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# Analysis of Head and Neck Dynamic Response of the U.S. Adult Military Population

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# ANALYSIS OF HEAD AND NECK DYNAMIC RESPONSE OF THE U.S. ADULT MILITARY POPULATION

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Human subject data collected in the program of impact acceleration tests being conducted at the Naval Biodynamics Laboratory were analyzed to investigate the relationships between dynamic head/neck response and biomechanical properties of the neck. Study of these data with head/neck motion simulation models has yielded important information pertinent to

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eventual construction of improved anthropomorphic dummies and has helped to improve the predictive capabilities of mathematical models.

A two-dimensional simulation model (MVMA 2-D) used to determine which biomechanical parameters are most important in influencing head/neck dynamics in -Gx impact. In addition, values for these parameters were established (if previously unknown) and sensitivity of response characteristics to variation of parameter values was estimated.

The development of a three-dimensional simulation model (VOM 3-D) was expanded on the basis of findings from the two-dimensional simulation work. Initial simulations of NBDL +Gy tests with the three-dimensional model indicate that this model will be of basic importance in establishing properties of the human neck which govern dynamic response to accelerations not parallel to the plane of symmetry of the body.

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# I. INTRODUCTION

The Biomedical and Biomathematics Departments of the Highway Safety Research Institute have completed Phase I of a study conducted in cooperation and conjunction with the Naval Biodynamics Laboratory: "Analysis of Head and Neck Dynamic Response of the U.S. Adult Military Population" (Contract No. N00014-81-K-0603, July 1981 - June 1982). Phase II of this study commenced without interruption on 1 July 1982.

The general purpose of this study is to analyze and utilize human subject data generated at NBDL with the goal of understanding and explaining the mechanisms involved in head and neck dynamic response. Much of the work involves use of computer models for simulation of subject response. Phase I effort involved use of both two-dimensional and three-dimensional models in studying response to -Gx and +Gy acceleration inputs. As a result of Phase I -Gx simulations with the MVMA Two-Dimensional Model (1-4), head and neck responses in the sagittal plane are now well understood. Use of the VOM Three-Dimensional Model (5,6) in Phase II for additional study of +Gy NBDL tests and also study of -Gx/+Gy tests will lead to an understanding of the mechanisms involved in a general three-dimensional response. Modeling and analysis efforts will be conducted with the ultimate objective of extracting, from NBDL data base, information on the head/neck system necessary to accomplish the primary objectives of the NBDL research effort: (1) to develop design criteria for construction of dummies which will closely reproduce man's response to crash acceleration, and (2) to define the envelopes of impact acceleration which result in injury.

## II. BACKGROUND

The program of impact acceleration tests being conducted at NBDL (7-17) using human volunteer subjects has been of particular importance among efforts over the past twenty-five years to gain an understanding of human impact response. This effort has resulted in the most extensive body of experimental data that exists for human head/neck dynamic response. This work has involved precise measurement of the complete input acceleration to the head and neck (measured at the first thoracic vertebra), precise measurement of the dynamic response of the head and neck to the input acceleration, and development of data acquisition and automatic processing systems.

The experimental data obtained by Ewing and Thomas at NBDL (formerly NAMRL) provide a unique opportunity to investigate the relationships between dynamic response and biomechanical properties of human subjects. Study of these data will yield important information for "improved" anthropomorphic dummy development and improved predictive capabilities of mathematical models. Extensive use was made of NAMRL data in a 1975-76 study by HSRI entitled "A Prediction of Response of the Head and Neck for the U.S. Adult Military Population to Dynamic Impact Acceleration from Selected Dynamic Test Subjects" (ONR Contract N00014-75-C-1077) (18,19).

# III. METHODS AND PROCEDURES

Methodology has been discussed in considerable detail with NBDL staff in two technical meetings which took place during Phase I. The discussion on methodology which follows in this section is abbreviated since the Scientific Director of the project at NBDL (Dr. D. J. Thomas) has indicated a preference for a brief Annual Report so that Phase II work can proceed with minimal interruption.

Technical meetings were as follows: 1) After a period during which startup work was carried out, Dr. Bowman and Dr. Schneider made a trip to Michoud Station September 17-18 for the purpose of meeting with NBDL staff. In meetings with Dr. J. Wenger, Dr. D.J. Thomas, Dr. C.L. Ewing, Cdr. Waldeisen, and Mr. L. Lustick, project procedures, methodology, and goals were discussed. It was agreed that HSRI would prepare a request for test data needed for analysis. 2) Mr. L. Lustick of NBDL met at HSRI with Dr. Bowman and Dr. Schneider June 2-3 for the purpose of reviewing work accomplished during the first year of the project. Phase I methodology and results were discussed as well as goals for the second year.

## A. Project Goals

The long-term objective of the University of Michigan project is to extract from the NBDL data base information on the head/neck system necessary to accomplish NBDL's basic research goals of developing an improved anthropomorphic dummy for dynamic crash testing and defining human injury tolerance levels in terms of dynamic response parameters. An important result of work during the first year of the project was the laying of a firm base for accomplishing the specific goals of the project. Thus, the first year's effort included development of procedures and software for working with NBDL dynamic response data and also for display and assessment of simulation response data. The primary specific goals of the first year were to establish, to the extent possible, the biomechanical properties of the human neck that pertain to: 1) dynamic response in the sagittal plane, i.e., responses that would result from x-vector acceleration inputs to the head/neck system (e.g., -Gx), and 2) dynamic response out of the sagittal plane, i.e., responses that would result from y-vector acceleration inputs (e.g., +Gy). Follow-on effort (Phase II) would then fully establish the nature of biomechanical coupling in the neck and explain NBDL test results for -Gx+Gy acceleration inputs. This coupling was examined to some extent even in the first year since head/neck system asymmetries cause coupled motions to occur even when there is a pure +Gy input. This project's primary overall goal is to find the simplest possible biomechanical description of the neck which will explain all important aspects of head/neck motion resulting from a completely general acceleration input. Such a biomechanical model will serve as a design plan for a dummy neck which: a) reproduces human dynamic response with reasonable accuracy, and b) is possible to construct.

B. Startup on -Gx Simulation Work

Our first effort on this project involved reviving data files and computer programs that were used in our 1975-1976 study. As the first part of our simulation work in the current project was to push off from the -Gx work done in the earlier study, we were able to expedite our start by using as a base the old sled test data, simulation model data sets, simulation results, and data processing programs. Effort was expended toward simplifying the procedure by which plot output is obtained for graphical representation of simulation results. This required revision of old software and development of new software.

The computer model used for -Gx simulations in the current study is the same as that used in the earlier project, viz., the MVMA Two-Dimensional Crash Victim Simulator, which was developed at, and is maintained by, the University of Michigan Highway Safety Research Institute.

C. Startup on +Gy and -Gx+Gy Simulation Work

NBDL work has showed that while important aspects of head/neck response to +Gy and -Gx+Gy inputs can be described in terms of just two degrees of freedom, the responses are not planar in nature. Thus, a three-dimensional head/neck model is required to investigate head/neck dynamics for inputs in these vector directions. The VOM (Vehicle Occupant Model) Three-Dimensional Model (5,6) developed at HSRI, was selected for use in this study for three primary reasons: 1) The model was developed by one of the Principal Investigators (Dr. Bowman) and therefore is the best understood of existing three-dimensional models and could with minimal difficulty be modified to meet project needs. 2) The model includes a forcing feature ideally suited to the type of T1-motion input planned for simulation work in this study. 3) Features of the neck model in VOM 3-D are in nearly a one-to-one correspondence with features of the MVMA 2-D neck model (also developed by Dr. Bowman). This facilitates comparison between -Gx simulations (MVMA 2-D) and three-dimensional simulations having components of excitation in both the x and y vector directions.

One of the first tasks performed on the present project was to revive the VOM 3-D model from computer tape, as it had not been used for several years, and make checkout simulations. Supplemental software was then developed to improve the utility of the model with regard to the anticipated needs of the project. Specifically, three types of software needs were identified. 1) A plotting package for VOM 3-D was developed by making modifications to the package already developed for use with MVMA 2-D. 2) The format of printout of simulation data was revised, making it much more useful and easier to examine. 3) Additional response-related quantities were calculated and included in tabular time-history printouts. The new quantities included ones that have been measured or calculated by NBDL in previous work with the test data, e.g., the so-called "RANGLE angle," which describes the orientation of the head angular velocity vector.

D. <u>-Gx Simulations with MVMA 2-D</u>

A primary goal of this project is to establish otherwise indeterminable human neck parameter values by modeling and by use of a large base of human subject dynamic test data. The determined <u>biomechanical</u> description of the head/neck system can then serve as the basis for construction of a <u>mechanical</u> head/neck analog in an anthropometric dummy. Only limited biomechanical data relating to the human neck are currently available in the literature. Most of that is from tests with cadavers.

In this study we have taken the best available biomechanical data as a base for our simulations. The basic procedure, then, is to fill in unavailable data and improve estimated data by comparing observed head/neck responses in NBDL tests with responses predicted by the simulation model. Differences between observed and predicted responses indicate necessary adjustments to estimated values for biomechanical parameters. The process of iterative comparison of observed and simulated responses, in addition to leading to an accurate biomechanical description of the human neck structure, also clarifies the causes of important aspects of the dynamic response and indicates sensitivity to variation of parameters that will be part of the mechanical analog design.

Simulations were made for -Gx sled runs at different acceleration levels (6g,15g) and also for different head/neck orientations (NUCU, NUCD, NFCU, NFCD). Simulations for more than a single "baseline" sled run configuration (e.g., 15g/NUCU) make possible the refinement of the analytical model and the biomechanical parameter values. More importantly, demonstration that the model (with established values) can predict responses properly for a range of conditions is necessary for validation of results.

E. Processing of NBDL +Gy Data

A procedure was established and software written for retrieving data from 1981-1982 NBDL magnetic tapes made to specifications described in the H.G. Williamson memorandum of 12

February 1982. These data were to be plotted together with simulation data as an aid for evaluation of simulation results. Also, NBDL T1-motion data were needed as a forcing input to the base of the neck in the simulations.

Coordinate transformations had to be performed on all NBDL data variables before the data could be plotted for meaningful comparison with VOM 3-D simulation results. The transformations necessary related to differences of four types:

1. The orientation of NBDL x-y-z axis systems is different from the VOM orientation. Specifically, the positive z axis is "up" for NBDL but "down" for VOM. Also, the y axes are in opposite directions.
2. The NBDL head anatomical coordinate system origin is at the midpoint of the line connecting the left and right external auditory meati. The VOM head coordinate system origin is at the head center of gravity (with instrumentation).
3. The axes of the NBDL head anatomical coordinate system lie in and perpendicular to the Frankfort plane. The axes of the VOM head coordinate system are along the principal axes for the head inertia tensor. In general the head principal axes are in an orientation with respect to the NBDL axes that is rotated in the midsagittal plane.
4. Euler angles are defined differently for VOM and NBDL data, both with respect to order of rotation and direction (sense) of rotation.

F. Analytical Model Development for VOM 3-D

Most of the three-dimensional simulation effort pertained to making analytical model and computer code modifications to VOM 3-D. The purpose of this work was to give this model all the capabilities of MVMA 2-D, as regards representation of the neck, that had been established to be important in -Gx work. In addition this work generalized all important features so that they may be expressed fully in three dimensions while reducing to MVMA 2-D equivalent representations for the special case of planar motion. For example, allowance is made for specification of nonlinear static loading curves for neck angular deflection (bending) - at condyles and C7/T1 separately - with general dependence on the direction toward which bending occurs. Such model features as this are state of the art and are not found in any other known three-dimensional crash victim simulation model. These and other features added to VOM 3-D in the second six months are itemized in the list below.

1. neck mass added
2. different neck properties for compression and elongation
3. hysteretic energy loss allowed with bilinear unloading from all types of neck deformation
4. different viscous damping for loading and unloading for all types of neck deformation
5. all biomechanical parameters for bending of neck are tabular functions of heading angle
6. asymmetric stop angles allowed for neck twist
7. simplified format for specifications of joint

viscoelastic properties and excitation of degrees of freedom

8. added off-axis joint sinuses for bending stops

9. added load/reload curves that are dependent on angular position of loading relative to that of unloading

G. -Gx and +Gy Simulations with VOM 3-D

The first simulations made with the VOM 3-D model were -Gx simulations. The purpose of this was to establish the ability of VOM 3-D to reproduce MVMA 2-D results when identical inputs are used for the two models.

Simulation work was then begun for NBDL +Gy runs. Run LX2313 (5.1g, Subject 93) was selected for the initial work. Sagittal plane neck properties determined in the -Gx work were retained for the +Gy simulations and made possible better than order of magnitude initial estimates for off-sagittal plane neck properties.

Data of Beier, et al. (20), were used in the development of head inertia properties for simulations with the three-dimensional model.

## IV. RESULTS AND DISCUSSION

### A. Baseline -Gx Simulations at 15g (NUCU)

The MVMA 2-D model was used to establish as accurately as possible the sagittal plane biomechanical parameters of the neck. Simulation results were compared against sled results averaged over five subjects. These simulations were of -Gx tests at 15g with neck-up, chin-up (NUCU) initial orientations. 1975 NAMRL data were used since newer data were not immediately available when the current project was begun.

Final results, which will be improved through study of head/ neck response for tests in other vector directions, represent a significant improvement over results from the 1975-1976 study. The comparison between test results and simulation results (15g) for the current study is illustrated in Figure 1 for head angular acceleration. The positive peaks agree well in phase and magnitude. The negative peak in the experimental data has a smaller amplitude than in the simulation data; the reason for this will be fully established in later work, but it is thought to relate to non-zero participation of yaw and roll modes in the sled tests. For comparison with Figure 1, Figure 2 illustrates 1975-1976 results for head angular acceleration.

MVMA 2-D neck biomechanical parameters relate to quasi-static loading properties, velocity-dependent damping, and quasi-static hysteretic energy loss. The 15g -Gx simulations have made reasonably clear the roles that individual parameters have in producing primary characteristics of head/neck dynamics. For example:

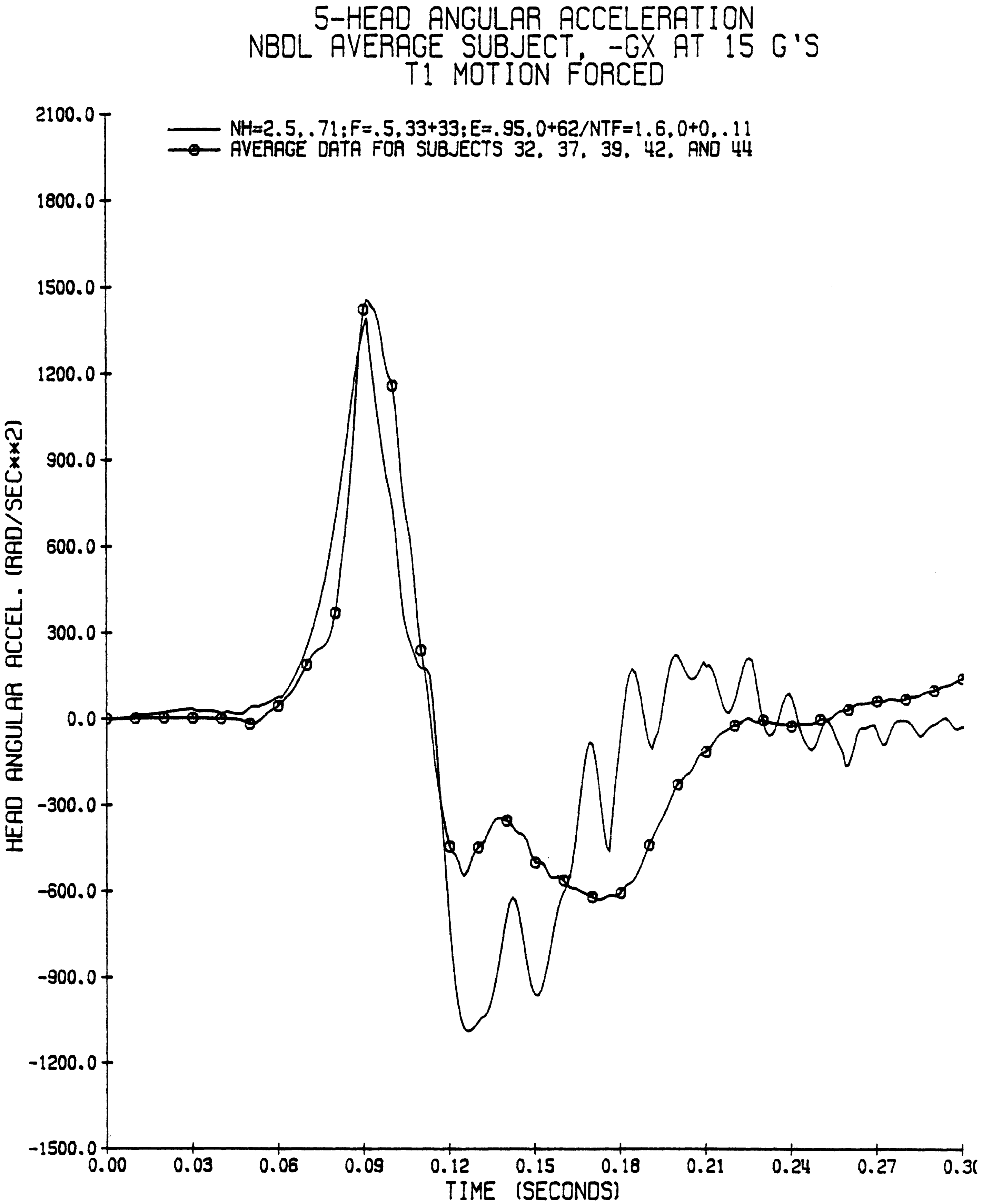


Fig. 1. Simulation and NBDL 1981-82 Results for Head Angular Acceleration for -Gx at 15 g

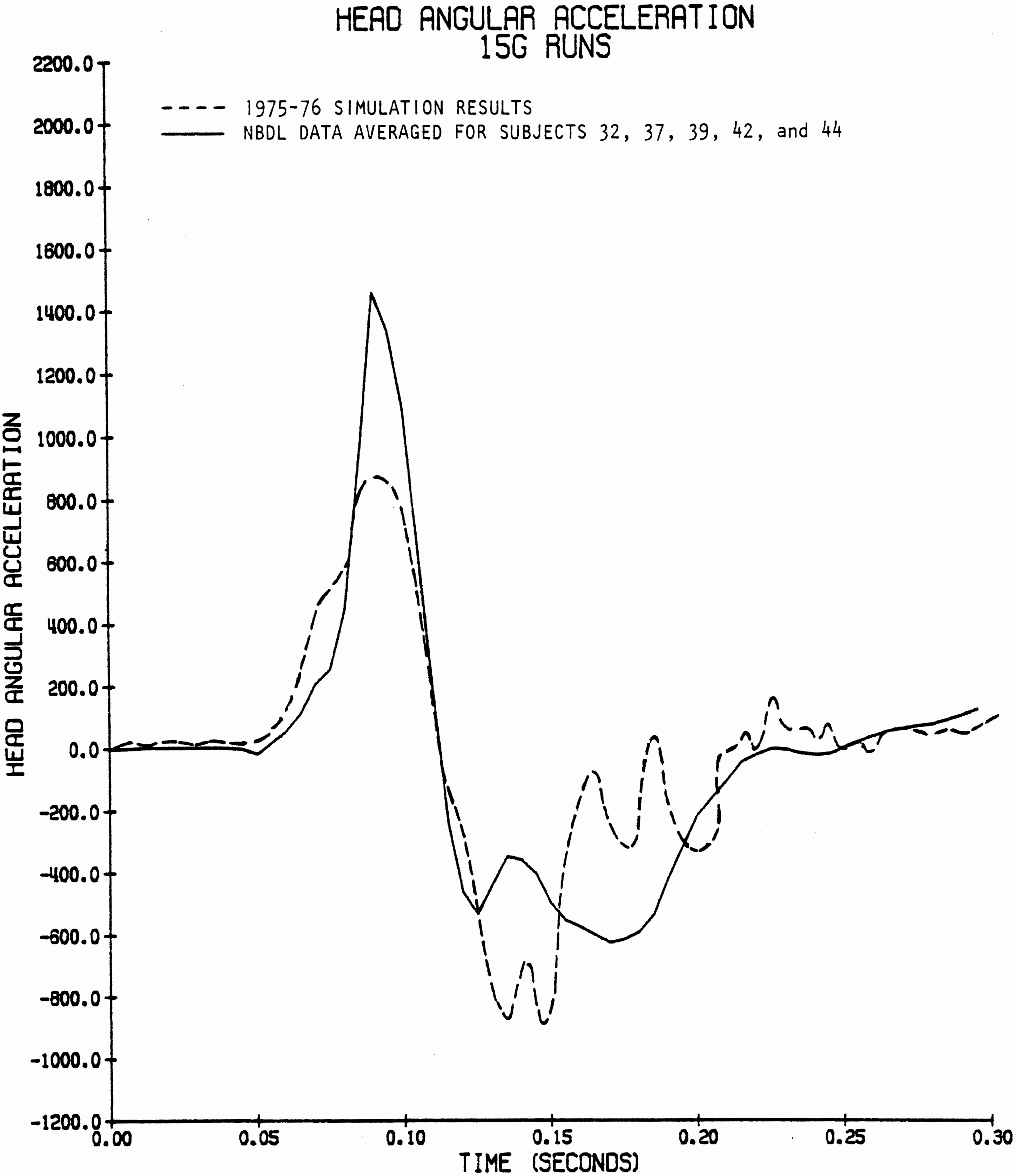


Fig. 2. Simulation and NBDL 1975-76 Results for Head Angular Acceleration for -Gx at 15 g

1) The normal extension at the condyles through the first 110 ms is strongly influenced by C7/T1 damping for loading in flexion and can result only if that damping is small.

2) The magnitude and shape of the positive peak in head angular acceleration are sensitive to proper phasing between head angle and tension force along the neck since it is the torque of this force acting about the head center of gravity which is primarily responsible for the angular acceleration of the head (76% at peak values as against 24% from the extension torque at the condyles). Parameters of primary influence are C7/T1 damping for loading in flexion, condyles damping for loading in extension, and neck elongation (tension) stiffness.

3) Smoothness and the low amplitude of head angular acceleration response after about 135 ms is strongly dependent on hysteretic energy loss for unloading from maximum neck elongation and maximum condyles flexion. In particular, the hysteresis for unloading from elongation must be nil while hysteretic energy loss from flexion unloading at the condyles must be no greater than about 50 percent.

B. Variation of Initial Head/Neck Orientation in -Gx Simulations

The effects of changing initial head/neck orientation in 15g -Gx impacts was investigated through simulations with the MVMA 2-D model. Experimental T1 motions for the NUCD, NFCU, and NFCD orientations were not available from the 1975-1976 study. Neither have appropriate data for more recent sled tests been included in materials provided to HSRI during the current study. Therefore, for the purpose of developing appropriate input data for the NUCD, NFCU, and NFCD simulations, initial head and neck angles were taken from the 19th Stapp paper by Ewing, et al. (12), and T1 motions for NUCD, NFCU, and NFCD were obtained by scaling NUCU T1 data in Tables 4 and 5 of that paper. Better data will be available in the follow-on study, but the simulation data obtained from the aforedescribed inputs already look good. Most of the effects of varying head/neck orientation as described in the Stapp paper are observed in the simulation responses. Of greatest significance is the MVMA 2-D prediction that the NFCD condition causes dynamic responses that differ markedly from those for the other orientations. In particular, maximum positive peaks in angular velocity and angular acceleration are preceded by a negative peak of comparable magnitude and all magnitudes for NFCD are severely reduced when compared with any of the other orientations. Figures 3 and 4 illustrate these simulation results for the four initial head/neck orientations.

The preliminary success of the MVMA 2-D model in simulating with reasonable accuracy the responses in -Gx for a complete range of head neck orientations bolsters confidence that 1) the analytical model represents the head and neck with at least good approximation, and 2) the set of biomechanical parameter values established in NUCU simulations approximate true values.

C. Variation of g Level in -Gx Simulations

The ability of the established biomechanical data to account

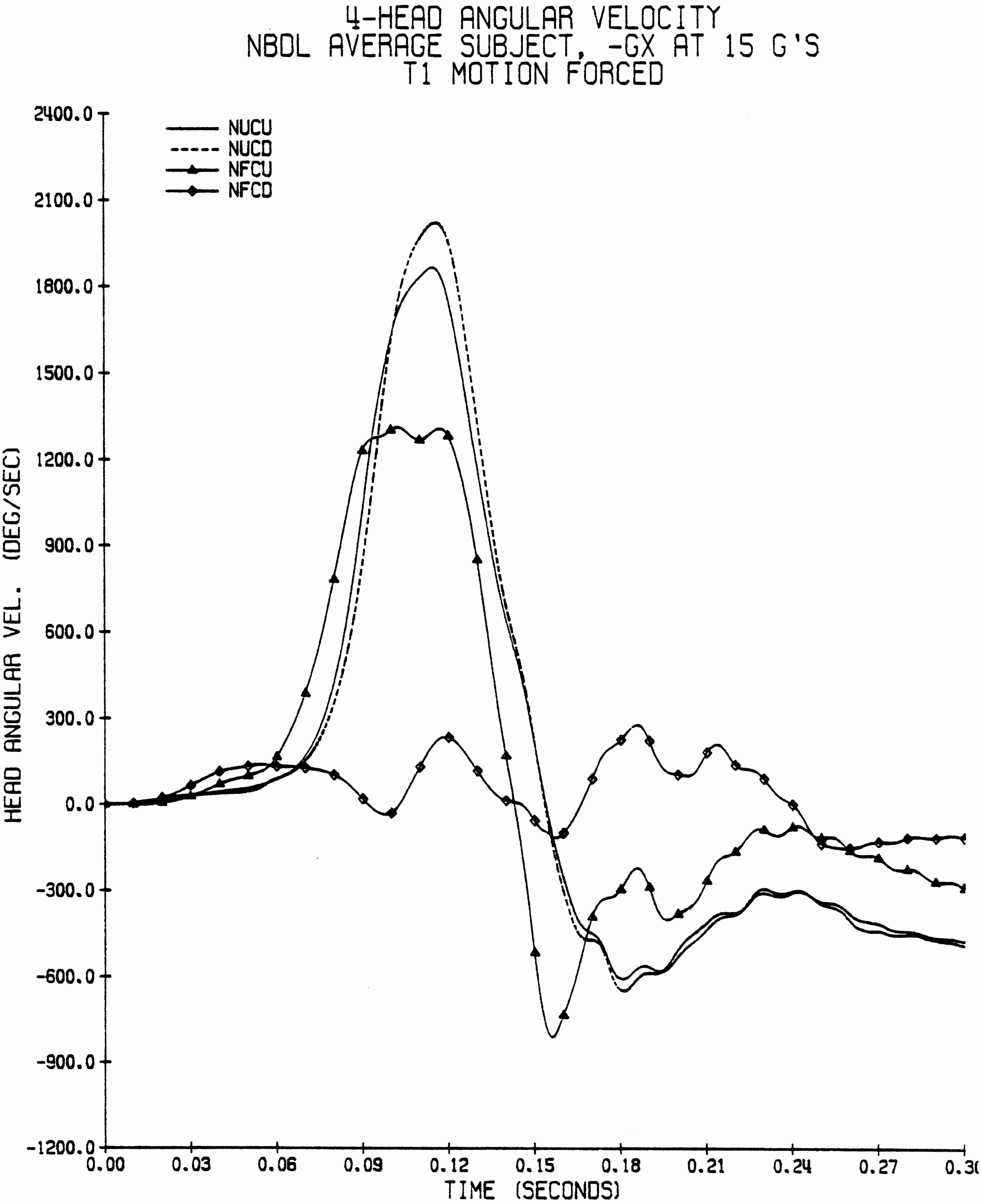


Fig. 3. Simulation Results for Head Angular Velocity for NUCU, NUCD, NFCU, and NFCD Initial Head/Neck Positions

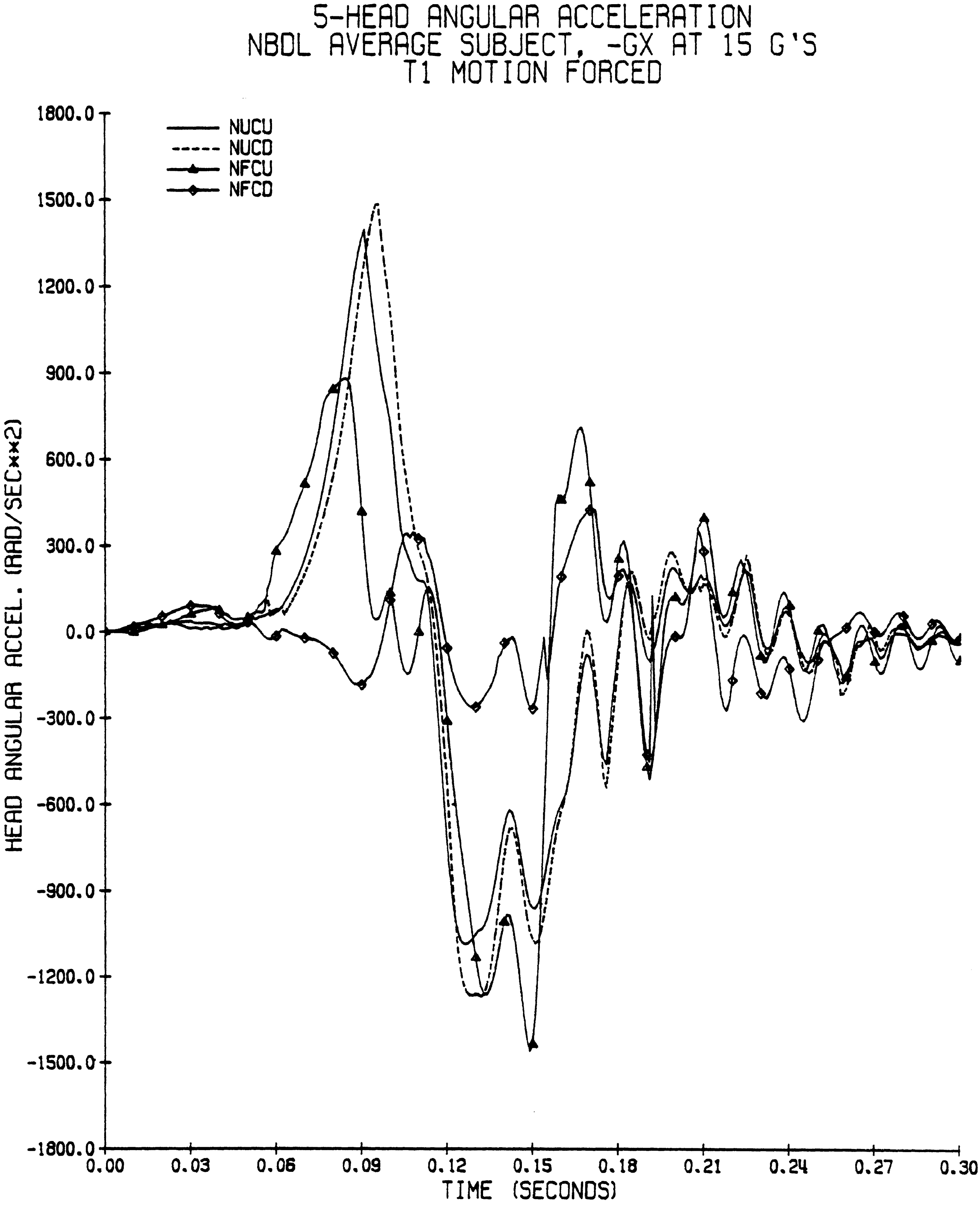


Fig. 4. Simulation Results for Head Angular Acceleration for NUCU, NUCD, NFCU, and NFCD Initial Head/Neck Positions

for magnitudes and phasing of dynamic responses in lower g-level -Gx tests was examined in a 6g simulation. Experimental and simulation results for head angular acceleration are shown in Figure 5. Agreement is not as good as obtained at 15g. This probably indicates a need to nonlinearize the loading curves for angular deflection of the neck, making them softer for small deflections and stiffer for larger deflections. Investigation of that possibility is planned.

D. Variation of Anthropometric Parameters in -Gx Simulations

In addition to the above described series of simulations, a set of six simulations was run in order to determine the sensitivity of responses to variation of anthropometric parameters (as opposed to biomechanical parameters), which will be different from subject to subject. Such parameters would normally not be varied in any series of simulations involving a given test subject since most are quantities which can be measured with reasonable accuracy, i.e., they are not values that can be considered estimates and thus subject to adjustment. The six simulations were comprised of a baseline run for a nominal 50th percentile adult male and five runs in which one of five anthropometric parameters was varied. These parameters were: neck length, S-I and A-P locations of head center of mass with respect to the occipital condyles, head mass, and head moment of inertia about the lateral principal axis. Parameter variations were from 50th percentile to 90th percentile values so that the variations in responses can be expected to represent near maximum departures from 50th percentile responses that will result over the entire

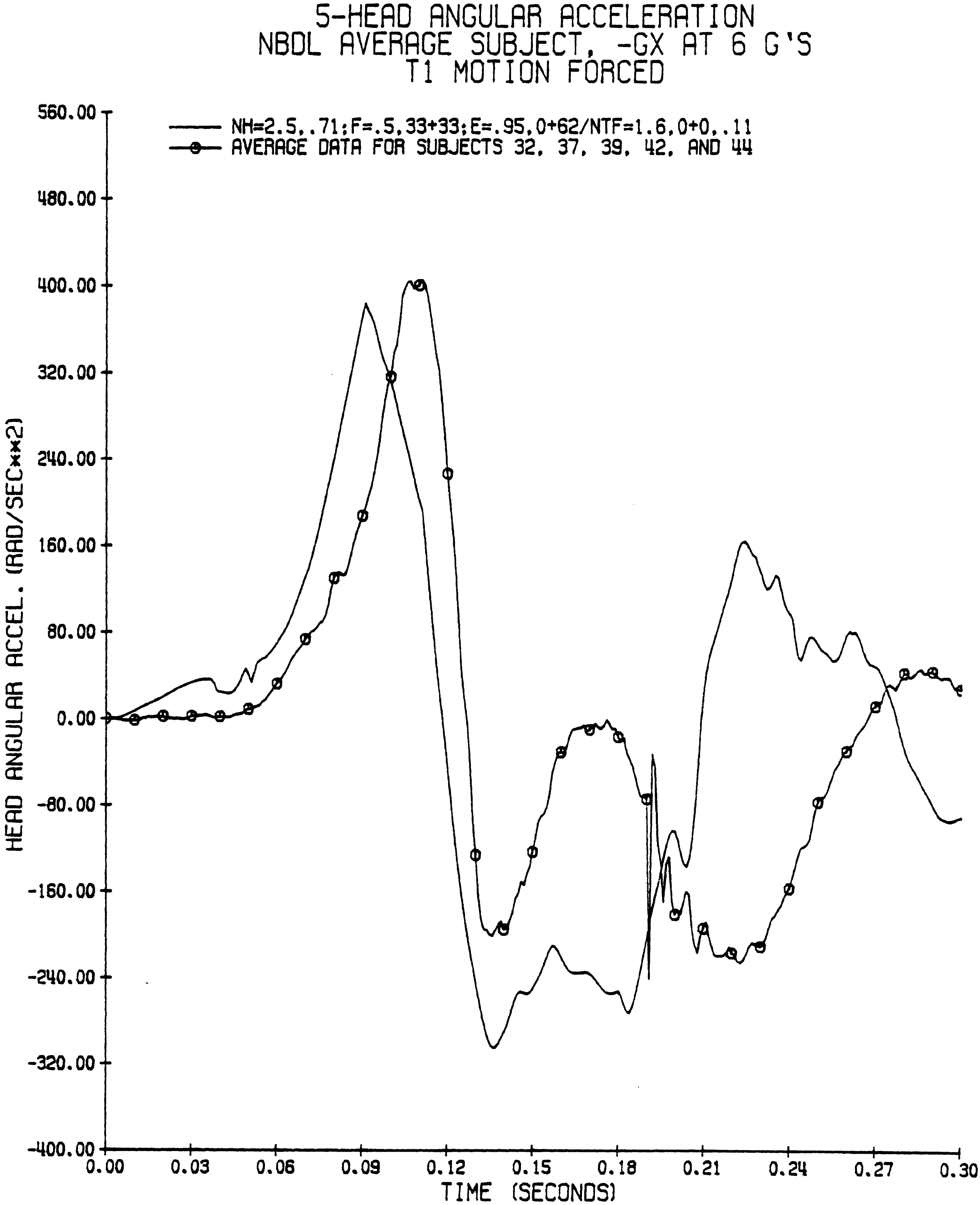


Fig. 5. Simulation and NBDL Results for Head Angular Acceleration for -Gx at 6 g

population. The preliminary findings, in brief, from these simulations are: a) Phasing of responses is unchanged by variation of any single head/neck anthropometric measure. b) Variation of S-I location of head center of mass has the smallest effect. Changes in head angular acceleration response are negligible. c) The variation of head moment of inertia has the most significant effect. The peak magnitudes (positive and negative) of head angular acceleration responses are changed by about five percent. d) The change in head mass causes about a two percent change in peak head angular acceleration response. e) Variations of neck length and A-P head center of mass location both have only small effects.

Since none of the head/neck anthropometric measures affects head angular acceleration response by more than five percent when varied from a 50th percentile value to a 90th percentile value, these preliminary findings suggest that head/neck anthropometry is probably not important in explaining variations between individuals (adults) in dynamic responses. Rather, we expect significant sensitivity to differences in neck biomechanics and initial conditions (e.g., head/neck orientation). Similar implications can probably be drawn from an independent NBDL study in which statistical analysis of response data showed no significant correlations between response parameters and anthropometric parameters. The simulation work done so far has not investigated the effects of maximum variation of several parameter values in combination. That is, the preliminary findings do not necessarily have any significant implications with regard to consistency of response differences between individuals of 50th percentile and 90th percentile height and weight (i.e., overall size), for whom most (not just one) of the head/neck anthropometry values can be expected to differ maximally. Rather, these findings have greater significance in relation to differences that might exist between individuals of similar height and weight.

E. Variation of Subject Strength in -Gx Simulations

Study of the effects of differing subject strengths is implicit in the procedure of progressively adjusting values for unestablished biomechanical parameters until an optimal match with experimental data is obtained. Thus, the importance of strength has been investigated to some degree in the 15g -Gx "average subject" simulations. A more critical examination of strength effects will result from HSRI simulations of single subjects in separate sled tests.

F. Comparison of MVMA 2-D and VOM 3-D in -Gx Simulations

After testing of new features of VOM 3-D in non-NBDL three-dimensional simulations, including matching of a run of the revised VOM 3-D with the unaltered model (side impact auto crash), VOM 3-D was tested against MVMA 2-D for the "average subject" in -Gx at 15g. A data set for VOM 3-D was prepared by direct transcription of values from the already established MVMA 2-D data set which yielded the MVMA 2-D results shown in Figure 1. VOM 3-D produced the results shown in Figures 6 and 7, which are plotted together with the MVMA 2-D results.

Differences between responses predicted by the two models are

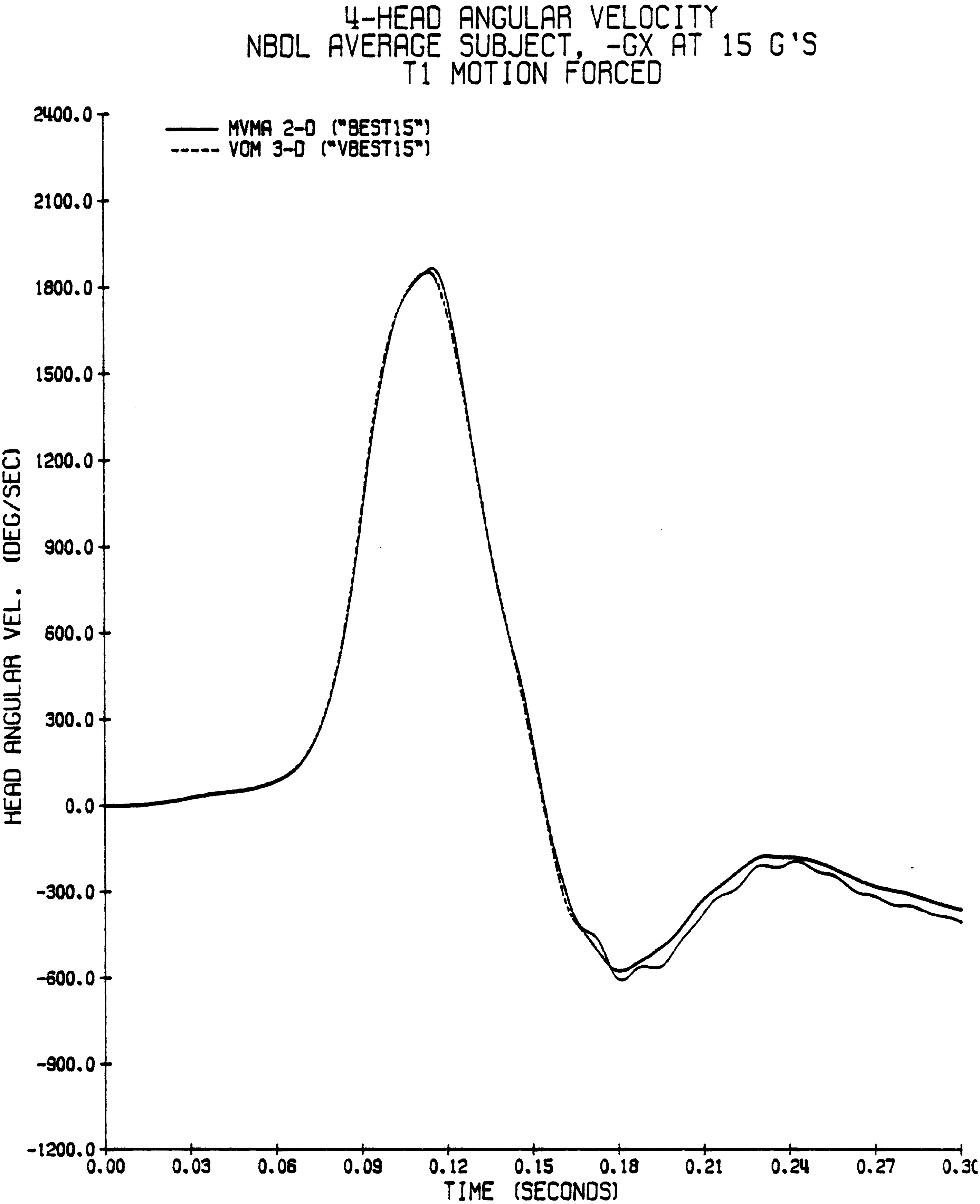


Fig. 6. MVMA 2-D and VOM-3-D Simulation Results for Head Angular Velocity for -Gx at 15 g

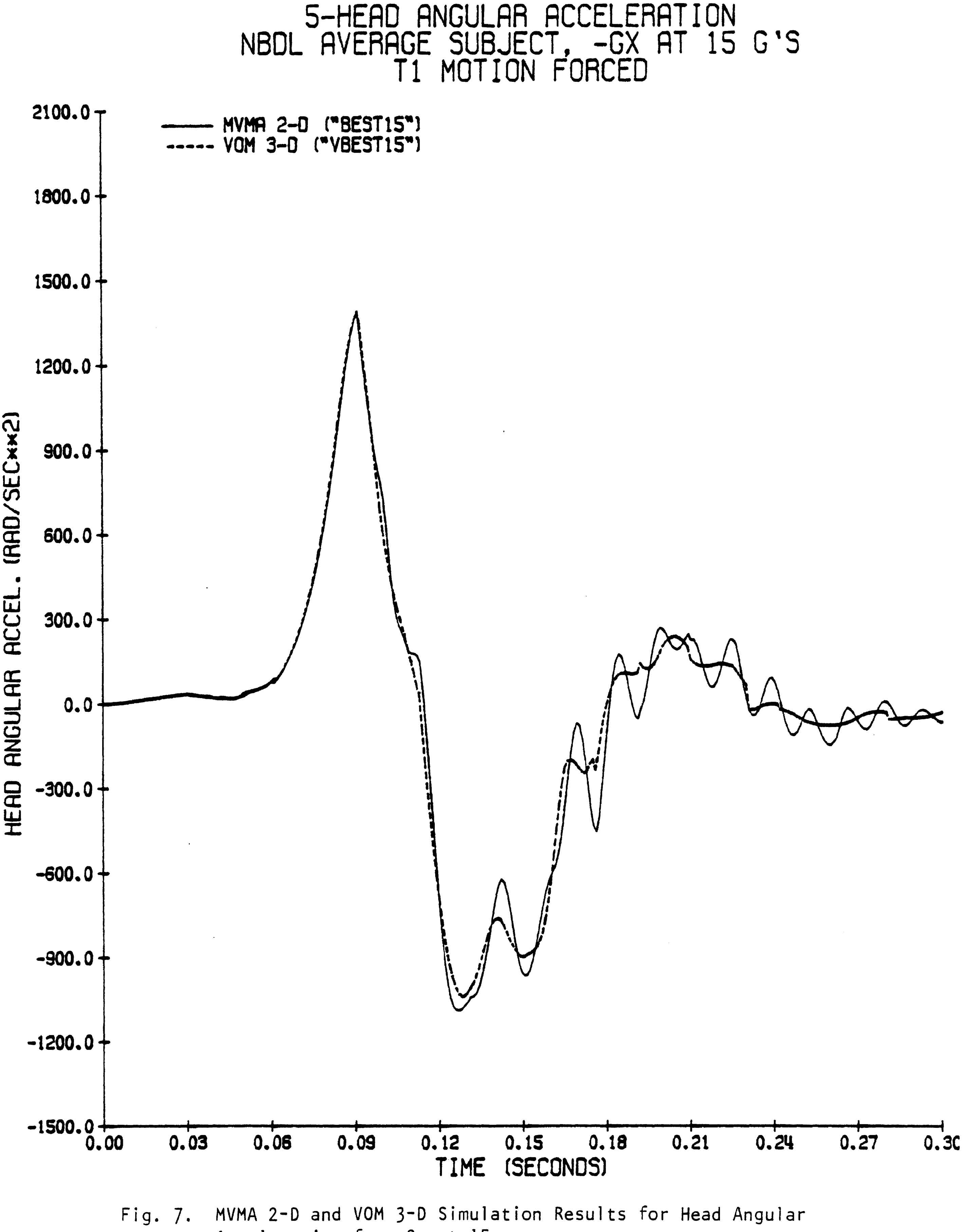


Fig. 7. MVMA 2-D and VOM 3-D Simulation Results for Head Angular Acceleration for -Gx at 15 g

minor and, in fact, probably fully explainable. The difference between the angular acceleration curves after 120 ms results primarily from the different methods used in the two models for driving the T1 motion. It is necessary to use an artificially introduced spring in the MVMA 2-D "driving element," and the spring rate used yields a natural frequency of 71 Hz. It is clearly this element which is responsible for the 70 Hz content seen in the response after 120 ms.

G. +Gy Simulations with VOM 3-D

Data for selected NBDL +Gy tests for Subject 93 were read from the computer tape provided during the second six months by NBDL. Formal examination of NBDL +Gy data done thus far has been for run LX2313 (5.1g). Data for input to VOM 3-D was prepared and film of the test provided by NBDL was examined in order that a preliminary understanding of +Gy dynamics might be developed. NBDL response data for run LX2313 were processed as discussed in Section III.E for the purpose of obtaining appropriate VOM 3-D initial conditions and also time histories for plotting with VOM 3-D results.

Early results from VOM 3-D simulations of run LX2313 are illustrated in Figures 8, 9, and 10, which show the three translational components of acceleration (in the laboratory frame) for the head anatomical origin. Phasing is good, and magnitudes are reasonable considering that these are early results and that values used for biomechanical parameters which affect motion out of the midsagittal plane were only order-of-magnitude estimates.

It may be observed that even the "chatter" after 190 ms

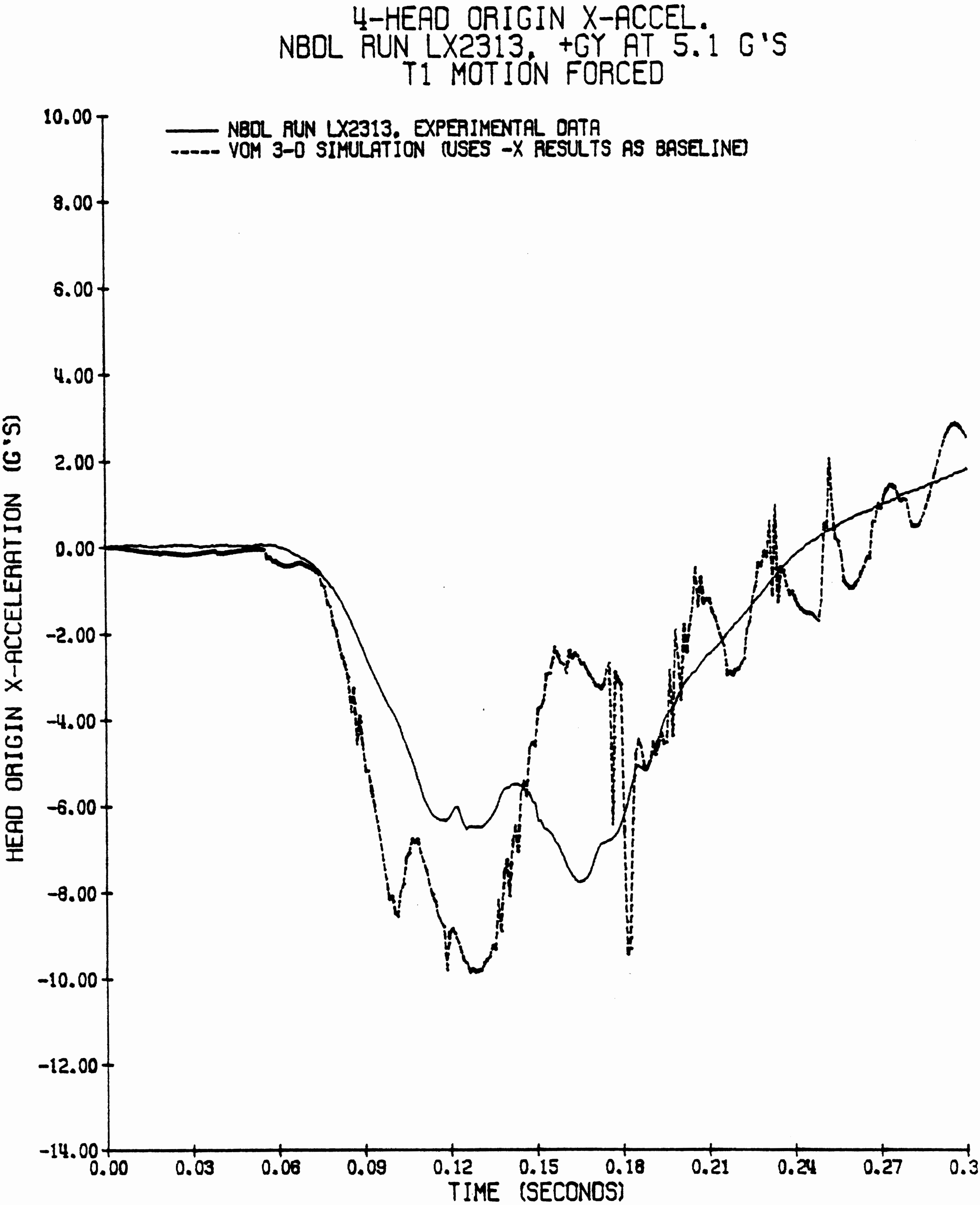


Fig. 8. Preliminary Simulation Results and NBDL Test Results for Laboratory Head Origin X-Acceleration for +Gy at 5 g

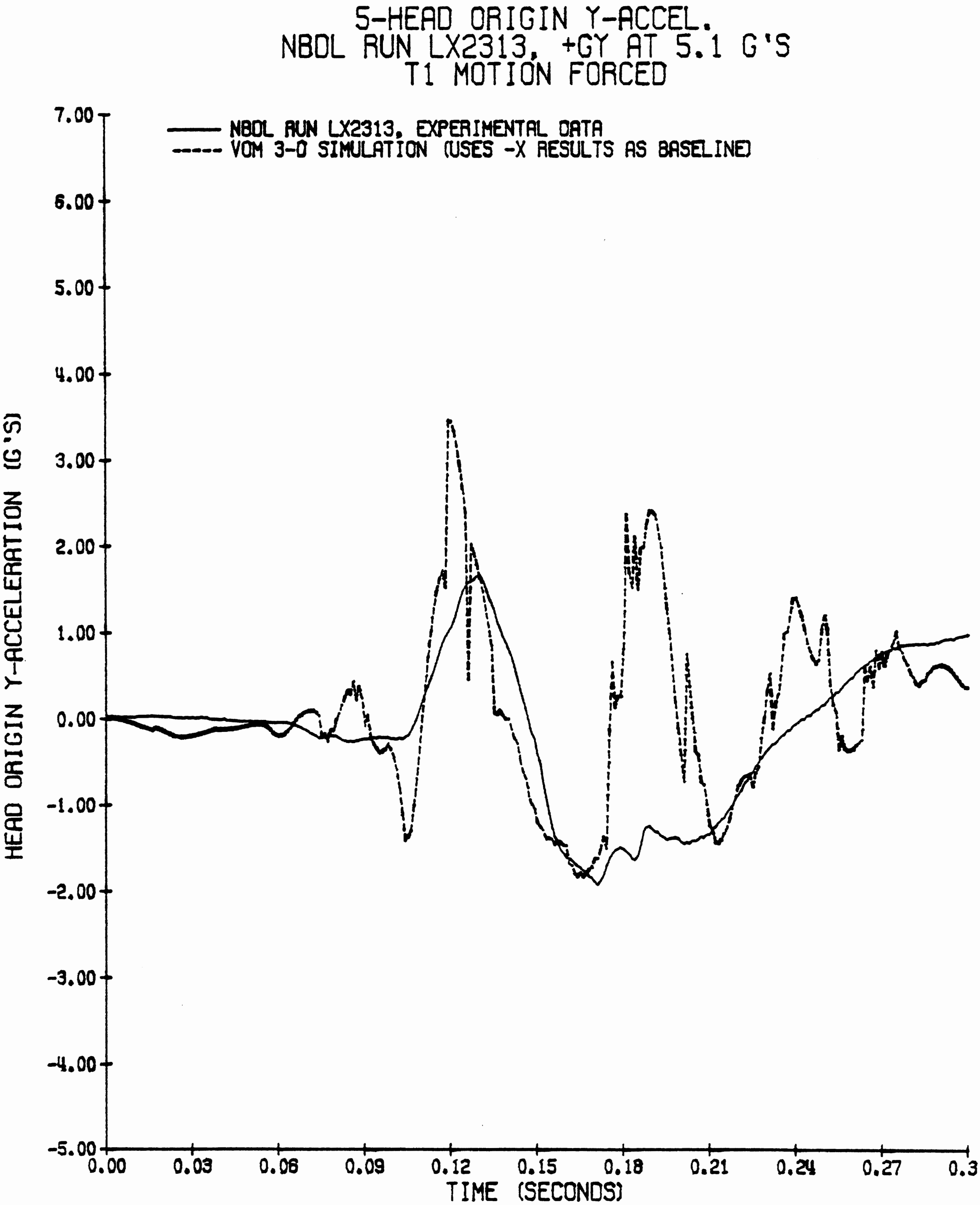


Fig. 9. Preliminary Simulation Results and NBDL Test Results for Laboratory Head Origin Y-Acceleration for +Gy at 5 g

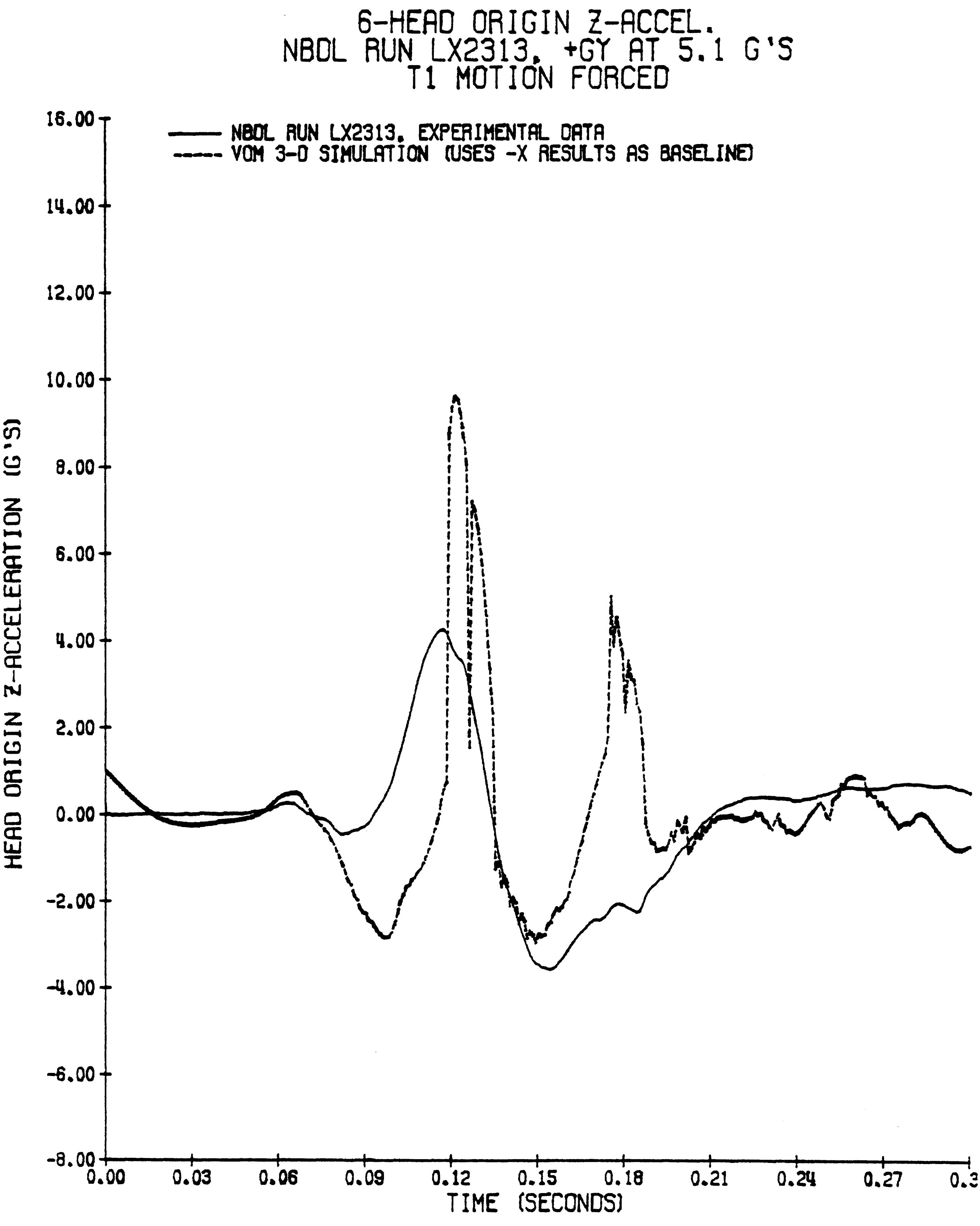


Fig. 10. Preliminary Simulation Results and NBDL Test Results for Laboratory Head Origin Z-Acceleration for +Gy at 5 g

follows the NBDL data moderately well in a mean value sense. This chatter is traceable to excessive activity at the lower neck joint, C7/T1, and probably results from too much hysteretic energy loss in load/unload/reload cycling. The biomechanical parameter governing hysteretic energy loss at C7/T1 was determined only for (midsagittal plane) flexion in the -Gx simulations (and not for extension) since only flexion occurred at C7/T1. There was therefore no evidence as to how hysteretic energy loss might vary as a function of the bending heading angle. This functional dependence (over 360°) as well as other unknown or estimated quantities will be determined by iterative adjustment through comparison of VOM 3-D results and NBDL data.

## V. REFERENCES

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