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DIGITAL REDESIGN OF THE NRC BELL 205 ARTIFICIAL FEEL SYSTEM

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Abstract

An artificial feel system is installed on fly-by-wire (FBW) aircraft so that pilots experience the perception of a conventionally controlled aircraft. Such a system is installed on the National Research Council of Canada's Bell 205 helicopter airborne simulator for control system and flight mechanics experiments. The purpose of this project is to implement a system on the airborne simulator that will remove the existing problems of the analogue system that are hampering research in areas of high gain FBW control. The first stage of the project was to create a comprehensive nonlinear simulation of the model following control algorithm and hardware. Guidelines for choosing an acceptable stick model are developed which will assist the NRC in eventually implementing sticks on the helicopter.

Details of the digital C program design for the target VME processor are outlined. The testing of the system using a single axis stick and a copy of the hardware installed on the Bell 205 is described. The calibration procedures and other installation details as well as preliminary ground and air testing are described.

Acronyms, Designations, and Abbreviations

ACS	Airborne Computing System
A/D	Analogue to Digital
D/A	Digital to Analogue
FCC	Flight Control Computer
FCS	Flight Control System
FFS	Force Feel System
FRL	Flight Research Laboratory
NASA	National Aeronautics and Space Administration
USAF	United States Air Force

Introduction

The NRC's Bell 205 Airborne Simulator is a test platform for helicopter control systems design and flight mechanics experiments (Fig [1]). Installed in the Bell 205 is a hydraulically powered control loading or 'artificial feel' system designed to give the evaluation pilot a feel for the aircraft as if it were manually controlled, even though it is fly-by-wire. Essentially, the system senses the forces applied by the pilot in 3 axes and processes these through an analogue electronic control system, which drives the stick or pedals to the desired position. As a result of inadequacies in the analogue system which are hampering experiments that the FRL would like to conduct in the near future involving the determination of the effects of feel system parameters on helicopter handling qualities, it was proposed to replace this with a more versatile digital system.

Overview of Force Feel System Technology

There are three basic types of force/artificial feel systems. The first are mechanical systems such as are installed in many production helicopters such as the Bell 412. The second is an electro-hydraulic system controlled by an analogue computer. Similar systems are currently installed on the NRC Bell 205 Airborne Simulator, the USAF variable stability NT-33A[1] and previously on the NASA/Army Ch-47B[2] variable stability helicopter. These last three are examples of programable feel systems installed on research aircraft where the feel system parameters can be varied. Other non-programable variants can be found on fly-by-wire aircraft such as the Airbus 320 or the F-16 Falcon. The third type of system is a digitally controlled force feel, the design of which is outlined in this report. To this date, this author has not seen evidence of the existence of this type of system installed on any aircraft in the world.

Justification for FFS Redesign

The primary reason for the digitization of the feel system on the Bell 205 is so that an assessment of the effect of feel system parameters on helicopter handling qualities can be performed. Although a considerable amount of work has been done in this area in the fixed wing world, these results do not necessarily translate well to rotary wing aircraft. Some papers[5][6] only look at the effect of feel system in specific cases. Only two papers[2][4] directly look into this problem.

Feel system parameters including mass, spring gradient and viscous friction, as well as non-linearities such as breakout force, static friction, hard stops, etc. are the defining quantities for the artificial feel system. Changing these parameters changes the stick motion and force cues that are sensed by the pilot. This, in turn, affects the pilot's perception of what the aircraft is doing and how it will react to an input. Thus the feel system parameters do have an effect on aircraft handling qualities as evaluated by the pilot. The question is what values of these parameters makes a good stick, i.e. well liked by the pilot?

There are many references that attempt to answer this question for the purpose of offering guidance when developing feel systems. However most of the work has been done for fixed wing aircraft. Two works[7][12] offer guidance for fighter sidestick controllers, while three others[8][9][11] discuss centre stick characteristics for fixed wing aircraft. However, of primary interest to this work is helicopter handling qualities as they relate to feel system. There appear to be only two papers which discuss this in detail[2][4].

The first reference[2] describes a handling qualities experiment designed to determine the effects of feel system on roll axis handling qualities. The experiment held the force gradient constant and varied viscous friction and inertia to effect changes in natural frequency and damping ratio. The authors state that inertia rather than natural frequency is the determining parameter with regards to handling qualities. The results suggested that a stick with an inertia between 5 and 7 lbm is a good stick. Yet this statement is made without any variation in spring gradient to determine the effects of this. As well, the damping ratios used were around 0.3 or 0.6, both of which are in the normal range. For example, it is likely that a 5 lbm stick with a higher spring gradient and a damping ration of 0.1 is a bad (negative effect on handling qualities) stick, and thus inertia alone is not enough to specify stick characteristics.

The second reference[4] is of larger scope and different values of spring gradient, mass, natural frequency and damping ratio are used for a total of 14 different stick models (plus four different isometric sticks). Also, this experiment was not limited to manoeuvres in a single axis, and many all-axis tasks are evaluated. As this was a preliminary exploratory study, no definite boundaries for stick parameters were found. However, the results did suggest some general observations that are extremely useful for determining the direction of future studies. Primarily, sticks with an undamped natural frequency of less than 9 rad/s or a damping ratio of less than 0.3 should be avoided. As well, spring gradients of at least 9.0 lb/in are acceptable if unreasonable force is not required for maximum displacement. Also, large amounts of overdamping can be tolerated by pilots.

There are military standards[3] which contain some guidelines for the selection of feel system parameters, including allowable breakout forces, spring gradients, and maximum applied forces. How these numbers were determined is classified, however there is evidence to suggest that they were obtained from early 1960's experiments. Thus the values are based on conventional, unaugmented machines and are not necessarily appropriate for modern helicopters or new designs. Also, no guidance is given for the selection of inertia, damping or stick natural frequency. The document also states the obvious requirement that the spring gradient may not be negative.

The only mention of the stick dynamics occurs in the discussion of small amplitude response to control inputs for the pitch and roll axes. With regards to bandwidth criteria, the document includes this section:

> "It is desirable to meet this criterion for both controller force and position inputs. If the bandwidth for force inputs falls outside the specified limits, flight testing should be conducted to determine that the force feel system is not excessively sluggish."

However, the document does not state any criteria for the acceptable or unacceptable dynamic characteristics of helicopter controllers.

In [10] there is some attempt to give some guidance as to design configurations for cockpit manipulators, however it is not overly helpful either:

> "Based on the data analyzed in this report, an acceptable feel system is attainable as long as the effective stick natural frequency is above 10 rad/s, or the effective mass is less than 5 lbm, with a stick damping ratio above 0.3. More detailed design guidelines require much more experimental data."

The main problem is that the data for these observations is based on both fixed wing and helicopter data. However, it is stated in this report as well that criteria for rotary wing aircraft do not necessarily coincide with the criteria for fixed wing:

> "...the region of acceptable gradients is probably higher for fixed-wing airplanes than for helicopters..."

Thus there is support for separate criteria for each type of aircraft.

As it now stands, there is data from only two limited scope experiments that attempt to describe the effects of feel system characteristics on helicopter handling qualities. This data is by no means in-depth enough to fully describe the effects of the feel system, and thus more experiments are necessary to better define limits for artificial feel system design for helicopters. As the existing feel system is limited in many ways, it is hampering research in this area and thus the digital redesign is justified.

Original Feel System

The original feel system is over 30 years old and is a combination of mechanical system and analogue controller. The mechanical system consists of components such as the stick, actuators, pedal assembly, hydraulic lines, etc... and were not affected by the changes to the feel system. Included in the actuator assemblies are position sensors and hydraulic

Moog valves for each of the three channels, roll, pitch and yaw.

The original artificial feel system consists of the lateral and longitudinal cyclic controls as well as the rudder controls. Each control contains strain gauges to measure the amount of pilot control force. The artificial feel system consists of two loops of analog computers, as shown in fig [2]. The inner loop runs the servo system by accepting position commands and the outer loop accepts input and controls the system. The servo system is driven by 1000 psi hydraulics and is bounded by a maximum frequency of approximately 3.5 Hz closed-loop, or 18 Hz open loop.

There is a problem with drift and, as such, the system must be periodically recalibrated. In addition, the existing setting controls are not particularly user friendly, nor can accurate values for required parameters be input. Thus the system suffers from repeatability problems. As well, the analogue model of the dynamics handles the non-linearities of the system poorly. One other problem with the existing system involves the electronic interaction between the inner and outer control loops. While the two loops are linked together, if the gain on the inner loop is turned up high enough, the system can go unstable. The analogue hardware is approaching the limit of its useful life and suffers from increasingly frequent malfunctions that are both expensive to repair and interfere with FRL scheduling. Thus the suitability and reliability of achievable controller characteristics is questioned.

Redesigned Feel System

The proposed system will replace the analog computer with a digital computer system. The new control system is best described as model-following, with operation as follows. Strain gauges are used to measure the force applied to the stick by the pilot. A model of the dynamics of the desired model is run, which results in a stick position versus time history. These reference signals are differenced with position sensor signals resulting in an error signal which is used to drive the hydraulic Moog valve. This has the effect of forcing the stick to the reference positions.

This new system will allow exact values of the required parameters that define the stick model to be input to the system, and thus drift and repeatability are no longer a problem. Also, higher loop gains can be used which will greatly increase the response speed and bandwidth of the system. The fact that the digital model of the system is discrete will also allow a more realistic handling of the non-linear elements through the use of if/then statements in the controller code.

Stick Model Requirements

The stick model is required to be representative of a real world physical system and should contain all the nonlinear elements to be found in such systems. The required elements of the model as well as acceptable assumptions about the modelling process are outlined as follows:

Inertia - The effects of aircraft loading were assumed to have no bearing on the forces reflected at the pilot's grip, thus a single mass may be used by the controller for each flight test.

Spring Gradient - Variable between zero and 10 lbf/in without affecting closed loop stability.

Viscous Friction - Force opposing motion and proportional to the velocity. The range should be from zero to approximately 5 lbf/in/sec. If zero is not achievable due to stability considerations then the minimum usable value must be determined.

Static Friction - Range from zero to 10 lbf.

Coulomb (Running/Kinetic) Friction - This may be modelled as a ratio of kinetic to static friction which would range from zero to one.

Breakout Force - The force which must be overcome before the stick will move out of the notch.

Notch - Area around neutral where some lost motion is present due to slop in mechanical linkages. The extent of the notch is from zero to +/- 0.5-in. The notch mass is any value up to that of the outer model, and enough friction (static or viscous as required) should be present to maintain loop stability.

Throw Limits - The total range of motion at the pilot's grip. This can range from +/- 2.0-in to +/- 8.0-in.

Trim - Two stick trim systems and one rudder trim system is required. The four way "coolie hat" switch should change the spring datum position at a constant, user-specified, rate. This rate should be variable from 0.25 to 2.0 in/sec. The other stick trim system consists of a designated button that would have the effect of removing all spring gradients when pressed, and then reinstituting it when the button is released, thus effectively changing the spring datum position. The rudder trim will be performed by use of a thumb wheel. The controller program must have a method by which a pilot selected gain may be placed on the thumb wheel input. This will enable control of the yaw trim system sensitivity.

Simulation Model

A dynamic simulation model of the Bell 205's artificial feel system and digital controller was created using Simulink, a sub-program of Matlab. This model was then shown to work correctly by using test values for the different parameters and confirming steady state values and response shapes.

Decoupling allowed the system to be modelled in one axis only. For each of the simulations, the integration method selected was the Euler method because it most closely resembles the trapezoid method used in the actual controller program. The trapezoid method was selected in order to reduce required computational time to allow the system to run at the required cycle rate.

Variation of Parameters

Simulation runs were performed in order to determine how combinations of different parameters would cause the system to react. Initially only the inner model parameters, spring gradient (k), mass (m) and viscous friction coefficient (Cv) were varied, picked within the range of expected operational values. For the purpose of testing, typical values were used for the notch and throw limits. The notch was set at 0.25-in, the notch mass and viscous friction coefficients were set equal to those used in the outer model and the throw limits were set at 8-in. With the notch parameters set this way, the k=0 case will be indicative of notch model stability since there is no spring gradient acting on the stick while it is in the notch.

The critically damped cases were tested first. The main simulations were performed using a square wave input, with a 2 lbf peak and 0.25 rad/s (0.0398 Hz) frequency. To determine the effect of input shape on the stability of the system, a subset of simulations was performed using sine inputs. The first set of simulations was at the same frequency as before and the second 2 Hz set was performed for a 2 second duration. The 2 Hz limit was chosen because this is the upper bound on voluntary, controlled human movement capabilities[13][14][15].

In none of the above cases was the effect of friction or breakout force examined. Thus two more sets of simulations were performed. The first set varied the breakout force using values of 1, 1.8, & 3 lbf and the second varied the static friction using the same values. The ratio of kinetic to static friction for this case was 0.75, a typical value.

Categorization of Response

Fig. [3] and Fig. [4] show examples of acceptable response. Fig. [3] has little damping and no spring gradient, and the position has moved to the throw limits where it remains until the force reverses direction. This case (with no spring gradient) is know as the 'limp noodle' and is preferred by many helicopter pilots. Fig. [4] has higher damping, which is a function of viscous friction and can be seen in the manner in which the stick approaches the steady state value. The steady state value is a function of the spring gradient. It must be remembered that "acceptability" is in terms of mathematical behaviour. An acceptable model represents one that is not overdamped, divergent or shows characteristics of limit cycling. However, some of these stick models may be completely unacceptable when tested in a helicopter with a pilot. Conversely an "unacceptable" stick may be quite good when the pilot's arm/neuromuscular system is included in the loop.

Fig. [5] shows a highly damped stick model where the viscous friction coefficient was too high to make this an acceptable model. Too much pilot force would be required to achieve a desired reaction, thus leading to pilot fatigue and slow response time.

Fig. [6] shows an underdamped stick model response with overshoot and a small amount of oscillation. Although stable, this type of response may be undesirable from a pilot's perspective, especially if the spring gradient is large. It may require the pilot to 'fight' with the stick in order to make the aircraft respond in an appropriate manner. Flight test has revealed that underdamped sticks (damping ratio of order 0.3) are undesirable.[4]

Simulation Results

The output plots are in time domain which is useful to determine at a glance whether or not the system response is acceptable. However, frequency domain parameters such as natural frequency (ω_n) and damping ratio (ζ) are useful to categorize the different responses.

Correlating the results from approximately 1200 simulations allows some general observations to be made with regards to system response. It must be remembered that these observations are based on mathematically behaviour and some values of parameters, particularly damping ratio, are out of normal range. The value of this section is to determine which sticks can be safely implemented, not what are acceptable to the pilot.

The linear model response showed a wide variety of response types. Table [1] shows the ranges of different parameters for each response type. An acceptable response generally has a relatively low natural frequency range when compared to the other response types, except for the highly damped case. The median damping ratio was unity, and the values of k, Cv and m were never more than three orders of magnitude away from each other, using the same units as indicated in Table [1].

The divergent response occurred when the damping ratio was very high (up to 25000) and the median damping ratio was 158. It should be noted that the value for Cv in the divergent case was never less than three orders of magnitude greater than m.

The highly damped case occurred when the damping ratio was high, from 2 to 2500. The natural frequencies for this case were also low, never more than 10 rad/sec. However, sticks with an undamped natural frequency less than 9 rad/s should be avoided[4]. In all the cases, k was considerably smaller in magnitude than the viscous friction coefficient.

The oscillation/overshoot case always has a damping ratio less than 1, as was expected. The value of k is usually much greater than the value of Cv. When the overshoot is small, it may be that the response is acceptable, especially if the mass is small and any oscillation could easily be damped out by the pilots arm.

The limit cycle case occurred only when the damping ratio was very small, usually in the order of 0.001. In this case k was always a minimum of 10 times larger than Cv and was usually four orders of magnitude higher.

Input wave shape had little effect on the output in terms of response type. This showed that even with non-linear elements such as the notch, the system behaves in a linear manner as input shape had no affect on system stability. The sine input did cause the limit cycle to start sooner, at slightly higher damping ratios. However, the damping ratios were still well below one and still fell within the categories listed in Table [1]. Otherwise, the response type predicted with the square input was also predicted with the sine input. The frequency of the input had no effect on the response type, as shown in a comparison. The response type predicted at 0.25 rad/sec (0.04 Hz) was the same at 12.56 rad/sec (2 Hz).

The addition of breakout force can affect the stability of the system. Additions of small amounts of breakout force appear to have little effect on the system. With the addition of 1 lbf of breakout force, the system response type is unchanged from the response type with no breakout force. However, when the breakout force is increased to 1.8 lb, it causes the system to limit cycle at lower values of k. This was expected because breakout force is essentially a step increase in spring force and hence effectively increases the effect of the spring gradient. When the breakout force was increased to 3 lbf, the system limit cycles almost immediately because of the large increase in restoring spring force.

Static friction had little effect on the predicted response type. Static friction effectively increases the damping and large amounts increase the possibility of a highly damped or divergent response type.

Choosing a Stick Model

In deciding upon the parameters to be chosen for a stick model, it must first be determined what characteristics of the stick are desired. Does the pilot want a 'limp noodle' where the spring gradient is zero? This is a valid case and many of the acceptable stick responses do have a spring gradient of zero. Does the pilot want a damped stick, or would they prefer almost no friction? Would the pilot like a heavy or near-zero-mass stick? Once the characteristics have been decided upon the different parameters must be chosen. A few guidelines might be helpful in choosing the parameters. Remember, however, that much of this does depend on pilot preference.

The following guidelines are for creating a stick that is mathematically acceptable. That is, not divergent or with tendencies to limit cycle. It must be noted that even though a stick may be mathematically acceptable, it may not be acceptable to the pilot with regards to feel. Guidelines with respect to pilot preference are limited, and were discussed previously.

To be stable, the mass should be at least 0.0001 slug. Any less and the stick accelerations will be excessive, and system response may be unstable. Spring gradients as high as 10 or more are acceptable, but high k may cause the stick to limit cycle, and Cv should be sufficiently large so that the damping ratio is high enough to prevent this. As well, note that if the spring gradient is high, the throw limits will probably need to be small so that excessive force is not required to move the stick through the full range of motion. The viscous damping coefficient should be kept below 3.0 in most cases, otherwise the stick model will be slow, and too much pilot force may be required to operate the aircraft effectively. Both Cv and k should be approximately the same order of magnitude (within three orders of magnitude), otherwise the system may be divergent or may limit cycle.

Hardware Requirements and Available System Hardware

The force feel system analogue hardware was replaced with a MVME167 digital computer, running the Motorola MC68040 32-bit processor. This is a local bus system running at 25 MHz with 8 megabytes of DRAM. A multi-tasking operating system, Microware's OS-9, was used on the system in order to facilitate the operation of several programs at once, including the user interface and the feel system cycle calculation. The force feel system cycle calculation will have priority and thus will be able to interrupt the other program when necessary to perform real-time computations.

Installed in the VME are one A/D board and one D/A board to facilitate the required input and output for the system. The D/A conversion process is done using the Acromag AVME9210 board. This board has 12 bit output resolution with 8 channels of output, 3 of which will be used for the feel system. The A/D conversion function is performed using the Acromag AVME9325 high speed analogue input board. This board has 12 bit resolution and a 5 microsecond per channel throughput rate. The board is configured for 32 single ended inputs, 22 of which are used for the feel system. This board is used for the discrete switches as well as the force, position and rudder trim thumb wheel inputs. The board's internal clock with triggering feature is also used to control the program cycle timing.

The following is a list of requirements for the computing system, as necessitated by the force feel system module:

At the force feel system cycle rate of 1000 Hz:

1) Read A/D
    - 3 forces
    - 3 positions
    - 1 rudder trim

2) Read discrete switches
    - 8 function switches
    - 4 coolie hat positions
    - 1 force relief button
    - 1 trim/operate switch

3) Output D/A
   - 3 position error commands

4) Data transfer between FFS and FCC
   - serial connection

5) Service console
   - FCC RS 232

Force Feel System Program

The artificial feel system controller was written in Microware Ultra C because this compiler is recommended for writing real-time programs for use with the OS-9 operating system. The code was written to follow closely the standards outlined in Ref. [16].

The program consists of two main parts; a portion to implement a user-entered stick model and a part designed for user interface, including file systems and options to create, modify, show and check stick models. The user interface portion is designed to work through any standard terminal, including the one installed in the aircraft. The implementation part is self contained and the only control the user has on real-time computation is to stop operation, start operation or change stick models.

Trim Systems

The function of the trim system is to allow a constant input to be entered by the pilot to hold the aircraft in trim during different phases of flight. In the case of the feel system, the trim function has the effect of changing the spring datum position and thus when the stick is released it will rest at a position with a constant offset from centre. The centre is simply the position where the position feedback signal has a value of zero volts.

The cyclic trim system is handled in two ways. the pilot can depress the force relief button, removing the spring gradient force. Then the stick is moved to the desired trim position and the button is released. This position is the new spring datum position. The software handles this by storing the stick position the instant the button is released and uses this as the offset from centre. The second method that can be used for cyclic trim is by way of the "coolie hat" switched. When this switch is pressed the spring datum position is changed at a user specified rate (in inches/sec) in the direction that the switch was pressed. The user specified rate is one of the parameters set in the stick model and is usually of the order of 0.5 in/sec.

Pedal (yaw) trim is also handled by considering the spring datum position as an offset from centre. However, the amount of offset is set by a thumb wheel on the collective control. The voltage change from centre is detected by the system and the offset is this change multiplied by a user specified gain. This gain is one of the parameters set in the stick model. Note that the trim systems in no way affect the location of the throw limits, as their position is relative to stick and pedal centre. However, the notch is modeled to be around the spring datum position and thus will move as the system is trimmed. The modelling was done this way to satisfy the requirements of the research staff at the FRL, and is based on the behaviour of standard mechanical feel systems installed in production helicopters.

When placed in the trim position, the trim operate switch will force the stick to the neutral position. At this point the location of the neutral position of the stick and pedals may be manually changed by using the force relief button and moving the stick to the desired centre. This function affects the absolute zero position of the stick and pedals, and thus will also affect the location of software throw limits. The strain gauges may also be zeroed when the system is in trim, to ensure that the force readings from the strain gauges are accurate. When the switch is returned to the operate position, normal operation will resume

Force Feel System Program Testing

The force feel system program was tested to eliminate any errors in the programming code. This was accomplished in two steps. First the code was modified to include a pilot forcing function equivalent to the 0.25 rad/sec frequency, 2 lbf peak pilot input used with the Simulink model. Next, this output was plotted with the Simulink results for equivalent stick models. Other parameters between the two models were also kept the same for consistency, including using similar integration schemes and the same time step of 0.005 secs.

The test cases selected for comparison were chosen from each category of response type with the addition of various non-linear elements. To simplify the process, sensor and servo models were excluded, as were sine inputs and sensor noise. Since the simulations indicated these elements had little effect on system stability, it is felt that this approach is valid.

The comparison between the FFS code and the Simulink model served to verify that the modelling of a real world mechanical force feel system is accurate. Two different methods of simulation were used and both arrived at identical results for 99 percent of cases tested. The discrepancies that did exist between the two models are attributed to small errors in the Simulink model which did not handle some of the non-linearities very well in some of the selected cases. For these, the FFS code was shown to be correct through manual calculation.

Implementation

Before installation in the Bell 205, the system was tested using a single axis bench version of the hardware. This process provided better insight into the workings of the hardware and allowed for problems to be resolved without tying up the helicopter for long periods of time. The problems that were solved include coding bugs, noise, and A/D board problems. Finally in January 1996 the system was installed in the Bell 205.

Calibration of the system inputs and outputs was performed using accepted calibration procedures. Strain gauges were calibrated using a force scale and recording readings at the A/D board of various levels of force. The position sensor was calibrated by arbitrarily commanding a position and recording the feedback voltage and measured position in inches.

Evaluation

During the final evaluation the system was found to perform well. Verification of steady state position values for a given force was used to validate performance. Testing indicated that requested damping ratios and natural frequencies were in fact reflected at the stick. It was found that it was possible to achieve a bandwidth as high as 60 rad/s without instability or hardware problems. This is indicated in the Bode plot for the closed loop system, Fig [7]. However, it was found that at these higher gains a lack of smoothness in stick motion developed. This was later found to be gain related and necessitated a reduction in gains. Therefore, the bandwidth of the system, based on 90 degrees of phase lag, was reduced to 30 rad/s in the longitudinal channel, 34 rad/s in the lateral channel, and 41 rad/s in the pedals. These are indicated in Figs. [8] through [10]. Initial flight testing of the system proved that operation in a vibration rich environment had no effect on digital feel system performance.

Conclusions

From the implementation of the digital force feel system, the following conclusions can be drawn:

(1) Digital control of a relatively high speed mechanical system powered by hydraulics is technically feasible.

(2) The digital feel system has solved many problems associated with its analog predecessor including low frequency drift, high gain instability and repeatability of stick models.

(3) The system has proved easier to use than the analog system, and more reliable. Increased user confidence and greater performance have both been realized.

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TABLE 1: RANGE OF PARAMETERS FOR EACH RESPONSE TYPE

RESPONSE TYPE	**ω_n (rad/s)**	**ζ**	**k/m (lbf/in-slug)**	**cv/m (lbf-s/in-slug)**	**k/cv (1/s)**
Acceptable	0-45	0-707 median=1	0-2000 median=0.2	0-600 median=1	0-1000 median=1
Divergent	0-316 median=4.5	1.58-25000 median=158	0-100000 median=20	1000-50000 median=3000	0-100 median=0.01
Limit Cycle	1.4-316 median=14	0-1 median=0.0015	2-100000 median=200	0-632 median=0.02	10-100000 median=10000
Highly Damped	0-10 median=0.14	2.2-2500 median=111	0-100 median=0.02	3-600 median=50	0-0.333 median=0.0003
Oscillation Overshoot	1-223 median=4.47	0-1 median=0.5	1-50000 median=20	0-447 median=3	1-10000 median = 10

FIGURE 1: BELL 205 AIRBORNE SIMULATOR

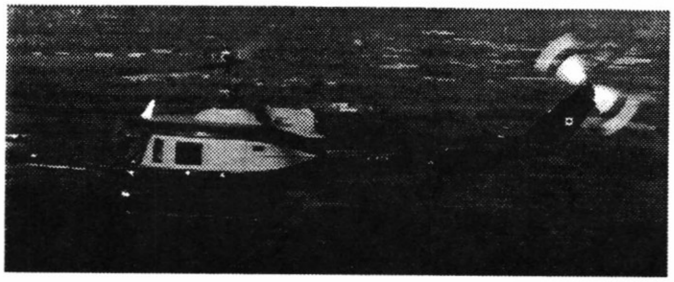
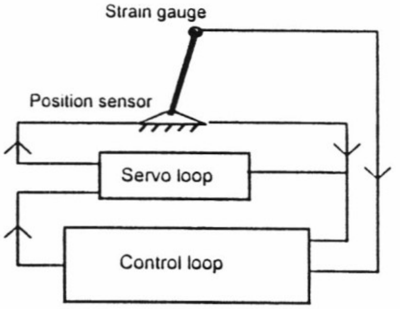


FIGURE 2: MODEL FOLLOWING FEEL SYSTEM



- Control loop calculates stick position based on mathematical model
- Servo loop forces stick to calculated position
- Original system was analogue
- New system replaces both loops with a digital computer

FIGURE 3: LIMP NOODLE STICK MODEL

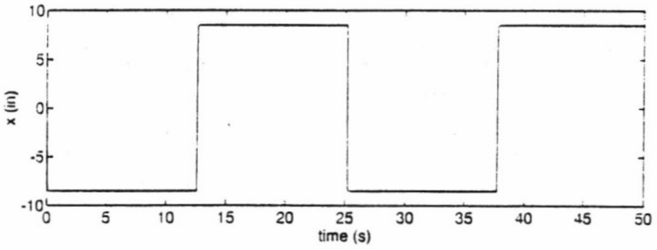


FIGURE 4: ACCEPTABLE STICK MODEL

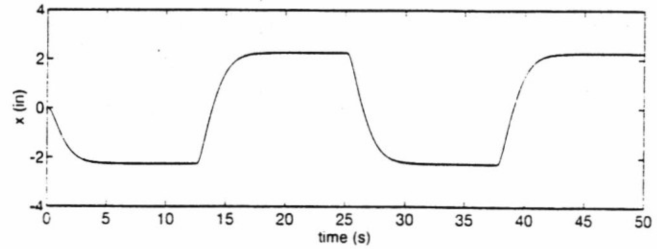


FIGURE 5: OVERDAMPED STICK MODEL

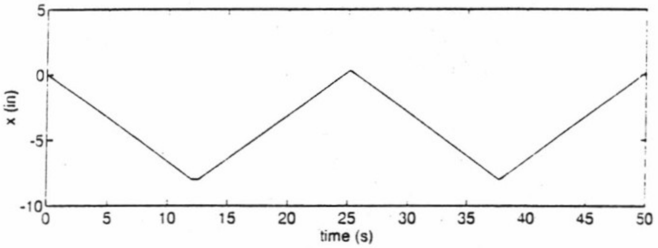


FIGURE 6: UNDERDAMPED STICK MODEL

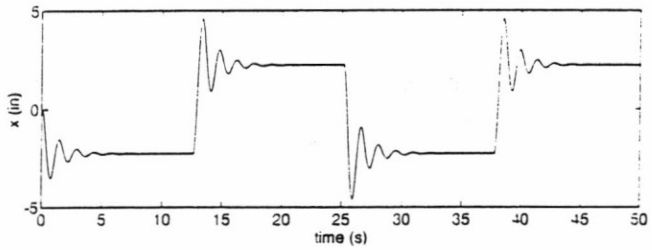


FIGURE 7: CLOSED LOOP FREQUENCY RESPONSE

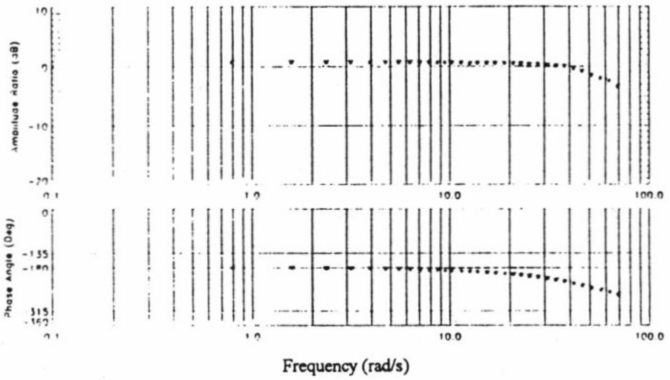


FIGURE 8: LONGITUDINAL STICK RESPONSE

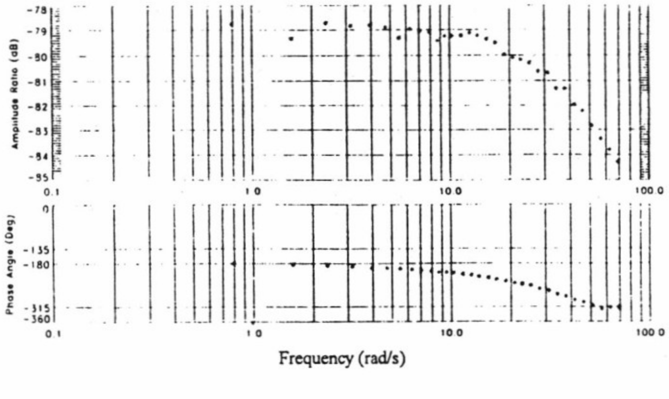


FIGURE 9: LATERAL STICK RESPONSE

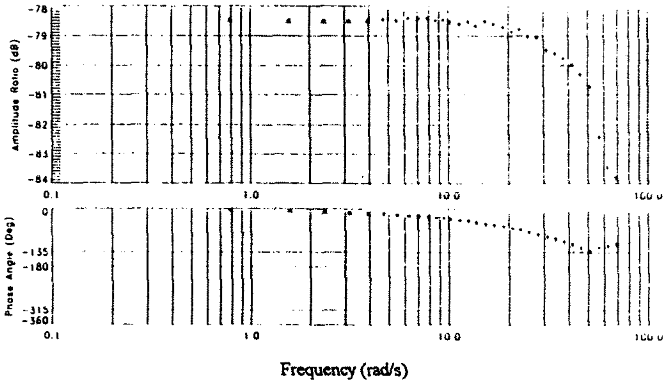


FIGURE 10: PEDAL RESPONSE