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THE INVOLUNTARY PARTICIPATION OF A HUMAN PILOT IN A HELICOPTER COLLECTIVE CONTROL LOOP

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Abstract

The results of a three phase study conducted to evaluate the effect of involuntary pilot control inputs due to helicopter vertical motion are presented. The first phase discusses an experiment conducted on the Sikorsky motion-base simulator to obtain bio-response data in the one to five Hertz frequency range for a pilot at the collective control of a helicopter. The transfer functions of involuntary control inputs to vertical vibration through the dynamics of the coupled seat/torso/limb/stick system are determined for pilots of various body types. The results of this phase show that participation with the collective stick is significant due to the lightly damped characteristics of vertical whole body resonance and the lack of arm position restraints or bracing for this control.

In the second phase, the collective axis pilot transfer function is coupled with a high order linear helicopter model that includes: rigid body, flexible fuselage, rotor flapping and lagging, inflow, and external load dynamics. The biomechanical feedback system results in closed-loop responses that have reduced aeroelastic stability. It is shown that the proximity of the human body's resonance to airframe bending and external load frequencies can be destabilizing, leading to the well known phenomena of pilot-assisted oscillations (PAO).

In the final phase, a Sikorsky low pass filter design is implemented in the collective control axis of the linear model to attenuate passive pilot feedthrough. By including this filter design the pilot/vehicle mode interactions are reduced, permitting an increase in vehicle stability margins. The presence of a control stick filter is shown to be a solution towards minimizing involuntary pilot participation.

1. Introduction

The pilot of a helicopter introduces dynamics in the control loop that are characterized by both active and passive components. These dynamics play an important role in vehicle design and human factors considerations, especially in today's highly maneuverable, high control bandwidth aircraft with complex mission task requirements. While much attention is now paid to crewstation design in a static sense, rarely is the same given to the dynamic integration of pilot and vehicle. The associated risk is that the simultaneous solution of vehicle and pilot dynamics may produce an aircraft susceptible to instabilities, or one which is completely unflyable. Thus, it is useful to determine and model pilot dynamics to gain insight into the pilot's effect on vehicle handling and stability, and also to optimize various display and manipulator interfaces.

Considerable research effort has been expended in recent years towards defining human controller and biodynamic characteristics [e.g. see References 1,3,4,7], which historically have been very difficult to model due to the non-linear properties of a human operator in a manual control task. Previous work in this field has therefore concentrated on describing-function analysis, which attempts to identify human performance for certain classes of inputs and controlled elements [see Ref 4 for an overview]. Magdeleno, et. al. [Ref. 1] conducted experiments to determine vibration feedthrough in a longitudinal pitch control task and derived biomechanical models for particular manipulator sensitivities and anthropometric types. Jex [Ref. 3] cites several studies which were conducted to examine pilot-induced oscillations, but generally for fixed-wing aircraft only.

The purpose of this paper is to investigate the vibration interference for a pilot in a collective loop closure, which arises from the helicopter's unique vertical degree of freedom. In a helicopter, the vibration-induced control inputs are most troublesome in the collective control axis, partly because there is little means of bracing the arm to minimize the acceleration transmission through the biomass. By the position of the stick the pilot is forced to freely extend the lower and upper arm with no position restraint other than the inherent neuromuscular system. In the cyclic control axes the pilot's lower arm is generally positioned against the leg, and acceleration transmission into the controls from seat motion is minimized in part by the restraints imposed by the limb/body structure. In an early study, Lytwyn [Ref. 2] pointed out the difficulties in collective by parametrically deriving combinations of seat damping and collective stick sensitivity that maintain vehicle stability.

An experiment was conducted on the Sikorsky Aircraft motion-base simulator to obtain individual bio-response data for a population of pilots at the controls of a helicopter, as shown in Figure 1. Pilots' collective stick motion was recorded while vertical, sinusoidal commands were applied to the simulator platform at discrete frequencies ranging from 1 to 5 Hz. Individuals performed a low-frequency tracking task utilizing the collective and cyclic controls in order to maintain natural grips. The experiment was open-loop, that is, control inputs were not fed back through a helicopter mathematical algorithm to produce a change in vibration.

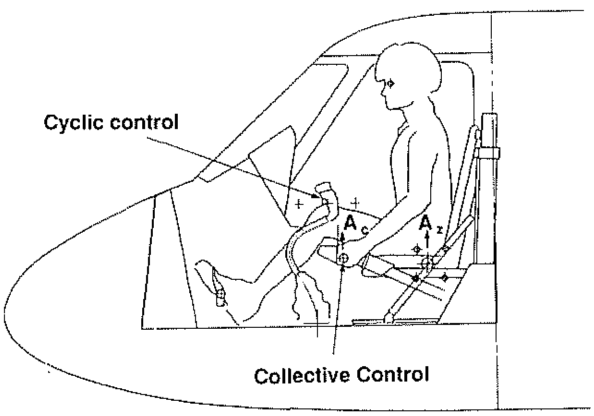


Fig. 1: Helicopter Seating/Stick Configuration

This study uses the pilot model derived from test data with a linear helicopter model to investigate the coupled relationship. The Sikorsky Aircraft non-linear, time domain, generic helicopter simulation model (GEN HEL), [Ref 8], was used to derive the linear state representation model, thus allowing the application of linear analysis techniques towards understanding the dynamic interactions. This high-order linear model [see Refs 10, 11 for a detailed description] includes the following degrees of freedom: rigid body, flexible fuselage, external load, rotor flapping and lagging, inflow, and servo and SAS (Stability Augmentation System) dynamics. System eigenvalues are shown that identify the dominant vehicle, external load and rotor modes. The interaction between pilot and vehicle is examined with the open and closed loop root locations, with and without external load, and the influence of the pilot is readily observed by the migrations of the coupled roots.

The pilot's involuntary participation in the control loop is recognized to be a potential problem which has prompted the development of various techniques to minimize the control inputs. One such technique is a low pass filter in the collective control run that attenuates stick motions at frequencies which destabilize the aircraft. A collective stick attenuator is implemented in the linear model and is shown to provide stable open loop gain and phase margins for the vehicle, with and without external load.

2. Pilot-Induced and Pilot-Assisted Oscillations

Fixed and rotary wing pilots alike are familiar with potential instabilities that arise from controlling dynamically complex machines. The destabilization of a vehicle due to active and/or passive pilot participation in the control loop is a well known phenomena called pilot-induced oscillations (PIO) and pilot-assisted oscillations (PAO), respectively. The following definitions are provided:

Pilot-Induced Oscillations (PIO) result from the pilot's inadvertent coupling with the helicopter dynamics via the active control from interpretation of visual, aural and motion cues.

Pilot-Assisted Oscillations (PAO) result from the pilot's inadvertent coupling with the helicopter dynamics via the passive input from biodynamic response to vibration.

PIO occur when the pilot inadvertently drives the vehicle unstable by applying control inputs that are in the wrong direction or have phase lag. This is not always detrimental to safety of flight, but can interfere with completion of a mission task. A common example of the problem is the helicopter's external load carrying mission, where the independent load dynamics can couple into the vehicle dynamics via elastic cables that hold the load, and produce delayed motion cues in the cockpit. The pilot reaction to the motion cues presented would normally be stabilizing, if not for the phase delays that develop. Once PIO is initiated, the pilot is forced to control a two body, mass-spring system without the benefit of an efficient lead strategy to compensate for the overall vehicle motion. Since active involvement in the control loop is occurring, PIO will cease when the pilot releases the controls, stops control motion, eases off on task precision or changes the control strategy.

PAO, on the other hand, are purely the result of involuntary participation in the control loop. The pilot is coupled to the vehicle by gripping the controls, and forms a closed-loop acceleration feedback system as long as that grip is maintained. The acceleration transmission through the biomass activates the controls through limb imbalance and possibly whole body resonance. In severe cockpit vibratory conditions the pilot's involuntary control motions can interfere with task performance and in extreme conditions cause divergent vehicle oscillations, despite attempts at active control. The problem is typically found in large, heavy-lift helicopters, because the proclivity of the pilot to inadvertently actuate the controls is amplified by the proximity of whole body resonance to airframe bending mode and external load mode frequencies. The actual degree of participation is highly dependent on the individual pilot and includes many factors such as experience, body type, and the active neuromuscular system which acts to minimize the coupling. As with PIO, PAO ceases when the pilot releases the controls.

3. Manual Control in a Vibration Environment

The man-machine system is governed in one sense by the ability of the human to act as an adaptive controller. The pilot's task precision is degraded by cockpit vibration, which is perceived through various human sensory mechanisms. Normally, the awareness of vibration results in muscular tensing and some means of elbow and wrist joint hinging to minimize the relative stick/torso motion. Since cognitive actions are intimately linked to "uncontrolled" response, it is worthwhile to examine the channels of sensory input chosen by the brain during a typical control task in a vibration environment.

Neural processes first sort and switch the multitude of human sensory inputs and then generate a motor response by transferring neuron information along the spinal cord from the brain to the active neuromuscluar system [a detailed description of the human sensory system is given in Ref. 4]. For a pilot in a loop closure, such as maintaining a precise hover with an external load, a neural filtering process occurs as the brain focuses on key feedbacks, as generalized in Figure 2. In this figure the pilot's visual feedback includes not only the perception of the external environment but also the reading of instruments. Visual cues enable the pilot to fly the helicopter along a desired flight path by simultaneously monitoring information from displays and peripheral activity. Hearing provides information related to vehicle performance such as engine and main rotor N/rev noise. Naturally the pilot can also receive voice transmissions and audio signals from cockpit warning devices which may motivate control movements. One of the most important motion cues is the perception of translational and rotational acceleration by the inner-ear semi-circular canals and otolith organs respectively. This vestibular feedback is one of the key advantages in the use of motion-base versus fixed-base simulators for realistic simulation studies. It is especially important in the analysis of pilot control motions to consider proprioceptive and tactile feedback. Proprioceptive implies the knowledge of muscular position, which is sometimes used to minimize vibration feedthrough by means of a conscious neuromuscular reaction to regions of stick travel that may have excessive jitter. This awareness of position provides a predictive cue to the pilot that can result in a deliberate avoidance of those stick regions, if possible. Finally, the tactile feedback indicates a pressure or resistance, for example from stick vibrations, which usually manifests a firmer or looser grip depending on the control strategy.

In the biomechanical response experiment it is expected that some variance exists between subjects due to individual reception of these vibration related feedbacks. In actual flight a pilot is forced to contend with many vibrations induced by the main and tail rotor rotation, fuselage bending, external load motion, and the engine/gearbox. The prolonged exposure to vibration and noise introduces fatigue and reduces the comfort and efficiency of the human operator [Ref. 5], making the pilot even more susceptible to involuntary participation.

4. Biomechanical Response Experiment

The objective of the biomechanical response experiment was to characterize the lumped mass and elasticity properties of the seat/torso/limb/stick system. Restraints applied by the seat, shoulder belt and control stick contribute dynamics to the system, yet are too coupled with biodynamics to separate. The simulator cockpit was set up with the conventional helicopter seat, and cyclic, collective and pedal controls. The visual system was turned off for the purposes of the experiment and a piloting task was designed utilizing the cockpit instrumentation. Three-axis accelerometers were mounted on the collective grip and at the center of the pilot's seat, and their measurements were recorded to disk through an A/D interface operating at a sample rate of 30 Hz. To simulate the helicopter cockpit environment the controls were set to typical strokes, breakouts and force gradients. However, to eliminate nonlinearities the deadband region of each stick was set to zero. Realistically this deadband is helpful in limiting vibratory stick motions from passing through the control run, but for the purposes of modeling passive pilot feedthrough it is assumed that the stick is moving constantly, as is true in a vertical control task. While individuals performed the task the motion platform was forced with vertical discrete frequency inputs ranging from 1-5 Hz in .5 Hz increments. The peak vertical acceleration was approximately .4 g's at all frequencies and the total run duration was approximately three minutes.

A total of six subjects with different body types and piloting experience participated in the experiment. Each subject performed the simple secondary task requiring low frequency motion of both sticks to prevent any unnatural relaxation of the controls. Cyclic stick was used in a fore-aft motion to control a needle indicator that moved sinusoidally about a trim point. Concurrently another needle indicator was driven with the same input and required collective stick motion. The objective was to keep each pointer at a center trim position by applying negating control motions which were summed with the pre-recorded sinusoidal

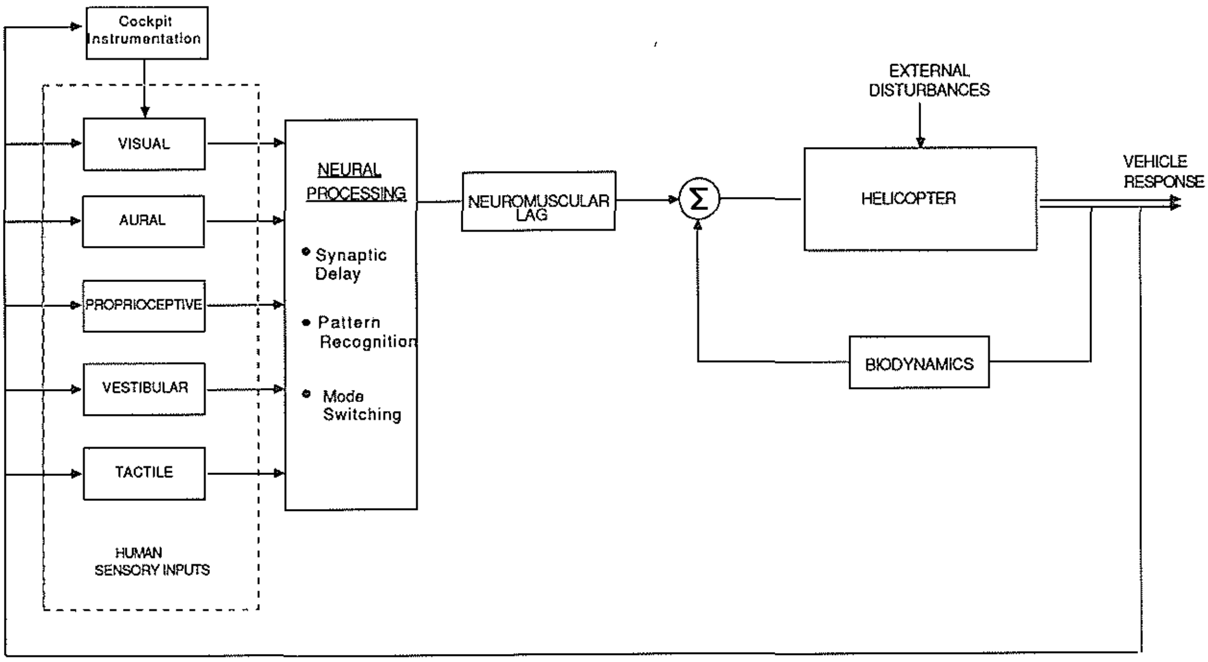


Fig 2: Pilot Loop Closure Diagram

inputs, forming resultant error signals which drove each indicator. There was no attempt to score the subjects and all received ample practice at the task. By design, the task inputs were of sufficiently low frequency to be spectrally separable from the passive inputs in the data reduction. Any derived transfer function from test data expresses only the passive biomechanical response, and does not model lead strategies to accomplish the given task or response to stimuli. However, inherent in the transfer function is any active neuromuscular activity corresponding to the subject's natural tendency to minimize stick vibration.

Preliminary time response data of collective stick grip acceleration indicated a time varying magnitude that is correlated with angular collective displacement. At low (down) positions, the shoulder displacements transmit almost directly into the stick through the extended arm position. At high positions, the arm is contracted and some torso motion is absorbed by the hinging of the wrist/elbow linkages before passing to the stick. The trend of magnitude response with limb geometry is shown in Figure 3 for a single run by one subject at an input frequency of 3 Hz. In this run the collective stick was moved sinusoidally from stop to stop for evaluation. For the purposes of data reduction the resolved vertical collective accelerometer data for each subject was windowed into stationary portions corresponding to positive and negative angular collective regions about trim. Since the actual task required approximately ± 5° of control travel about trim, the magnitude variation in this range is considered insignificant.

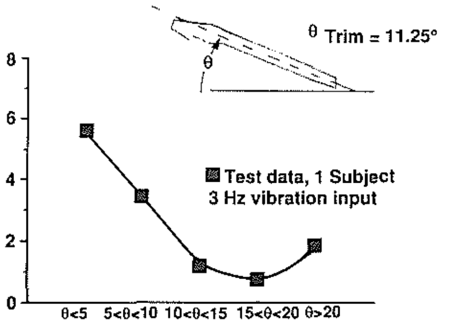
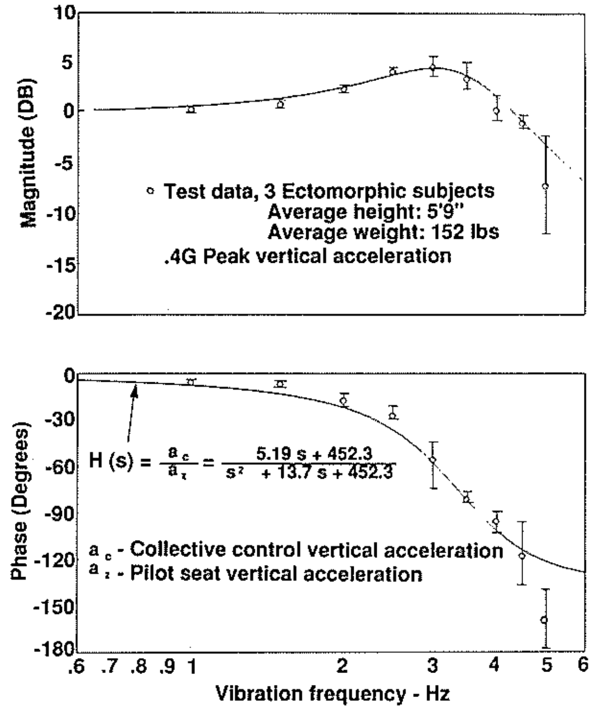


Fig 3: Effect of Angular Collective Position in Bio-Pilot Magnitude Response

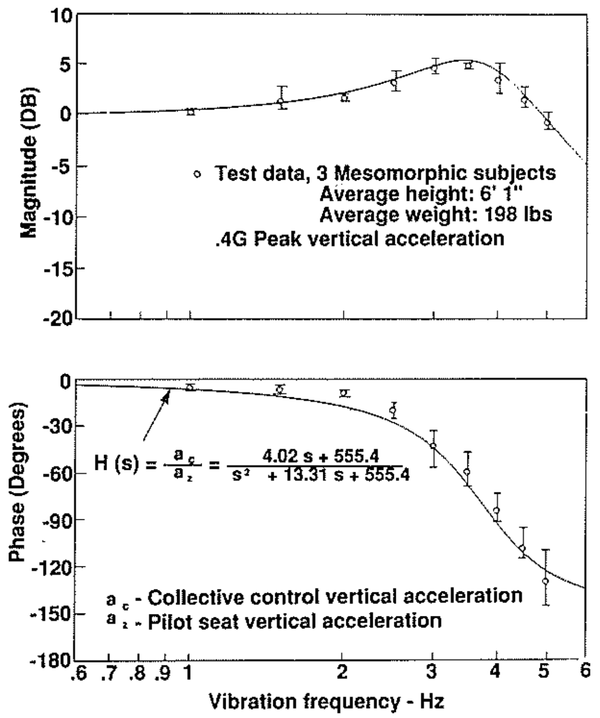
5. Pilot Model

A positive (up) acceleration transmitted through the pilot seat and biomass produces a downward relative motion of the stick due to the mass, spring characteristics of the lumped bio-mechanical system. This motion is opposed by the inertial properties of the agonist-antagonist muscle pairs which resist the applied force. The muscular system in general can be considered a very complicated series of springs and dampers which react differently to different inputs, and therefore can be very difficult to model at that level. To generalize the differences in anthropometric types the responses were averaged for three distinctly mesomorphic (husky physical build) subjects, and for three distinctly ectomorphic (slight physical build) subjects.

The transmissibility measurements for the two anthropometric types are presented independently in Figure 4a and 4b, with second-order analytical transfer functions fit to the data. The responses are for the negative stick region (between the trim point and -5 degrees) and the vertical bars are the range between subjects at each input frequency. As expected the low frequency magnitude responses to about 2 Hz are near 0 db and have less than 10° of phase, implying very little relative motion. The lumped torso/limb/stick resonance occurs in the 3-4 Hz range. Generalized shoulder acceleration response studies have shown whole body resonance in the 4-5 Hz frequency range [Refs. 1,6]. A lower resonant frequency result is due to the added limb dynamics, which in addition to passive transmission also includes the attempt of the active neuromuscular reflex system to suppress vibration. The effect of increased muscular tensing is to reduce time delay and increase the transmissibility gain. In general, the subjects conciously reacted to whole body resonance by varying arm rigidness in order to optimize the task precision. Individual reactions explain the increased variance between subjects with increasing vibration frequency.



a: Ectomorphic Subjects



b: Mesomorphic Subjects

Fig 4: Averaged Transmissibility Frequency Response

The mesomorph subjects tended to have a more damped response with less phase lag than the ectomorphs, implying less participation. The ectomorphic subjects are probably more prone to participate in the system due to their lower mass rather than any height difference with the mesomorphic subjects. In addition, the resonant frequency was 3.39 Hz for the ectomorphs versus 3.75 Hz for the mesomorphs, closer to whole body resonance frequencies. It was found that the positive stick region responses exhibited much less phase lag and lower magnitude, validating video tape observations of the subjects that relative collective stick motion is less sensitive to whole body resonance with a contracted arm position.

These test results highlight the response deviations possible with different individuals, and the difficulty in deriving a generalized pilot model. The bio-response experiment was dependent on not only human physical characteristics, but also compliance properties of the stick and seat, the amplitude and direction of input, and the control axis of interest. Although not all of these issues are addressed in this study, it is important to reference any conclusions in the closed-loop analysis to the particular configuration tested, and to resist extrapolating bio-models to different man-machine interfaces.

6. Linear Helicopter Model

To represent the high-order dynamics associated with a heavy lift helicopter, a Sikorsky analytic, non-linear GEN HEL simulation model is linearized to provide the state-space vehicle representation. Non-linear GEN HEL is a large angle, free flight helicopter simulation formulated according to physical laws. The main rotor is represented as an independent body from the fuselage with flapping and lagging blade degrees of freedom and lagged inflow dynamics. Normalized rotor airfoil data as a function of Mach number and angle of attack provide the blade element aerodynamic characteristics which are resolved into main rotor forces and moments at the hub. These are combined with fuselage, tail rotor, and empennage forces and moments to obtain the translational and rotational accelerations of the vehicle. The flexible fuselage effects are modeled with modal coefficients that define displacements at certain fuselage stations, including the cockpit floor or equivalently the pilot seat. In addition GEN HEL has the flexibility to simulate a six degree of freedom external load.

The basic linear helicopter model is simulated with 28 states and 4 inputs, with an additional 12 states provided for external load, as shown in Figure 5.

$$[\dot{X}] = [A]\,[X] + [B]\,[U]$$

$$U = [A1S\ B1S\ \theta_{mr}\ \theta_{tr}]^T$$

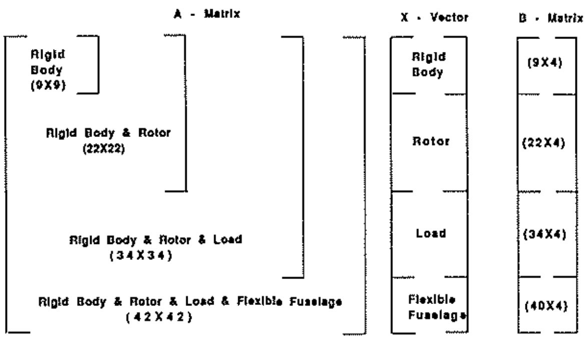


Fig 5: Linear Model Matrix Formulation

The matrix form is:

$$dX/dt = [A]\,x + [B]\,u$$

$$Y = [C]\,x + [D]\,u$$

where:

dX/dt	=	Time derivative of state variable
x	=	State Variables
u	=	Input Variables
[A]	=	Plant State Matrix
[B]	=	Plant Control Matrix
Y	=	Plant Outputs
[C]	=	Plant State Output Matrix
[D]	=	Plant Control Output Matrix

The first nine state variables consist of the rigid body translational and rotational velocities and the pitch, roll and yaw Euler angles: u, v, w, p, q, r, θ, ϕ, ψ respectively. The next twelve state variables represent the rotor flapping, lagging and inflow dynamics: a0f, a1f, b1f, a0l, a1l, b1l, Dwo, and their respective velocities. Diftler [Ref. 11] gives a detailed discussion of the importance of rotor dynamics on overall model fidelity. The flexible fuselage is modeled by the addition of six more states which represent the three bending modes: the u1, u2, u3 displacement coordinates and their respective velocities. Rigid body plus flexible fuselage plus rotor comprise the basic 28 state helicopter model. To provide external load simulation, a six degree of freedom body is modeled in the same manner as the rigid fuselage model, with translational, rotational accelerations and pitch, roll and yaw Euler angles:

$$u_{el},\ v_{el},\ w_{el},\ p_{el},\ q_{el},\ r_{el},\ \theta_{el},\ \phi_{el},\ \psi_{el},$$

respectively. Three additional load states are required to define the x, y, z relative distances of the load and helicopter centers of gravity, making a total of twelve load states. The total helicopter plus external load yields a 40 state linear model. For the purposes of the pilot/vehicle analysis, an extra output was added to the Y output vector to provide pilot seat acceleration by a linear combination of the A and B matrix state rates. The linear equation for vertical pilot seat acceleration is:

$$Az = \dot{w} - Xps{*}\dot{q} + Yps{*}\dot{p} + KZCP1{*}\dot{u}1 + KZCP2{*}\dot{u}2 + KZCP3{*}\dot{u}3$$

where:

Xps	=	Longitudinal distance of pilot seat from A/C center of gravity
Yps	=	Lateral distance of pilot seat from A/C center of gravity

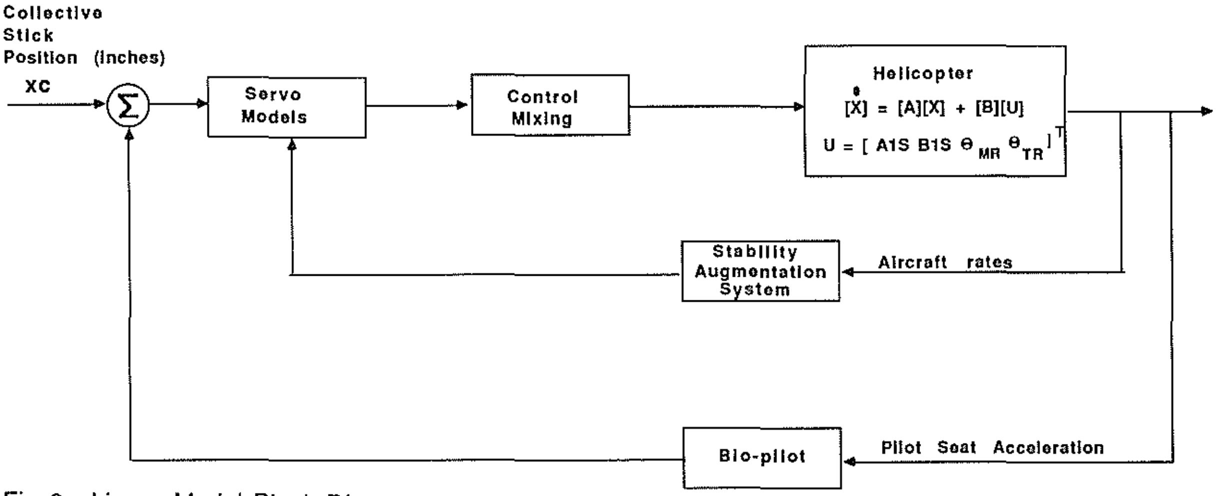


Fig 6: Linear Model Block Diagram

KZCP1 = 1st Mode Influence Gain

KZCP2 = 2nd Mode Influence Gain

KZCP3 = 3rd Mode Influence Gain

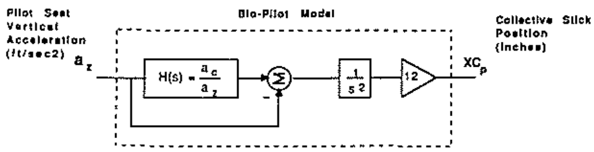


Fig 7: Generalized Bio-Pilot Model

The flexible fuselage influence gains are uniquely defined for the pilot seat location.

To correctly simulate the actual flight vehicle, the linear model is expanded further to account for the stability augmentation feedback system, the control mixing and the servo dynamics, as shown in Figure 6. The stability augmentation is a simplified rate feedback system that calculates inner-loop commands directly to a summing junction before the servos, where stick inputs are added and then passed through the servo transfer functions before being mixed into the main and tail rotor blade pitch commands.

The pilot biodynamic linear model is implemented as a feedback to the collective stick. The transmissibility transfer function obtained in the experiment is modified to provide collective stick position as a function of vertical cockpit acceleration, as shown in Figure 7. This is accomplished by first subtracting the cockpit floor acceleration from the collective stick acceleration to give the relative control motion, which is then integrated twice to give control displacement.

The effect of collective stick input is a simultaneous change in all main rotor blade pitch angles, which if in the positive direction (control up), becomes a net thrust increase and an upwards aircraft rigid body acceleration. With elastic fuselage properties the cockpit area is near the node of the airframe first and second bending modes and hence experiences a downward acceleration relative to the body. A typical heavy lift helicopter has a primarily vertical first bending mode, and a torsional second bending mode within the 3-5 Hz frequency range, close to the pilot resonant frequency. In addition external load modes are present in the 2-4 Hz frequency range which vary according to single/dual point suspension configuration and sling stiffness characteristics. The vertical energy present in the cockpit is evident in the power spectrum shown in Figure 8 for the helicopter simulation model with a 20,000 lb single point external load suspended by a nylon sling.

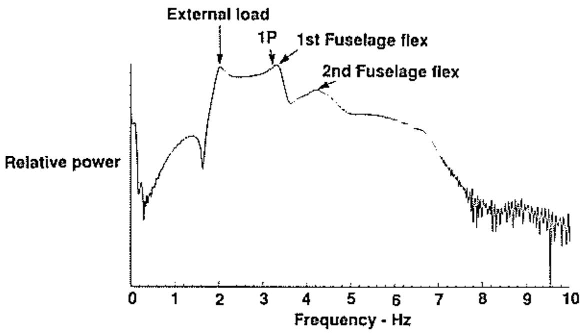


Fig 8: Vertical Vibration Spectra at the Pilot's Seat (20,000 lb Single Point External Load)

The poles of the helicopter A-matrix for this configuration are shown in Figure 9. Strong modes within the proximity of pilot resonance in the 3-4 Hz bandwidth include not only the lightly damped first and second fuselage flex modes and load vertical mode, but also main rotor flap and lag collective modes which are sensitive to vertical motion.

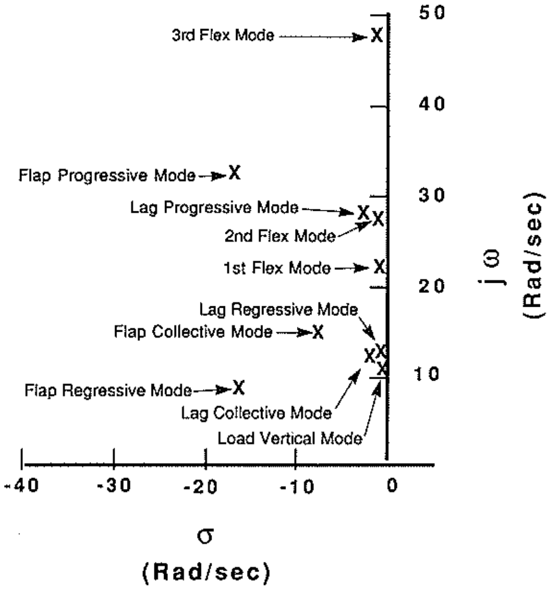


Fig 9: A-Matrix Helicopter Eigenvalues (20,000 lb Single Point External Load - Hover)

7. Pilot Participation without External Load

The effect of pilot participation in the collective loop is illustrated in Figure 10. The pole locations for zero gain pilot feedback represent the helicopter with a closed-loop stability augmentation system. Therefore, the basic rotor modes have shifted relative to the plant A-matrix poles presented earlier in Figure 9. The inclusion of pilot dynamics results in closed-loop instability as the coupled pilot root traverses the imaginary axis at a feedback gain less than one. It should be noted that except at zero feedback gain, the roots represent coupled pilot/vehicle/rotor modes, and cannot be considered independent of each other. For example, the collective flap mode affects the collective lag mode as the blade center of mass moves inboard or outboard with changing flapping, tending to speed up or slow down the rotor (the figure skater effect), while also contributing to body vertical motion and flex modes at the same time.

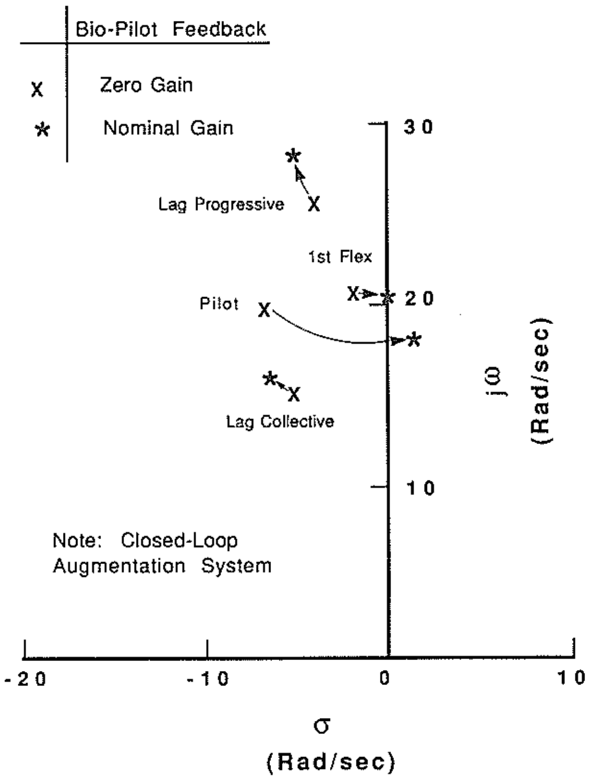


Fig 10: Effect of Bio-Pilot Feedback (Baseline Hover)

In the root locus of Figure 10 the rotor modes tend to become more damped, while the coupled pilot/1st fuselage flex mode becomes less damped. The latter result is expected since the forcing function applied by the pilot at the collective stick is manifested as main rotor thrust changes, which excite the vehicle's nodal points about a main rotor hub fulcrum. In effect, the pilot sits at the end of a flexible Ibeam which is being shaken sinusoidally about its center.

8. Pilot Participation with External Load

The pilot feedback root locus for the helicopter with a 20,000 lb single point external load is shown in Figure 11. The roots exhibit different trajectories than the baseline case as a result of load dynamics, which also affect the initial mode frequencies and dampings. With external load it is the flap collective mode that's driven across the imaginary axis while the pilot mode becomes more damped. The flap collective mode is nominally well damped, but is excited to resonance when coupled with load and pilot modes.

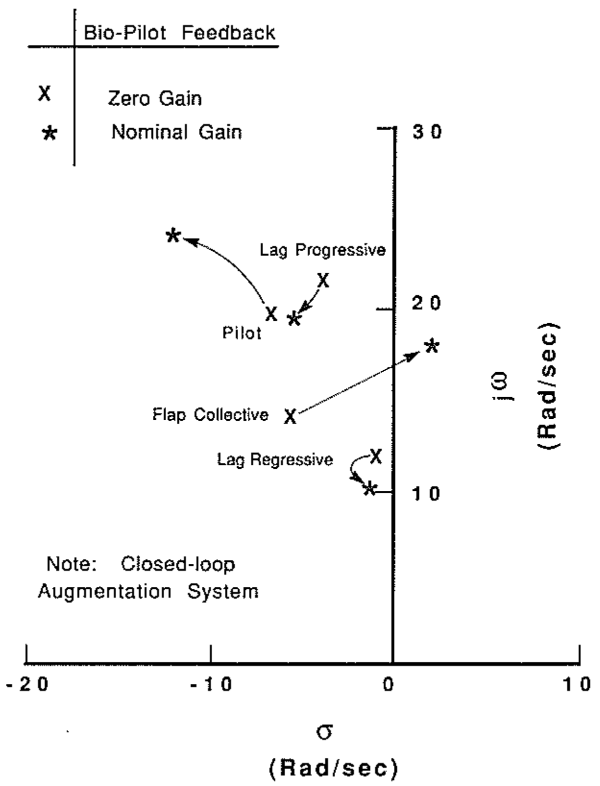


Fig 11: Effect of Bio-Pilot Feedback (20,000 lb Single Point External Load - Hover)

The load mode is a very lightly damped vertical mode with a frequency determined by the equation

$$\omega = \frac{1}{2\pi}\sqrt{\frac{K_L}{M_L}\left(1 + \frac{M_L}{M_F}\right)}$$

Where,

M_L = External load mass, lbs-sec^2/ft

M_F = Helicopter mass, lbs-sec^2/ft

K_L = Sling stiffness, lbs/ft

The frequency of this vertical mode increases directly with the external load to helicopter mass ratio and the sling stiffness. In external load carrying missions the pilot's workload is increased tremendously to avoid vertical disturbances which may excite the load mode, causing what is commonly called vertical bounce. Even slight relative motions may cause pilot reactions which precipitate PIO and/or PAO.

9. Effect of Collective Stick Attenuator

The minimization of passive pilot control motions is usually accomplished by mechanical solutions such as a viscous damper mounted on the stick itself, and a friction screw on the collective lever which allows the pilot to manually adjust the level of impedence. A more comprehensive solution is a control stick attenuator, which is a filter implemented as software in the airborne Automatic Flight Control System (AFCS) computer and is designed to cancel stick motions in each axis at frequencies which are destabilizing to the helicopter. The collective stick attenuator utilizes a fixed 1.5 Hz low pass filter designed to remove control motions induced by fuselage bending, and a switchable 0.5 Hz filter for external load induced motions. The time constant of the filter switches with the detection of stick frequency.

The effect of the collective attenuator on vehicle open-loop gain and phase margins is presented in Figure 12 for the baseline helicopter, and helicopter with single point suspension external load weights ranging from 10,000 lb to 30,000 lb. The negative gain margin for all vehicle configurations without the collective attenuator is consistent with the root locus plots shown before. The introduction of external load decreases the gain margin due to the increased cockpit magnitude response resulting from coupled modes, although the margin varies little with load weight since the frequency of the 180 degree phase crossover is well beyond the lightly damped load frequency.

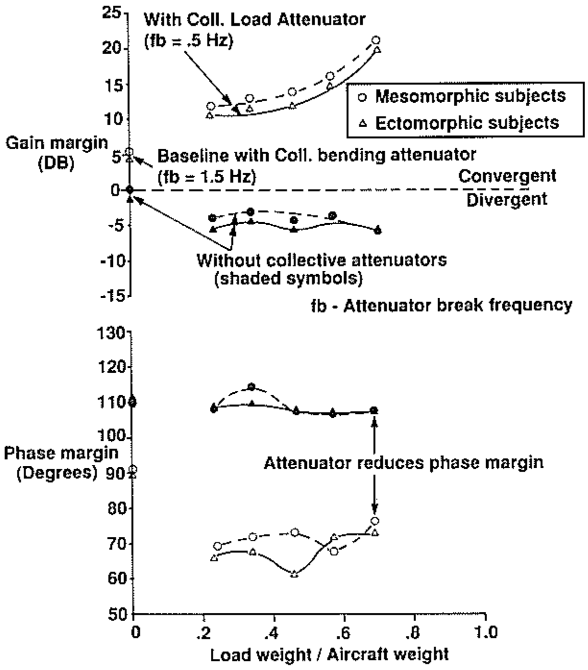


Fig 12: Effect of Collective Attenuator on Helicopter Open-Loop Stability Margins

The ectomorphic subjects show a consistently lower gain and phase margin as expected from their higher transmissibilities determined in the experiment. In considering the effect of the attenuator it is shown that stability margins are positive for each vehicle configuration. By adding the low pass filter, the 180 degree phase crossover occurs at lower frequency where the magnitude response is stable. However, the filter does add phase lag which reduces the phase margin, although there is still plenty available. The trend of increasing gain margin with external load weight results from the notch filter behavior of the pole-zero pair at the load frequency, where increasing load weight deepens the notch, providing more margin. It is clear that attenuating the biodynamic input provides stability, although at the expense of reducing the pilot's control bandwidth.

10. Conclusions

1. Vertical vibration in a helicopter cockpit can cause the pilot to involuntarily actuate the collective control. Experiment has shown that collective stick resonance in a biomechanical system occurs in the frequency range of 3-4 Hz and varies slightly with anthropometric type.

2. The angular position of the collective stick significantly affects the biomechanical magnitude and phase response. Low (down) positions generate much more participation from the human operator because the collective stick is more exposed to whole body resonance through the extended arm geometry.

3. The involuntary participation of the pilot in the collective loop can produce divergent motion of the helicopter, with and without external load. This assumes the pilot remains in the loop at all times.

4. The divergent motion results from coupled pilot/vehicle/rotor and external load mode interactions.

5. Helicopter divergence from PAO can be stopped by removal of the hand from the collective stick.

6. Helicopter motions induced by involuntary pilot participation are convergent with a collective stick attenuator that filters the passive feedthrough to the rotor system.

11. References

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