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1. Problems in Modeling Man-Machine Control Behavior in Biodynamic Environments

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The purpose of this presentation is to review some current problems in modeling man-machine control behavior in a biodynamic environment. It is given in two parts: (1) a review of the models which are appropriate for manual control behavior and the added elements necessary to deal with biodynamic interfaces, and (2) a review of some biodynamic interface pilot/vehicle problems which have occurred, been solved, or need to be solved.

MODELS

Basic Manual Control Models

The types of models evolved in the field of man-machine systems are behavioral (i.e., input-to-output) models rather than mechanistic analog models, although the lumped parameter analog models are often used for particular subsystems within the human operator. The development of these models and empirical data is the result of over two decades of research which received its initial impetus during World War II. Manual control technology has been used in numerous practical applications, such as: prediction of military and commercial aircraft handling qualities (and to quantification of the relevant procurement specifications), problems of manned vehicular control systems, and the design of better displays and controls for manned systems (e.g., see refs. 1 through 3, and the bibliography in refs. 1 and 11).

Starting with some basic principles, we will look at an increasingly complex array of models required to interface the man with the machine in a biodynamic environment. Our models are limited to the wide class of tasks which require an operator to act as a very precise sensorimotor link in a closed-loop system. Examples of such tasks are: driving a car, piloting an aircraft, aiming a weapon or telescope, and threading a needle. In such tasks the human operates as an adaptive, learning controller. Subsequent encounters with the same task result in improved behavior, which eventually evolves towards that which is most appropriate for the task. This strategy is remarkably consistent from person to person.

Figure 1 shows the "standard" block diagram for man-machine control situations. Starting from the left, the mission or task context is defined as a set of "forcing functions" comprising command inputs to be followed, and disturbances to be regulated against. Displays couple the command and feedback information to the human operator, who produces the necessary control actions to operate the controlled element in the desired manner. The output motions of the system are then displayed directly or indirectly to the human operator. This completes a feedback loop in which the goal of the operator is to reduce the observed errors between the actual or implied commands and the outputs. Because human behavior in such tasks evolves towards repeatable forms of response, it is thereby meaningful to measure it, to model it, and to seek its underlying laws.

The measured human control behavior in closed-loop tasks has been found to depend on many variables:

- Task variables.—forcing function displays, control stick, and controlled element
- Environmental variables.—vibration, temperature, g-level, and breathing atmosphere

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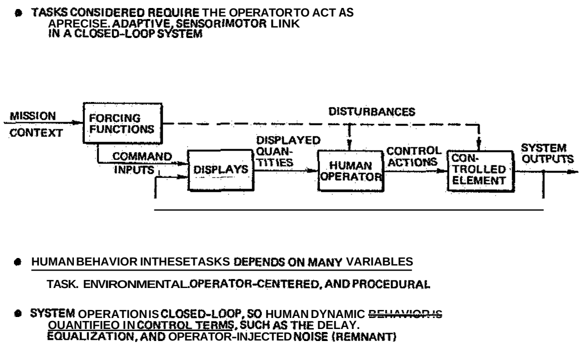

FIGURE 1.—Basic principles for man-machine control situations.

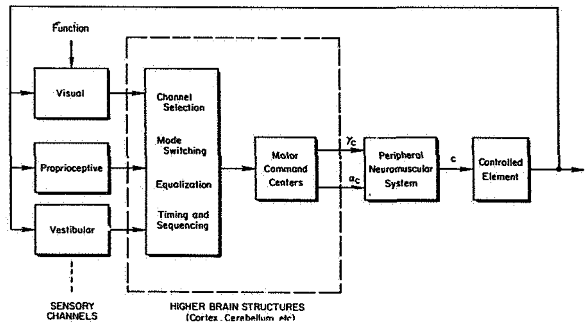

FIGURE 2.—Generalized man-machine system.

- Operator-centered variables.—anxiety, motivation, workload, and fatigue
- Procedural variables.—practice, transfer of training, order of presentation, and even the measurement technique.

We generally try to suppress the procedural variables by suitable experimental design and thorough training, so it is the first three which are of main interest. The effects on both models and parameters of the task variables are fairly well understood (refs. 1 and 8), but measuring the effects of environmental and operator-centered variables are still in an embryonic status.

Because man-machine control systems generally operate in a closed-loop manner, human control behavior is most suitably quantified in terms of control theory. Such concepts as feedback loops, dynamic stability, dynamic loop delays, equalization, and operator-injected noise ("remnant") are central concepts to all man-machine-control models.

Now let's expand the human operator block of figure 1. Here in figure 2 we have a more generalized block system diagram. At the left are shown the three main forms of sensory input, i.e., the visual, proprioceptive, and vestibular neural signals. They interact with the higher brain structures in, as yet, only vaguely understood ways. Within the cortex and the cerebellum a number of processes occur. Among these are channel selection (when more than one channel must be operated concurrently), mode switching between various types of internal loop structure, equalization (in the form of rate anticipating or smoothing), and the timing and sequencing of various discrete events in cases where that is appropriate. All of these operations take a finite amount of time, but as learning proceeds and the same forcing function is encountered again, less time is taken to handle and command the appropriate motor actions. These emanate from the higher brain structure in the form of alpha and gamma motor neuron signals which operate the neuromuscular servo system. A completely accurate and comprehensive neuromuscular model has yet to be evolved; nevertheless, a lot is known. I will expand on this neuromuscular system model later.

The structure of the models for man-machine control systems is not fixed, but can actually change as learning proceeds. This hierarchy of open- and closed-loop feedback structures has been termed the Successive Organization of Perception (SOP) theory of learning (refs. 4 and 5). In figure 3 we see that in the most basic phase the operator merely seeks to correct the errors between the command and response. This "compensatory" loop structure is the only structure allowed when the input or forcing functions are completely unpredictable.

In the second phase the operator takes advantage of any ((coherency," or patterns, in his input (or which he perceives proprioceptively from his control forces) to form other signal paths which can cause the output to follow the input more accurately. Any residual errors are then corrected in a compensatory manner. This so-called "pursuit" loop structure is the most general form of operator control, yet the elements within the blocks at this point can only be inferred, because there is but one input and one output from which the properties of several

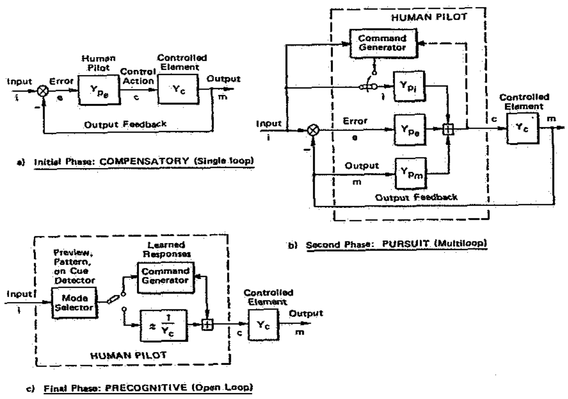

FIGURE 3.—Phases in the successive organization of perception.

blocks must be determined. Consequently, definitive models for the pursuit structures are not well established. Fortunately, it is the error correction portion of this loop which determines the dynamic stability of the man-machine system, so the feedback properties derived for compensatory loop structures continue to dominate the pursuit level of internal organization.

In the final phase, given commands to which prelearned responses are appropriate, the operator can evolve towards a preprogrammed open-loop controller. For example, he could use preview, pattern prediction, or cue detection to select and trigger off a previously learned response. In doing this he incurs increased decision time and a chance of major error. Nevertheless, most of our normal discrete stimulus/response type of actions are correctly modeled in this form. In this case such complexities as closed-loop stability and circulating noise transmission in the control loops cease to be a problem, and the theories of probabilistic learning and optimal control theory play a dominant modeling role.

The ability of the human to form such complex loop structures and to take advantage of the predictability of a command signal leads to great difficulty in the measurement of his dynamic response properties. Unlike the "passive" dynamic models of the body, which mast biodynamicists are used to dealing with, it is not possible to obtain meaningful control response properties of a human controller by forcing him with a pure sinusoid swept through the low-frequency band. Faced with such a predictable input, the operator will rapidly progress through the SOP learning stages. The result is an output which can be closely in synchronism with the input sinusoid up to the limiting neuromuscular bandwidth (on the order of 4 Hz).

Consequently, *to obtain useful dynamic response measures the human operator must be forced with a random-appearing forcing function of fairly low bandwidth* with most of its power below **1 Hz.** Experience has shown that the most efficient way to do this is to provide a sum of randomly phased sinusoids. To prevent the appearance of repetitive wave-forms these are spaced roughly logarithmically in frequency while avoiding simple harmonic frequency ratios. The Successive Organization of Perception considerations make the selection of forcing functions for man-machine measurements a subtle art, requiring great finesse. Just remember that many of the simple frequency-sweep techniques familiar to systems engineers will not work with man-machine systems, and that more sophisticated nonlinear describing function techniques are necessary (e.g., see refs. 6 and 7).

Biodynamic Interfaces

Now consider the additional elements required to interface man and machine in a biodynamic environment. At the top of figure 4 is the now-familiar control loop, including display, human operator, controlled element, and feedback. At the bottom are those additional elements required in a biodynamic environment. There are three

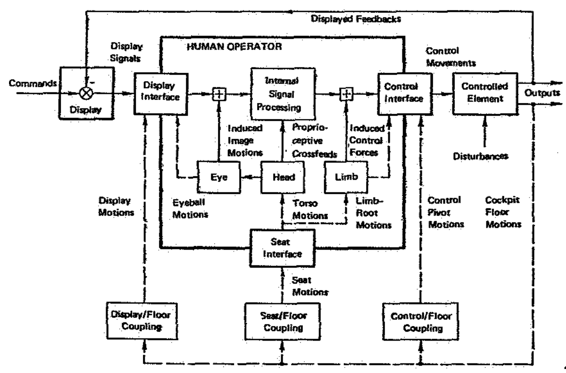

FIGURE 4.—Biodynamic interfaces for man-machine control.

primary biodynamic interfaces of the human operator: at the display, the seat, and the controls. Each of these is, in turn, coupled to the structure **(floor)** of the controlled element via passive or possibly active means. An example of active couplings are the vibration isolation seats currently undergoing tests at U.S. Air Force and NASA facilities.

In a dynamic vibration environment the display, seat, and control can each be vibrating at different large amplitudes and with different phases, so that merely perceiving the display and gripping the stick may become difficult *per se.* The human torso, and through it the motions of the head, eye, and limbs, also may be induced to move out of phase with their respective interfaces. Consequently, a number of spurious (and occasionally favorable) control signals can be developed by the man-machine system in a biodynamic environment. For example, eyeball motions can cause image motions which in turn lead to spurious control signals. Head motions and varying acceleration vectors can cause spurious vestibular signals to be developed, leading to eye motions (nystagmus) or to a number of illusions (i.e., the oculogravic illusion) (ref. **20).** Forces may be applied to the control by the vibration-induced motions between the limb and control pivot. In many cases the mass of the limb (or more correctly, its dynamic impedance properties) acting at the top of the stick act as a "bobweight." This makes the control system unusually sensitive to axial, normal, or transverse accelerations of the coupled pilot-vehicle system. The "bobweight effect" is observed in some automobiles, where resting the hands loosely at the top of the wheel (versus at the bottom) gives rise to markedly different transient responses to side-gusts.

While the modeling **of** the *mechanical* elements between the man and machine interfaces is a straightforward but tedious process, the modeling of the biodynamic feedbacks and interactions is not. Comprehensive biodynamic models such as the ones described in reference **30** are necessary to assess the simultaneous motions **of** the head, eye, and limbs. Even more complex and subtle models are required to handle induced image motions (ref. 42), vestibular crossfeeds (refs. **20** and **21),** and induced control forces (refs. **15** and **16).** As a result, such models are in a more primitive state of development than the basic human operator models.

Example—Model for Limb/Control Interface

To illustrate the additional complexities which can occur, let us look in more detail at what is inside the block previously labeled "control interface" in figure **4.** Figure **5** shows a somewhat simplified, lumped-parameter model for the limb-to-control interface. Its input (from the left) is the command from the central nervous system, and its output (at the right) is the control position. Relative motions may exist between the limb-root (on the torso) and the control pivot.

The middle of figure **5** shows the muscle servo system as a lumped-parameter analog of the agonist/antagonist pair of muscles that actuate the limb. The parameters with arrows through them are some of the many "variable constants" which plague the biodynamic modeling field. These constants are dependent primarily on the tension in the muscle system as set by the gamma

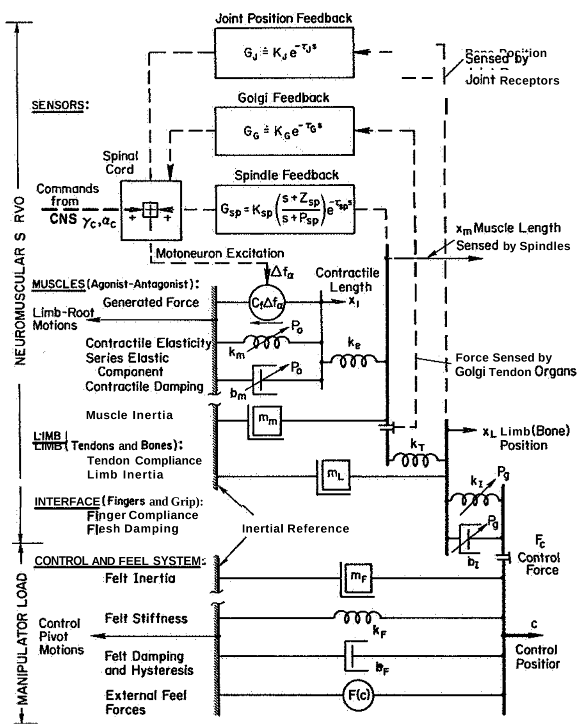

FIGURE 5.—Model for limb-manipulator interfaces.

motor neuron excitation (see refs. 8 and 9). The resulting muscle actuation forces are coupled elastically through the muscle inertia, then through the tendon compliance into the limb inertia to move the bone. Various sensory paths are shown at the top to complete this servo loop. We believe the spindle feedbacks play a dominant role in fine control motions, but Golgi-organ feedbacks and joint-position-receptors are also known to be involved under certain circumstances. The control stick itself is moved through the interface compliance. The picture is not complete without consideration of the "feel system" dynamic properties, including its effective mass, spring rate, damping, nonlinearities, etc.

Any physiologist will attest that this is a somewhat oversimplified neuromuscular model. Nevertheless, we have found it is sufficiently comprehensive to reveal the various dynamic modes observed in neuromuscular describing functions; handle such phenomena as high frequency limb tremor (which occurs at frequencies near 10 **Hz** (ref. 10)); accommodate manipulator feel systems ranging from rigid to free sticks and all forms in between; and correctly account for relative movement between limb root and control pivot. This model can also handle the situation where the limb is acting as bobweight at the end of the feel system, and complicated by its own internal compliances and feedbacks as well. It is well suited to modeling vibration effects such as mechanical feedthrough, resonant modes, and neuromuscular tonus effects on the vibration response.

To illustrate how this limb-manipulator model relates to the vibration problem, consider the case where the manipulator is a light, stiffly sprung control stick operated by finger or wrist action. Systems analysis like that in reference 9 yields the loci of the closed-spindle-loop roots for the neuromuscular dynamics, as shown in figure **6.** Notice that at least two lightly damped modes (ω_N and ω_T) exist within the range from 0 to 10 Hz, and the feel system mode, ω_F, can easily come down into this range for high-mass stick grips. The existence **of** these modes is verified by examination of earlier measurements by Sutton and Sykes (ref. **11)** on hand ('unsteadiness" power spectra when pushing' at various average force levels (as indicated on a galvanometer) against a

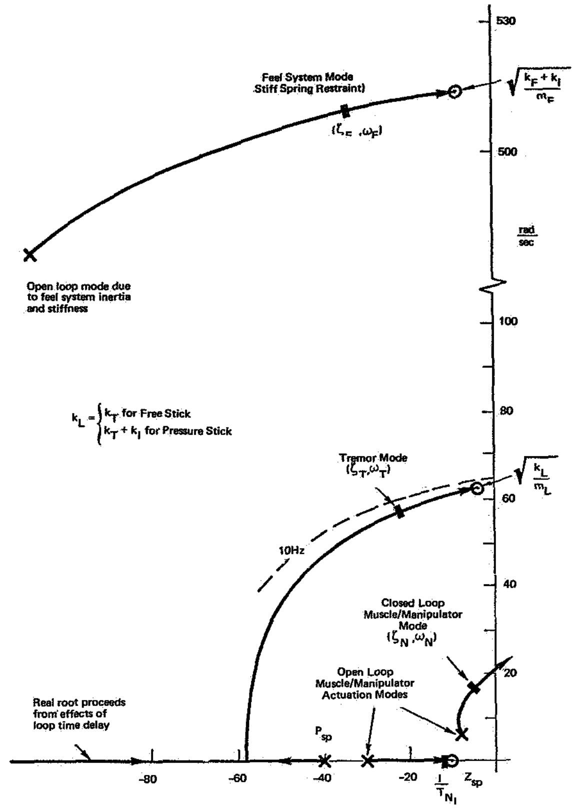

FIGURE 6.—Root locus diagram showing limb-manipulator interface dynamics with a stiffly sprung finger **control** stick.

pressure control (i.e., the case modeled in figure **6).** These data are shown in figure 7 in the form **of** displacement power spectral density plots. The various limb-manipulator modes corresponding to figure **6** are also identified here. The model implications are borne out, and the data clearly show the increase in certain mode resonances (due to lower damping ratio) with neuromuscular tension (here proportional to the average applied force). External vibration motions imposed on the torso or hand or between them both may be expected to result in similar resonances during vehicular control tasks. The particular model details depend on the control and limb configuration used, and several simplifying rearrangement of parameters can often be achieved in a particular case.

It is easy to draw increasingly complex models to represent increasingly precise details. The art comes in knowing how to extract the essential features from a complex model such as this one

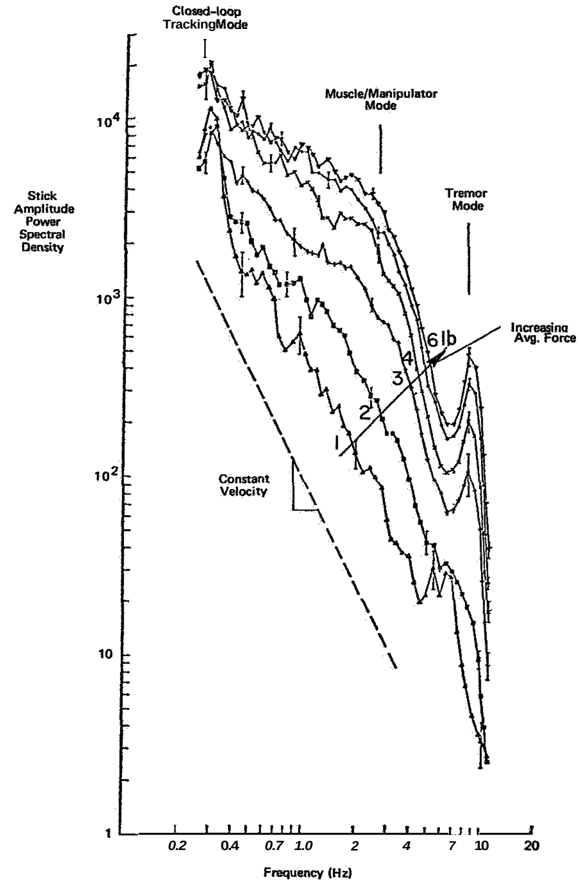

FIGURE 7.—Typical control (error) unsteadiness power spectra for various steady forces on a pressure stick (adapted from ref. 11).

in order to use it to solve practical problems. For ordinary manual control purposes we do not need the complete limb/manipulator model shown here. We simply represent its effects by a simple time delay, or at most a third-order system representing its primary lags and resonance (e.g., ref. **12**). However, under some of the new biodynamic conditions of interest, a model such as figure **5** will be essential. It behooves us all to make sure that efficient, yet well validated, biodynamic interface models are available when they are needed.

SOME BIODYNAMIC PROBLEMS AND THEIR STATUS

I'd like to end this presentation with a review of some specific problems in which biodynamic man-machine interfaces are involved. On the left side of table **1** are some of the important current problem areas, ranging from best to least researched areas. On the right side is an assessment of their status. The first column tells whether sufficiently detailed models are available to represent the phenomena observed. The second column shows by the checks or question marks whether these models have been empirically validated, so that one could have confidence in their use. The last column mentions some of the specific aerospace vehicles on which problems of the type mentioned have occurred, and in some cases solved, by application of biodynamic man-machine models. Let us look at some of these, in succession.

Pilot-Induced Oscillations

Pilot-induced oscillations (PIO) are caused by any of a number of coupling phenomena between the pilot and his vehicle system. By definition, they cease when the pilot releases the controls, or locks them rigidly. Reference **15** gives an overall background of this commonly encountered class of problems. Of the many forms of pilot-induced oscillations, the two of primary interest here are those caused by "limb-bobweight" effects or by "limb-impedance" effects.

Limb-bobweight effects are caused when the accelerations imposed by the control-induced motion of the vehicle are coupled, via the limb's unbalance, back into the control system, thereby forming a closed loop acceleration feedback system. If the mass overbalance of the pilot's arm on the controls has the correct sign and phase lag, this effect can drive the pilot vehicle system to violently unstable oscillations. (For example, in an early T–38, the oscillations reached $\pm 9\ G_z$ at **1.0** Hs! (ref. **16**.)) This can occur even with the pilot acting as a fairly passive element with his hand resting "loosely" on the stick. Analysis of this type of effect using conventional feedback models of the vehicle system, and relatively crude models for the limb's effective inertia have been performed in connection with a number of specific problems that have occurred during flight tests. Among the earliest work is that of Absug on the Douglas A 4 D (ref. 17), of the Northrop people and ourselves on the early T–38 (refs. **16** and 18),

TABLE 1.—*Some Biodynamic Man-Machine Control Problems and Their Status*

Problem	Status		
	Models available	Models validated	Examples
Pilot-Induced oscillations			
Limb-bobweight effects	Good	✓	A–4D, T–38, AH–56
Limb-impedance effects	Some	?	"Feel" system simulators
Effects of motion cues on:			
Tracking performance	Good	✓	NASA–ARC, LRC
Bending-modes excited by:		✓	
Pilot-remnant	Good	(Some)	Saturn–V, B–70, C–5
Vibration effects on:			
Tracking performance	Some	(Pending)	UH1–B, A–5
Isolation seat design	Partial	Some	Barry seat, H–21
Steady-G effects on:			
Tracking performance	Partial	...	Ames F–104B and centrifuge
Head-mounted sights	...	...	...
Steering motions induced by:			
Terrain or road	...	...	Jeep
Rough waves	...	...	SRN–4

and more recently by Lockheed on the rigid-rotor AH–56 helicopter, (ref. 19). One lesson learned from all these analyses is that fairly crude models of biodynamic systems can often be used for these problems, but fairly complete models for the vehicle's control system and the limb/manipulator coupling must be included in order to accurately represent the system dynamics in the frequency range near 1 to 3 Hz.

In a few instances, simply grabbing the control of an automatic flight control system has caused the system to shake, "quiver," "nibble," or vibrate in some other manner. This is felt to be due to coupling with the limb's complex impedance characteristics, which are included in the model given in figure 5. Anecdotes describing such cases abound in the feel-system simulation field; nevertheless this is an area in which little systematic research has been done and still less has been published.

Effects of Perceived Motion Cues

As illustrated earlier, vehicle motions enter a vehicle control loop through a number of paths, including the vestibular and proprioceptive (seat of the pants) feedbacks which are summed with the visual cues in normal man-machine control. Reasonably good models for the vestibular system crossfeeds now exist. Reference 20 contains a comprehensive review of the vestibular phenomena of interest in man-machine control, and references 21 through 23 summarize some of the recent research on motion cues. Other work is being done on the 5- and 6-degree-of-freedom moving-base simulators at the NASA-Ames Research Center (refs. 23 and 24). This is an important problem area which is presently undergoing a very fruitful phase of research.

Bending-Mode Excitation

The large aerospace vehicles controlled by pilots are becoming more and more flexible as their length increases and their diameter decreases; for example, the DC8–63 transport, B–70 bomber, and Saturn V booster. The first body-bending modes of these vehicles often lie in the range from 1 to 5 Hz, and the pilot is usually situated ahead of the main nodal point. Movement of the elevator or rudder strongly excites this bending mode, thereby inducing vibrations at the cockpit. This induced vibration acts on the pilot in a number of ways, some mentioned previously. For example, the vibrations can, through limb bobweigth effects, couple into a neutral or divergent oscillation. Particularly in the range near 5 Hz, such motions can also involve unpleasant head and torso vibrations. Because the flight path control commands do not demand responses in this frequency range, the pilot does not intentionally excite these bending modes. However, the wideband pilot-induced remnant noise described earlier in this presentation covers a wider frequency range, and it is the primary source of bending excitation.

Recently, good models to detect the existence of a bending mode excitation problem and to guide the solution (in terms of appropriate stick filtering) are available, and there have been some attempts to validate these models. One of the better documented cases is the analysis of the manual backup control system for the Saturn V booster reported in reference 25. The simulation studies for the vehicle show the dramatic importance of the remnant terms in exciting a 2 **Hz** body bending mode. Subsequent computer simulations at NASA Ames Research Center showed that the analytical man-machine models, including the remnant inputs, could successfully predict the problem and its solution, even though the magnitudes of remnant-induced bending mode excitation were not accurately predicted (ref. 26).

Vibration Effects

Vibration effects on subjective "ride quality" and tolerance of a vibration environment have been well researched and extensively reported (e.g., as summarized in refs. 27 through 30). Vibration effects on man-machine tracking performance are much more scarce, and they have involved relatively crude measurements compared with the kind of behavioral parameters we have been talking about here (refs. 31 through 33). The net tracking error includes both coherent (input correlated) and remnant (noise) contributions, each of which can be influenced in different directions by the direct **or** indirect effects of vibration. For example, tensing up muscles in the presence of mild vibration reduces the neuromuscular timing delays, thereby tending to increase the system bandwidth, but it may also result in higher gain and reduced stability margins, thereby tending to increase the resonances. Effects of the various vibration parameters on remnant are still unknown. Two of the more recent efforts to use modern manual control measurement and techniques are related to low altitude high speed flight (ref. 33), and to weapon aiming from a vibrating helicopter (ref. 34). The latter is still a current problem.

There is current interest in the design of "vibration isolation seats" designed to uncouple the pilot from his vibrating cockpit environment. As noted in figure **4,** this is but one of the *three* interfaces which must be considered in interfacing man-machine performance with the biodynamic environment, so much remains to be done in modeling and validating this interesting problem area. Research using an active vibration isolation seat designed by Barry Controls (ref. 35) is underway both at the 6570th AMRL and at NASA. *Complete* man-machine system models of the type described here are well suited to this problem area. Ideally, this work should be carried along in parallel with the experimental research, both to help in the experimental design, selection of measurements and data analysis, and to reveal concurrent technical advances which should accompany such seats (e.g., vibration-compensated displays and controls).

Steady-G Effects

One of the most studied biodynamic inputs is that of steady accelerations on various bodily functions. Various specialized studies have been done in the last two decades on the effective man-machine performance under steady g's (e.g., refs. 36 through 39). This line of research seemed to reach a plateau a few years ago and is only recently picking up speed again. The much more comprehensive models which are now available for describing the man-machine performance can guide the selection of tasks measurements, and data reduction analysis procedures (e.g., ref. 37 is a pioneering example). There is evidence that those involved in centrifuge research, many of whom are medical people, psychologists, or mechanical engineers, have recently begun to include modern man-machine control techniques in their research. This area urgently needs biodynamic modeling.

A most fascinating problem I wish to mention is that of using head-mounted sights under high-g maneuvering conditions. If any of you have tried to track a moving satellite with a pair of binoculars held against your head, you will understand what a frustrating problem this can be. (It's the remnant that blurs the image!) Now imagine doing this if your head and optics weighed **5** times as much, and you will have an idea of the problem of a pilot trying to track an enemy aircraft with a helmet-mounted magnifying sight during a **5** G_z turn. Some excellent design research has been done on the applications and design features for head-mounted sights (e.g., ref. **40).** Yet, to our knowledge, comprehensive models of the type described here for the ***combined*** system of target, sight, head and eye neuromuscular system, vehicle, and maneuver kinematics have not yet been applied. Here is a problem ideally suited to biodynamic man/machine analysis, and the payoff will be high in terms of problem areas uncovered and avoided, design parameters delineated, and experimental research guidelines exposed.

The last area noted in table **1** has been around the longest, yet has received the least research to date. This is the problem of spurious steering control motions of vehicles traversing rough terrain, or its counterpart **of** high-speed ships crossing rough waves. Although some Jeeps had problems from this cause, the advent of high-sensitivity, low-friction power steering makes modern vehicles particularly vulnerable. **A** suitable model for this phenomenon must include the vehicle pitch, roll, heave, and lateral dynamics (including the suspension effects), seat dynamics, torso effects and a limb-steering wheel model similar **to** that discussed previously herein. Small perturbation linearized analysis is appropriate for modeling surface-induced control motion, but the representation of the torso-limb-control ensemble remains a formidable task for future research. Fortunately, adequate facilities to validate the models presently exist in the form of pitch-roll heave motion simulators and transverse motion simulators at places such as NASA and the U.S. Army Tank and Automotive Command.

Concluding Remarks

In summary, I feel that the field of modeling man-machine control behavior in a biodynamic environment is an extremely fertile one, which is about to enter a new and fruitful era. It will have to draw heavily on the classical lumped-parameter biodynamic response models, especially in the representation of body, limb, head and eye coupling effects (e.g., refs. **30** and **41).** In turn, some of the more sophisticated feedback neuromuscular models and measurement techniques should be of value in biodynamic research, particularly where muscle tension (applied intentionally **or** unconsciously) has a large influence on the results.

A joint Systems Technology, Inc./USAF research program is currently in progress on the effects of vibration on manual control behavior and performance, under the technical direction of Captain D. Wilburn of the Bionics and Biodynamics Branch, 6570th Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base.

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