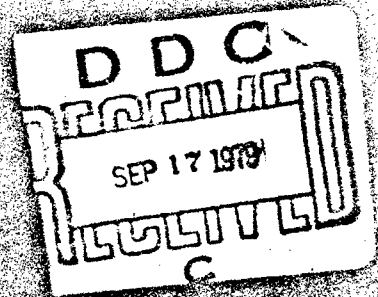
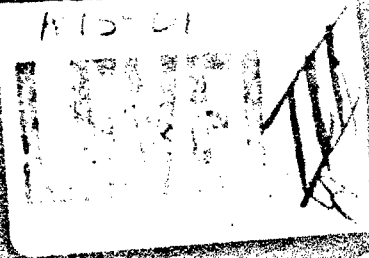


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SYSTEMS TECHNOLOGY, INC.



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Final Scientific Report No. 1037-1



MODELING BIODYNAMIC EFFECTS OF VIBRATION  
Fifth Year — Final Scientific Report

August 1979

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The biomechanical feedthrough of vertical and/or fore-aft vibration from a seat, to (and through) various parts of the torso, limbs, hands, and head, to a spring-restrained control stick has been modeled over a 5-year effort using prior Air Force and other data bases. This final report summarizes the project results and provides a User's Guide to BIODYN-78, an interactive, remote-access, digital computer program for exercising the model.		

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The model involves 77 postural and physiological parameters to define a broad range of seating/control/display arrangements from supine to erect. An internal routine automatically trims the Torso/Head/Limb system at the desired angles and computes linearized equations of motion, which are solved for their eigenvalues and resulting transfer functions using highly refined computing routines. In distinction from most past models, this model represents several degrees-of-freedom simultaneously, e.g., vertical and fore/aft shoulder motion, angular head-bobbing, constrained elbow motion, stick-grip-interface force, muscle forces, and stick angular motion, among many others. These features make the BIODYN-78 model well suited for: routine computations of biomechanical transmissibilities, (e.g., those required as inputs to other programs (PIVIB, USAM) for pilot/vehicle closed loop performance calculations), matching of test data, systematic analysis of variations in body parameters (e.g., to explore population extremes), optimization of control stick "feel" parameters (i.e., to analyze Pilot Induced Oscillations), or to compute control transients due to accelerations imposed on the pilot by maneuvers.

The fifth-year effort covered two objectives. The first objective of the FY 1978 program was to evolve a model for the effects of head vertical plane vibrations on eye and image motions; (as influenced by the vestibulo-ocular and fixation reflexes). This was met by the model detailed in the Fourth Interim Scientific Report and summarized in Appendix A\* herein.

The second objective was preparation of the User's Guide (included here as Appendix B†), and the formal demonstration of BIODYN-78 operation using a remote-access terminal in the Aerospace Medical Research Laboratory (at WPAFB, Ohio).

\* Progress in Measuring and Modeling the Effects of Low Frequency Vibration on Performance, Paper No. 232

† "User's Guide to BIODYN-78, An Interactive Computer Program for Modeling Biodynamic Feedthrough to a Pilot's Hands and Head, TR-1037-2

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## A. BACKGROUND

### 1. Scope

This final (fifth-year) report on the project briefly reviews the objectives and work covered in the prior four and one-half years, and describes in more detail the work done in the last half of the fifth year, i.e., May-December 1978. (The last Interim Scientific Report covered work into half of FY '78 because that offered a more logical reporting break point.) The main text describes the results and recommendations, while two appendices give more details:

- Appendix A — Contains a status report on the state-of-the-art in modeling biodynamic effects on aircrew manual-task performance (Ref. 1). It was an invited paper presented at the AGARD Aerospace Medical Panel Specialists Meeting, Paris, Nov. 1978.
- Appendix B — Includes a brief "User's Guide to BIODYN-78, An Interactive Computer Program for Modeling Biodynamic Feedthrough to a Pilot's Hands and Head" (Ref. 2).

### 2. Objectives

The various phases of this research program have the primary objective of developing analytical dynamic models of the biomechanical effects of vibration on a pilot's control behavior and performance, which could be used by aerospace system engineers and applied researchers in this field. The prior criteria set by AFOSR for such engineering models are that they should:

- a. Be based on a sound empirical data base.
- b. Capture the essential phenomena of interest to the users, without excessive restrictions or details.
- c. Be compatible with more detailed "microscopic" model results.
- d. Be put in a form usable by others; at, above, and below in the hierarchy of applications.

The prior four years' work attempted to meet the first three objectives, and this final phase meets the last objective.

The specific work items of the fifth year contract were to:

- Add a detailed model for the effects of vertical vibration on the head-eye motions (including both "fixation-reflex" loops and "vestibulo-ocular reflex" loops).
- Put the 1978 biomechanical model (prior to eye-motion effects) in a time-shared computer program accessible to any interested and qualified user, including output of biomechanical transfer functions required as inputs to the AMRL/BEN "PIVIB-76" tracking performance program.
- (Carried over from FY '77) on an informal basis, assist AMRL/BB with the analysis of the head-bobbing experiments of Dr. P. Werner for possible use in validating the BIODYN model at low frequencies.

Before describing the results of this year's work, we will present a brief overview of the approach used and the work performed during various phases of this project, to give a proper perspective to this final report.

### 3. Approach

Our approach is to use control systems theory and dynamic analysis techniques to assist in the measurement and modeling of pilot behavior (i.e., frequency responses, describing functions, dynamic feedthrough functions, etc.) and performance (e.g., rms errors, coherency to forcing functions, stability margins, visual impairment, etc.), under various types of vibration (sinusoidal, random, vertical, lateral, etc.). The empirical data base relies on prior published experimental data and on new experimental data provided by the 6770 AMRL/BB Branch at Wright-Patterson Air Force Base (under the overall direction of Dr. H. von Gierke).

The biomechanical models derived use lumped-parameter approximations to the dominant body/limb/head configurations likely to be encountered in pilots of aircraft, where an erect or semi-supine posture is present, often with some redundant constraints on motions, due to seat restraints, arm-rests, or control-stick gripping. The motions have been separated into a



lateral set (sway inputs) and a vertical-plane set (heave and surge inputs). Only the vertical-plane set has been carried beyond the basic modeling stage, because of its dominant importance for high-load-factor maneuvers and because of scarcity of data for the lateral set (Ref. 23).

Our models differ from the three most commonly used types of biomechanical models, which include:

- a. One-input, one-direction-output models such as the vertical input, vertical output whole-body vibration models used decades ago by Coermann (Ref. 3) expanded by von Gierke and Goldman (e.g., Ref. 4) and Payne (Ref. 5) and most recently extended to nonlinear effects of high  $G_z$  by Mertens (Ref. 6). These models are only intended to represent specific outputs in the same direction as the input (i.e., vertical shoulder or head motion outputs), and they cannot, in general, simultaneously represent multiple outputs (e.g., head angle, arm angle, shoulder heaving, etc.) or multiple inputs (e.g., heave and surge).
- b. Open-chain, planar, passive models such as the numerous body-trajectory models developed for crash research at Calspan and elsewhere (Refs. 7 and 8) and applied by Kaleps (Ref. 9). Such models and the efficient canonical-form equations used therein are excellent for integrating large, unimpeded motions but are not appropriate for constrained or high-frequency vibrational motions.
- c. Nonlinear, continuous-media, or detailed-joint models such as the spinal-column models of Ref. 10, and neck models of Ref. 11. These very detailed models of every joint, and nonlinear visco-elastic connecting elements are the "microscopic" models referred to earlier. They can represent all the possible modes, degrees of freedom and inputs, but are too expensive to exercise for most routine problems of pilot-vehicle optimization, where only the dominant modes need be modeled.

The present models are aimed at pilot-vehicle control interface problems in biodynamic environments (e.g., tracking an enemy fighter at high load-factor, wherein transonic wing-buffeting is shaking the aircraft randomly in the 1-20 Hz frequency range). To meet these needs our models have the following features, many of which differ from those preceding:

- a. "Homologous elements," capable of representing simultaneously the several degrees of freedom of the dominant modes for the: torso/arm/hand/stick and torso/neck/head/eye/display chains. These chains involve closed kinematic and neuromuscular loops, and their models can accept inputs in several degrees of freedom, simultaneously.
- b. All-posture, nonlinear kinematics (supine to seated); linearized about a given equilibrium posture (appropriate for the relatively small vibrational motions present).
- c. A physical equations-of-motion approach, in which a given (lumped) parameter appears only once in each equation. This greatly facilitates parameter matching when fitting a model to empirical data.
- d. Element masses are retained (not divided into the damping and compliance as is customary in modal equations), so that some mass elements can be finite or zero, without blowing up the equations.
- e. Extensive use of linearized transfer-function formats and factored roots is used to present the resulting dynamics in a form most useful to systems dynamicists (e.g., as frequencies and damping-ratios of various transfer function numerator and denominator factors).
- f. Provision of active adjustable, neuromuscular loops for the limb, including "filtered" spindle and golgi feedback effects. These influence the limb's apparent impedance to vibrational relative motions between torso and hand or head.

Further details of our approach are given in Appendix A (i.e., Ref. 1). Our approach to supplying the numerous coefficients involved is to use actual dimensions, masses, and rotary inertias whenever possible, based on cadaver data or, in some cases, on direct measurement (e.g., forearm weights for light and heavy test subjects). The compliance and damping coefficients are then selected by a combination of prior data and model fitting to match particular modes of empirical data.

To fit such complex models (over 20th order) to various experimental results, a special technique was developed, the "Multiloop Model Fitting Procedure," which is described in our Second Interim Scientific Report. (Ref. 15). Suffice it to say here that this technique allows the matrix expansion of a given transfer function numerator and denominator, in

terms of summed matrix-products with each parameter which is to be varied, thus permitting a far more efficient parameter optimization procedure. The frequency response vectors at fifteen frequencies in three different degrees-of-freedom are simultaneously fitted by a weighted-least-squares-criterion. Over the program, roughly one-quarter of our effort was spent in developing and using these model fitting procedures to refine and validate the models.

#### 4. Chronology and Reports Issued

Figure 1 shows the chronology of this AFOSR program, in relation to the related experimental work at the USAF Aerospace Medical Research Laboratory, Biodynamics Branch, at WPAFB (under Dr. von Gierke) and at the Office of Naval Research/Human Factors, Inc., Ship Motion Generator Facility, then at Goleta, CA (under cognizance of Dr. Arthur Callahan of ONR and the USN Surface Effect Ship Project). Table 1 summarizes some of the reports prepared under the Air Force vibration programs.

The first two years of this program covered a detailed reanalysis of systematic vertical and sway vibration experiments using sinusoidal vibrations. Simplified transmissibility models were developed for torso-limb for both vertical and sway inputs. Performance data from both sinusoidal and new quasi-random vertical vibration data were correlated and shown to be primarily dependent upon the "characteristic-frequency" of vibration (frequency of upward axis crossings of vertical acceleration) and its amplitude (Refs. 14 and 15).

The third year covered intensive development of the Multiloop Fitting Procedure, inclusion of a one-element head bobbing mode to the vertical model and addition of an arm-rest constraint on limb fore-aft sliding motion. Although it complicates the equations the last item is important because numerous pilot-vehicle situations involve an armrest (e.g., side-sticks and center-sticks with the arm rested on the knee). Extensive model fitting to the previous transmissibility data was performed, and needed refinements were revealed (e.g., a better head/neck model, Ref. 16).

1974-1975 1976 1977 1978 1979

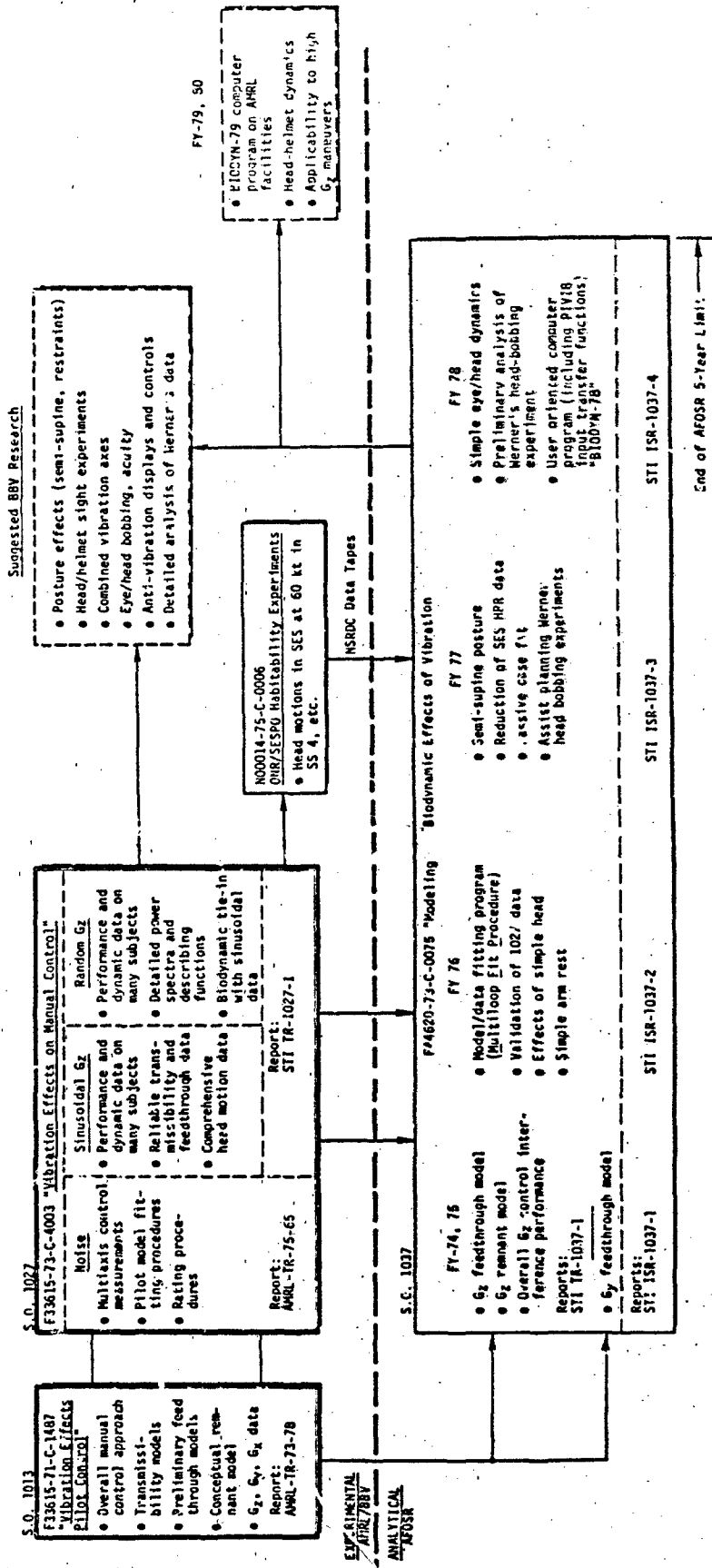


Figure 1. Chronology of Related STI Projects for AMRL/BBand AFOSR

TABLE 1. REPORTS SUBMITTED BY STI ON AIR FORCE  
VIBRATION PROGRAMS

AF WRL/BBV

Contract F44637-73-2-47

1. WRL-TR-73-78, Manual Control Performance and Dynamic Response During Sinusoidal Vibration, by R. W. Allen, H. R. Jex, and R. E. Magdaleno, Oct. 1973 (WRL-TR-73-78).
2. In WRL-TR-73-89, "Vibration Effects on Manual Control Performance," by R. W. Allen, H. R. Jex, and R. E. Magdaleno, in Proc. of 8th Ann. Conf. on Manual Control, 1972, pp. 319-342.

Contract F44637-73-2-403

3. WRL-TR-73-65, Effects of Wideband Auditory Noise on Manual Control Performance and Dynamic Response, by R. W. Allen, R. E. Magdaleno, and H. R. Jex, Mar. 1973 (WRL-TR-73-65; AD A018007).
4. STI TR-1037-1, Effects of Vertical Sinusoidal and Random Vibration on Manual Control Performance, by R. W. Allen, R. E. Magdaleno, and H. R. Jex, June 1974.

AFOSR/Life Sciences

Contract F44637-73-2-0075

5. "Vertical Vibration Interference on a Pitch Attitude Control Task," by R. E. Magdaleno, R. W. Allen, and H. R. Jex, Proc. of 10th Ann. Conf. on Manual Control, WPAFB, Apr. 1974, pp. 575-604.
6. STI TR-1037-1, Biodynamic Models for Vertical Vibration Interference on Pilot/Aircraft Pitch Control, by R. E. Magdaleno, R. W. Allen, and H. R. Jex, Sept. 1974.
7. STI ICR-1037-1, Modeling Biodynamic Effects of Vibration; First Year Interim Scientific Report, by R. E. Magdaleno and H. R. Jex, Sept. 1974.
8. AFOSR TR-1254TR, Modeling Biodynamic Effects of Vibration; Second Year Interim Scientific Report, by R. E. Magdaleno and R. W. Allen, July 1975 (AFOSR-TR-1254TR; AD A018011).
9. STI ICR-1037-3, Modeling Biodynamic Effects of Vibration; Third Year Interim Scientific Report, by H. R. Jex and R. E. Magdaleno, Oct. 1976.
10. "Biomechanical Models for Vibration Feedthrough to Hands and Head for a Semi-supine Pilot," by H. R. Jex and R. E. Magdaleno, in Aviation, Space, and Environmental Medicine, Vol. 49, No. 1, Jan. 1978, pp. 30-316.
11. STI WP-1037-5, A Linearized Model for Vibration Effects on the Eye Control System, by R. E. Magdaleno and H. R. Jex, Aug. 1975.
12. STI ICR-1037-4, Modeling Biodynamic Effects of Vibration; Fourth Year Interim Scientific Report, by H. R. Jex and R. E. Magdaleno, Sept. 1978.
13. STI P-232, "Progress in Measuring and Modeling the Effects of Low Frequency Vibration on Performance," by H. R. Jex and R. E. Magdaleno, presented at AGARD Aerospace Medical Panel Specialists' Meeting, Paris, France, Nov. 1976.
14. STI ICR-1037-5, Modeling Biodynamic Effects of Vibration, by H. R. Jex and R. E. Magdaleno, Aug. 1979.

The fourth year included developing the indicated passive neck/head model, and its validation by some experimental data. We assisted Dr. Peter Werner at AMRL/BB in planning a series of head-bobbing experiments on the WPAFB Vertical Accelerator facility to cover the scarce-data range of 0.5 to 5 Hz and 0.4 to 0.8 Gz. Meanwhile, some head-point-of-regard data taken as a byproduct of a U.S. Navy program (on the "habitability" of high-speed Surface Effect Ships bouncing over rough waters) became available. Through the cooperative efforts of AFOSR, ONR, and the David Taylor Naval Ship Research and Development Center (DTNSRDC), several digital tapes of head motion under various random input and postural conditions (resting, reading, tracking) were processed, providing a rich and reliable data base which has not yet been fully analyzed. The refined model will fit head-point-of-regard motions in the "passive" and "reading" cases but, as noted in last year's Interim Scientific Report (Fig. 3 of Ref. 19), there is evidence for active neuromuscular head control in the "head-tracking" postural condition. This remains for future work. During this fourth period we extended the equations to cover semisupine postures and axial (fore-aft) acceleration inputs.

It became apparent during this time that visual performance decrements due to vibration were dependent on the eye's image motions induced by head motions, and that the eye's sophisticated control system would require an equally sophisticated model to cope with the recently established motion properties of the "fixation-reflex" (more properly, a closed target-tracking loop) and the "vestibulo-ocular reflex" (inertial-motion compensation loop). This model was begun in the fourth year and finished during the first portion of the fifth year, so it was reported in last year's ISR. The eye-in-head model was developed for vertical angular motions of the head, but is also applicable to head yawing motions with suitably adjusted parameters. It seems to correlate well with some recent English data on visual acuity under vertical vibration, and offers a final link in the chain between biodynamic inputs to the body and decrements in visual performance. Further experimental data and pursuit of the implications of this model on the use of helmet-mounted-displays seems warranted. (See the discussion in last year's ISR, Ref. 19, and in Appendix A herein).

This summary brings us to the final half of the fifth and last year, which is reported on herein.

## B. WORK DURING FY 1978

### 1. Completion of Model for Vibration Effects on the Eye Control System

As noted above, the eye-control model begun in FY 1977 was finished during the first half of FY 1978 and was included as Appendix B of last year's summary report (Ref. 18, included in Ref. 19). An overview of that model and some key results is given herein in Appendix A (Ref. 1). Consequently, we will not describe it here. It is being submitted to an archival journal.

The state-of-art- survey paper included here as Appendix A was an invited presentation at the AGARD Acrospace Medical Panel Specialist's Meeting in Paris during November 1979. At the suggestion of Dr. von Gierke of AMRL/BB, it describes the approach and typical results for work on vibration effects done both by Systems Technology, Inc. (predominantly on biomechanical and visual performance modeling) and by Bolt, Beranek and Newman (predominantly on operator tracking performance).

During visits to some vibration laboratories in Europe subsequent to that presentation,\* the relevance of our biodynamic models to a number of AGARD-related experiments and problems was discussed:

- At DFVLR - Institute for Aviation Medicine (Bad Godesburg, West Germany). Drs. H. L. Vogt and H. Mertens were interested in reconciling their uni-directional vertical vibration model with the STI model. The appropriate combinations of STI and DFVLR parameters was discussed, and a further communication has been received from Dr. Mertens. If we can establish the proper relationships between these two models and parameters, then the STI model can use the extensive data of DFVLR on the covariation of various torso and limb compliances with steady  $G_z$  level to extend our model to simulate the rapid-onset of load factor. Such experiments are currently of great interest at AMRL/BB.
- Max Planck Institute for Agricultural Research (Bad Kreuznach, West Germany). Dr. H. Dupuis, who has had a significant role in establishing the ISO-Ride Quality Criteria, is doing work

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\*These visits were not made on AFOSR funds.

on the effects of the NATO Main Battle Tank vibrations on the gunner's perceptual problems. The gunner holds his head against a hard-padded rest to minimize whole-body vibration effects, but higher frequencies cause the eyeball to have rotary resonances with resulting image blur. Dr. Dupuis noted that the eye-control-resonance frequency and damping used in our eye-control model (estimated from earlier laboratory data on eye saccades) coincided closely with his recent experimental findings using a corneal-reflective TV tracking scheme. He was also interested in our posturally complete model for representing several degrees-of-freedom simultaneously, as an improvement over the one-direction models commonly used, and he supplied a number of useful references on limb and hand vibration effects.

- Krupp Hospital's Neurological Clinic (Essen, West Germany). Dr. Thomas H. Brandt is doing work for the NASA Space Shuttle Vestibular Experiment and in clinical evaluation of vestibular system deficiency. They were contemplating a device for creating sudden angular impulses to the head to check the operation of the vestibulo-ocular reflex before the fixation reflex could re-stabilize the line of sight. They had been having problems, which our model explained. Discussion of the model implications suggested an alternative angular vibration approach, with inputs in the frequency range which exhibits low sensitivity to fixation loop dynamics but high sensitivity to the vestibular loop cross-feeds. Development of this clinical application is recommended.
- RAF Institute of Aviation Medicine (Farnborough, England). Dr. Alan Benson's colleague Dr. Graham Barnes has done much work on measuring and modeling the vestibulo-ocular-reflex and nystagmus effects of rotary head motions (our model builds strongly on this work). He has offered to review Ref. 18, and to supply some more recent data on the effects of visual scene complexity on the fixation loop gain, specifically to help fill in a data-gap mentioned in our writeup.

At the separate RAE Human Engineering Division, under the direction of Mr. Geoff Allen, his colleague, G. F. Rowland agreed to supply some essential data on pilot seat-posture and dimensions missing from his detailed studies of head vertical motions as influenced by seating posture. Especially interesting are the "back-off-seat" posture which produced dramatic reductions in vertical head motions under vertical vibrations. If our model can "explain" these independent data, then a powerful validation and impetus to new applications will have been obtained. However, as of the end of this contract (December 1978) the information had not yet arrived.



These researchers would be interested in using the BIODYN model to help fit and codify their data, if it were available in a readily exercisable form. If this could be done on an information-exchange basis, then it would be to USAF's advantage to work out some arrangement for a time-shared-network version, by which USAF would gain the fitted data as part of a much broader, "fitted" data base at relatively little cost, while the users would gain the program's advantage at no software development cost. We will return to this suggestion, later.

## 2. Computerized Transmissibility Model — "BIODYN-1978"

### a. Objectives

As noted in the background section, one criterion of a mature math model is that it is in a form readily understandable and usable on the problems it is intended to solve. Some of the intended roles for this biomechanical interface model are as follows:

- To guide experimenters on the most useful locations and frequencies for vibration measurements, and to fit data from past and current experiments.
- In a case-by-case "user-interactive" mode by R and D lab personnel to develop a particular model posture or parameter ensemble, or in a "batch-mode" to systematically map out a range of vibration effects.
- To be routinely used by aerospace development engineers in solving practical design problems such as Pilot Induced Oscillations (often due to limb-stick "bobweight" effects); posture effects from High-Acceleration-Cockpit (HAC) design alternatives (e.g. semisupine seating, head or torso support compliance); stick location and arm-rest effects, etc.
- To permit flight control system engineers to optimize combined vehicle/aircrew ride-qualities and visual performance effects, through use of vibration filters, dampers, and suppressors (a la B-1); or for display blur minimization through choice of viewing distance, angle or filtering, etc.

- To provide the biomechanical seat-to-hand and seat-to-head transmissibility and limb/stick impedance transfer functions required by the AMRL/BBN Pilot VIBration (PIVIB) tracking performance program (Ref. 20). Such biomechanical functions must be supplied by the user of PIVIB, and are a natural application of our present model.

The time-shared computerized program we have put together to accomplish these objectives is called "BIODYN-78"; the number specifying the model year or "vintage" of the model, since additions are contemplated in the future. For example, we plan to include the head-eye model, described earlier, in the BIODYN-79 version.

b. Approach

The BIODYN-78 model includes a chain of interacting parallel and serial second-order (mass/spring/damper) elements, with complex neural and force feedbacks. Details were given in earlier reports and in Ref. 17, and the mechanical arrangement is shown in Fig. 2 of the Appendix B herein (Ref. 2). Figure 2, reproduced from Ref. 1, summarizes the functional blocks of BIODYN-78 and denotes the number of parameters involved in each. It also shows the relationship of BIODYN-78 to the PIVIB and possible future BIODYN versions.

The equations-of-motion for BIODYN-78 have been written in a "second order element" matrix form with generalized (all angle) parameters. Any particular set of postural, neuromuscular, stick and display dimensions are then input as a file to the program. The program internally sets up the general equations and evaluates the linearized coefficients for perturbations about the equilibrium posture. The program then evaluates the desired transfer functions (from a "CHOICES" file) via Cramer's rule yielding a denominator and various numerators of rather high order — often reaching 20th order.

Fairly sophisticated factorization routines, evolved during two decades of factoring aircraft/control system dynamics equations, are used to give the predominantly second-order poles and zeroes, many of which are lightly damped. Although these routines are considered proprietary

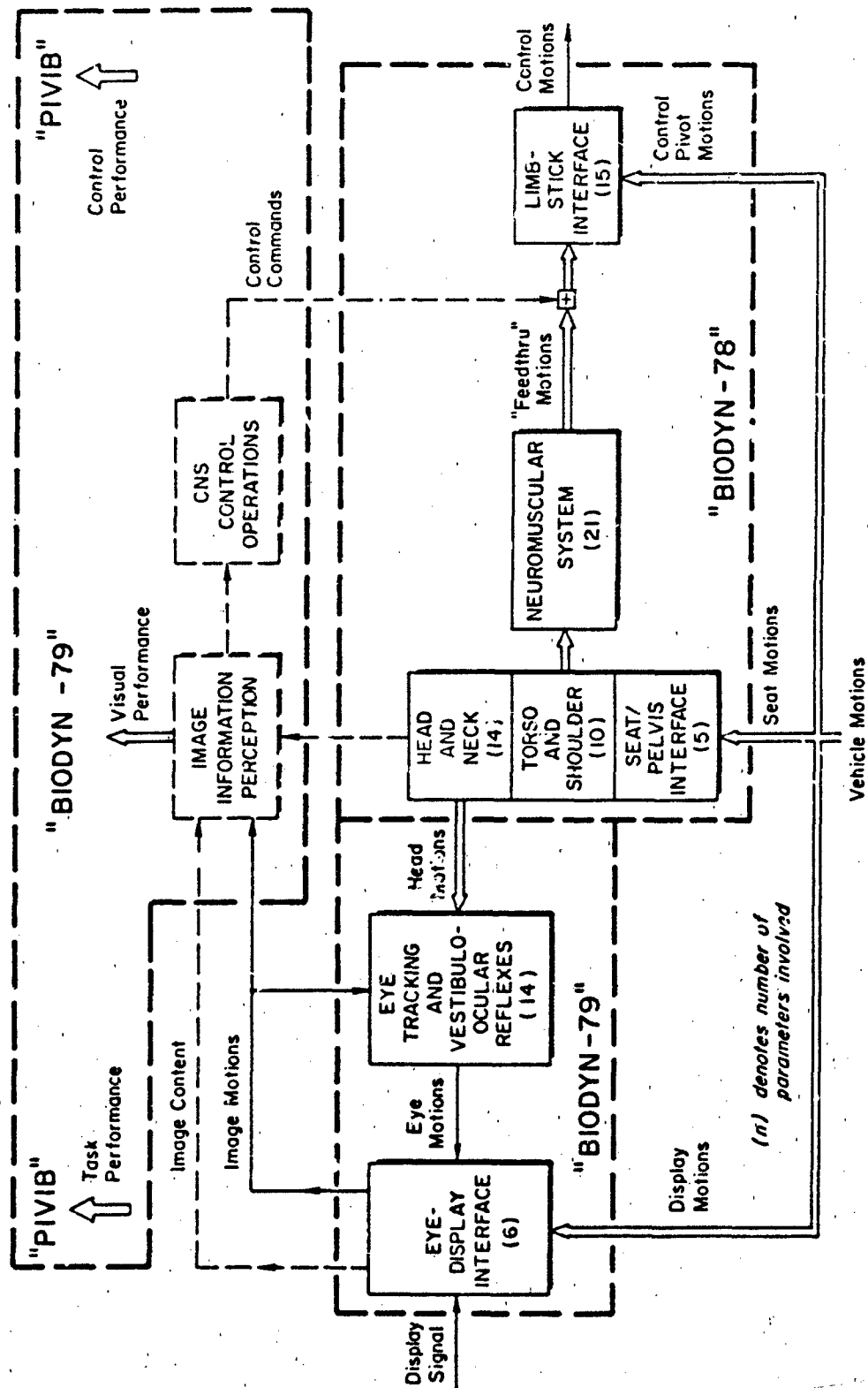


Figure 2. Overview of Functional Elements in BIODYN-78, BIODYN-79 and PIVIB Programs

STI developments, they have been incorporated into the accessible BIODYN-78 program with minimal documentation.

The primary outputs of BIODYN-78 are the factored transfer functions between the selected input (vertical or fore-aft platform acceleration or stick force) and any of the 36-odd equation-of-motion variables, such as head-bobbing angle, stick motion (control transmissibility), shoulder motion, muscle force, grip force, etc.

To maximize the ease of accessing and using BIODYN-78 we have put it into a commercial remote-time-shared computer network (Tymshare Inc.), which is readily accessible anywhere in the USA and in certain parts of Europe (via satellite).

The use of Tymshare for BIODYN-78 has several advantages:

- It makes BIODYN-78 potentially available to any user with a low speed terminal (10 or 30 cps) and acoustic coupler, who has or can get a Tymshare-Inc./STI operating agreement. Simplified procedures for accessing BIODYN are being worked on (write the authors for updated information).
- Tymshare's powerful EDITOR is available for modifying existing files or creating new Input Files of parameters. Excellent User's manuals are available for using Tymshare in the simplest possible ways, such that a non-programmer can easily operate the program.
- Costs of re-writing and documenting our extensive Tymshare-oriented software were minimized, as none of this is necessary to use BIODYN-78.

Although BIODYN-78 is currently resident in the Tymshare Inc. network for the reasons given above, it has recently been adapted to, and test run on Control Data Corporation's CDC time-shared network. For the same inputs identical outputs resulted.

Running times are comparable for Tymshares PDP-10 or CDC's CYBER 175. The main advantage in using Tymshare Inc. as the residence for BIODYN-78 is the ready availability, therein, of STI's Unified Servo Analysis program (Ref. 21) for manipulating and plotting the results.

c. Overview of Procedures

A simplified flow diagram for the procedures used in applying BIODYN-78 is given in Fig. 3. The User accesses Tymshare, Inc. (with suitable passwords, etc.) and asks for one of the already filed sets of parameters for various postures and situations as listed in the User's Guide Catalog; or he can create new ones from scratch. If some of the parameters need to be changed, he uses Tymshare's EDITOR to change the appropriate numbers on given lines of the selected INPUT File (and renames it accordingly), or he can use the selected set without modification. This process could take from one minute to one hour depending on the number of parameters to be changed and checked.

The user then identifies the desired transfer functions via a "CHOICES" file wherein each desired output/input vibration direction is listed. This process takes from 1-10 minutes depending on the number of new choices. For details see the User's Guide (Appendix B).

The user then activates the program by typing "GO BIODYN", and within seconds the equations of motion are solved for the desired transfer functions and the results are then printed. Selected output files, so identified in the CHOICES File, can be saved for later plotting or recall. From "GO" to printout often takes less time than it did to read this paragraph. This computational speed makes it feasible for a user to sit at a terminal and iteratively alter the INPUT and CHOICE files to zero-in on the characteristics of a desired biodynamic transfer function or mode.

The outputs can be easily selected to provide any of the several transmissibility or impedance transfer functions called for by the PIVIB pilot-vibration performance program, mentioned earlier.

For further manipulation of the resulting transfer functions, such as frequency response (Bode) plots, calculating rms output in response to an input spectra, etc., the output files can be readily accessed by the user's (or other Tymshare-resident) analysis programs. A typical set is the STI Unified Servo Analysis Method (USAM) programs which permit a variety of systems computations and plots for multiloop pilot-vehicle systems of this type (Ref. 21). Although such extent programs are not an intrinsic part

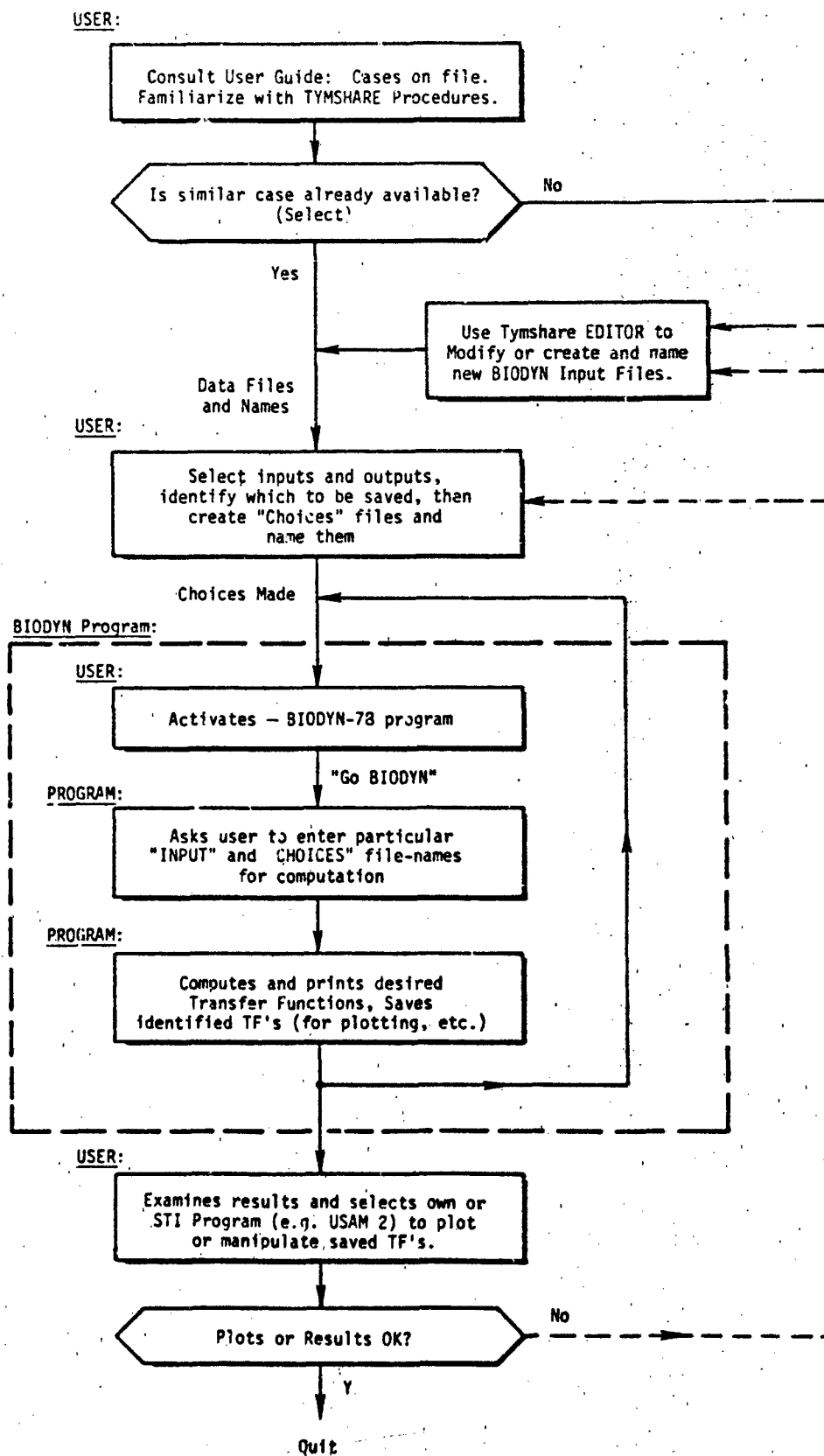


Figure 3. Procedural Flow in Using BIODYN-78

of BIODYN-78, the BIODYN output files can be easily transferred to them in the Tymshare system.

A more detailed "User's Guide to BIODYN-78" has been prepared, and it is included herein as Appendix B (Ref. 2). This is a brief guide for the ordinary user of BIODYN, who is somewhat knowledgeable in dynamics, but it is not intended for those interested in adapting BIODYN to their own computers or in modifying it. For background in operating the Tymshare programs in general, we recommend the potential user read the basic Tymshare XEXEC Manual (Ref. 22), as well as the BIODYN 78 User's Guide (Ref. 2). Given a valid Tymshare/STI access agreement, the typical aircraft engineer user can be getting useful answers to biodynamic interface problems within a few hours.

d. Formal Demonstration of Program

To demonstrate the simplicity of using BIODYN-78, a demonstration was given on 16 March 1979 at AMRL/EM (WPAFB, Ohio), where a suitable terminal/printer and acoustic coupler were readily available. The demonstration was attended by several persons from AMRL/BB, and a few from AFFDL/FGC (who are interested in using BIODYN for Pilot Induced oscillation problems). The attendees were allowed to suggest changes in parameters which might be of interest to them, and these were rapidly computed, printed out and plotted via a simple typewriter plotting routine which is part of STI's USAM program (Ref. 21).

Examples typical of the demonstrated cases are given in Figs. 4 and 5. Figure 4 shows the terminal printout for the standard test case, which is that used in Ref. 17 and is explained in detail in Appendix B (Ref. 2). Here, the user has selected a measure of head-bobbing; the head angular acceleration in pitch ( $\ddot{\theta}$ , rad/s<sup>2</sup>) in response to vertical acceleration of the platform ( $a_{zp}$ , m/s<sup>2</sup>). The resulting transfer function factor files are printed out below and are saved for later plotting (note: frequencies are in rad/sec). Figure 5 shows the "quick-look terminal Bode plot" of this transfer wherein the proximity of the "head-bobbing" and "torso surge" modes at 28-30 rad/s ( $\approx$  5 Hz) is apparent. This plot is not currently part of BIODYN-78 per se but is available on Tymshare through STI's Unified Servo Analysis Method (Ref. 21). The time required to obtain these printouts and plot was about 10 min.

-TYPE B.19

List INPUT file

```

STIFF STICK
1.372 .29 .44 .0120 40.
1.017 .305 .5 .0152 145.
.31 2. 13900. .557805E-04 .01 .61 13900. 1.
14. 1290.08 29585.27
2. 1. 80. 40. 2.43123 104.39969 1. 71519. 0.
5. .0909 0. 0. .020437003 .09090909 .08988764
.8 16. 0. .5 .05555555 0. 0. 1.
18. .15 .8 10. 16.75 500.
4.34 .3 .039 5. .00 1. .0 70. 0.
13. .3 5. .75
0. .1 0. -20. .25 50. .05 -30.

```

NOTE: User entries are  
underlined

-TYPE C.TMP

List CHOICES file

```

DTH/DZP
XXX
C /AZP

```

-GO BIODYN

Activate BIODYN

ENTER INPUT FILE NAME: B.19

Program prompts  
for file names

ENTER CHOICES FILE NAME: C.TMP

11-Jun-79 21:42

CASE: STIFF STICK

Case Identifier

DENOMINATOR:

TRANSFER FUNCTION COMPONENTS:

```

.27577E-17
( 16.593 ) ( 58.788 ) ( 97.341 ) ( 282.17 )
( 357.45 )
(( .26496 , 10.914 , 2.8917 , 10.524 ))
(( .20252 , 12.943 , 2.6213 , 12.675 ))
(( .35427 , 26.761 , 9.4806 , 25.025 ))
(( .15112 , 29.611 , 4.4747 , 29.270 ))
(( .85762 , 32.953 , 28.261 , 16.947 ))
(( .19124 , 57.483 , 10.993 , 56.422 ))
< .11873E+10 >

```

High Frequency gain  
(Denominator)

First-order poles

Second-order poles  
( $\zeta, \omega, \zeta\omega, \omega\sqrt{1-\zeta^2}$ )

Low frequency gain  
(Denominator)

NUMERATOR: DTH/DZP FILE NAME? DTH.TMP  
NEW FILE

Program prompts for  
file name

```

-.12319E-18
( .00000 ) ( .00000 ) ( 16.593 ) ( 18.284 )
( 95.827 ) ( 232.81 ) ( 498.67 )
(( .45587 , 10.396 , 4.7392 , 9.2528 ))
(( .97554E-01 , 16.243 , 1.5806 , 16.125 ))
(( .84071 , 33.835 , 2.4445 , 18.321 ))
(( .23595 , 51.815 , 12.226 , 50.352 ))
(( -.26361 , 284.74 , -75.060 , 274.66 ))
< -.29394E+67 >

```

High frequency gain  
(Numerator)

First-order zeros

(Second-order zeros)

Low frequency gain  
(Numerator)

NUMERATOR: C /AZP

```

.38029E-10
( 11.000 ) ( 14.817 ) ( 22.250 ) ( 23.472 )
( -38.117 ) ( 100.00 )
(( .19965 , 12.356 , 2.4668 , 12.107 ))
(( .85427 , 17.818 , 15.222 , 9.2626 ))
(( .14663 , 28.904 , 4.2381 , 28.591 ))
(( .97001 , 107.05 , 103.84 , 26.020 ))
< -.57327E+10 >

```

Similar to  
above

TRU = 37.02 11-Jun-79 21:43

EXIT

Figure 4. Typical BJODYN-78 Computer Printout  
for Example Case



WHAT NOW ? FIN } User entries are underlined:  
FILE NAME ? DTH.TMP } Selects file-name  
for plotting  
WHAT NOW ? BPL } Requests "Bode-Plot"  
ENTER WO WF: 1.,100. } and sets frequency range

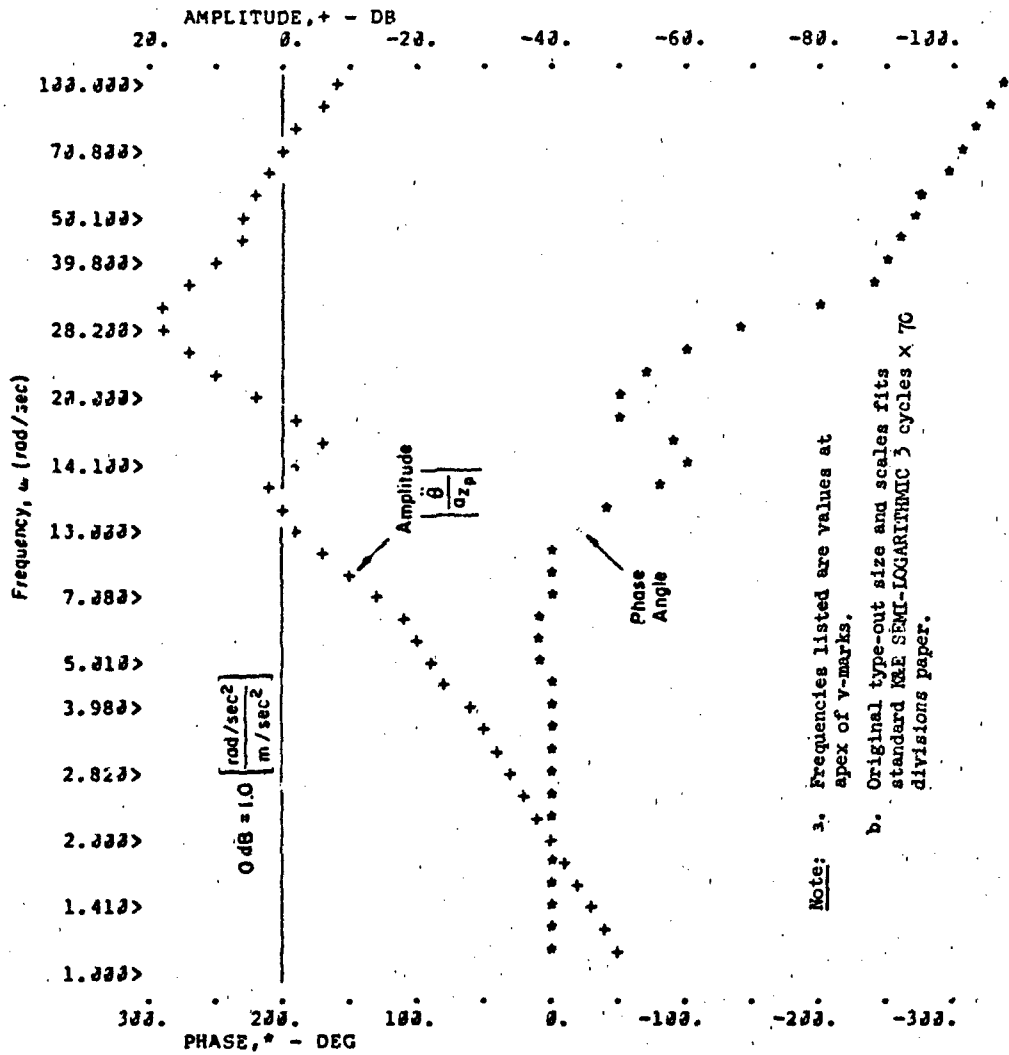


Figure 5. Typical USAM2 Terminal Bode Plot for Check Case

The formal demonstration and the attached User's Guide (Appendix B) completes the primary development of our biomechanical model for feed-through of vibrations to a pilot's hands and head.

### C. CONCLUSIONS

Through the use of modern computer techniques and closed-loop neuromuscular models, the biomechanical feedthrough of seat vibration of the various parts of the torso, head, arm and hands (on a restrained control stick) has been fairly accurately and efficiently modeled.

The situation requires a model having 80-odd postural and physiological parameters to define properly the general case of vertical and/or fore-aft vibrations. An internal routine automatically trims the Torso/Head/Limb system at the desired angles and computes linearized equations, which are solved for their eigenvalues and resulting transfer functions in seconds. In distinction from most past models, this model represents simultaneously several degrees-of-freedom e.g., vertical shoulder motion, angular head-bobbing motion, constrained elbow motion, stick-grip-interface force, and stick angular motion, among many others. These features make the BIODYN-78 model well suited for: routine computations of biomechanical transmissibilities, (e.g. those required as inputs to the PIVIB Program of Ref. 20), matching of test data, systematic analysis of variations in body parameters (e.g. to explore population extremes), optimization of control stick "feel" parameters (i.e., to understand or avoid Pilot Induced Oscillation), or to compute control transients due to accelerations imposed on the pilot by external forces.

Table 2 compares the final results reported here, as well as in prior Interim Scientific Reports, with the criteria imposed on page 1.

This fifth-year effort was focused on the last objective. The User's Guide (included here as Appendix B), and the formal demonstration of BIODYN-78 operation using a remote-access terminal in the Aerospace Medical Research Laboratory (at WPAFB, Ohio), completely meet that objective. The other objective of the FY 1978 program was to evolve a model for the effects

TABLE 2. ASSESSMENT AGAINST AFOSR CRITERIA FOR ENGINEERING MODELS

<u>CRITERION</u>	<u>ASSESSMENT</u>
a. Based on sound empirical data	<ul style="list-style-type: none"> <li>● Model has been fit to several comprehensive sets of quasi-random vibration data.</li> </ul>
b. Capture essential phenomena of interest to users, without excessive restrictions or details.	<ul style="list-style-type: none"> <li>● Can cope with all likely pilot postures, including supine.</li> <li>● Can handle problems of various kinds of stick, arm rests, torso restraints (linearized).</li> <li>● Shows common resonant body modes seen in several sets of wideband data (0.5 to 20 Hz).</li> </ul>
c. Compatible with more detailed physiological models.	<ul style="list-style-type: none"> <li>● Shows dominant modes at limbs, shoulder and head/neck, but lacks detail for rib-cage, visceral and pelvic motions.</li> <li>● Needs comparison against more recent detailed models of Belytschko, Kaleps, etc.</li> </ul>
d. Put in form usable by others.	<ul style="list-style-type: none"> <li>● Is now in a national time-shared computer service, accessible by standard remote telephone terminals.</li> <li>● Users Guide and test case available to any potential user.</li> <li>● Access procedures need to be made more readily available to general users.</li> </ul>

of head vertical plane vibrations on eye and image motions; (as influenced by the vestibulo-ocular and fixation reflexes). This was met by the model detailed in the previous ISR (Ref. 19) and summarized in Appendix A here.

In summary, nearly all of the goals of this 5-year program have been met, with some re-direction away from detailed lateral vibration models (ours remains the simple one we presented in Ref. 23) towards the more detailed head and eye motions, noted above. This latter work has not yet been incorporated into the computerized BIODYN-78 program. Since it seems to explain some of the image motion and visual acuity differences between vibrating targets and vibrating heads, (see Appendix A) this link promises to complete the chain of dynamic elements between seat vibration inputs and visual performance decrements, including head-mounted-displays.

#### D. RECOMMENDATIONS

Even though the BIODYN-78 model is now in a readily usable, computerized form; complete with a User's Guide; some further improvements are needed:

- a. The ease of access of general users to the Tymshare resident BIODYN-78 program must be improved. At present, a user must contact STI for a special users agreement (at no profit to STI), in order to gain access to the program. Having STI assist new users in applying BIODYN-78 is fine, but the procedure is awkward for military facilities and some large companies with their own in-house computer facilities. We recommend that some means be worked out for Tymshare support of BIODYN, possibly with an optional STI advisory role.
- b. The present program only prints out or files the requested transfer functions in pole-zero numerical format. The addition of a quick-look computer Bode-plotting routine (such as demonstrated herein via our USAM program), would greatly facilitate the use of BIODYN in routine experimental and engineering development projects.
- c. The head-eye model should be incorporated into BIODYN for use in analyzing aircrew visual performance under vibration.
- d. Efforts to publicize the availability of BIODYN-78 to interested researchers and development engineers should be undertaken, to assure that the whole program reaches its potential usefulness to the aerospace and clinical community.

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APPENDIX A

PROGRESS IN MEASURING AND MODELING THE EFFECTS OF  
LOW FREQUENCY VIBRATION ON PERFORMANCE

SYSTEMS TECHNOLOGY, INC.

13768 SOUTH HAWTHORNE BOULEVARD • HAWTHORNE, CALIFORNIA 90250 • PHONE (213) 679-2281

Paper No. 232

PROGRESS IN MEASURING AND MODELING THE EFFECTS OF  
LOW FREQUENCY VIBRATION ON PERFORMANCE

Henry R. Jex  
Raymond E. Magdaleno

Presented at the AGARD Aerospace  
Medical Panel Specialist Meeting  
Paris, France  
November 7-10, 1978



PROGRESS IN MEASURING AND MODELING THE EFFECTS OF  
LOW FREQUENCY VIBRATION ON PERFORMANCE

by  
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SUMMARY

Several facets of the comprehensive biodynamic modeling program presented at the AGARD Aerospace Medical Panel Meeting at Oslo, 1974, have been successfully completed and are reported here. The objectives and approach (an ensemble of physical models of just-adequate complexity, with adjustable or adaptive parameters) are first reviewed.

The development of a variety of lumped parameter models to explain and codify the known data on low-frequency vibration effects and to predict likely effects in new situations has been brought to a useful level. These are described with presentations of typical validation data:

- a) BIODYN-78, a user-interactive computer program which is capable of modeling the biomechanical properties of a variety of pilot/crewman posture and control situations in which active neuromuscular systems are involved.
- b) PIVIB, a user-instructed batch program (developed by others) for modeling effects of vibration on tracking performance, and which requires information supplied by BIODYN-78 in its use.

The relationship and applications of these and other related new models are discussed with respect to their development status and potential applications.

Specific recommendations are made for more refined experimental data (e.g., simultaneous accelerations on various body locations and better postural and dynamic mode shapes via cinematography, etc.) and interface compatibility among various models.

OBJECTIVES

This is a progress report on recent work and achievements in measuring and modeling the effects of low-frequency vibration (0.2-20 Hz) on the performance (visual, tracking, etc.) of vehicular crewman. Although the main research relates to pilots and operators of equipment in aircraft, there are examples from high-speed ships, and the resulting technology certainly applies to land vehicles.

Typical problems for which these models are being developed are shown in Fig. 1. Vibration effects on performance usually occur at the operator interfaces with his environment, such as: the seating/restraint system (and any isolation features such as cushions or springs); displays (whether or not they

EYE/HEAD/HELMET DYNAMICS:

- Analyze vibration interference with vision
- Biodynamic design of helmet-mounted displays under high  $G_z$  and buffet

DISPLAYS:

- Analyze display mounting, isolation, stabilization concepts
- Analyze effects of size, viewing distance, orientation, etc.

CONTROLS/MOTOR COORDINATION:

- Analyze competing control configurations (e.g., fly-by-wire vs. center stick) for (a) effects of rough air excited bending modes for large aircraft, or (b) high  $g$  buffet for fighters
- Design vibration resistant controls

RESTRAINT/SEATING AND ISOLATION SYSTEMS:

- Analyze performance consequences of competing restraints and cushions
- Design new restraint and isolation systems
- Analyze performance effects of various postural situations (i.e., supine seating)
- Ride quality implications on various tests and locations in aircraft

OVERALL

- Optimize among various tradeoffs prior to testing, also simulations to operational situations
- Predict pilot control/vehicle motion interactions (e.g., pilot induced oscillations)

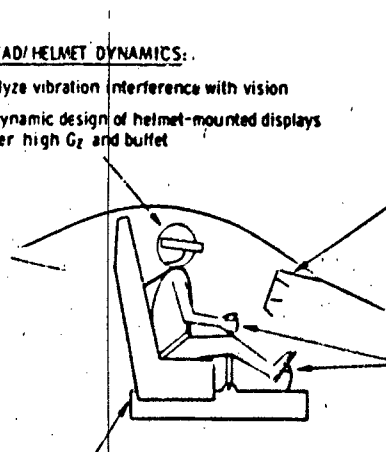


Figure 1. Problem Areas of Interest

move with the seat or cockpit); controls (especially tracking control sticks or devices held and aimed by the operator); eye/head motions as they affect the perceived image motions (and effect of helmets and helmet-mounted sights). Finally, there are the overall tradeoffs between better seating and restraints versus better controls versus better displays (e.g., vibration-compensated displays, head-mounted displays, etc.). For such problems as these, one needs "uniformly valid first approximation" models, which can capture the essential features of a variety of vibration interface problems in a computationally efficient manner. That is the overall goal of this research.

## APPROACH

### Overall

A more detailed discussion of these problems and possible approaches toward solving them was presented at the Aerospace Medical Panel Specialist's on "Vibration and Combined Stresses in Advanced Systems," at Oslo, Norway, in April 1974 (Ref. 1). After reviewing the relevant definitions and measures of task performance, behavior, stresses, and strains, that paper considered three approaches:

- A purely experimental investigation of all possible situations (which would never be even partially completed).
- An ad hoc simulation of each problem as it arose (which gives relevant data for the case at hand but cannot be extrapolated to new situations).
- A comprehensive, empirically based theory (which requires carefully coordinated cycles of modeling, validation/refinement experiments, and the development of a user-oriented "catalog" of models and data that can be extrapolated to new situations even before a proper ad hoc simulation can be developed).

The comprehensive theory approach was recommended in Ref. 1 for a number of reasons, given therein, and the USAF Office of Scientific Research and Aerospace Medical Research Laboratory have sponsored the majority of the program. This paper reports progress as of mid 1978, at which time the first really usable, albeit embryonic models are available.

### Scope and Status

As noted above and discussed in Refs. 1-3, the basic approach is to use simplified physical models with dynamic elements analogous to those of the body/limb/head/eye system and their interfaces with the seat, display, and controls. The complete three-dimensional assemblage of bones, muscles, and organs, plus the complex neuromuscular control system, is far too complex to model efficiently enough for practical solutions of the problems described, and such complexity is not really needed. Instead, only those elements required for a likely class of problems, such as those of Fig. 1, are employed.

Most of this work to date has emphasized vertical and fore/aft vibration (e.g., Refs. 4-6), with some work on lateral vibration (e.g., Refs. 2 and 7) and very limited work on combined vibrations (e.g., Ref. 8).

Figure 2 shows the fundamental model structure used for evaluating biodynamic interference with visual and control tasks, adapted from Ref. 1. The main blocks delineate the "human operator," "controlled element" (which is also the source of vibrations via the disturbance inputs), and "manipulated object" (such as a book, aimed device, or simply a visually fixated external object). The main interfaces at the display, seat, and controls are also shown. Within each major block are the main elements we have modeled, e.g., seat-interface, body, head, eyes, limb, etc. We will expand on these later.

The checks (✓) or question marks (?) beside each element denote the status of its math model. The earlier (1974) status is shown dashed to reveal where progress has been made. There are few "?" left, implying that the models are approaching a new level of maturity in which they are ready for more widespread validation, refinement, and application.

The selection of specific models from the available ensemble starts with Fig. 2, using its blocks to define the task and its measures of performance; the controlled element with its dynamic elements including structural modes, seat-response properties, and control excitation of vehicle motions; the forcing functions (commands to be followed and disturbances to be suppressed or which produce vibration); the interface properties such as display distances and sizes; control stick "feel" properties; etc. The specification of all the dynamic elements of Fig. 2 is essential to any application and requires a fairly complex model structure and an input-descriptor file containing several dozen parameters.

The next step is the calculation of the biodynamic "feedthrough" or transmissibility to the seat, head, eyes, and image motions (for visual performance effects) and/or to limb and control stick (for manual control performance). All of the models used here have special features to allow the redundant and active neuromuscular forces due to body/limb coupling with the control sticks or arm rests to be efficiently modeled. The manual control situation precludes the use of the passive "open chain" anthropomorphic models now highly developed for crash research (e.g., Ref. 9).

The model and user's program we have been developing to compute these biomechanical transmissibilities is called "BIODYN-78" (BIODYNamics, and the number denotes the model year), and its scope and role are depicted on Fig. 3, which is an expansion of the center region of Fig. 2 (Ref. 10). Even for relatively simple situations involving tracking a CRT display with a spring-restrained control stick, there are numerous biodynamic elements in the causal chain, and dozens more parameters must be specified to define the operator's size, posture, tenseness (neuromuscular gains), eye-to-display locations, etc. As noted by the numbers in parentheses in Fig. 3, there are 7 seat/pelvis/interface parameters (such as seat force gradient, damping, lower body effective mass, compliance and damping), 10 torso parameters,

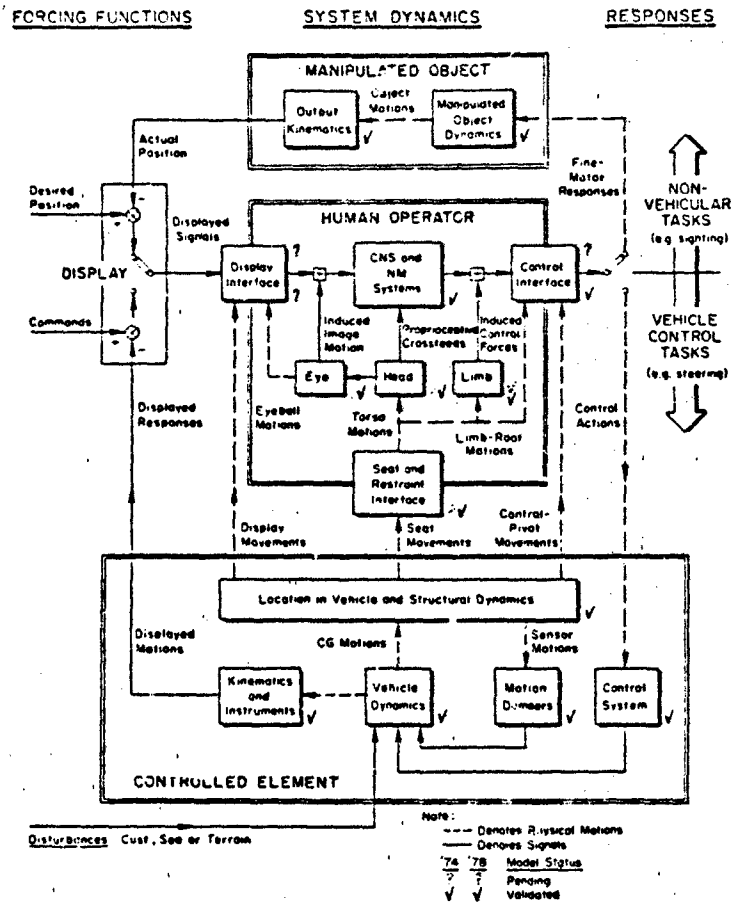


Figure 2. Overall Model Structure for Evaluating Biodynamic Interference

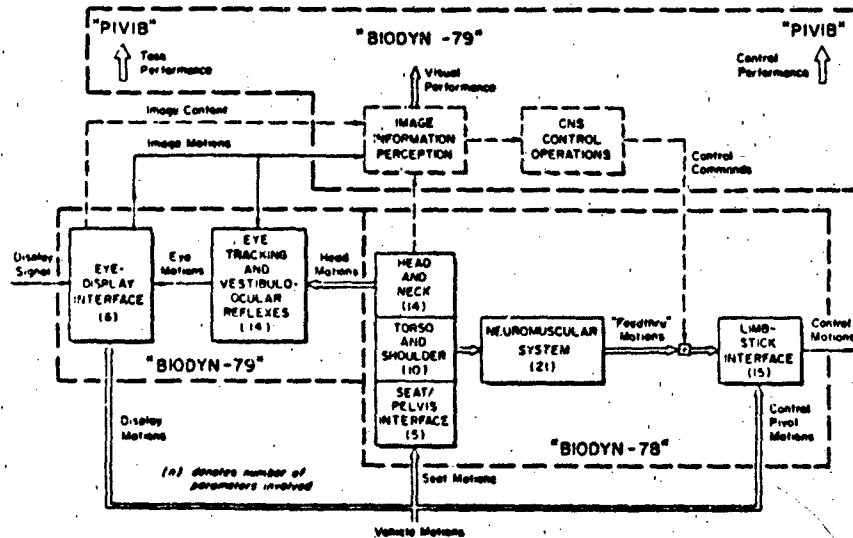


Figure 3. Modeling of Operator Elements and Interfaces

21 neuromuscular (NM) items, 15 limb/stick interface or arm rest parameters, and 14 head/neck/shoulder parameters. These are in the 1978 version, which computes limb/stick transmissibility or force impedance as well as head-point-of-regard and translation, shoulder motions, etc., as illustrated in Fig. 4. Only the main body links are shown in Fig. 4a. The basic equations of motion are nonlinear in the postural and neuromuscular variables, but the equations are automatically trimmed about the average operating point and linearized equations are used to compute the vibration effects.

A first cut at a model for vibration-induced image motions has been made (Ref. 11) which takes as inputs the head rotations and translations and accounts for the vestibulo-ocular reflex (which roughly stabilizes the eye inertially up to about 6-8 Hz) and the fixation reflex (which can follow display image motions up to about 1-2 Hz). It is denoted on Fig. 5 as "BIODYN-79" in anticipation of its inclusion in the current BIODYN-78 computer program, and is illustrated in Fig. 5. About 14 eye/head quantities are specified along with five or six display interface parameters. (For details see Ref. 11.) We also plan to include the additional effects of a helmet and helmet-mounted displays or sights in the 1979 version.

As the third step the computed vibration-induced motions of the head, stick, shoulder, and points of regard (at the display) of the head and eye are used to determine the visual task performance decrements via empirical relationships between these motions and perceptual or motor performance (e.g., detection errors, tracking "indifference threshold," etc.). The connection between the net performance of various tasks and the computed (or actual limb or head) motions remains the weakest link in the chain from vibration input to measured task performance.

Further systematic experiments of the type originally performed by Drazin (Ref. 12) and lately by Benson and Barnes (Refs. 13 and 14) need to be performed to provide a data base for this final link in the visual performance chain.

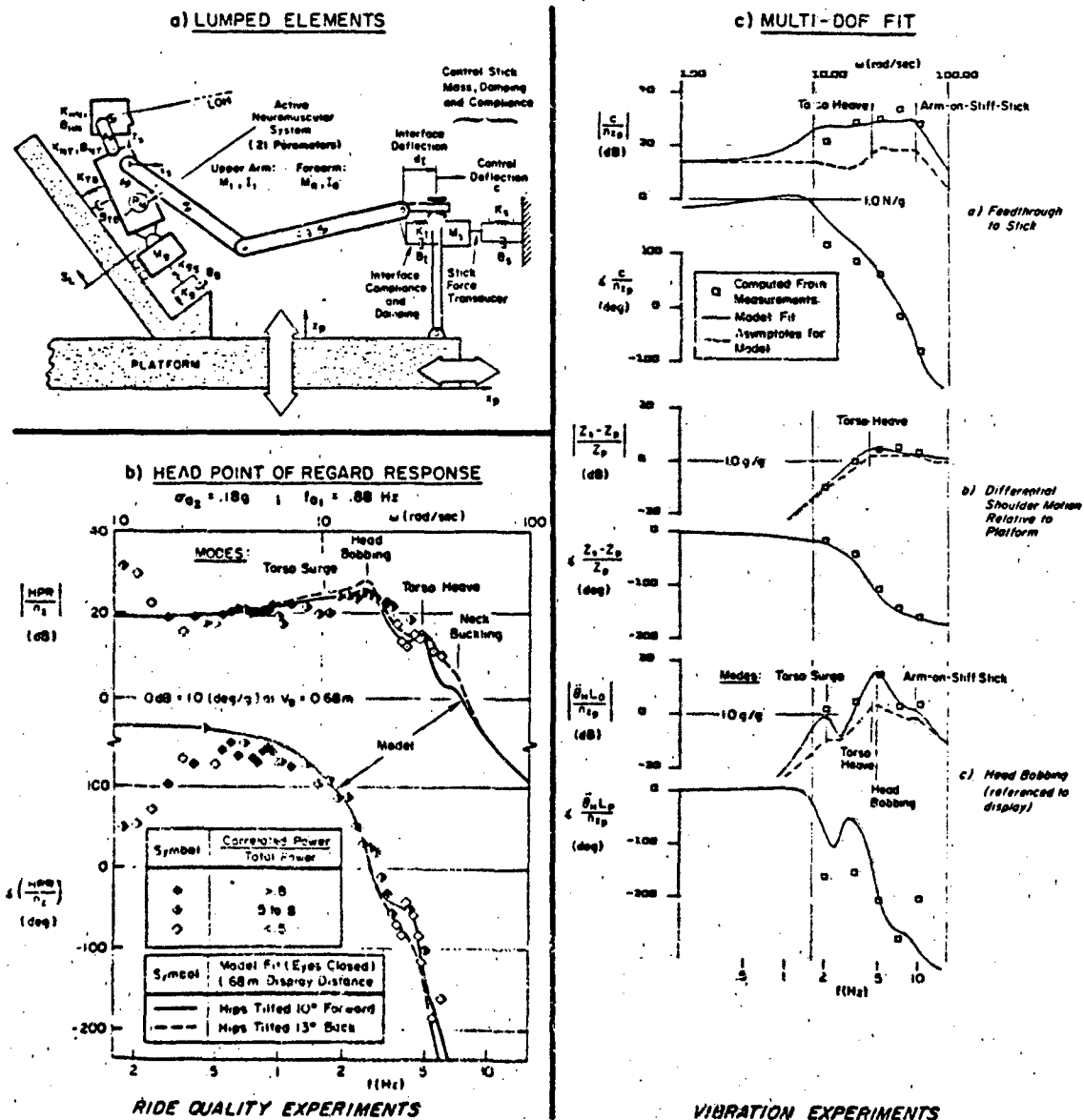


Figure 4. Control Feedthrough Model and Validation

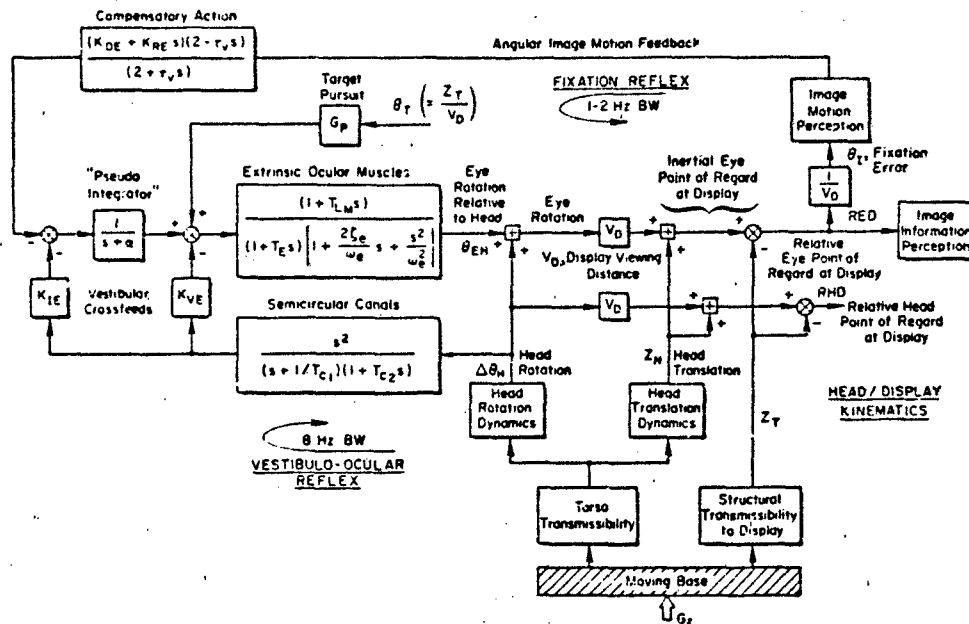
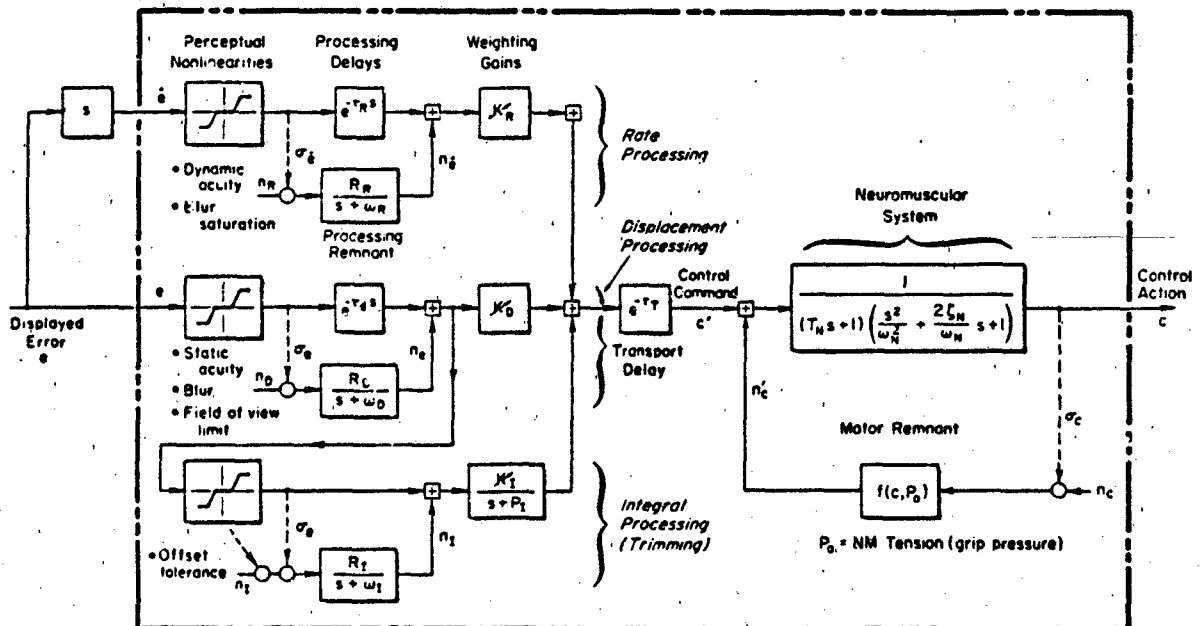


Figure 5. Model for Image Motions Due to Head Vibration

When tracking performance (or performance on a manipulated object task) is desired, the fourth, and most difficult, step is necessary. All of the vehicle dynamics and biomechanical transmittances must be included in a complex model of the human operator's adaptive tracking strategies. The "classical" models for doing this are typified by those of McRuer and his associates (e.g., Refs. 15 and 16). They use lumped-parameter submodels for the perceptual, equalization, and neuromuscular processes, with adjustable parameters which covary with various task variables, including vibration (e.g., see Ref. 2). A current version of this, the so-called "Compleat" Human Tracker model is summarized in Fig. 6.

The modern equivalent to this is the optimal control theory model of Kleinman, et al. (e.g., Ref. 17), in which the catalog and adaptation "rules" of the classical human operator model are replaced by an



Systems:	PERCEPTUAL	PROCESSING AND COMPENSATION (Control)	NEUROMUSCULAR
Effects:	<ul style="list-style-type: none"> <li>• Sensitivity</li> <li>• Thresholds</li> <li>• Saturations</li> </ul>	<ul style="list-style-type: none"> <li>• Adjustable gains <math>K</math></li> <li>• Processing delays</li> <li>• Remnant (noise) due to time variations and nonlinearities</li> </ul>	<ul style="list-style-type: none"> <li>• <math>T_N, \omega_N, \zeta_N = f(\text{NM tension})</math></li> <li>• Motor remnant, tremor</li> </ul>

Figure 6. Typical Human Operator Performance Model

optimal control law algorithm whose cost functional is adjusted (based on fitting empirical data) to provide the covarying parameter trends observed in experiments.

The optimal control model for tracking has been highly refined and applied to modeling performance under various axes and types of vibration by Levison (e.g., Refs. 6-8) and has been put in a user-oriented computer program as "PIVIB" (PIlot VIBration, Ref. 18), which in accordance with our dating scheme will be designated herein as "PIVIB-77." As implied on Fig. 3, PIVIB-77 can use BIODYN-78 (or experimental data, if available) to provide the various biomechanical transmissibilities required. The current PIVIB has some oversimplified assumptions regarding the performance decrements due to head-point-of-regard motion (e.g., it does not yet properly account for vestibular or image tracking effects of the eye's control system). Nevertheless, it does give a good first approximation to performance changes for a wide range of task variables (such as input spectra, stick scaling, vibration-induced blur threshold). As should be expected from the discussion of Figs. 2 and 3, hundreds of parameters are required in the PIVIB input files, because it has to cover all of the elements in Fig. 2.

We have shown that each of the four steps in assessing vibration effects on performance now has math models of varying degrees of confidence and ease of use. The selection of individual models depends on the axes of vibration and of manual control, the type of vibration, and the availability of purely empirical data (e.g., experimental frequency responses) or the need for prediction before the experiment or design is frozen.

### VALIDATIONS

The biomechanical model, BIODYN-78, and its antecedents have been progressively refined and validated as experimental data of suitable format and quality became available. Typical fits of the body, limb, and head-point-of-regard data are shown in Fig. 4c from one of a series of experiments with quasi-random vibration (i.e., the sum of five sinusoids of non-simple-harmonic ratios). Further details are given in Ref. 3. The main point to note from Fig. 4c is that one model (albeit complex) simultaneously fits all of the several degrees of freedom measured. More experiments are needed with simultaneous measurements at several well-defined body points, e.g., shoulder, sternum, head (2 places), and arm bones or joints, along with the main seat input (e.g., via a 10 cm "ISO" disk with accelerometers between the buttocks and seat). Since small differences between large accelerations are important, very high grade instrumentation and inputs are required.

Figure 4b shows another example, also described in Ref. 3, where wideband vehicle vertical motions in the 0.5 to 5 Hz range (from the high-speed ship simulation program described at Oslo in Ref. 1) were imposed on crewmen sitting in various degrees of postural relaxation (here relaxed, eyes closed). The main point is that the multimodal character of the data is well matched by the model. One subject noted that he "tilted his hips forward" (dashed line in Fig. 4b) to relieve some of the head bobbing; the model correctly captures this effect.

The head/eye/control image motion model of Fig. 5 is much less well validated, but it shows promise. It relies on the fact that under most low-frequency vibrations the eye only moves a degree or two (not enough to trigger visual saccades) and thereby permits a quasi-linear modeling.

At the bottom of Fig. 7 are some image motion predictions made for three types of display/head interface: target alone moved (head fixed); target fixed (head and eye moved); and a head-mounted display (image moving with the head). Notice the different bandwidths of image (error) motion, as mentioned earlier — poor for target moved and good for head moved. More interestingly, the head-mounted display gives rise to large image motion errors because the counterpitching tendency of the eyes works against a head-mounted display. Vibration-induced decrements in digit reading accuracy as measured recently by Benson and Barnes' experiments, are shown at the top of Fig. 7. The similarity of trends in computed image

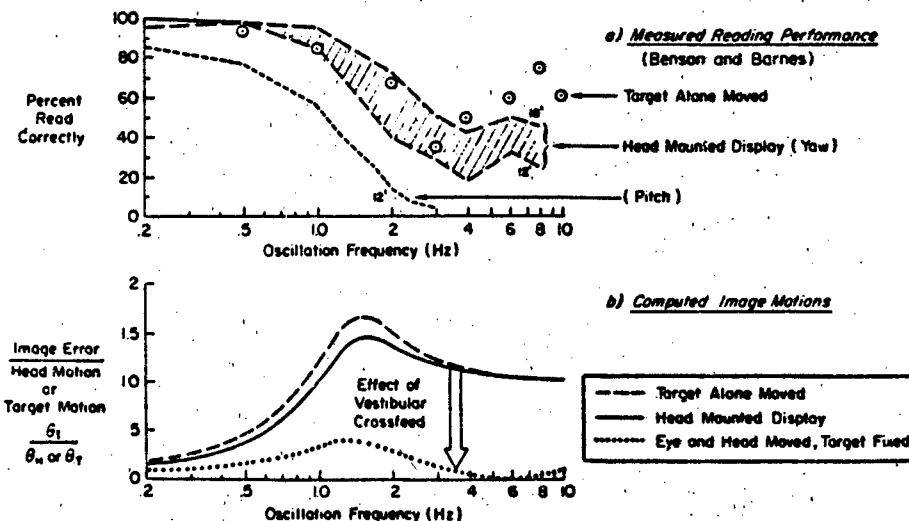


Figure 7. Computed Image Motions and Digit Reading Performance

motion and measured accuracy suggests some validation for assuming that visual performance can be related to image motion. Again, much more experimentation is needed, and we recommend that eye motion be measured in as many cases as feasible.

The overall ability of the complex PIVIB-77 model structure and algorithms to model manual control performance is demonstrated in Fig. 8, which includes overall error scores (top) and control actions (bottom) from three different experiments performed at the USAF Aerospace Medical Research Laboratory. A couple of general points are illustrated by Fig. 8:

- The PIVIB model (after adjustment of its algorithms) was able to fit all three experiments fairly well without further changes, both for error and control action.
- The effects of vibration versus static on task error are generally not very large and are often within the range of individual subjects. Adversely sensitive control stick gains or postures can greatly increase the vibration effects, especially on the rms control activity, as shown.
- Big effects occur due to input scaling, stick and display scaling, etc. These effects are currently modeled by PIVIB.

PIVIB is not computationally very efficient, because it incorporates optimum Kalman filter subroutines which require the solution of Riccati equations. However, it has been put in usable form with a user's guide, and it is ready to be tested and further refined.

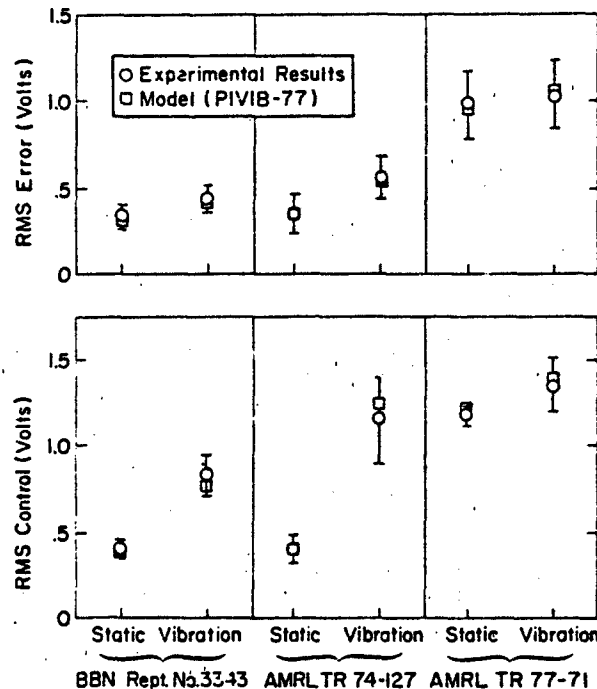


Figure 8. Vibration Effects on Tracking Performance Measures vs. PIVIB Model (From Ref. 8)

PREDICTIONS

An objective of these models is to permit prediction of problem areas or solutions before actual simulation data are available. One such prediction of BIODYN-78 is shown in Fig. 9, which compares the head-line-of-sight transmissibility (which the eyes have to compensate for) for a standard 15 deg tilt-back fighter aircraft seat with an advanced 65 deg tilt-back seat designed for High Acceleration Cockpits (HAC) (for details see Ref. 3). An order of magnitude increased sensitivity to vibration-induced head bobbing is predicted if the head or neck is not supported (as assumed here). Vibration experiments on such configurations seem warranted, with comprehensive measurements of seat and torso motion, head and limb motions, and tracking and visual identification task performance.

Other predictions have been made as to the influence of an arm rest on vibration feedthrough (depends on the percentage of arm weight carried by the rest and on the limb angles involved) and on the effects of various postures.

The usefulness of such models for this sort of prediction, parameter-tradeoff study depends on how convenient is its access and how easy it is to modify the parameters. BIODYN-78 has been designed for user-interactive operations on the Tymshare, Inc., timeshared computer network, and it could eventually be accessed by anyone with a simple teletype terminal with telephone coupler to Tymshare (not yet available, however). Among the advantages are the very convenient, well documented, and powerful Editor and Executive modes for Tymshare, which make it easy to change the variables, select new inputs or outputs,

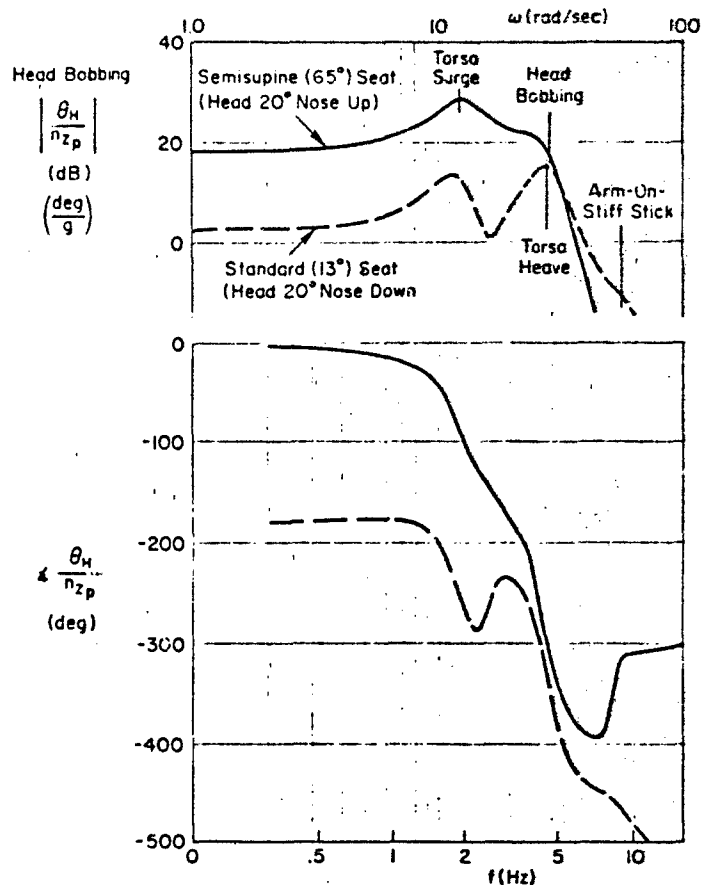


Figure 9. Use of Model for Problem Prediction  
(Increased Head Motions in High-G Seats)

and store and plot the results on a simple terminal. We hope that this scheme can be made more available for general use and we encourage others to do the same. PIVIB is a batch-oriented program presently available on the WPAFB CDC-6600 computer for USAF projects only.

#### PROBLEMS

Neither BIODYN-78 nor PIVIB-77 are complete programs, and numerous gaps and weak areas exist which need attention. Some of these are as follows:

- 1) BIODYN-78 needs to be extended to incorporate the lateral model previously derived in Ref. 2, the head-eye model of Ref. 11, and helmets and helmet-mounted displays and active neuromuscular control of the head/neck system.
- 2) PIVIB-77 needs better interface models with respect to image motion effects, free stick effects, as well as a more convenient interactive mode of operation (in addition to the efficient batch mode).
- 3) The links between head, hand, and eye motions and visual perception effects need to be forged on a sound scientific basis. The theory should be used to guide the experimental plans and measurements.
- 4) The validity of the neck-head-vestibular-eye system needs to be extended to very low frequencies (below 0.5 Hz) where some anomalies have consistently shown up (e.g., see Fig. 4b). Eye movement data are essential here, and postural controls must be imposed.
- 5) More users have to try to apply these models to their data. One ideal candidate is Rowlands' extensive compilation of seat to head and shoulder transmissibilities under a wide variety of postures (Ref. 19). The main obstacle here is the lack of documented postural information (e.g., two-view photos) or of vibrational "mode shapes" at the salient peaks and dips of each frequency response (e.g., via high-speed cinematography). Please document your postures and dimensions for each subject!
- 6) The movement of the eyes under vibration is very difficult to measure, because nothing of any mass can be attached to the face (electro-oculograms are no good when facial tissues jiggle around) and the motions are very small. The TV scanning oculometer such as Honeywell's would seem ideal, but its effective sampling lag is excessive for vibration work.



To illustrate one of the more challenging problems, consider Fig. 10, which compares tracking scores (actually "critical instability" levels,  $\lambda_c$ , to which tracking performance is strongly correlated, see Ref. 3) for a number of naval crewmen for the static case versus wideband ship motion conditions generating severe kinetosis (motion sickness) in each subject (all shown are those which aborted the motion condition sooner or later and the degree of kinetosis is shown by the numbers by each symbol). The results show that:

- When reasonably motivated (as here), typical crews will retain about 50 percent of their static performance even when feeling quite queasy.
- As kinetosis proceeds to frank nausea, the tracking performance suddenly deteriorates.
- The performance decrements from kinetosis lie within the range of performance of different individuals.

Modeling the highly nonlinear progress of kinetosis (enhanced by low-frequency vibration in the 0.2-0.5 Hz region) and performance thereafter stands as a key challenge for the next AGARD AMP Specialist's Meeting on Vibration Effects.

Subscripts denote kinetosis rating at time  
 1 = none, 2 = stomach awareness, 4 = moderate nausea,  
 5 = severe nausea, 6 = vomiting

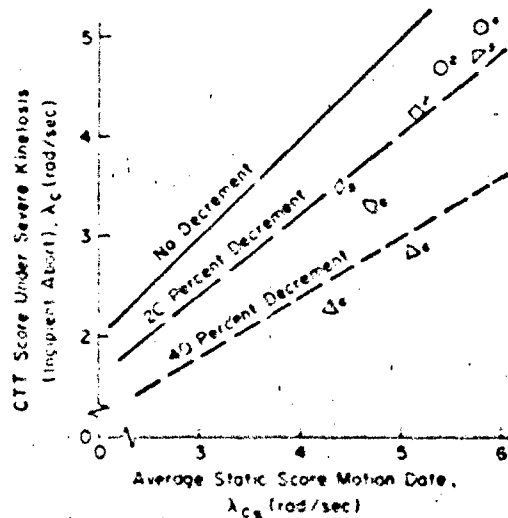


Figure 10: Tracking Performance Decrement During Severe Kinetosis

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#### ACKNOWLEDGMENT

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APPENDIX B

"USER'S GUIDE TO BIODYN-78, AN INTERACTIVE COMPUTER  
PROGRAM FOR MODELING BIODYNAMIC FEEDTHROUGH  
TO A PILOT'S HANDS AND HEAD"

SYSTEMS TECHNOLOGY, INC.

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Technical Report No. 1037-2

"USER'S GUIDE TO BIODYN-78, AN INTERACTIVE COMPUTER  
PROGRAM FOR MODELING BIODYNAMIC FEEDTHROUGH  
TO A PILOT'S HANDS AND HEAD"

Raymond E. Magdaleno  
Henry R. Jex

July 1979

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"USER'S GUIDE TO BIODYN-78, AN INTERACTIVE COMPUTER  
PROGRAM FOR MODELING BIODYNAMIC FEEDTHROUGH  
TO A PILOT'S HANDS AND HEAD"

A. INTRODUCTION

BIODYN-78 is a self-contained program for calculating transmissibilities (transfer functions) between vibration inputs (vertical and/or fore-aft) and various biodynamic outputs for a seated pilot gripping a center- or side-stick and viewing a display while (possibly) engaged in a tracking task. Model rationale, development, and validation were reported in Ref. 1, included here as an appendix.

The purpose of this guide is to briefly review and update the model's geometric and functional parameters, and to describe the two files needed to run BIODYN-78 (model parameter "INPUT" and transfer function "CHOICES"). A "test case" example execution, using the parameters from one of the validating experiments (Ref. 1), is used to illustrate typical outputs.

The BIODYN-78 program was developed on the Tymshare, Inc. timesharing computer network (US/ and Europe). The reasons for having BIODYN-78 resident on such a facility are:

- Ease of access by a simple typewriter terminal with modem, without "batch" delays. (The program runs each case in seconds.)
- Ease of creating, modifying, storing, and manipulating files of input and output data using the resident EDITOR program.
- Availability of excellent Users' Manuals to cover the basic procedures in using a given facility. This is especially important because BIODYN is intended for routine use by aircraft system design engineers who often are not computer experts.

In view of the last point above, we will provide minimal information on the basic computer procedures and file operations, and will assume that the user is familiar with Tymshare's XEXEC manual (Ref. 2).

While BIODYN-78 resides in Tymshare, Inc.'s PDP-10 based timesharing network, it has also been recently test run on Control Data Corp.'s CYBERNET NOS-175 Service (interactive mode), with identical ease and results. If there are any questions on the use of BIODYN-78 on these facilities, please contact either of the authors at:

Systems Technology, Inc.  
13766 S. Hawthorne Blvd.  
Hawthorne, CA 90250

(213) 679-2281

A simplified flow diagram for the procedures used in applying BIODYN-78 is given Fig. 1. The user accesses Tymshare, Inc. (with suitable passwords, etc.) and asks for one of the already filed sets of model INPUT parameters for various postures and situations as listed in the "Catalog," given later herein, or creates new ones from scratch. (Note, the "Catalog" files are "READ-ONLY" so they cannot be inadvertently deleted.) If some of the parameters need to be changed, the user employs Tymshare's EDITOR to change the appropriate numbers on given lines of the selected "INPUT" file (and refiles it appropriately), or he can use the selected set without modification. This process could take from one minute to one hour depending on the number of parameters to be changed and checked.

The user then identifies the desired transfer functions via a "CHOICES" file wherein each desired output/input vibration direction is listed. This process takes from 1 to 10 minutes depending on the number of new choices.

The user then activates the program by typing "GO BIODYN", and within seconds the process described above is executed and the results are then typed out in the selected format. Selected output files, so identified in the "CHOICES" file, can be saved for later plotting or recall. From "GO" to printout often takes less time than it did to read this paragraph. This computational speed makes it feasible for a user to sit at a terminal and iteratively alter the INPUT and CHOICES files to iterate on the characteristics of a desired biodynamic transfer function or mode.

For further manipulation of the resulting transfer functions, such as frequency response (Bode) plots, calculating rms output in response to an input spectra, etc., the output files can readily be accessed by the user's

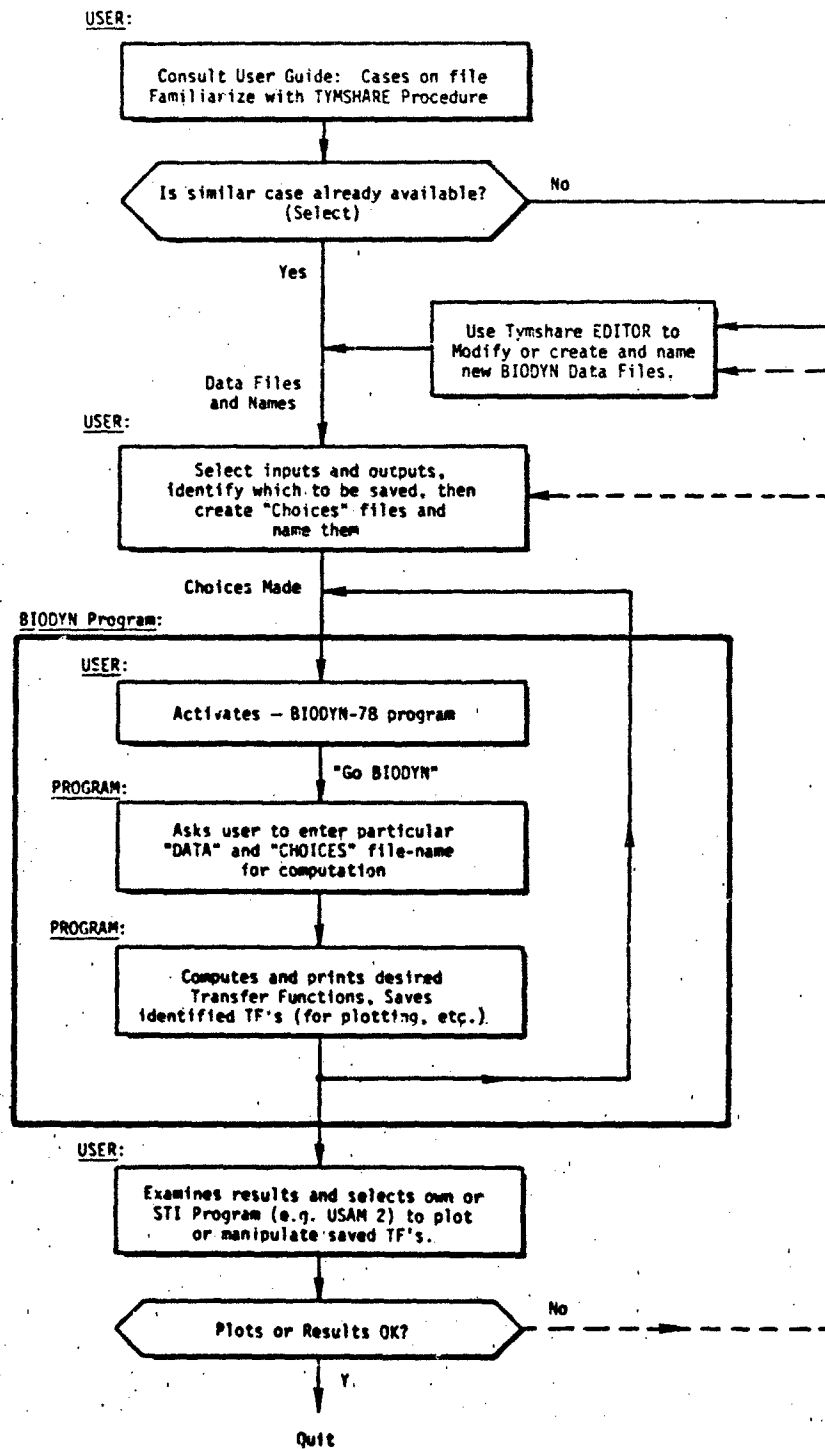


Figure 1. Procedural Flow in Using BIODYN-78

(or other Tymshare-resident) analysis programs. A typical set is the STI Unified Servo Analysis Method (USAM) programs which permit a variety of systems computations and plots for multiloop pilot-vehicle systems of this type (Ref. 3). Although such extant programs are not an intrinsic part of BIODYN-78, the BIODYN output files can be easily transferred to them in the Tymshare system.

## B. MODEL AND PARAMETERS

### 1. Model Description

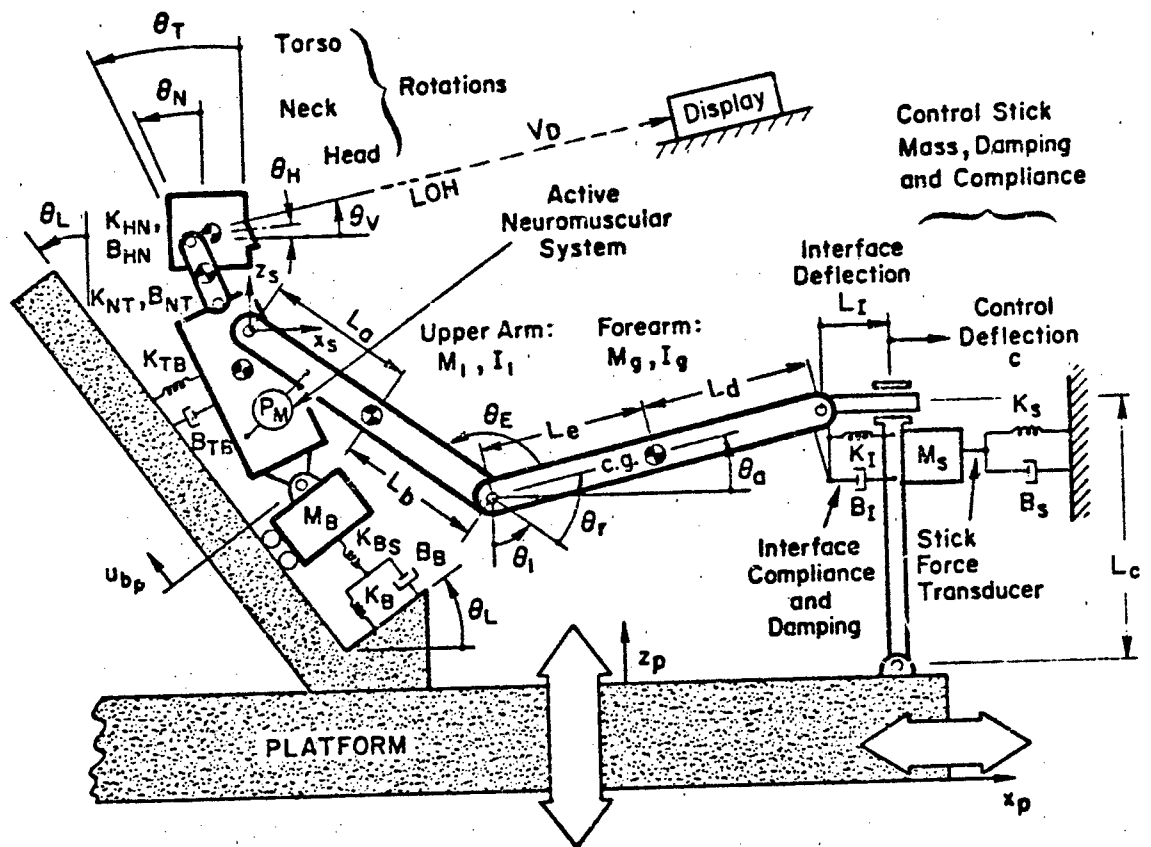
Figure 2 (updated from Fig. 2 of Ref. 1) presents the biomechanical model and defines many of the necessary parameters that describe the nominal (or trim) situation. It utilizes a "homologous," or life-like representation, of the major body segments in their orientations; simplified to a minimum number of lumped parameter equivalents. The biomechanical features include:

- Semisupine torso; sliding hip plus rocking chest supported on a compliant buttocks/seat.
- Head bobbing on an articulated neck with passive compliance.
- Upper arm and forearm links plus grip-interface compliance, driven by an active neuromuscular system.
- Arm-rest restraints (optional).
- Stick "feel system" dynamics.

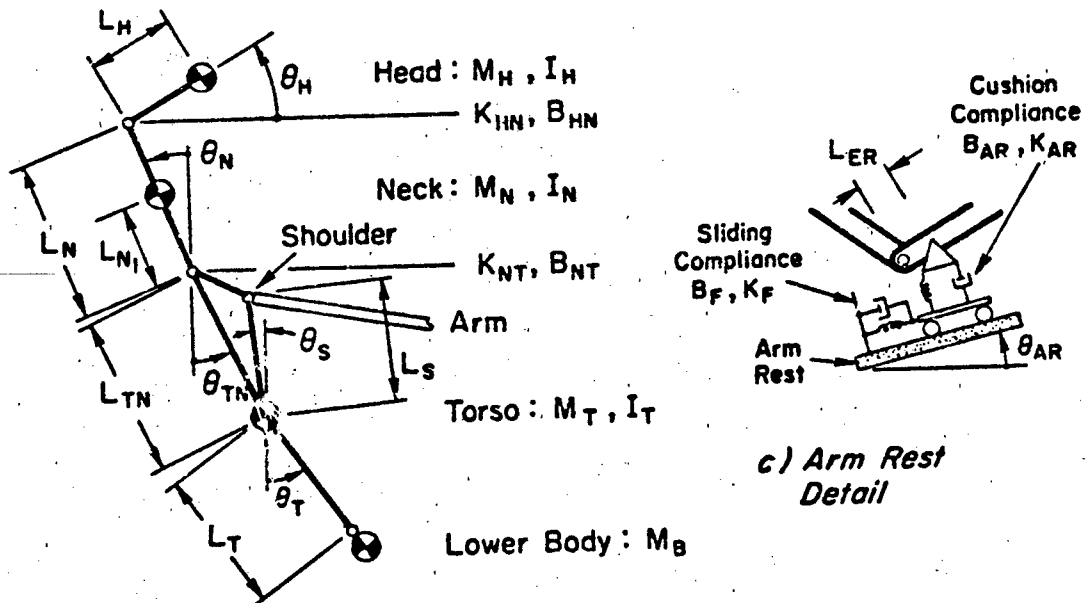
This simplified model was derived to describe the motions of the head and arm elements; the "pin-joint" node between upper and lower torso segments is not meant to represent any physical feature.

The active neuromuscular system shown in Fig. 2 is a schematic representation of the net effect of the complex agonist/antagonist muscle pairs controlling the upper arm. A linearized neuromuscular system representation is shown in Fig. 3, which further relates this to the effective sensors of muscle length and force as well as proprioceptive senses from the stick grip interface which completes a loop through central processing. Unless the neuromuscular properties are being investigated, we recommend using





a) Basic Elements



b) Body Parameters

c) Arm Rest Detail

Figure 2. Biomechanical Model

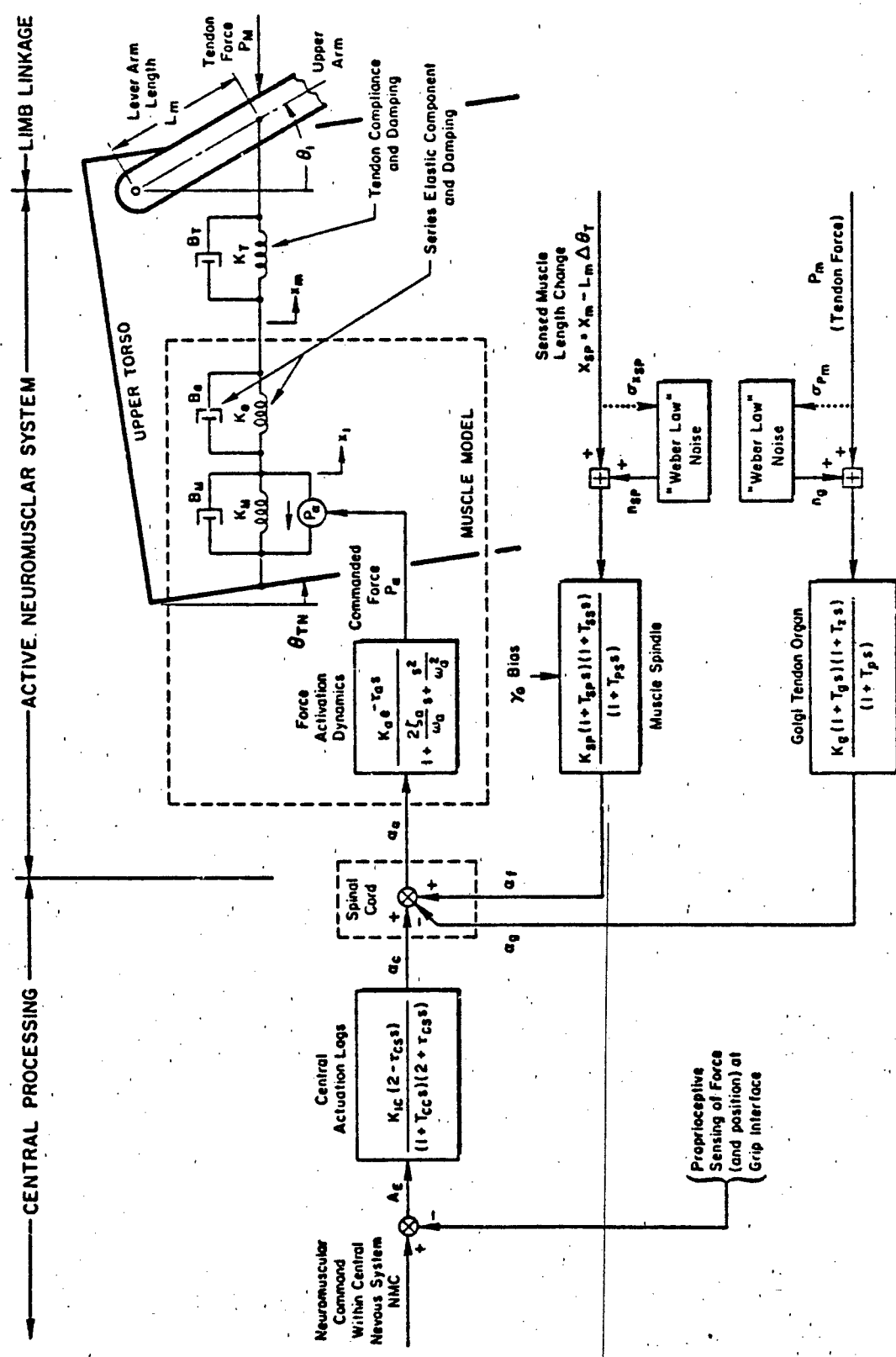


Figure 3. Linearized Neuromuscular System

the given values which are representative of any normal person's arm-hand system, and generally yield reasonably damped neuromuscular servo properties. Reference 4 may be consulted for further information on this neuromuscular model.

## 2. Parameter Definitions

Table 1\* presents the parameter definitions and typical values used in the Ref. 1 validating experiments. This is an updated version of Table A-1 in Ref. 1, wherein some definitions have been added (e.g., stick length, arm rest parameters) and a few typographical errors have been corrected.

The equations-of-motion for BIODYN-78 have been written in a "second order element" matrix form using generalized (all angle) parameters. When a particular set of postural, neuromuscular, stick and display dimensions are input as a file, then the program internally sets up the general equations and evaluates the linearized coefficients for perturbations about the equilibrium posture.

## C. FILES

### 1. General

Two files are needed to execute BIODYN. The INPUT file specifies the 80-odd parameters for a given model, while the CHOICES file specifies the transfer functions (output variables/forcing function) to be computed, printed, and (optionally) saved on file.

For situations involving a seated operator, the user can access either of the two model cases currently resident in the Tymshare system for use in BIODYN. The file names are cataloged below, listings later herein. These cases were used to validate experimental data as described and discussed in Ref. 1 (Appendix, herein).

---

\*This Table, and all subsequent Tables are located at the end of this report.

BIODYN-78 CATALOG

<u>FILE NAME</u>	<u>DESIGNATION IN REF. 1 (ALSO TABLE 1)</u>	<u>COMMENTS</u>
B.19	"VIBRATION EXPERIMENTS"	Used here as "test case"; pilot in standard 13 deg seat, hand on center-stick
B.51	"RIDE QUALITY EXPERIMENTS"	Relaxed, seated operator, facing a display, hands in lap

These files are used in various ways, depending on the application.

For example:

- Model fitting to a given set of data. Select a set of transfer functions representing the measured outputs/inputs (e.g., stick or head motions to vertical acceleration). Create a set of model INPUT files bracketing the likely parameters, and/or progressively change the INPUT file as answers are inspected.
- Choosing measurement points for a future experiment. Create one model INPUT file for a representative posture, and two others reflecting the likely extremes. Create a CHOICES file to cover each likely measurement point.

Use of the Tymshare's very convenient EDITOR greatly simplifies the selection, modification, or creation of the model parameter files or output choices. Sections 1-3 of the Tymshare XEXEC Manual (Ref. 2) should be read before performing these functions.

## 2. Model INPUT Files

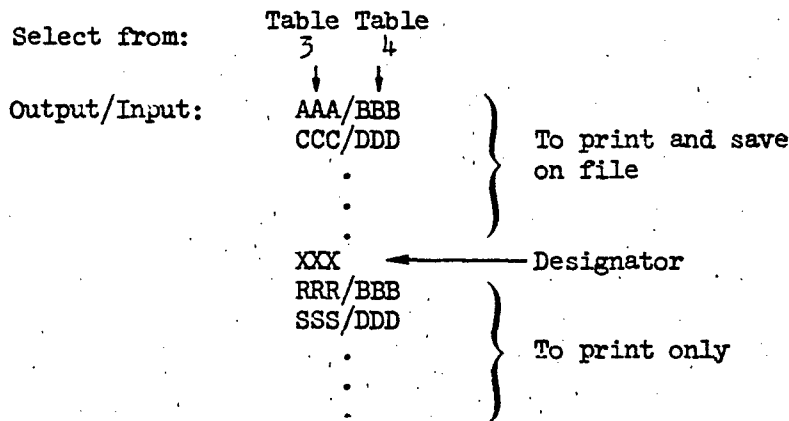
Table 2 documents the Catalog "INPUT" files for the "Vibration and Ride Quality" experiments data listed in Table 1. Note how associated groups of parameters in the vertical arrangement of Table 1 are changed to horizontal groups of parameters, as many as nine numbers in a horizontal line in Table 2. The first line is a "title" line ( $\leq 60$  characters), whereas the contents of the other eleven lines are indicated by the separators in

Table 1. Finally, in Table 2 note the "free form" array format, wherein one or more blank spaces are used to separate the numbers in a clear manner.

### 3. Transfer Function CHOICES File

Table 3 summarizes all of the response variables, describing the various model variables of Fig. 3, as well as element perturbation movements and some interface forces of Fig. 2. These are available as outputs in response to the inputs (forcing functions) summarized in Table 4. In general, the user requests transfer functions using pairs of three-character column codes selected from Tables 3 and 4.

The transfer functions are specified in a vertical list, putting first, all those that are to be both printed out and saved on file (user supplies file names during program execution) and then, below a symbol "XXX" designator, all those which are just to be printed out. The general CHOICES file format is thus:



These will be illustrated in the Check Case example, to follow.

The response variables given in Table 3 for shoulder and head translatory motion are defined as relative to the platform. The inertial shoulder and head responses can be obtained by using a set of "special" platform deflection forcing functions (denoted by BXP or BZP) as shown below:

<u>CHOICES FILE ENTRY</u>	<u>RESULT</u>	<u>TRANSFER FUNCTION</u>
$\emptyset Z1/BZP$	$\frac{z_s}{z_p}$	$\frac{\text{inertial shoulder (vert.)}}{\text{platform motion (vert.)}}$
$\emptyset XS/BXP$	$\frac{x_s}{x_p}$	$\frac{\text{inertial shoulder (horiz.)}}{\text{platform motion (horiz.)}}$
DZH/BZP	$\frac{z_h}{z_p}$	$\frac{\text{inertial head (vert.)}}{\text{platform motion (vert.)}}$

IMPORTANT NOTE:  $\emptyset$  denotes a typed blank

#### 4. Saved Transfer Function Files

As the program computes each numerator which is to be saved (those above the XXX in the CHOICES file), it stops and prompts the user to type in a file name under which the transfer function is to be stored. File naming must follow Tymshare, Inc. conventions, e.g., as given in Section 3 of the Tymshare XEXEC Manual (Ref. 2). In general, the name can have up to six characters, followed (optionally) by a period and up to three more characters. The first character must be a letter; the others can be any combination of numbers and letters. A "temporary" file (automatically erased at the end of a session) is designated by a .TMP at the end of the file name.

For those transfer functions saved on file the following format is used; FORTRAN formats are shown in (parentheses), for those who may wish to read the files.

NZ1, NZ2, NP1, NP2, K (5X, 4(I3,1H, ), E12.6)

$1/T_{z1}$	}	first order zeros (one per line)
$1/T_{z2}$		
.		
.		

(5X, E12.6)

$\zeta_{z1}, \omega_{z1}$	}	second order zeros ( $\zeta_{z1}, \omega_{z1}$ ) per line (5X, E12.6, 1H,, E12.6)
$\zeta_{z2}, \omega_{z2}$		
.		
.		
$1/T_{p1}$	}	first order poles (one per line) (5X, E12.6)
$1/T_{p2}$		
.		
.		
$\zeta_{p1}, \omega_{p1}$	}	second order poles ( $\zeta_{p1}, \omega_{p1}$ ) per line (5X, E12.6, 1H,, E12.6)
$\zeta_{p2}, \omega_{p2}$		
.		
.		

where:

NZ1 = Number of first-order zeros  
 NZ2 = Number of second-order zero pairs  
 NP1 = Number of first-order poles  
 NP2 = Number of second-order pole pairs  
 K = Gain of high-frequency asymptote (units of output/  
 input dimensions)

An example is shown later.

These saved files may be used later, in other Tymshare-resident programs, such as reformatting, plotting, incorporation in overall system models, etc. A Bode Plot example is shown later.

## D. COMPUTER OPERATIONS AND BIODYN EXECUTION

### 1. Example "Check Case"

Given the INPUT and CHOICES files, the BIODYN program can be executed very simply. Figure 4 is an example of actual computer operations involved in, first, printing out files to be used (recommended practice in case of errors), and, second, actual execution of BIODYN-78. This check case uses file B.19 (the Vibration Feedthrough experiments).

The underlined items in Fig. 4 identify those typed in by the user (terminated by a "carriage return") — all other printing was done by BIODYN or by Tymshare's operating system (called XEXEC, the same name as Ref. 2). XEXEC prints a prompt (-) at the beginning of a line when it is ready to accept a command and waits there for a user response. The circled numbers on the left in Fig. 4 identify items discussed below.

- ① User issues command to "TYPE" out "INPUT" file name B.19, followed by a carriage return. Then XEXEC lists out file contents.
- ② Same for "CHOICES" file (this file was composed earlier using EDITOR, Ref. 2).
- ③ User issues "GO" command followed by file name "BIODYN" and program execution begins.
- ④ BIODYN prompts user for "INPUT" file name. After his response, B.19, program sets up equations of motion.
- ⑤ BIODYN prompts for a "CHOICES" file name and user types C.TMP. Execution continues as program prints date and time followed by the case title (taken from the first line of file B.19 listed above).
- ⑥ The denominator is computed and printed. The first number listed is the gain of the high frequency asymptote.
- ⑦ First order poles are listed, up to four per line.
- ⑧ Second order poles are listed as:  $(\zeta, \omega, \zeta\omega, \omega\sqrt{1-\zeta^2})$
- ⑨ Gain of the denominator low-frequency asymptote.





- ⑩ Biodyn prompts the user for a file name to store the transfer function. User responds with DTH. TMP and BIODYN then checks the user file directory and indicates that this is either an OLD FILE, or NEW FILE as here, and awaits a user response. If the user types a carriage return the information is written onto the file, destroying the previous contents. If the user enters any other character followed by a carriage return, no information is written onto the given file name — thus sparing the user from destroying possibly valuable information. Instead, the program prompts RE-ENTER FILE NAME. After user responds, the program indicates OLD FILE or NEW FILE, etc.
- ⑪ The numerator is printed out following the same format as ⑥ to ⑨.
- ⑫ The next numerator in the CHOICES file is printed out.
- ⑬ As there are no more items in the CHOICES file, the program reports the number of TRUs used. (\$.13 each), prints date and time and then the program terminates with EXIT.
- ⑭ The dash indicates that XEXEC is awaiting a command. At this point the user can return to ① or ③, and repeat this entire process with another INPUT and CHOICES file pair.

Note that each transfer function is to be interpreted as

$$\text{Transfer Function} \equiv \frac{N_{\text{output}}}{\Delta} (s) = \frac{\kappa \left\{ \prod \left( s + \frac{1}{T_z} \right) \right\} \cdot \left\{ \prod (s^2 + 2\zeta_z \omega_z s + \omega_z^2) \right\}}{\left\{ \prod \left( s + \frac{1}{T_p} \right) \right\} \cdot \left\{ \prod (s^2 + 2\zeta_p \omega_p s + \omega_p^2) \right\}}$$

where  $\Pi$  denotes a product of first- or second-order roots, and  $\kappa$  is the so-called "root locus gain" (of the high frequency asymptote):

$$\kappa = \frac{\text{High Frequency Gain of Numerator}}{\text{High Frequency Gain of Denominator}}$$

and the various first and second order poles and zero are indicated in Fig. 4.

## 2. Saved File Printout

The transfer functions that are saved on file can be called up later by other programs for Bode plotting or other additional calculations. Figure 5 is an example printout of the file DTH.TMP that was saved on file (Fig. 4). This follows the format given earlier in the subsection on Saved Transfer Function Files.

```
- TYPE DTH.TMP  
  7, 5, 5, 6, -.446729E-01  
  .000000E+00  
  .000000E+00  
  .165902E+02  
  .182845E+02  
  .958270E+02  
  .232815E+03  
  .498672E+03  
  .455870E+00, .103959E+02  
  .975536E-01, .162027E+02  
  .840709E+00, .338348E+02  
  .235948E+00, .518149E+02  
  -.263614E+00, .284736E+03  
  .165930E+02  
  .587883E+02  
  .973407E+02  
  .282173E+03  
  .357448E+03  
  .264963E+00, .109137E+02  
  .202525E+00, .129429E+02  
  .354269E+00, .267610E+02  
  .151120E+00, .296106E+02  
  .857619E+00, .329528E+02  
  .191240E+00, .574830E+02
```

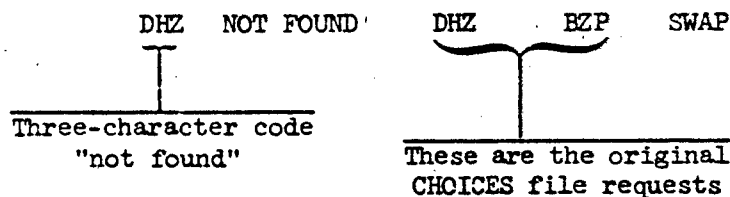
Figure 5. Example Printout of a Saved File  
(User entries are underlined)

### 3. Error Messages

There are two types of user errors that can trigger various messages — spelling errors in the CHOICES file and numerical errors in the INPUT file.

a. Spelling errors. In the CHOICES file a misspelled response variable or forcing function cannot be detected by the program unless it results in a three-character code that is not in Table 3 or 4.

Thus, for example, a transfer function request of DHZ/BZP cannot produce a numerator since DHZ is not a response variable (Table 3). In this case, the following message will be printed where the numerator would have been printed



The same type of message results for a not-found forcing function, i.e., the "not found" characters are always printed first followed by both portions of the original request.

b. Numerical. A number of error messages can result from grossly inappropriate numerical selections. The equations of motion have been written in a manner such that most masses and many other elements can be set to zero, e.g., the many zeroed elements for the Ride Quality Experiments (Table 1). However, if the user also zeros up  $K_m$  or  $K_e$  or  $K_f$  then the error message

NULL MATRIX

will appear in the output in place of the DENOMINATOR. For other numerical selections this message might appear among some of the numerators. In general, the user should examine the INPUT data to check for typing errors,

e.g., a massless unrestrained head such that  $\Delta\theta_H$  is indeterminate (NULL MATRIX will result).

A number of other error messages of varying degrees of severity and user response can occur. OVERFLOWS and UNDERFLOWS are printed by the operating system. If only one of each of these occurs, they probably occur in intermediate calculations and can often be ignored if an otherwise normal printout (e.g., Fig. 4) follows, since roots are not accepted until they satisfy a convergence criteria.

Some of these problems can be solved by judicious parameter selection, viz., in the Vibration Experiments (Table 1) the neck mass and inertia were set to zero. The latter caused no problems in the equations of motion, whereas very small values would produce an additional quadratic mode at very high frequencies that would appear both in the denominator and all numerators. These high frequency "nuisance modes" are not important to any system responses, yet keeping them in forces the root-finding routine to hunt them down with attendant OVERFLOW messages if they are greater than about 1000 rad/sec. Similar problems can result for very small values of some dampers, again pushing roots to very high frequencies such that the following message might appear:

#### EXCESS OR INCORRECT ROOT FOUND

Thus it is better to avoid using very small values of masses and dampers for those elements not important in the user's application. The authors urge the potential user to study the differences between the parameter sets (Table 1) used in the Vibration Experiments (17th order denominator) and the Ride Quality Experiments (9th order denominator). The variety of elements "zeroed up" in each study helped remove "nuisance modes" such that there were no error messages.

Finally, to prevent "runaways" (rare but potentially costly), the following message may occur:

50 ITERATIONS WITHOUT CONVERGENCE, CONTINUE? (Y OR N):

The user responds with either Y or N, followed by a carriage return. The first response continues the root search for up to 50 more iterations while the latter accepts the roots found so far. If no OVERFLOWS have occurred the authors recommend responding with Y since the user's parameter set may have an unusual Root configuration and allowing the program to continue may produce convergence for all roots before this message occurs again. Responding N followed by carriage return will stop the search and report out all roots found so far, but not all that may be present. BIODYN will continue normally with the next item in the CHOICES file. A special investigation found that each root found for the Vibration Experiments or the Ride Quality Experiments required much less than 50 iterations.

#### 4. Example Bode Plot of a Saved File

Figure 6 illustrates the use of STI's TYMSHARE resident Unified Servo Analysis Method (USAM) program (Ref. 3) to access the transfer function stored on file name DTH.TMP (Fig. 4) and subsequent terminal Bode plot. While this USAM program is not a part of BIODYN, it is readily available for this coarse printer plot, as well as better resolution ZETA graphics Ref. 3 documents.

#### 5. Use in PIVIB Program

The performance computation program "PIVIB" described in Ref. 5 requires various biodynamic feedthrough transfer functions to be supplied, and BIODYN-78 is appropriate for this purpose. BIODYN computes the X, Z, and  $\theta$  outputs required in pole, zero, and gain form (designated POLE $\theta$  in PIVIB).

For example, for the feedthrough to the control stick from vertical or fore-aft vibration the CHOICES file entries would be as follows:

PIVIB		BIODYN	
Data File Entry*		BIODYN Model Transfer Function	Choices Entry
Vertical	STICKXFR LONG	$c/a_{zp}$	$\%C/AZP$
Fore-aft	(see Ref. 5)	$c/a_{xp}$	$\%C/AXP$

\*Reference 5, Paragraph 7.2.3

Similar procedures are used for any other biodynamic transfer function required in the BIOTR Submodule in PIVIB. While BIODYN uses the international standard units (SI system) throughout, PIVIB uses a variety of english units, and so gains and dimensions must be scaled accordingly.

-GO (Y7LIB)USAM2

11-JUN-79

21:47

WHAT NOW ? FIN

FILE NAME ? DTH.TMP

User entries are underlined:

Selects file-name  
for plotting

WHAT NOW ? BPL

ENTER WO,WF: 1.,100.

Requests "Bode-Plot"  
and sets frequency range

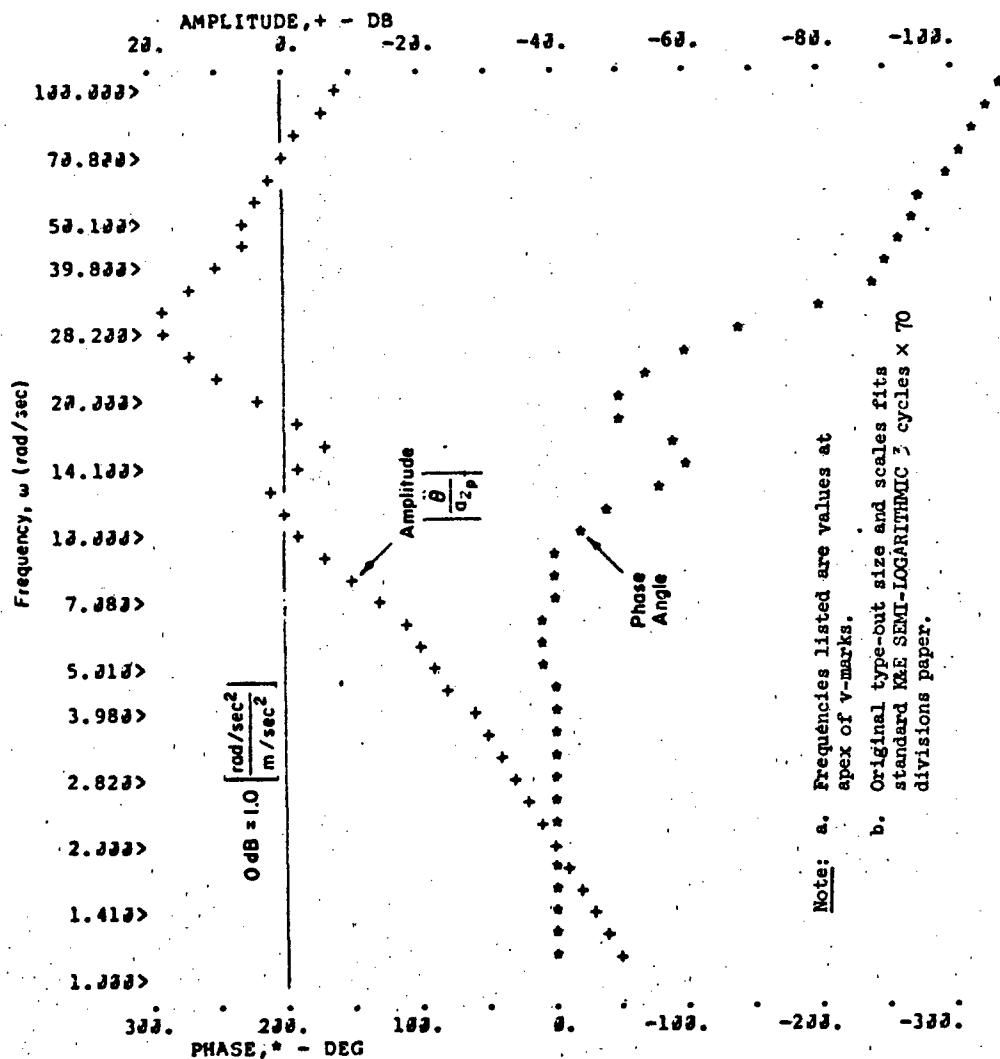


Figure 6. Typical USAM2 Terminal Bode Plot for Check Case



## REFERENCES

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2. XEXEC; TYMCOM-X Manual, Tymshare, Inc., Cupertino, California, Dec. 1974.
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4. Magdaleno, R. E., D. T. McRuer, Experimental Validation and Analytical Elaboration For Models of the Pilot's Neuromuscular Subsystem In Tracking Tasks, NASA CR 1757, Apr. 1971.
5. Berliner, Jeffrey E., and William H. Levison, PIVIB: A Computer Program for Analysis of Pilot Biodynamic and Tracking Response to Vibration, Bolt, Beranek and Newman, Rept. No. 3457, Dec. 1976.

TABLE 1. PARAMETER DEFINITIONS AND TYPICAL VALUES

FILE LINE NO.	TYPICAL VALUES			PARA- METER	FORTRAN NAME	DEFINITION	
	VIBRATION EXPERIMENTS*	RIDE QUALITY EXPERIMENTS*	UNITS				
1	B.19	B.51				File Name	
	"STIFF STICK"	"HEAD, NECK, TORSO ONLY"				Case Identifier	
2	1.372	0.0	kg	M <sub>1</sub>	XM1	Upper arm mass	Upper Arm
	0.29	0.29	m	L <sub>1</sub>	D1	Upper arm length (= L <sub>a</sub> + L <sub>b</sub> )	
	0.44	0.44	m/m	L <sub>a</sub> /L <sub>1</sub>	R1	Upper arm c.g. (fractional distance)	
	0.012	0.0	kg·m <sup>2</sup>	I <sub>1</sub>	Z1	Upper arm inertia	
	40.	40.	deg	θ <sub>1</sub>	T1	Upper arm angle	
3	1.017	0.0	kg	M <sub>2</sub>	XM2	Lower arm mass	Forearm
	0.305	0.305	m	L <sub>2</sub>	D2	Lower arm length (= L <sub>e</sub> + L <sub>d</sub> )	
	0.5	0.5	m/m	L <sub>d</sub> /L <sub>2</sub>	R2	Lower arm c.g. (fractional distance)	
	0.152	0.0	kg·m <sup>2</sup>	I <sub>2</sub>	Z2	Lower arm inertia	
	145.	145.	deg	θ <sub>E</sub>	TE	Elbow angle	
4	0.31	0.0	kg	M <sub>S</sub>	XMS	Stick mass (referred to grip)	Control Stick and Grip Inter- face
	2.	0.0	N/m/s	B <sub>S</sub>	BS	Stick damper	
	13900.	13900.	N/m	K <sub>S</sub>	XKS	Stick gradient	
	.0000558	.0000558	m/N	C <sub>I</sub>	CI	Grip interface compliance, K <sub>I</sub> <sup>-1</sup>	
	0.01	0.0	s	B <sub>I</sub> /K <sub>I</sub>	TIF	Grip interface time constant	
	0.61	0.61	m	L <sub>C</sub>	XLC	Stick length (pivot to center of grip)	
	13900.	13900.	N/m	K <sub>sc</sub>	XKSC	Scale factor (multiplies stick displacement)	
	1.0	1.0	-	-	CKS	Stick compliance parameter (CKS = 0 means that K <sub>S</sub> = ∞)	
5	14.	14.	kg	M <sub>B</sub>	XMB	Lower body mass (Hips)	Lower Body
	1290.	315.	n/m/s	B <sub>B</sub>	BB	Lower body/seat cushion damper	
	29585.	49360.	N/m	K <sub>B</sub>	XKB	Lower body/seat cushion stiffness	

\*Source of data in Appendix A

TABLE 1. (Continued)

FILE LINE NO.	TYPICAL VALUES			PARA- METER	FORTRAN NAME	DEFINITION	
	VIBRATION EXPERIMENTS*	RIDE QUALITY EXPERIMENTS*	UNITS				
6	2.	2.	N/m	$K_M$	XKM	Spring in neuromuscular system	Muscle Model
	1.	0.0	N/m/s	$B_M$	BM	"Hills law" damper	
	80.	80.	N/m	$K_T$	XKT	Tendon gradient	
	40.	40.	N/m	$K_e$	XKE	Series elastic element gradient	
	2.431	0.0	N/m/s	$B_e$	BE	Series elastic element damper	
	104.4	0.0	-	$S_i$	SI	Overall scale factor for muscle elements	
	1.	1.	-	-	-	Dummy variable	
	71519.	119322.	N/m	$K_{B_s}$	GK1	Series spring gradient in lower body	
0.	0.	N/m/s	$B_T$	BT	Tendon damper		
7	5.	0.0	N/m	$K_{sp}$	XKSP	Muscle spindle model gain	Spindle Feedback
	1/11.	0.0	s	$T_{sp}$	TSP	Muscle spindle lead time constant	
	0.0	0.0	s	$T_{ps}$	TPS	Muscle spindle lag time constant	
	0.0	0.0	s	$T_{ss}$	TSS	Muscle spindle high frequency lead time constant	
	.02044	0.0	N/N	$K_{1c}$	XK1C	Neuromuscular actuation gain	Control Actuation
	1/11.	0.0	s	$T_{cc}$	TCC	Neuromuscular actuation lag	
0.089	0.0	s	$\tau_{cs}$	TCS	Neuromuscular actuation time delay		
8	0.8	0.0	-	$\zeta_a$	ZA	Damping in force activation dynamics	NM Force Activation
	16.	0.0	rad/s	$\omega_a$	WA	Natural frequency in force activation dynamics	
	0.0	0.0	s	$\tau_a$	TAA	Time delay in force activation dynamics	
	0.5	0.0	N/N	$K_g$	XKG	Golgi tendon organ model gain	Golgi Feedback
	1/18	0.0	s	$T_g$	TG	Golgi tendon organ lead time constant	
	0.0	0.0	s	$T_z$	TZ	Golgi tendon organ lead time constant	
	0.0	0.0	s	$T_p$	TP	Golgi tendon organ lag time constant	
1.	1.	N/N	$K_a$	XKAA	Gain of force activation dynamics	NM Force Activation	

TABLE 1. (Continued)

FILE LINE NO.	TYPICAL VALUES			PARA- METER	FORTRAN NAME	DEFINITION	
	VIBRATION EXPERIMENTS*	RIPE QUALITY EXPERIMENTS*	UNITS				
9	18.	18.	kg	M <sub>T</sub>	XMT	Torso mass	Torso
	0.15	0.3	m	L <sub>T</sub>	XLT	Torso c.g. to hips pivot length	
	0.8	0.8	kg·m <sup>2</sup>	I <sub>T</sub>	ZIT	Torso inertia	
	10.	-15.	deg	θ <sub>T</sub>	TET	Angle of XLT from vertical	
	16.75	40.	$\frac{N \cdot m}{rad/s}$	B <sub>TB</sub>	BTB	Torso damping	
	500.	500.	$\frac{N \cdot m}{rad}$	K <sub>TB</sub>	XKTB	Torso stiffness	
10	4.34	3.1	kg	M <sub>H</sub>	XMH	Head mass	Head/Neck
	0.3	0.15	m	L <sub>TN</sub>	XLTN	Torso c.g. to neck/ torso pivot	
	0.039	0.0303	kg·m <sup>2</sup>	I <sub>H</sub>	ZIH	Head inertia	
	5.	-5.	deg	θ <sub>TN</sub>	THTN	Angle of XLTN	
	0.0	0.126	$\frac{N \cdot m}{rad/s}$	B <sub>HN</sub>	BHN	Head/neck damper	
	1.	15.	$\frac{N \cdot m}{rad}$	K <sub>HN</sub>	XKHN	Head/neck stiffness	
	0.0	0.025	m	L <sub>H</sub>	XLH	Head c.g. to head/ neck pivot length	
	70.	60.	deg	θ <sub>H</sub>	TH	Angle of XLH	
	0.0	1.	-	C <sub>H</sub>	CH	Head/neck compliance parameter (CH = 0. Locks had on neck)	
11	13.	13.	deg	θ <sub>L</sub>	THL	Seat (hips) tilt angle	Torso
	0.3	0.3	m	L <sub>s</sub>	XLS	Torso c.g. to shoulder length	
	5.	-5.	deg	θ <sub>s</sub>	THS	Angle of XLS	
	0.75	0.6853	m	V <sub>D</sub>	VD	Viewing distance	Display
	0.0	0.0	N/m/s	B <sub>AR</sub>	BAR	Arm rest damper (normal)	Arm Rest
	0.0	0.0	N/m	K <sub>AR</sub>	XKAR	Arm rest stiffness (normal)	
	0.0	0.0	N/m/s	B <sub>T</sub>	BAT	Arm rest damper (tangential)	
	0.0	0.0	N/m	K <sub>T</sub>	XKAT	Arm rest stiffness (tangential)	
	0.0	0.0	m	L <sub>ER</sub>	XLER	Elbow to arm rest distance	
	0.0	0.0	-	-	ARME	Fraction of arm weight on arm rest	

TABLE 1. (Concluded)

FILE LEVEL NO.	TYPICAL VALUES			PARA- METER	FORTRAN NAME	DEFINITION	
	VIBRATION EXPERIMENTS*	RISE QUALITY EXPERIMENTS*	UNITS				
12	0.0	1.24	kg	$M_N$	XMN	Neck mass	Neck/Torso
	0.1	.12444	m	$L_N$	XLN	Neck length	
	0.0	0.0024	kg·m <sup>2</sup>	$I_N$	ZLN	Neck inertia	
	-20.	-30.	deg	$\theta_N$	THN	Angle of XLN	
	0.25	0.0	$\frac{N \cdot m}{rad/s}$	$B_{NT}$	BNT	Neck/torso damper	
	50.	50.	$\frac{N \cdot m}{rad}$	$K_{NT}$	XNNT	Neck/torso stiffness	
	0.05	.06222	m	$L_{N1}$	XLN1	Neck c.g. to neck/torso pivot	
-30.	-30.	deg	$\theta_V$	THV	angle of line of sight	Display	

TABLE 2. LISTING OF BIODYN-78 CATALOG FILES

VIBRATION EXPERIMENTS  
(file name B.19)

STIFF STICK

1.372 .29 .44 .0120 40.  
 1.017 .305 .5 .0152 145.  
 .31 2. 13900. .557805E-04 .01 .61 13900. 1.  
 14. 1290.08 29585.27  
 2. 1. 80. 40. 2.43123 104.39969 1. 71519. 0.  
 5. .0909 0. 0. .020437203 .09090939 .08988764  
 .8 16. 0. .5 .05555555 0. 0. 1.  
 18. .15 .8 10. 16.75 500.  
 4.34 .3 .039 5. .00 1. .0 70. 0.  
 13. .3 5. .75  
 0. .1 0. -20. .25 50. .05 -30.

RIDE QUALITY EXPERIMENTS  
(file name B.51)

HEAD-NECK-TOE50 ONLY

0.000 .27 .44 .0000 40.  
 0. .305 .5 .0000 145.  
 .00 0. 13900. .557805E-04 .00 .61 13900. 1.  
 14. 315. 49360.  
 2. 0. 30. 40. 0. 0. 1. 119322. 0.  
 0.  
 0.  
 18. .30 .8 -15. 40. 500.  
 3.1 .15 .0303 -5. .126 15.0 .025 60. 1.  
 13. .3 -5. .6853  
 1.24 .12444 .0024 -30. .00 50. .06222 -30.

TABLE 3. RESPONSE VARIABLES

MATRIX COLUMN NUMBER	RESPONSE VARIABLE NAME	MATRIX COLUMN CODE*	UNITS	POSITIVE DIRECTION	DEFINITION AND USAGE
1	C	MCY	m or M	Forward	Stick output ( $k_c$ s used to scale as force)
2	$f_{ca}$	FCA	N	Forward on Stick	Interface force at stick grip
3	$\Delta z_1$	MZ1	m	Upward	Vertical shoulder deflection relative to platform ( $z_3 - z_p$ )
4	$\Delta \theta_1$	DT1	rad	Pitch up	Upper arm angle
5	$\Delta \theta_2$	DTA	rad	Pitch up	Lower arm angle
6	$f_{1y}$	F1Y	N	Up on upper arm	Vertical interface force at elbow
7	$F_M$	MFM	N	forward	Muscle model force referred to upper arm c.g.
8	$L_1$	ML1	m	forward	Grip interface deflection (stick relative to lower arm)
9	$F_{1X}$	F1X	N	Forward on upper arm	Horizontal interface force at elbow
10	$x_m$	MOM	m		Internal state in muscle model
11	$f_{ns}$	FNS	N	Forward on upper arm	Horizontal interface force at shoulder/upper arm
12	$f_{vs}$	FVS	N	Up on upper arm	Vertical interface force at shoulder/upper arm
13	$x_s$	MXS	m	Forward	Horizontal shoulder deflection relative to platform ( $x_s - x_p$ )
14	$\Delta \theta_T$	DTT	rad	Pitch up	Torso rotation
15	$f_{nh}$	FNH	N	Forward on head	Head/neck interface force
16	$\Delta \theta_H$	DTH	rad	Pitch up	Head rotation
17	$f_{vh}$	FVH	N	Up on head	Head/neck interface force
18	$f_{by}$	FBY	N	Up on Torso	Vertical hips/torso interface force
19	$f_{bx}$	FBX	N	Forward on hips	Hips/torso interface force

\*Note: Small "m" represents a typed-blank space.  
 †Note:  $\Delta \theta_1$  (Column 4) means small signal perturbation of  $\theta_1$  given in Fig. 2

TABLE 3. (CONCLUDED)

MATRIX COLUMN NUMBER	RESPONSE VARIABLE NAME	MATRIX COLUMN CODE*	UNITS	POSITIVE DIRECTION	DEFINITION AND USAGE
20	$u_p$	U <sub>UP</sub>	m	Up the seat back	Internal state in hip model.
21	$u_{bp}$	U <sub>BP</sub>	m	Up the seat back	Hip deflection relative to platform (parallel to seatback)
22	$x_1$	$\dot{y}_1$	rad	Pitch up	Internal state in muscle model
23	$\Delta\theta_N$	D <sub>IN</sub>	rad	Forward on neck	Neck rotation
24	$f_{iN}$	F <sub>NN</sub>	N	Up on neck	Neck/torso horizontal interface force
25	$f_{vN}$	F <sub>VN</sub>	N	Up relative to display	Neck/torso vertical interface force
26	$R_{iPR}$	R <sub>PD</sub>	deg		Head Point of Regard relative to a display on the platform
27	$\alpha_a$	$\dot{y}_{AA}$	N		Muscle model command out of spinal cord
28	$P_a$	$\dot{y}_{FA}$	N		Commanded force out of force activation dynamics
29		F <sub>AA</sub>	N		Internal state in force activation dynamics
30	$\alpha_g$	$\dot{y}_{AG}$	N		Output of golgi tendon organ sensors
31	$\alpha_c$	$\dot{y}_{AC}$	N		Spinal cord command
32	$A_E$	$\dot{y}_{AE}$	N		Error between neuromuscular command and proprioceptive sense of stick force
33	$x_{sp}$	X <sub>SP</sub>	m		Muscle length change sensed by spindle model
34		D <sub>PN</sub>	m		Relative normal deflection of arm and rest
35		D <sub>RT</sub>	m		Relative tangential deflection of arm and rest
36		D <sub>ZH</sub>	m		Vertical component of head motion relative to platform

\*Note: Small "y" represents a typed-blank space.



TABLE 4. FORCING FUNCTION VARIABLES

COLUMN NUMBER	FORCING FUNCTION VARIABLE NAME	COLUMN CODE*	UNITS	POSITIVE DIRECTION	DEFINITION AND USAGE
1	$a_{zp}$	AZP	g	Upward	Platform acceleration (vertical)
2	$z_p$	DZP	m	Upward	Platform deflection (vertical)
3	$a_{xp}$	AXP	g	Forward	Platform acceleration (horizontal)
4	$x_p$	DXP	m	Forward	Platform deflection (horizontal)
5		MPD	N	Forward	Force input to stick (for testing)
6		EZP	m	Upward	Special Platform deflection (vertical)†
7		BXP	m	Forward	Special Platform deflection (horizontal)†

\*Small "y" represents a typed-blank space.

†These are used to get transfer functions of  
Inertial shoulder (or head) motion  
Platform motion