONS OF MOTION

TABLE 1

FLIGHT CONDITIONS (EQUILIBRIUM)

h = 3000 ft (level flight)
W = 11500 lb
U = 175 mph = 256.67 ft/sec
ρ = 0.002177 slug/ft^3
C_T = 0.045
h^* = 0.2
I_X = 16900 slug-ft^2
I_Y = 27600 slug-ft^2
I_Z = 40600 slug-ft^2
I_{XZ} = 1400 slug-ft^2

α^o = -1.3^o
$\bar{c}$ = 6.5 ft
b = 65 ft
S = 420 ft^2
δ_{flap} = 0

TURBULENCE CONDITIONS

$\sigma_v = \sigma_w = 3$ fps

TABLE 1 (continued)

NOMINAL STABILITY DERIVATIVES

Longitudinal Derivatives

$C_L = 0.3818$

$C_D = 0.045$

$C_M = 0.035$

$C_{L_\alpha} = 5.7295$

$C_{D_\alpha} = 0.1432$

$C_{m_\alpha} = -1.9098$

$C_{L_{\dot\alpha}} = 1.52$

$C_{D_{\dot\alpha}} = 0$

$C_{m_{\dot\alpha}} = -5.9$

$C_{L_q} = 5.504$

$C_{D_q} = 0$

$C_{m_q} = -23.948$

$C_{X_n} = -2\ C_D$

$C_{Z_n} = -2\ C_L$

$C_{X_\alpha} = C_L - C_{D_\alpha}$

$C_{Z_\alpha} = -C_{L_\alpha} - C_{D_0}$

$C_{X_{\dot\alpha}} = -C_{D_{\dot\alpha}}$

$C_{Z_{\dot\alpha}} = -C_{L_{\dot\alpha}}$

$C_{X_q} = -C_{D_q}$

$C_{Z_q} = -C_{L_q}$

Lateral Derivatives

$C_{y_\beta} = -0.89$

$C_{\ell_\beta} = -0.12$

$C_{n_\beta} = 0.1215$

$C_{y_p} = -0.1$

$C_{\ell_p} = -0.5488$

$C_{n_p} = 0.006$

$C_{y_r} = 0.5$

$C_{\ell_r} = 0.13$

$C_{n_r} = -0.1855$

Control Derivatives

$C_{y_{\beta_r}} = 0.39$

$C_{y_{\delta_a}} = 0.00348$

$C_{\ell_{\delta_a}} = 0.2055$

$C_{\ell_{\delta_r}} = 0.0398$

$C_{n_{\delta_r}} = -0.1$

$C_{n_{\delta_a}} = -0.01$

$C_{m_{\delta_e}} = -1.79$

$C_{L_{\delta_e}} = 0.45$

ratio, ζ were computed. Also, the number of cycles to half amplitude, $C_{1/2}$, the time to half amplitude, $T_{1/2}$, and the roll-to-sideslip parameter, $|\phi/v_e|$ for the Dutch Roll mode were found.

The analog flight simulator was programmed with various combinations of stability derivatives to cover, as well as possible, the regions in which handling qualities are most often defined for the short period and Dutch Roll aircraft modes. Coupled to the analog computer was an electronic noise generator adjusted to disturb the simulated aircraft with 3 ft/sec RMS turbulent gusts in the normal and lateral directions. This was accomplished by superimposing the random electronic signal on the α and β variables in the analog equations of motion.

For each different aircraft configuration, the simulator was operated at least 12 times while a pilot flew the simulator attempting to maintain straight and level flight for over 200 seconds. The normal and transverse accelerations as functions of time were computed and RMS quantities were found by the computer. The associated comfort rating for each flight was found by using an empirically-derived comfort model developed at the University of Virginia (6). See Table 2. The average rating for each aircraft configuration was found and converted into a passenger satisfaction level by a statistically-determined transformation (7), shown in Figure 2.

The values of passenger satisfaction due to variations in the short-period handling qualities are plotted in Figure 3. The solid lines in this figure indicate the presently accepted boundaries for short-period handling qualities. The dashed lines indicate lines of constant ride quality, as suggested by the data points. The trend is for increasing passenger satisfaction as the damping ratio and the undamped natural frequency increase.

The effects of variations of Dutch Roll parameters on ride quality are shown in Figures 4 and 5. The solid line indicates boundaries for regions of acceptable Dutch Roll handling. Ride quality and passenger acceptance generally improve as $C_{1/2}$, $T_{1/2}$ and $|\phi/v_e|$ decrease, although the trends are not as clear as those of the short-period mode. Also, it appears that the changes in longitudinal short-period parameters had a greater effect on ride quality than did the changes in the Dutch Roll parameters.

TABLE 2

COMFORT MODEL

$$C = 2 + 13.8\, a_N + 4.52\, a_T - 2.816\sqrt{a_N a_T}$$

where

a_N = normal RMS acceleration (g's)

a_T = transverse RMS acceleration (g's)

C = comfort rating where:

- 1 - very comfortable
- 2 - comfortable
- 3 - neutral
- 4 - uncomfortable
- 5 - very uncomfortable

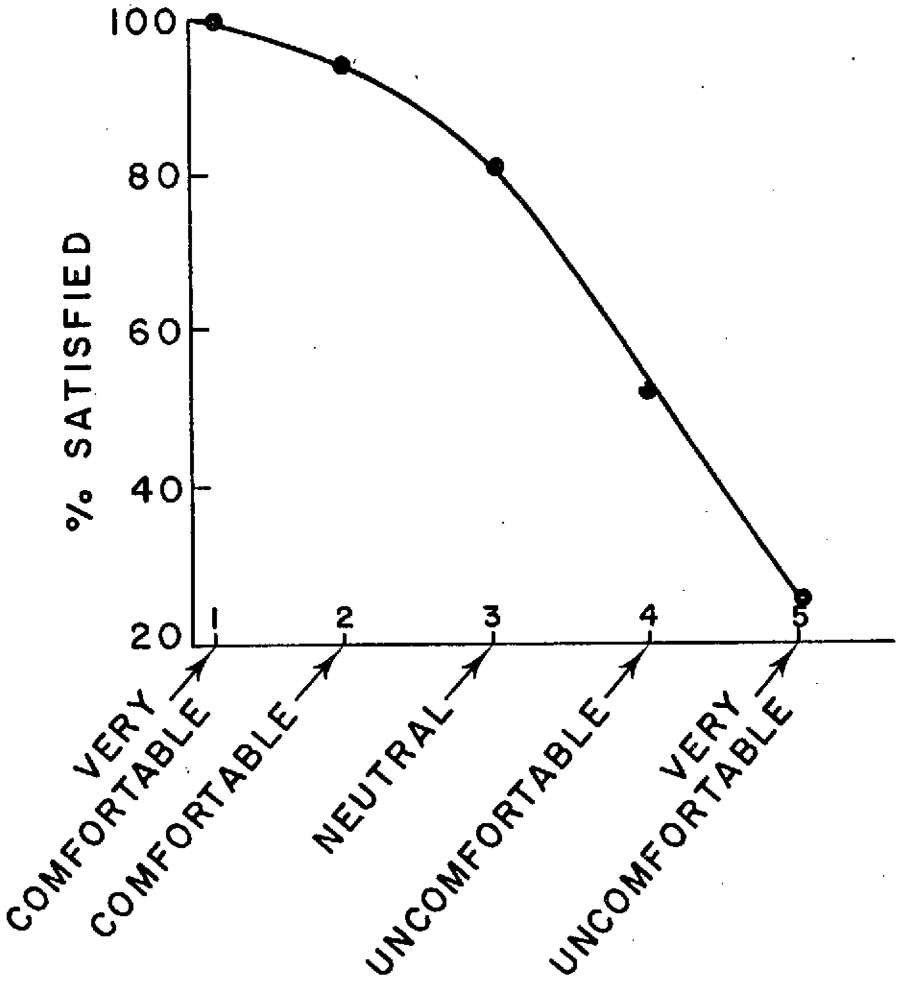


FIGURE 2. RELATIONSHIP BETWEEN PASSENGER SATISFACTION AND COMFORT RATING

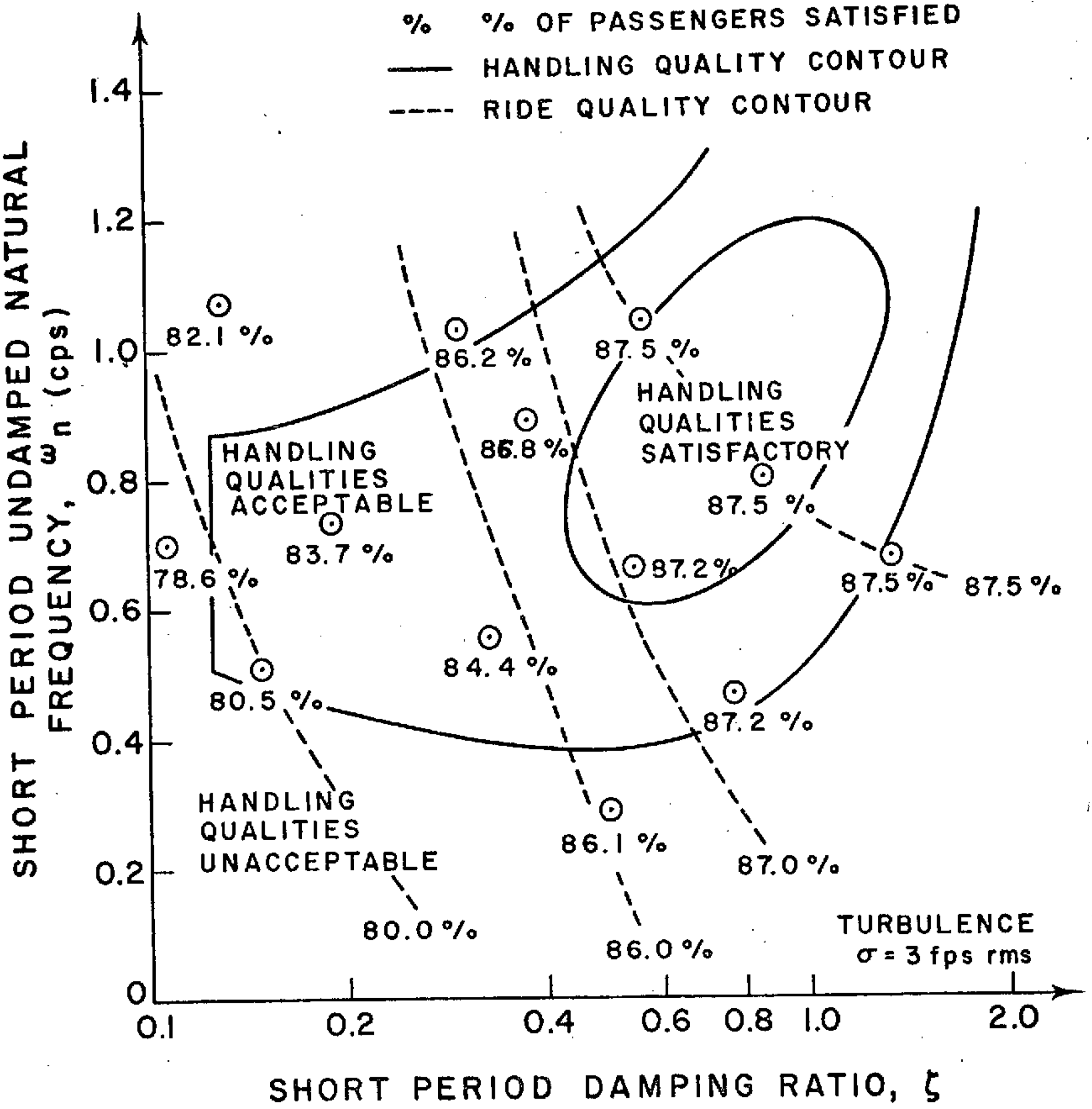


FIGURE 3. SHORT PERIOD HANDLING QUALITIES

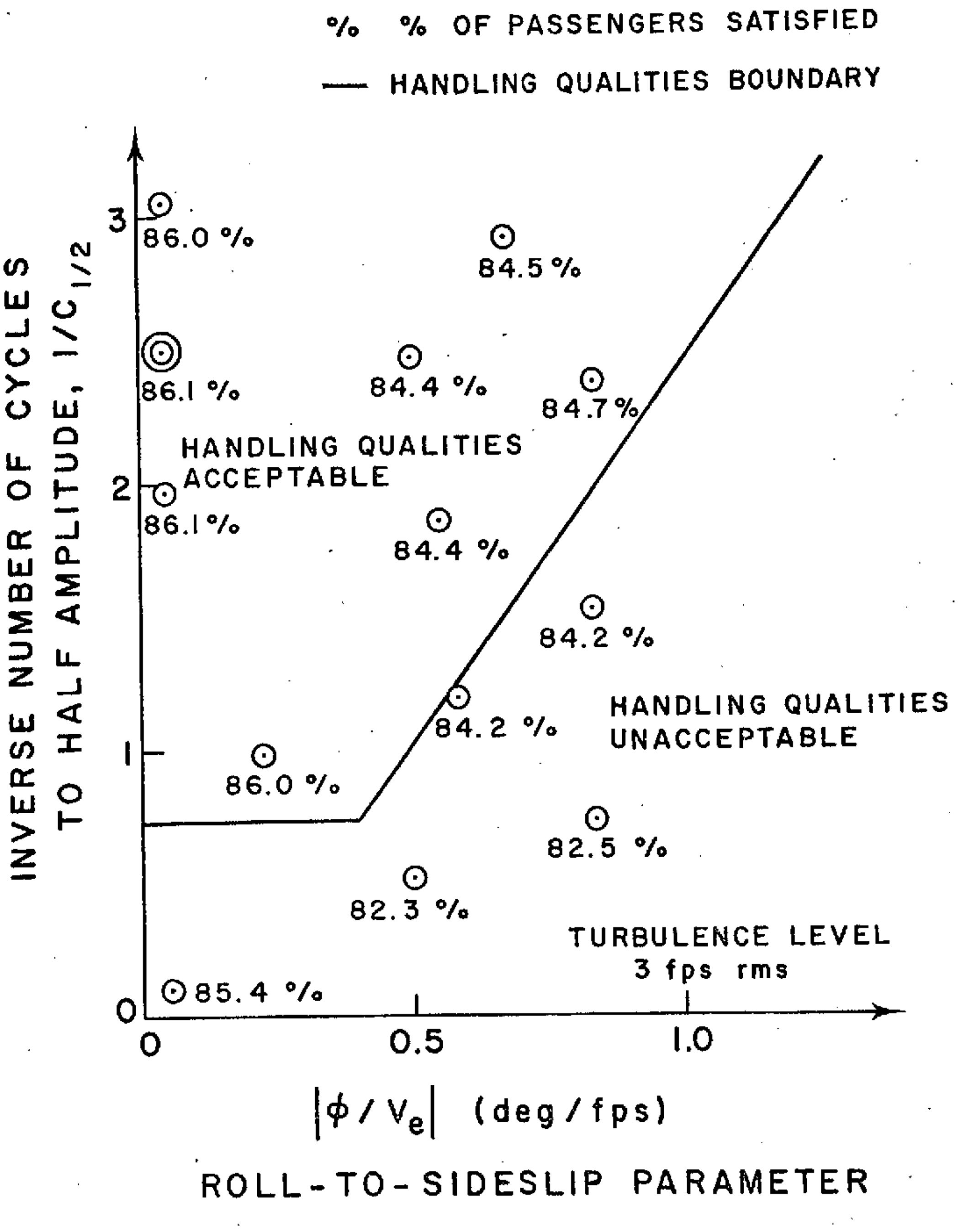


FIGURE 4. DUTCH ROLL HANDLING QUALITIES

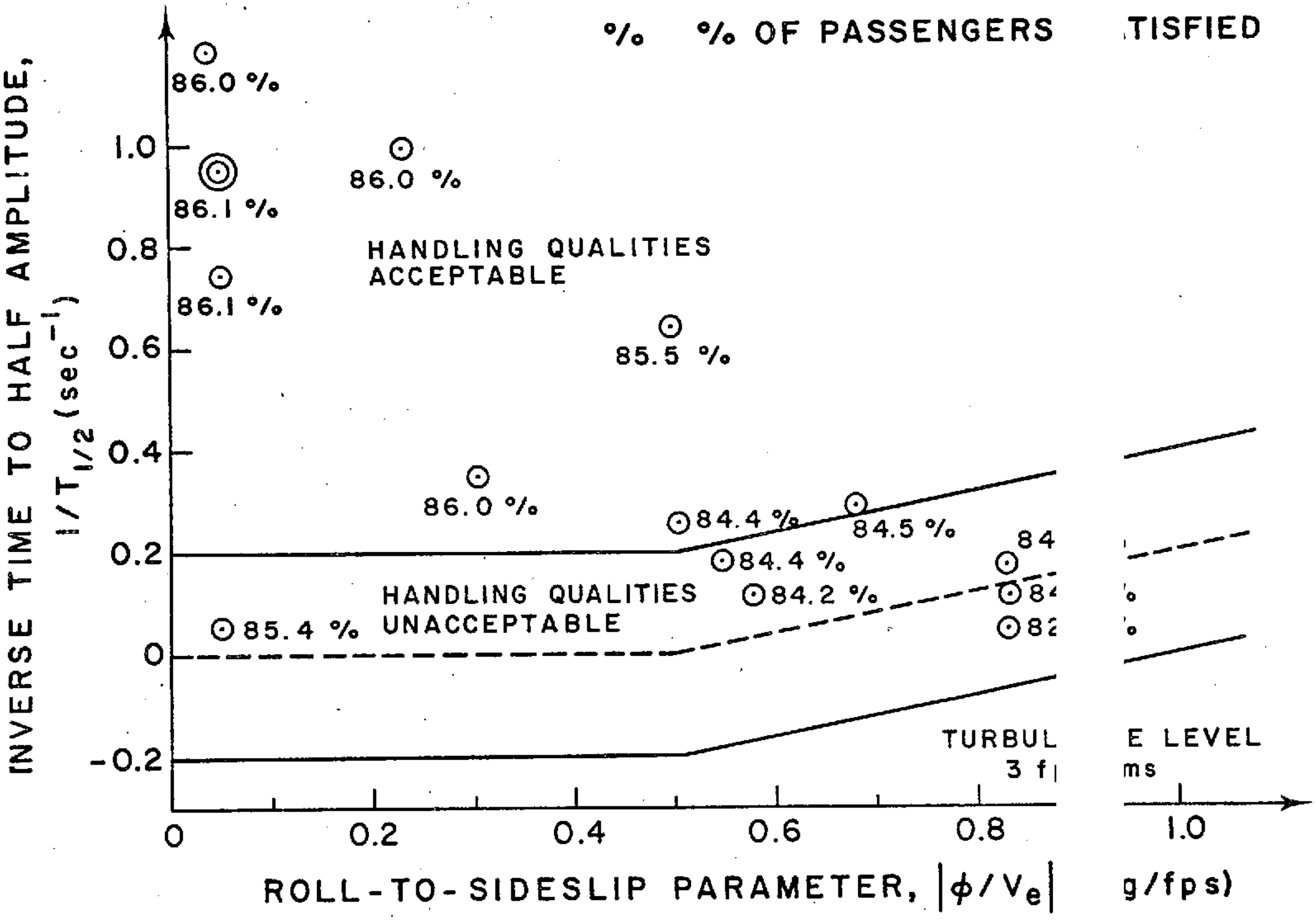


FIGURE 5. DUTCH ROLL HANDLING QUALITIES

Based on the experience gained and data collected in this series of tests, further tests were conducted on a motion-based simulator at NASA's Langley Research Center.

SIMULATOR EXPERIMENTS AT THE NASA LANGLEY RESEARCH CENTER

The Visual Motion Simulator (VMS) at the NASA Langley Research Center was programmed with 27 different sets of aircraft stability derivatives in order to vary the handling qualities and measure the corresponding effects on ride quality. It is planned that each set of stability derivatives will be run three times in segments of 16 minutes each. Each 16-minute segment consists of the following subsegments. For the first 10 minutes, the pilot flies straight and level in turbulence of 5 fps rms. During this time, the ride-quality subject on board the simulator is asked to evaluate the ride quality every two minutes. For the next two minutes, the pilot executes a two-minute turn in which the aircraft changes heading by 180°, during which the aircraft descends 1000 feet in altitude and then climbs to the original altitude. The ride-quality subject is asked for his evaluation of the ride of this two-minute segment. The pilot is then asked to execute a second two-minute turn, similar to the first, and return to the original aircraft heading. Again, the ride-quality subject is asked to evalute the ride of this segment. In the final two minutes of each run, the pilot is instructed to separately pulse the elevator, aileron, and rudder to enable him to better evaluate the handling qualities of the particular configuration being investigated. Simultaneously, the ride-quality subject is asked to respond to the comfort levels of the motions produced by each of the control pulses. Following the run, the pilot is asked to complete a questionnaire and rate his ability to maintain straight and level flight, and give his opinion of the overall handling qualities of the case being studied. Also, the ride-quality subject is asked to give an overall rating of the ride quality of the configuration.

During each run, continuous strip chart recordings are made showing time histories of the three linear accelerations and three angular rates of the aircraft in the body axes. The parameters of elevator, aileron, and rudder deflections, throttle position, altitude, rate of climb, airspeed, and heading are also displayed in this manner, as well as a time channel indicating the times when ride-quality responses are to be taken. A sample output is shown in Figure 6.

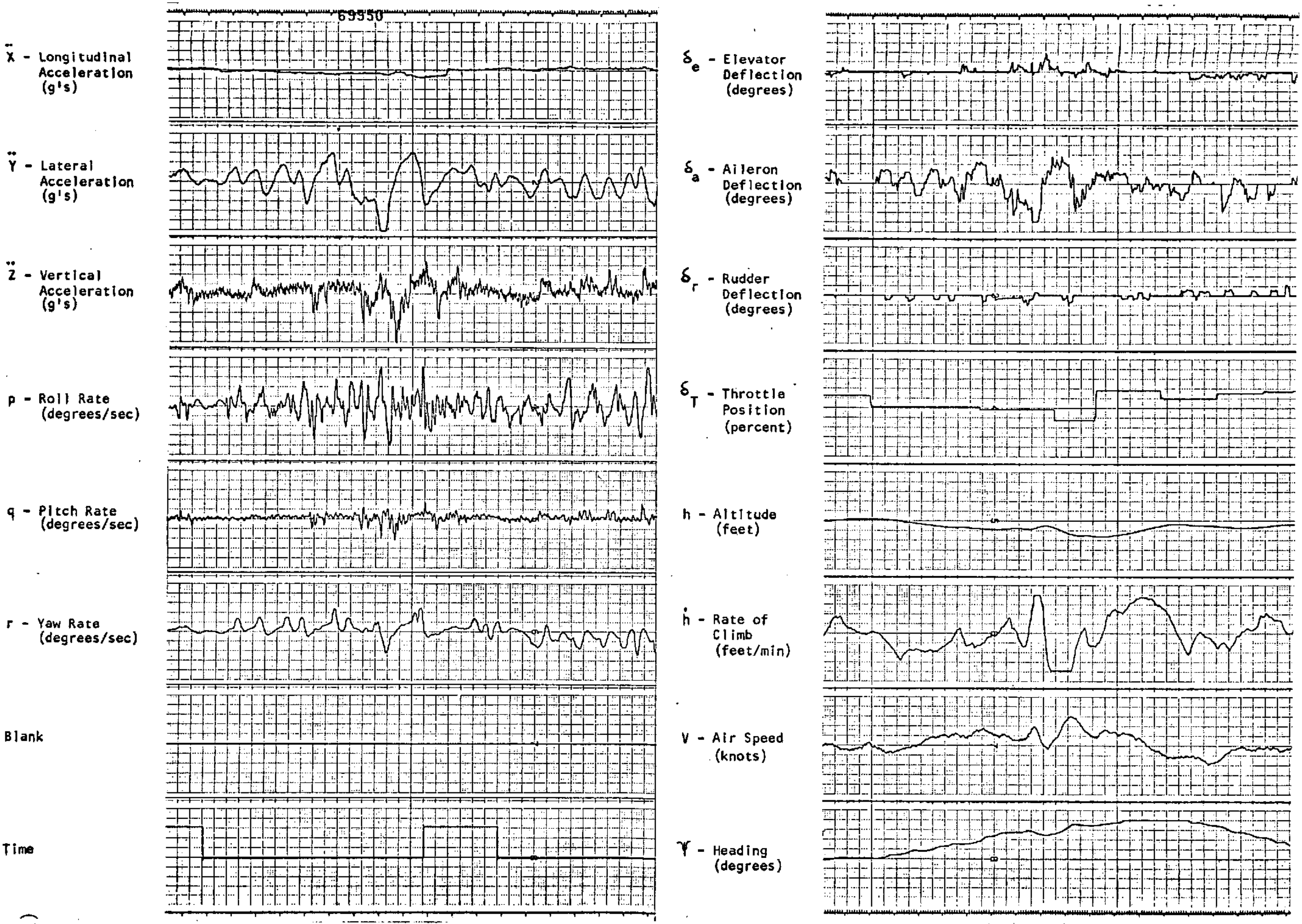
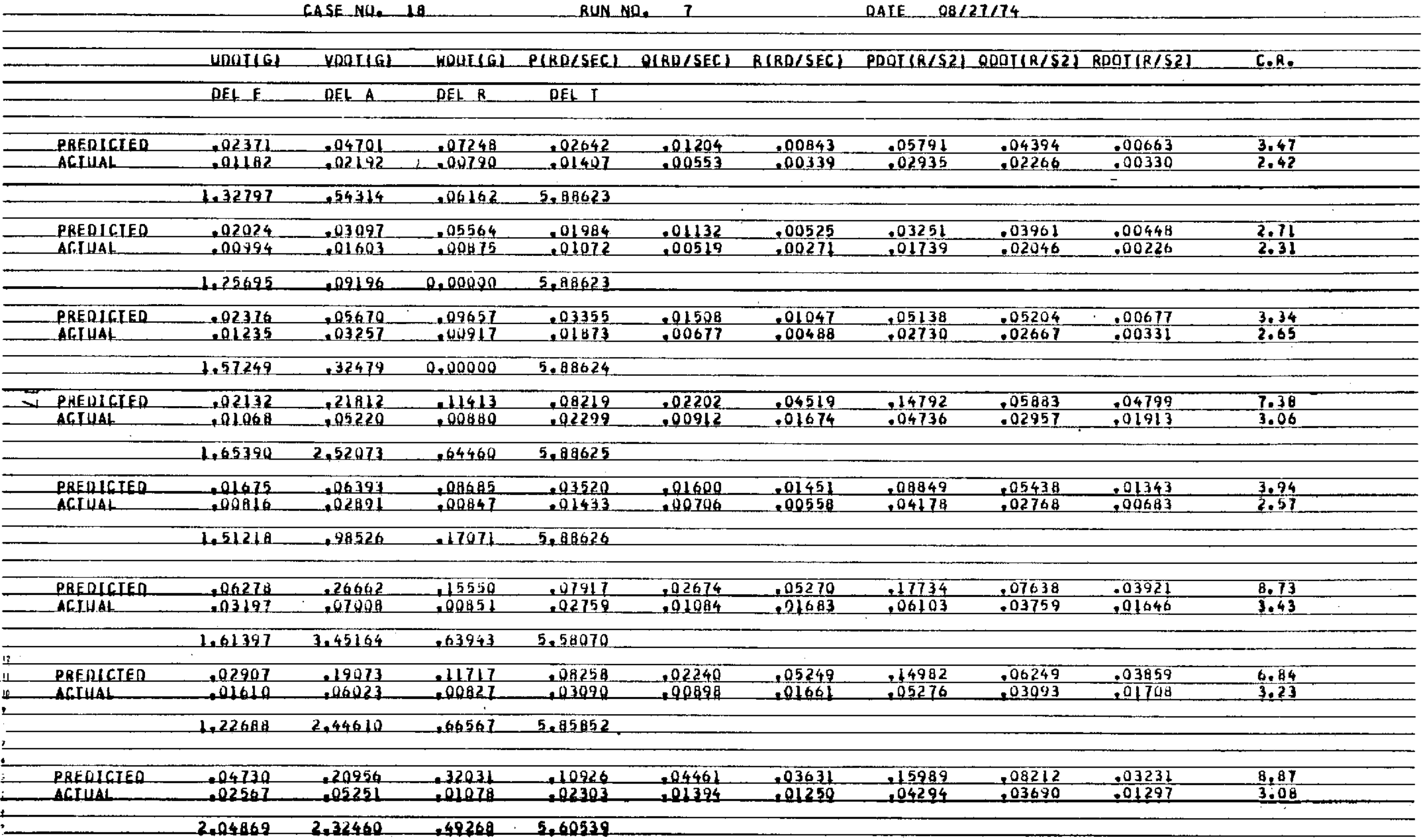


FIGURE 6. TYPICAL DATA TRACES

In addition to these measurements, the main program, which controls the simulator, computes rms values for the three linear accelerations, three angular accelerations, three angular rates, and all control deflections for each two-minute segment of each run. A sample output is shown in Figure 7. Rms values of the motion parameters are evaluated for both the values predicted for the real aircraft by the 6 degree-of-freedom equations of motion, and the values computed to drive the simulator after the washout system is accounted for. Finally, an inertial package is placed aboard the simulator to sense and record the motion of the simulator itself for comparison with the values of the computed parameters and to evaluate the errors between the driving signals after washout and the actual motion sensed in the cabin of the simulator.



```
                    CASE NO.  18                RUN NO.   7                   DATE   08/27/74

              UDOT(G)   VDOT(G)   WDOT(G)  P(RD/SEC)  Q(RD/SEC)  R(RD/SEC)  PDOT(R/S2) QDOT(R/S2) RDOT(R/S2)      C.R.

              DEL E     DEL A     DEL R     DEL T


   PREDICTED   .02371    .04701    .07248    .02642    .01204     .00843     .05791     .04394     .00663        3.47
   ACTUAL      .01182    .02192    .00790    .01407    .00553     .00339     .02935     .02266     .00330        2.42

              1.32797    .54314    .06162   5.88623

   PREDICTED   .02024    .03097    .05564    .01984    .01132     .00525     .03251     .03961     .00448        2.71
   ACTUAL      .00994    .01603    .00875    .01072    .00519     .00271     .01739     .02046     .00226        2.31

              1.25695    .09196   0.00000   5.88623

   PREDICTED   .02376    .05670    .09657    .03355    .01508     .01047     .05138     .05204     .00677        3.34
   ACTUAL      .01235    .03257    .00917    .01873    .00677     .00488     .02730     .02667     .00331        2.65

              1.57249    .32479   0.00000   5.88624

   PREDICTED   .02132    .21812    .11413    .08219    .02202     .04519     .14792     .05883     .04799        7.38
   ACTUAL      .01068    .05220    .00880    .02299    .00912     .01674     .04736     .02957     .01913        3.06

              1.65390   2.52073    .64460   5.88625

   PREDICTED   .01675    .06393    .08685    .03520    .01600     .01451     .08849     .05438     .01343        3.94
   ACTUAL      .00816    .02891    .00847    .01433    .00706     .00558     .04178     .02768     .00683        2.57

              1.51218    .98526    .17071   5.88626


   PREDICTED   .06278    .26662    .15550    .07917    .02674     .05270     .17734     .07638     .03921        8.73
   ACTUAL      .03197    .07008    .00851    .02759    .01084     .01683     .06103     .03759     .01646        3.43

              1.61397   3.45164    .63943   5.58070

   PREDICTED   .02907    .19073    .11717    .08258    .02240     .05249     .14982     .06249     .03859        6.84
   ACTUAL      .01610    .06023    .00827    .03090    .00898     .01661     .05276     .03093     .01708        3.23

              1.22688   2.44610    .66567   5.85852


   PREDICTED   .04730    .20956    .32031    .10926    .04461     .03631     .15989     .08212     .03231        8.87
   ACTUAL      .02567    .05251    .01078    .02303    .01394     .01250     .04294     .03690     .01297        3.08

              2.04869   2.32460    .49268   5.60539
```

FIGURE 7. TYPICAL COMPUTER OUTPUT
]

SCHEDULE

Progress is continuing on a normal basis and completion of the VMS runs is anticipated for late September or early October. Data analysis is an ongoing project and should be completed by December with a final report following shortly.

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