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**FORCE DETERMINATION SENSITIVITIES STUDY FOR FULL-
SCALE HELICOPTER GROUND VIBRATION TESTING**

Nick Calapodas and Keith Hoff

September 1989

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INTRODUCTION

One of the fundamental objectives of the U.S. Army Aviation Applied Technology Directorate's (AATD's) research and development efforts is to increase the reliability of the Army's airmobility force, which consists primarily of rotary-wing aircraft. Excessive vibrations have always been a problem for helicopters due to the vibratory airloads generated by the main rotor as it moves edgewise through the air. Maintenance and parts replacement cost awareness requires that potential vibration problems and their effects be diagnosed as early as possible in the helicopter development and fielding cycle. Although vibration levels have been lowered considerably by improved design and a variety of isolation or absorber systems, they are still of concern because rotorcraft are being flown faster and in more violent maneuvers where vibration levels are highest. In addition, more delicate instruments, more demanding visual and tactile tasks, and demands for accurate sensor and weapon pointing lead to requirements for very low vibration levels throughout much of the aircraft.

In general, the highest vibratory loads are generated by the main rotor and occur at blade passage frequencies, although there may be significant loads at other frequencies and from other sources. Vibration-reduction treatment, such as design of a rotor absorber or isolator, requires knowledge of rotor hub force and moment magnitudes and phasings. Simply reducing the largest hub load without consideration of other hub loads could worsen vibrations.

A methodology known as Force Determination (FD) which was developed in the early 1970's is applicable to early diagnosis of vibration-induced problems. FD is a method for determining the magnitudes and phasings of externally applied vibratory forces and moments using measured flight acceleration and ground vibration dynamic calibration test data obtained from transducers located on the airframe of a helicopter. Both types of testing, i.e., ground vibration and flight, are always conducted during the developmental phase of a helicopter. The method is nonrestrictive, and any point on the airframe anticipated to be subjected to externally applied vibratory forcing can be considered.

The subject method originated at Kaman Aerospace Corporation and was demonstrated under AATD funding. A laboratory verification program was conducted in the mid-1970's and the methodology was further demonstrated on an AH-1G COBRA in the late 1970's with very satisfactory results. These efforts are reported in References [1] and [2].

The objective of this program was to evaluate the limitations and accuracy of the FD method. This was accomplished by conducting controlled laboratory experiments to identify and minimize various sources of discrepancies between measured and calculated vibratory loads. This report presents the results of numerous sensitivity studies to assess the validity of FD for predicting magnitudes and phases of externally applied vibratory loads.

DESCRIPTION OF THEORY

The theory on which FD is based is presented in References [1] and [2] and is summarized below.

The frequency domain matrix equation relating the vector of N response coordinates (i.e., accelerations at given locations and directions) to the vector of M forcing coordinates (oscillatory steady-state loads acting on a linear system) is given by

$$\begin{Bmatrix} \ddot{y}_1(\omega) \\ \ddot{y}_2(\omega) \\ \vdots \\ \ddot{y}_N(\omega) \end{Bmatrix} = \begin{bmatrix} \ddot{Y}_{11}(\omega) & \ddot{Y}_{12}(\omega) & \dots & \ddot{Y}_{1M}(\omega) \\ \ddot{Y}_{21}(\omega) & \ddot{Y}_{22}(\omega) & \dots & \ddot{Y}_{2M}(\omega) \\ \vdots & \vdots & & \vdots \\ \ddot{Y}_{N1}(\omega) & \ddot{Y}_{N2}(\omega) & \dots & \ddot{Y}_{NM}(\omega) \end{bmatrix} \begin{Bmatrix} F_1(\omega) \\ F_2(\omega) \\ \vdots \\ F_M(\omega) \end{Bmatrix}$$

or $\{\ddot{y}\} = [\ddot{Y}]\{F\}$

where

$\ddot{y}_i(\omega)$ is the Fourier transform of the flight acceleration response associated with response coordinate i at an operational frequency ω .

$F_j(\omega)$ is the Fourier transform of the externally applied vibratory load associated with forcing coordinate j at an operational frequency ω .

$\ddot{Y}_{ij}(\omega)$ is the acceleration mobility (transfer function) between response coordinate i and forcing coordinate j ; by reciprocity, $\ddot{Y}_{ij} = \ddot{Y}_{ji}$. The matrix containing the mobilities is referred to as the airframe calibration mobility matrix and is obtained during ground vibration testing.

All the quantities in the above equation are complex numbers. For $N > M$, the least-squares estimate of the forcing coordinate vector can be obtained as

$$\{\hat{F}\} = \left[\left[[\ddot{Y}]^{*T} [\ddot{Y}] \right]^{-1} [\ddot{Y}]^{*T} \right] \{\ddot{y}\}$$

where

$[\ddot{Y}]^{*T}$ is the conjugate transpose of $[\ddot{Y}]$ and

$\{\hat{F}\}$ is the vector of calculated externally applied loads.

The accuracy of the calculated loads can be assessed by comparing flight accelerations, $\{\ddot{y}\}$, against calculated accelerations, $\{\ddot{\hat{y}}\}$, determined using the calculated loads, i.e.,

$\{\ddot{y}\} = [\ddot{Y}]\{\hat{F}\}$, or by comparing flight accelerations against accelerations measured during ground flying for the same flight condition.

In the former case, when $N = M$, both $\{\hat{\ddot{y}}\}$ and $\{\ddot{y}\}$ will check exactly, regardless of whether the calculated loads are correct or not. However, N is usually much larger than M , introducing a large degree of mathematical independence via redundancy of response parameters.

The present application of FD assumes linear structural response. However, if the response is not linear, mobility matrices as a function of the vibratory load amplitudes would be necessary to determine the vibratory loads.

Considerable engineering judgment is required to identify the forcing coordinates that contribute to the in-flight vibratory accelerations. It is not acceptable to simply assume loads acting in various directions at arbitrary locations. The success of the method depends on both the accuracy of the calibration mobilities and the proper selection of the forcing coordinates.

VIBRATION TEST FACILITY

In recent years, an intensive effort was undertaken to develop a ground vibration test facility at AATD. Under this effort, a test fixture was fabricated that could accommodate aircraft up to UH-60 Black Hawk size; data acquisition, processing, and analysis equipment was procured, integrated and checked out; and pertinent software was developed and verified. The ground vibration test facility is briefly described below; details are furnished in Reference [3]. Central to this facility is a Fourier Analyzer System, shown in Figure 1, that has the capability of acquiring and processing large amounts of data. A two-channel Dynamic Signal Analyzer is available which is primarily used during preliminary testing to obtain a "quick" view of the test article's response. The Fourier Analyzer System is configured with a preprocessor that allows band selectable frequency analysis (zoom) capability, a digital magnetic tape recorder, a 125-megabyte hard disk system, and a 64-channel multiplexer with sample and hold capability. Piezoresistive accelerometers are used. Their outputs are routed through a bank of signal conditioners configured with various ranges of low-pass filters and, subsequently, into the multiplexer.

Usually all data processing is performed off line. The data processing operation consists of developing transfer functions by sequentially extracting four channels at a time (reference and responses). Although the Fourier analysis software employs utilities resident in the system's library, considerable effort was expended to automate it, check it out, and make it user-friendly. The present status of the Fourier analysis software requires minimum operator's input, such as the index number of the beginning record on the tape or disk, number of FFT (Fast Fourier Transformation) averages, bandwidth, number of data channels, and number of the reference channel. All data extraction and transfer function development is performed automatically. As an example of data processing turnaround time, during calibration testing of the full-scale helicopter, transfer functions for data from five shake test configurations, each having 27 accelerometers and 5 averages, were developed within approximately 2.5 hours. Transfer functions are stored on hard disk systems for further analysis. In-house developed software automatically extracts dynamic parameters from the transfer functions, such as the real and imaginary components at a desired frequency, converts them to engineering units and stores them in operator-selected files to be used with dynamic analysis software.

A control system was recently procured and software is currently being developed in-house that will have the capability to simultaneously control magnitudes and phases of up to ten hydraulic and/or electromagnetic exciters.



Figure 1. AATD ground vibration data acquisition and analysis system.

DYNAMIC MODEL FORCE DETERMINATION TESTING

The FD method was applied to the simulated airframe dynamic model, shown in Figure 2, as a dress rehearsal prior to applying the method to a full-scale helicopter. A similar effort conducted during initial development of the method is described in Reference [1]. The model was designed to simulate the essential dynamic characteristics of a typical helicopter, with a stiff cabin and a rather soft tail boom.

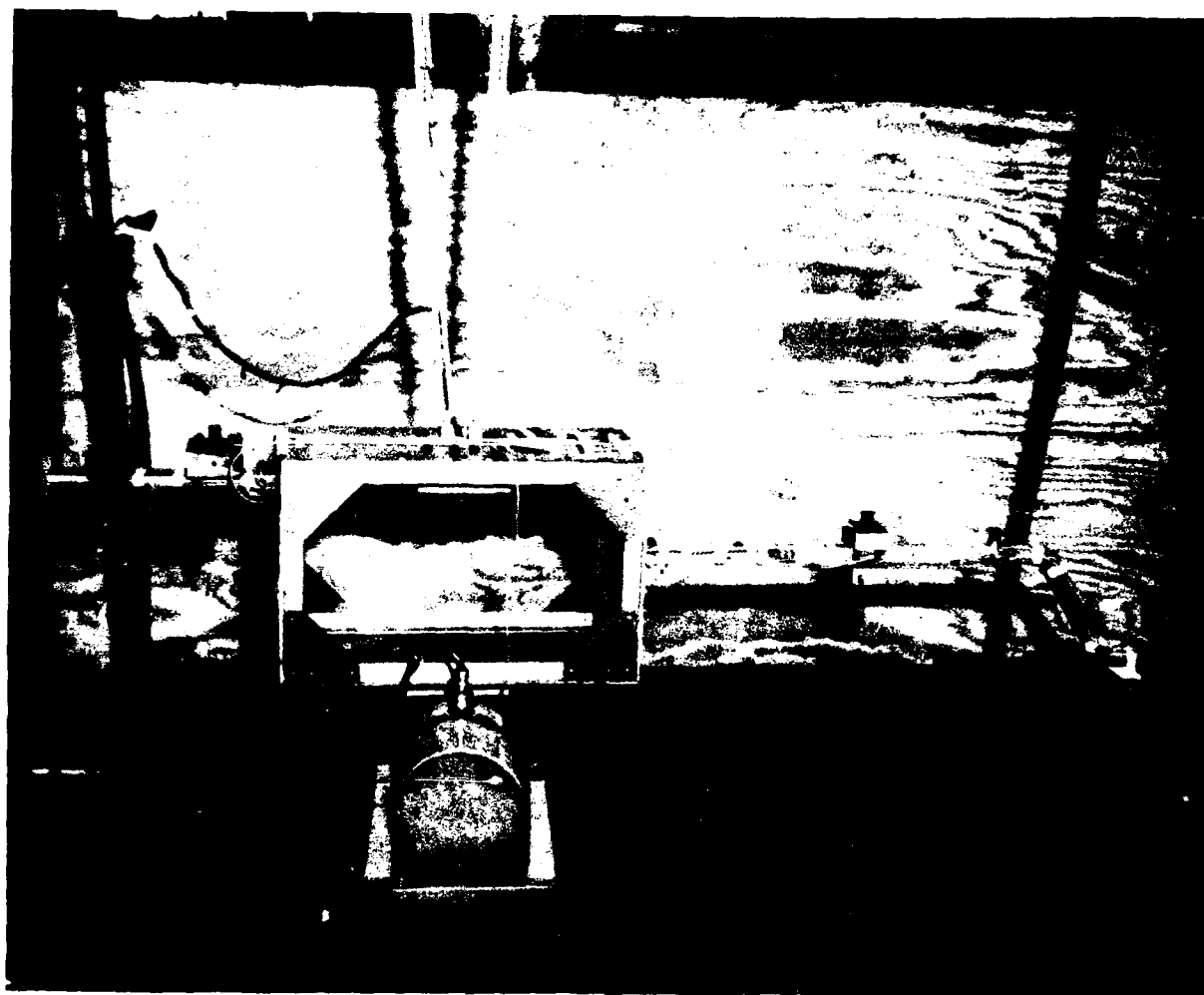


Figure 2. Dynamic model configuration.

TEST CONFIGURATION, PROCEDURES AND INSTRUMENTATION

The model was suspended upside down to facilitate mounting of the shakers at the desired locations. The location and orientation of the accelerometers is shown in Figure 3. The suspension system was designed to keep the rigid body response below 2 Hz. Prior to applying the FD method to the model, natural frequency placement and reciprocity tests

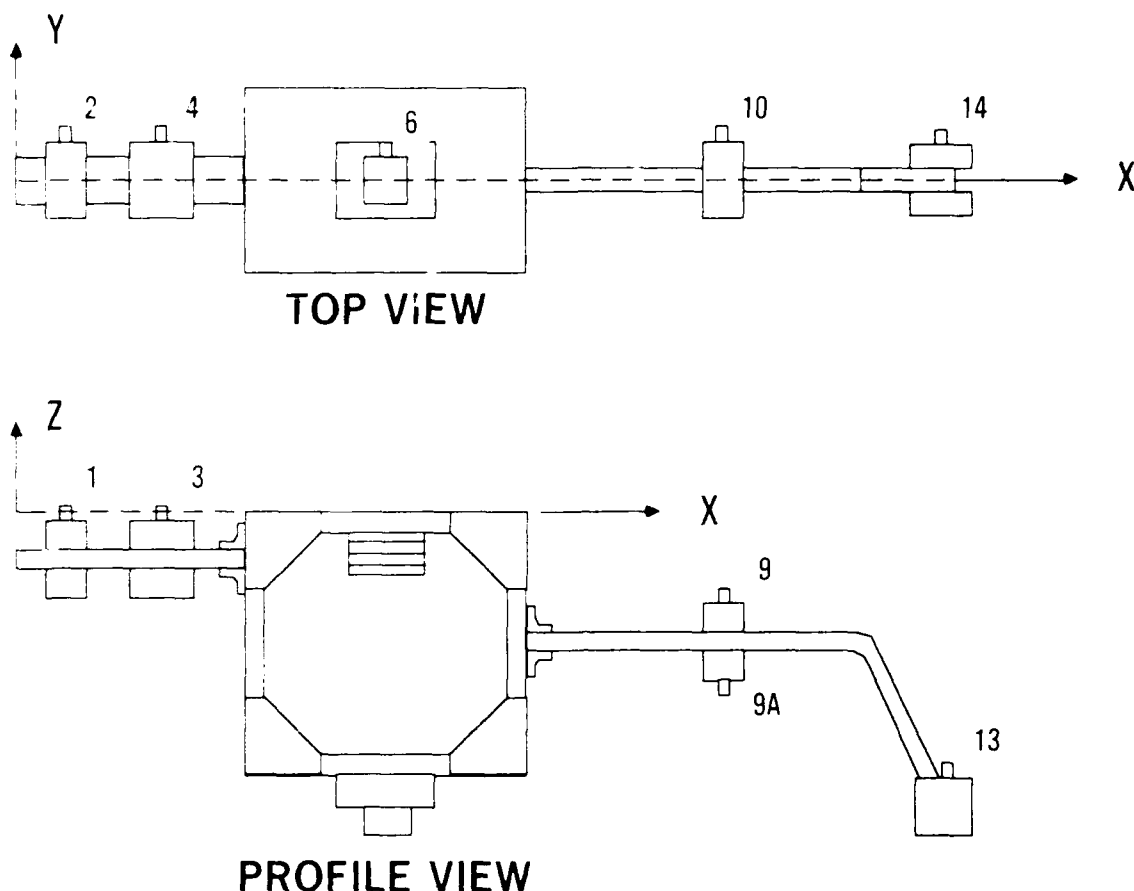


Figure 3. Dynamic model instrumentation.

were conducted to select the frequency to be used for flight simulation. The model was excited in the vertical direction at the hub and station 9A (mid-tail-boom). Results are shown in Table 1 and Figure 4. Also, a force/response linearity study was conducted to assure that calibration mobilities obtained were in a constant mobility range (i.e., mobility remains independent of the excitation magnitude). The results for the vertical excitation are shown in Table 2. The FD methodology requires that calibration mobilities be obtained for locations where the flight loads to be calculated are applied. The airframe should be calibrated by applying the excitations in a given direction and at a given location one at a time. However, when flight simulation is performed, several exciters are attached, which has some effect on the inertia and stiffness of the system being tested. A flight configuration was selected consisting of two vibratory loads (main rotor hub vertical and lateral) applied using two 25-pound electromagnetic shakers with identical hardware attachments. Considering the stiffness constraints of the shakers when attached to the model, calibration was performed with one and two shakers attached to determine if the interaction significantly changes the calibration mobilities. The frequency results, shown in Table 3, indicate that for the purpose of this effort the effect of the interaction is negligible.

Table 1. DYNAMIC MODEL RECIPROCITY TESTING

Mode No.	Vertical Natural Frequencies		
	Shaking at Hub Response at 9A	Shaking at 9A Response at Hub	Percent Difference
1	17.6	17.6	0.0
2	39.3	39.3	0.0
3	72.0	72.0	0.0
4	75.9	75.6	0.4
5	97.8	97.5	0.3

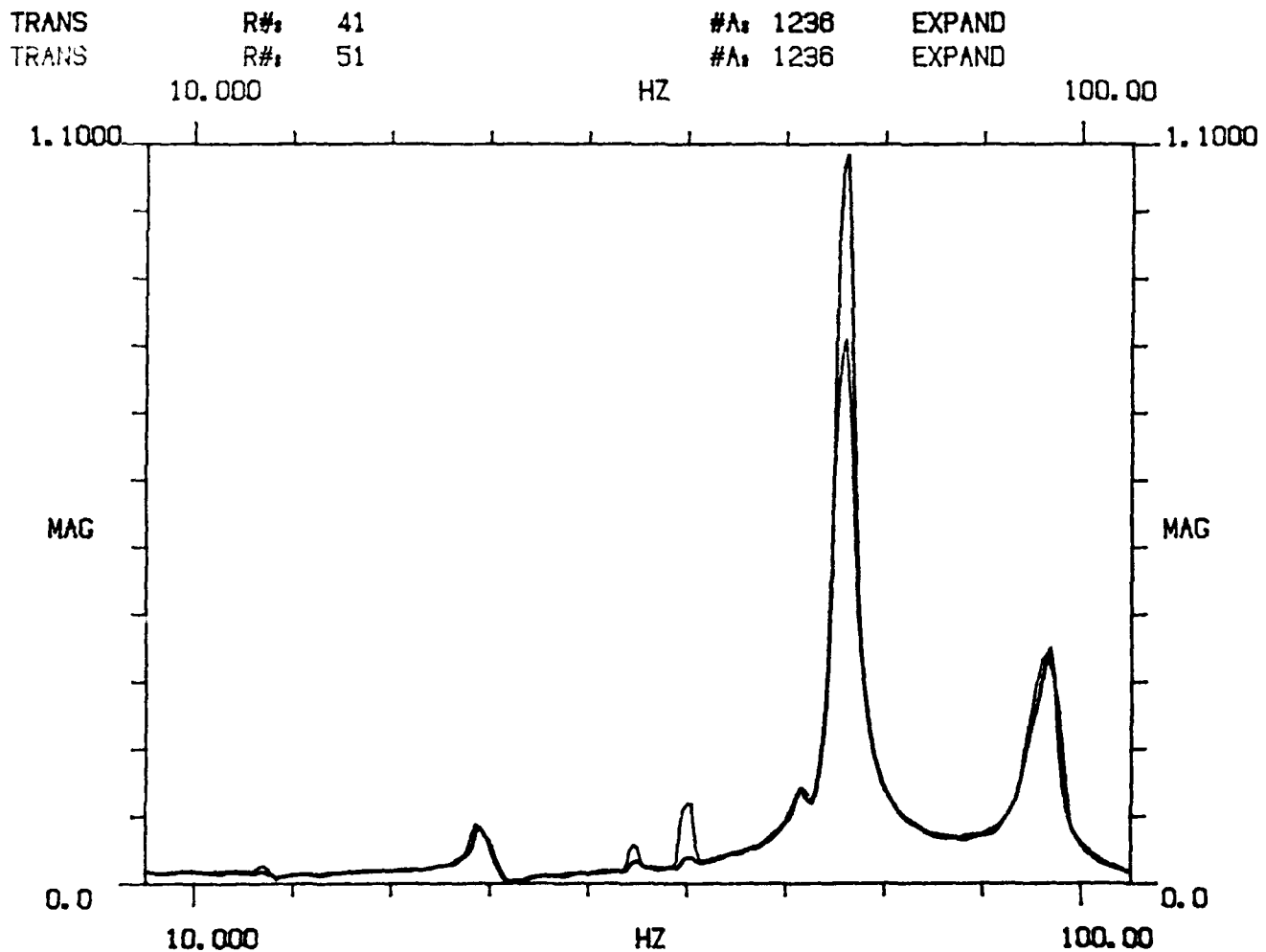


Figure 4. Dynamic model reciprocity test results.

Table 2. FORCE LEVEL STUDY

Vertical and Lateral Shaker Attached Hub Vertical Excitation at 20 Hz Driving Point Measurement	
Force (lb)	Mobility (g's/lb)
1	0.10347
2	0.09739
3	0.09891
4	0.09785
5	0.09688
6	0.09729
7	0.09653
8	0.09562
9	0.09528

Table 3. DYNAMIC MODEL MULTI-SHAKER INTERACTION

Vertical Natural Frequencies			
Mode No.	Both Shakers Attached	Lateral Shaker Disconnected	Percent Difference
1	18.0	17.6	2.2
2	39.5	39.3	0.5
3	72.5	72.0	0.7
4	76.0	75.9	0.1
5	97.8	97.8	0.0

Lateral Natural Frequencies			
Mode No.	Both Shakers Attached	Lateral Shaker Disconnected	Percent Difference
1	18.9	18.8	0.5
2	56.5	—	—
3	72.3	72.1	0.3
4	98.1	96.3	.1.8

DYNAMIC MODEL CALIBRATION, GROUND FLYING AND TEST RESULTS

Model calibration was performed with both shakers attached, one active at a time, using a sinusoidal excitation of 6 pounds and slow frequency sweeps between 18.5 and 22.5 Hz. The operational frequency was selected to be at 20.04 Hz, and the respective calibration mobilities were obtained and used to calculate simulated flight loads. The simulated flight accelerations were generated by simultaneously shaking at the hub with 6.1945 pounds vertically and with 2.2078 pounds laterally at 20.04 Hz. A transfer function was generated between the two load cell signals (lateral/vertical) indicating a phase shift of 141.59 degrees. To obtain phase relationships among accelerometers, transfer functions were developed for each accelerometer response with respect to a reference accelerometer. The amplitude of response for each accelerometer was obtained by multiplying the respective transfer function by the autospectrum of the reference accelerometer. The reference accelerometer must be located at a response coordinate that yields response with low noise content and substantial magnitude.

In this case, accelerometer No. 13, which is located on the fin in the vertical direction as shown in Figure 3, was chosen as the reference. The calculated loads, calibration mobilities, and simulated flight accelerations are shown in Tables 4, 5, and 6, respectively. The error between the applied and the calculated loads was less than 2%.

The results of this task demonstrated the validity of the data acquisition, processing, and FD software. This preliminary application provided the necessary check of the in-house developed methodology prior to proceeding with the application of the FD method on a full-scale helicopter.

Table 4. DYNAMIC MODEL APPLIED AND CALCULATED LOAD COMPARISON

Aircraft: Model	Serial No.: N/A
Gross Weight: 47.54 lb	CG Location: Sta 21.51
Flight Condition: N/A	Speed: N/A

Force Coord	Magnitude			Phase		
	Applied	Calculated	Percent Error	Applied	Calculated	Percent Error
Vert Hub	6.195	6.223	0.45	Reference		
Lat Hub	2.208	2.165	-1.95	141.59	142.43	0.006

Table 5. DYNAMIC MODEL CALIBRATION MOBILITIES

Force D.O.F. No. 1 (Hub Vertical)		
Calib. Mob. No.	Real	Imag
1	0.0393	0.00003
2	0.0062	-0.00008
3	0.0041	0.00023
4	0.0022	0.00010
5	0.0004	0.00026
6	-0.0229	0.00036
7	-0.0019	-0.00007
8	0.0983	-0.00055
9	0.0085	-0.00026

Force D.O.F. No. 2 (Hub Lateral)		
Calib. Mob. No.	Real	Imag
1	0.0007	0.00001
2	0.1210	0.00041
3	0.0069	-0.00066
4	0.0731	0.00211
5	-0.1973	-0.00215
6	0.0002	-0.00011
7	0.0000	-0.00025
8	0.0015	-0.00026
9	0.2194	0.00510

Table 6. DYNAMIC MODEL SIMULATED FLIGHT ACCELERATIONS

D.O.F. No.	Real	Imag
1	0.2187	0.1068
2	-0.2304	0.0703
3	0.0192	0.0175
4	-0.1328	0.0357
5	0.4051	-0.0873
6	-0.1277	-0.0578
7	-0.0163	-0.0072
8	0.5580	0.2487
9	-0.4256	0.1230

OH-58A FORCE DETERMINATION TESTING

AIRCRAFT DESCRIPTION AND INSTRUMENTATION

An OH-58A was selected to be used as the test helicopter because of the availability of a flightworthy helicopter (SN 71-20388) and a non-flightworthy (ground operational) one (SN 68-16977). The non-flightworthy helicopter was selected for the test because it was the first time that AATD was to conduct a ground vibration test on a full-scale helicopter. Test procedures needed to be developed and verified. The flightworthy helicopter was required to allow gathering of flight accelerations for potential follow-on work. Configuration changes which were made to the test aircraft are identified below. The subject aircraft was configured for a representative flight condition, i.e., 2650 pounds gross weight (GW) and center of gravity (CG) located at station 106.5.

1. Crew and passenger doors removed.
2. Cowlings removed.
3. Windshields removed (damaged).
4. Engine replaced with a dummy engine of equal weight and similar inertia distribution.
5. Modified main rotor hub retaining nut installed.
6. Tail rotor drive shaft and hanger bearings removed.
7. Tail rotor blades replaced by dummy masses.
8. Dummy transmission to engine driveshaft installed.
9. Pilot stick controls locked.
10. Tail rotor control rods (push/pull tubes) removed.
11. Turbine engine oil added to simulate fuel.
12. Weights to simulate crew and passenger added.
13. Landing skids tied.
14. Avionics replaced with inoperable sets.
15. Main rotor blades removed.
16. Modified rotor blade retaining pins installed to secure suspension attachments.

The airframe was instrumented with 28 piezoresistive accelerometers with frequency response from DC to 1 kHz and $\pm 25g$ acceleration limit. The accelerometers were mounted at hard points on aluminum blocks with their sensitivity axes parallel to the relevant excitation axis, thus eliminating the need to analytically coordinate transform the responses. The location and direction of the accelerometers are shown in Figure 5 and Table 7. Thirteen accelerometers were placed vertically, nine laterally, and six longitudinally. The accelerometer located vertically at the hub was placed to measure mobilities in support of another program and was not used in this effort. There are no firm guidelines for selecting the number of accelerometers or their placement. Accelerometer redundancy is required by the FD method; it is reasonable to have accelerometers at points where loads are introduced into the airframe, such as the transmission and engine mounts, and on components that are expected to have significant vibratory response, such as the tail boom.

Table 7. ACCELEROMETER LOCATIONS

Aircraft Position	Description	Accelerometer Direction
1	Nose	Vert, Lat
2	Copilot Floor	Vert, Lat, F/Aft
3	Pilot Floor	Vert
4	Cabin Ceiling	Vert, Lat
5	Transmission Mount, Right	Vert, Lat, F/Aft
6	Transmission Mount, Left	Vert
7	Engine, Top	Vert, Lat, F/Aft
8	Mid-Tail Boom	Vert, Lat
9	Stabilizer, Right	Vert, Lat, F/Aft
10	Horizontal Stabilizer, Left	Vert
11	Tail Rotor Gearbox	Vert, Lat, F/Aft
12	Top of Vertical Fin	Vert, Lat, F/Aft
13	Hub	Vert

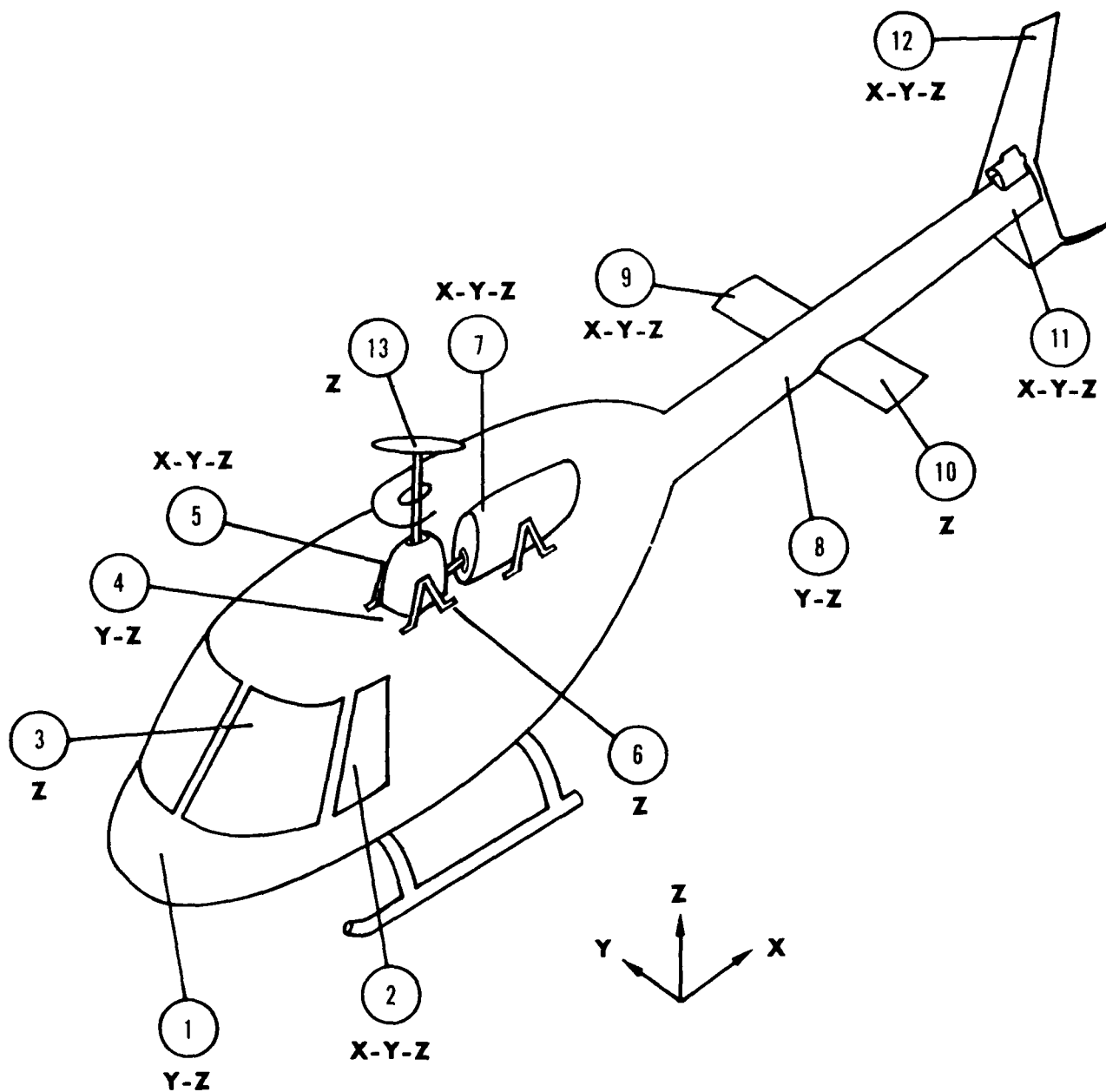


Figure 5. OH-58A helicopter instrumentation locations.

TEST CONFIGURATION AND EQUIPMENT

The test aircraft was suspended from the main rotor (M/R) hub using a bungee cord isolation system. Two main rotor blade retaining pins were fabricated with fittings which allowed the attachment of the isolation system brackets. The isolation system was designed to keep airframe rigid body responses below 1.5 Hz. Also, a new M/R hub retaining nut was fabricated to allow the installation of up to three exciters. The aircraft is shown suspended in Figure 6, and details of the isolation system and hub retaining nut can be seen in Figure 7. An electromagnetic shaker was used during the natural frequency placement testing;



Figure 6. OH-58A suspension and load application configuration.



Figure 7. Main rotor hub load excitation attachment.

however, hub excitation for calibration and simulated flight was performed with 1,000-pound (1-kip) hydraulic actuators, each configured with a 1-kip load cell. A line tamer was used to prevent surges in the hydraulic lines. A 100-pound maximum force output electromagnetic shaker with a load cell was used to provide excitation at the tail rotor gearbox, as shown in Figure 6. The amplitude and phase of the output of various exciters were manually set using individual function generators. The output of the hub vertical actuator was selected as the reference and the output of the remaining actuators was phase related to it.

TEST PROCEDURES AND DATA ANALYSIS

The sequence of test conducted on the OH-58A helicopter is similar to that implemented on the dynamic model. Single-point sinusoidal excitations with frequency sweeps were applied at the main rotor hub in the vertical and lateral directions to determine the natural frequencies of the airframe and subcomponents and their proximity to the 2P operational frequency (M/R 2 per rev), 11.87 Hz. This determination was necessary in that if the operational frequency is near a natural frequency, mobility values tend to drift because a small shift in frequency has a substantial effect on the dynamic response. Because this was the first time a shake test was performed on the full-scale helicopter, a conservative approach was used. Each M/R hub force level initially was approximately 50 pounds and was increased in 50-pound increments on subsequent sweeps until an optimum level of approximately 300 pounds was reached, as shown in Figure 8. A similar process was performed for the tail rotor force level. The airframe natural frequencies nearest to the operational frequency were placed at about 8.2 Hz and 15.5 Hz, which comfortably straddle the 2P (11.8 Hz) frequency. Reciprocity was checked only in the lateral direction by applying a 20-pound sinusoidal excitation near the tail rotor gearbox and at the M/R hub. Force level studies were performed at 11.8 Hz by applying individual excitations at the main rotor hub in the vertical, lateral, and fore/aft directions and near the tail rotor gearbox in the lateral direction. The results are indicated in Figures 9, 10, 11, and 12, respectively. Four airframe stations were monitored in all cases (nose, mid-tail-boom, tail rotor gearbox, and vertical fin), and the range of 250-400 pounds for the vertical load and 200-350 pounds for the lateral load produced mobilities which for practical purposes remained constant with increasing load magnitudes. The force level study with excitation applied near the tail rotor gearbox indicates that the tail boom's structural characteristics have a significant effect on the main fuselage's response, and this response reaches the constant mobility range with relatively small force.

The FD software used was developed under a contractual effort identified in Reference 1. It was coded in Hewlett-Packard (HP) BASIC language for execution on an HP 9825. The software was converted in-house to FORTRAN IV, pre- and post-processor modules were added, and the output format was modified. The pre- and post-processors modules consist of modules that check the validity of input and output data, respectively. For example, in the pre-processing stage, the calibration mobility data is validated and the process discussed in the section titled Dynamic Model Calibration, Ground Flying and Test Results is performed. An example of the post-processing stage is to recalculate the accelerations using the calculated loads and determine variances with flight accelerations.

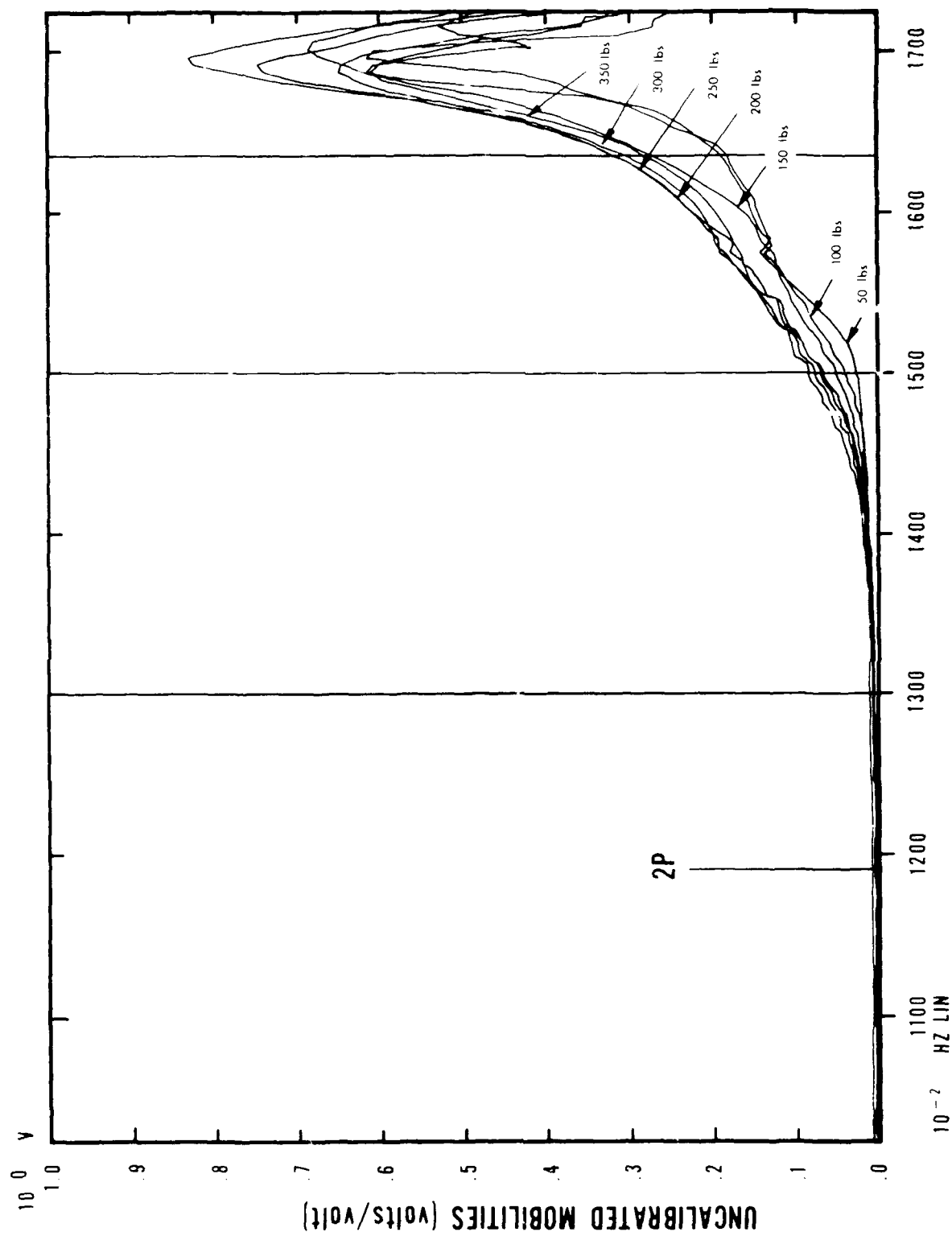


Figure 8. OH-58A vertical tail fin response due to main rotor hub lateral excitations.

TEST FREQUENCY - 11.8 [Hz]

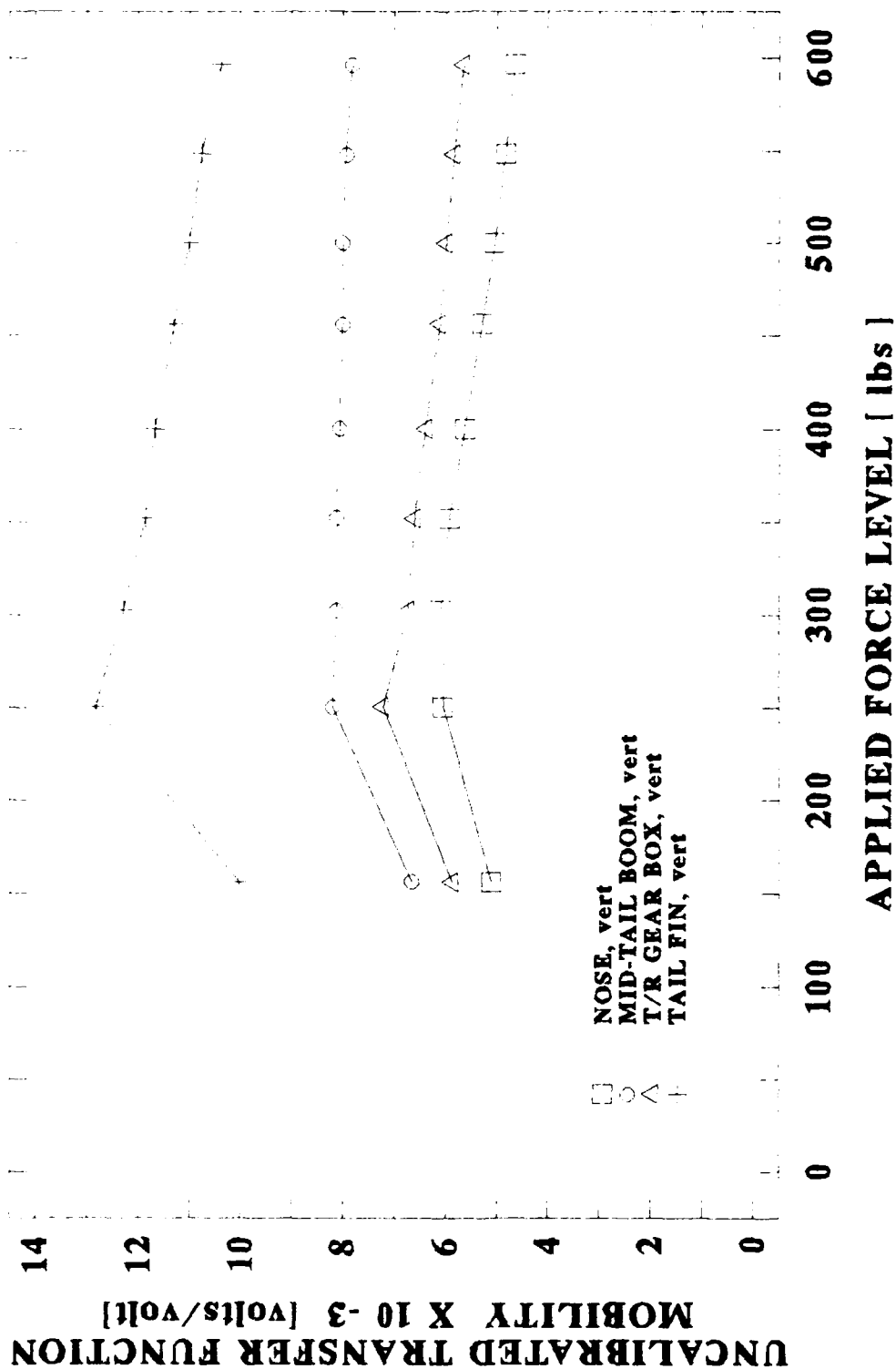


Figure 9. Airframe linearity - vertical excitation at the main rotor hub.

TEST FREQUENCY - 11.8 [Hz]

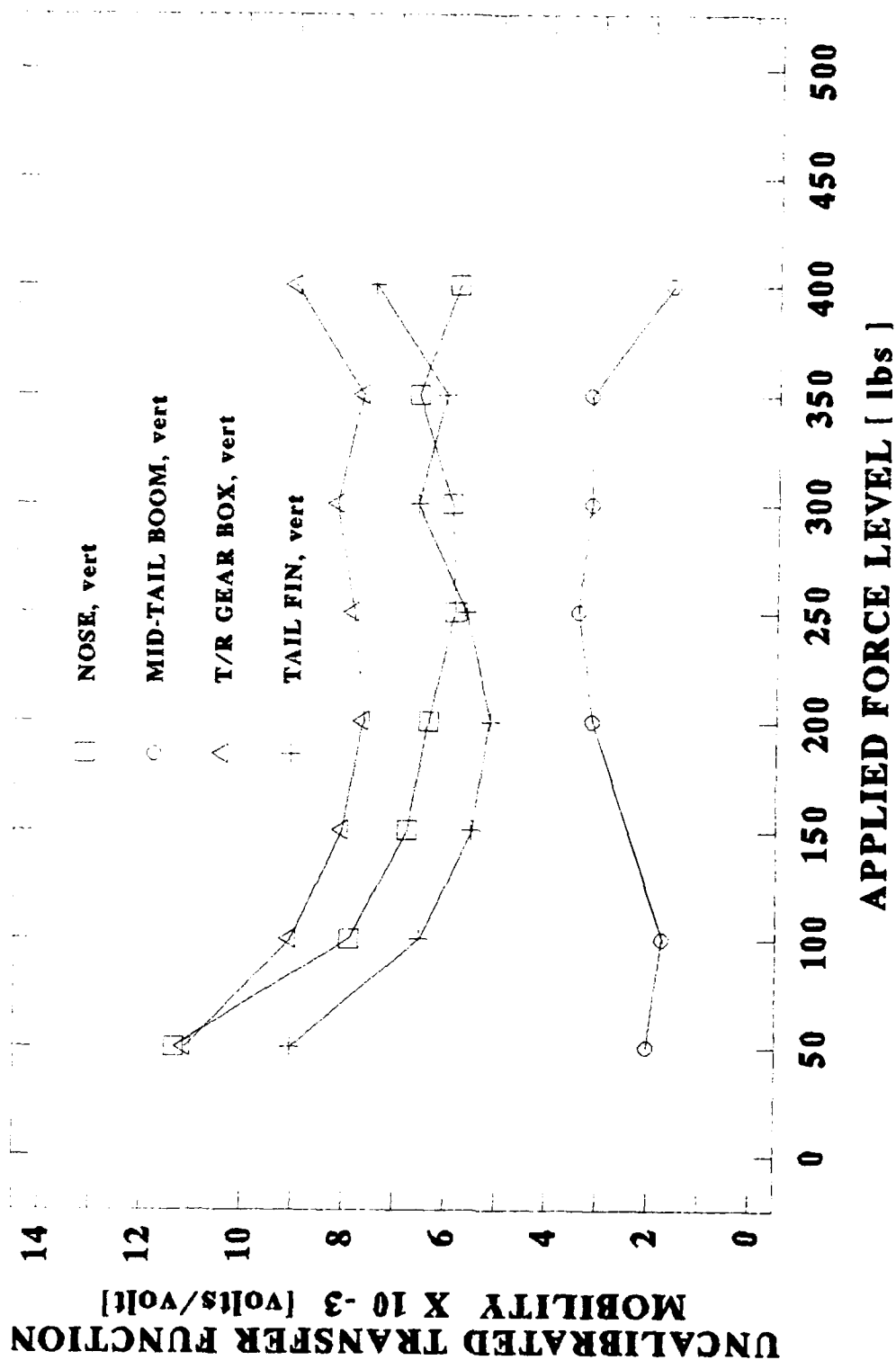


Figure 10. Airframe linearity - lateral excitation at the main rotor hub.

TEST FREQUENCY - 11.8 [Hz]

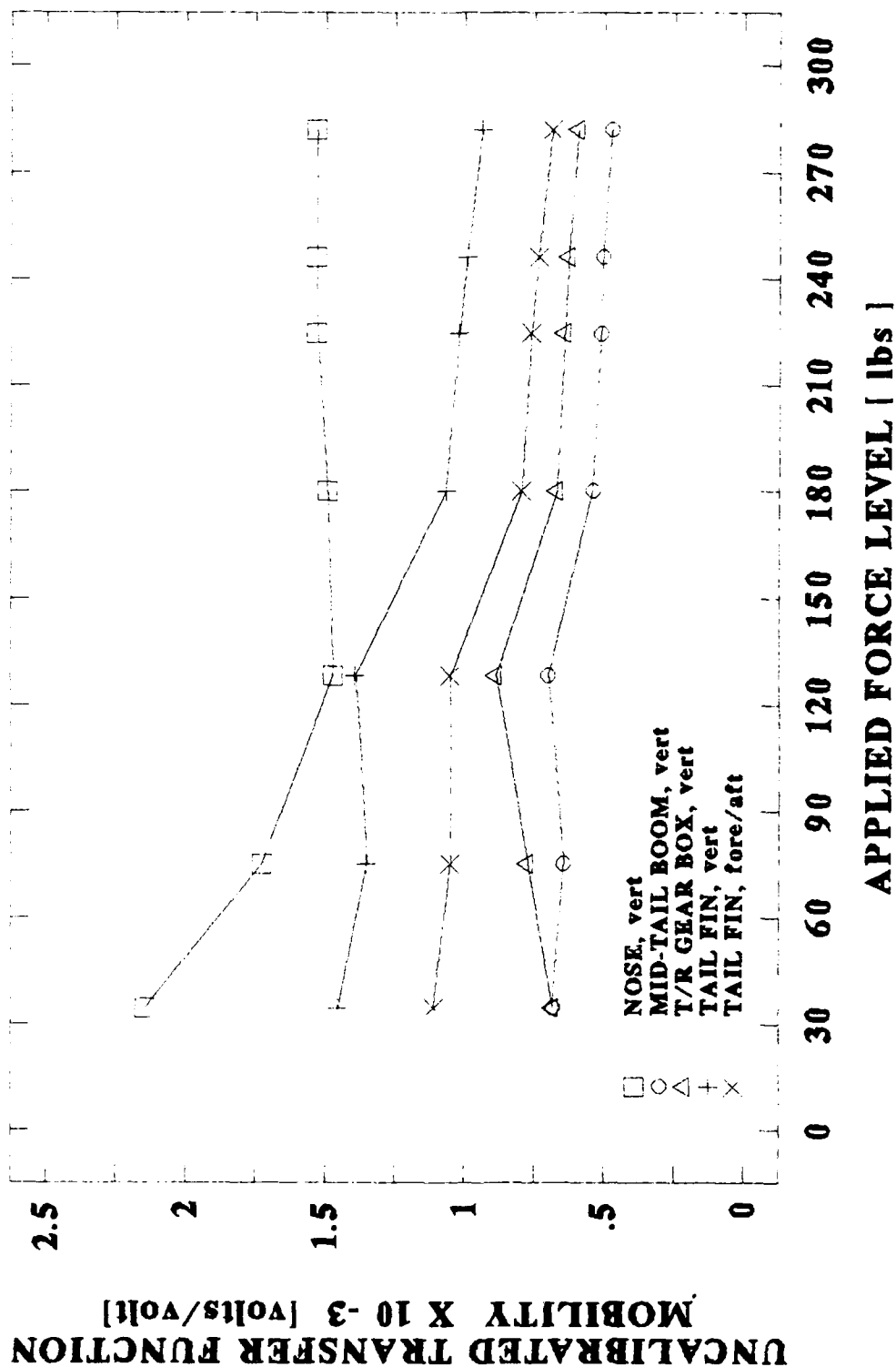


Figure 11. Airframe linearity - fore/aft excitation at the main rotor hub.

TEST FREQUENCY - 11.8 [Hz]

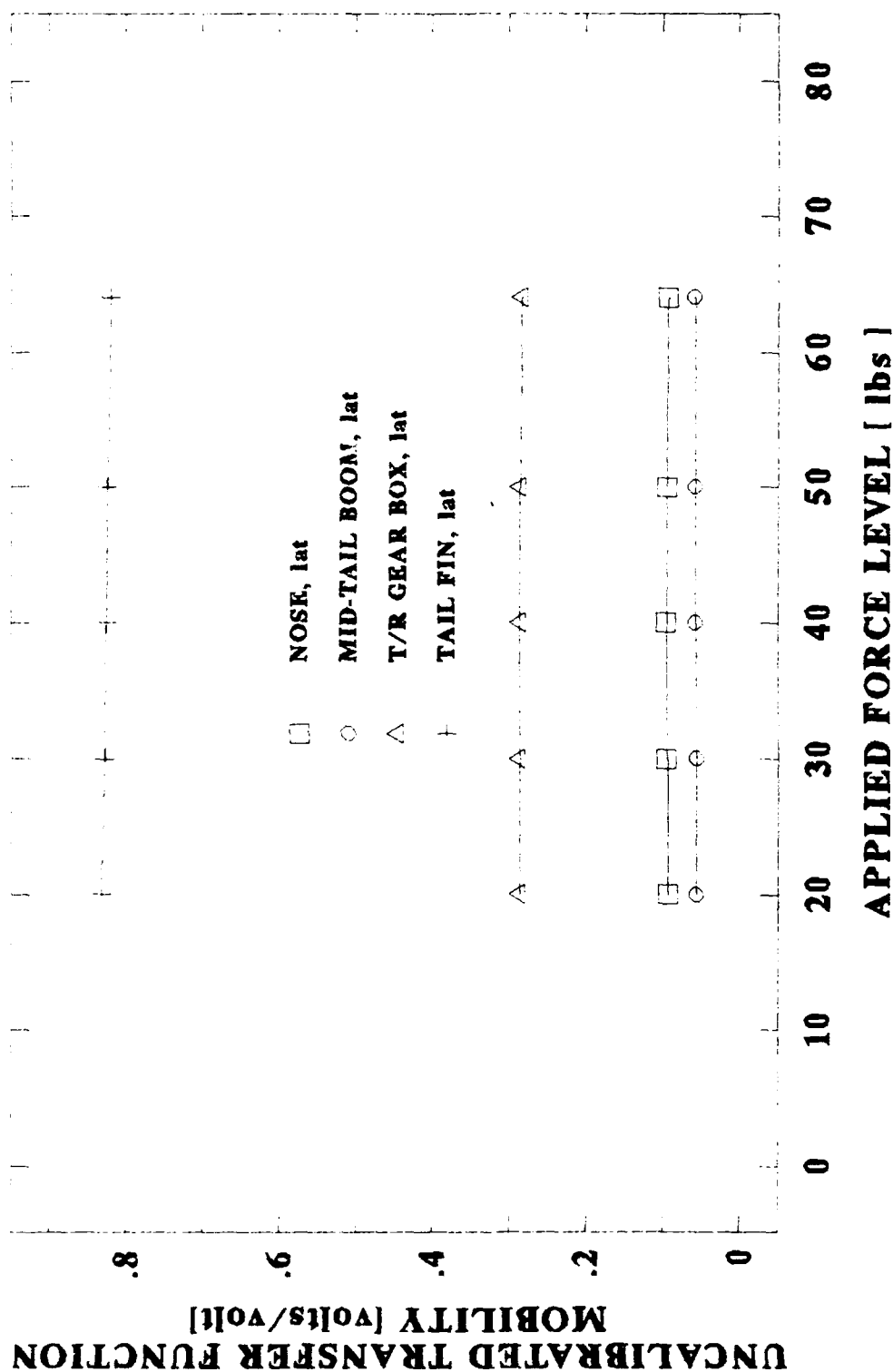


Figure 12. OH-58A airframe linearity - lateral excitation at the tail rotor gearbox.

GROUND FLYING AND TEST RESULTS

The ground flying results are presented in the appendix in the form of bar charts and numerical values. Ground flying was conducted by using up to a total of four excitation loads: three main rotor oscillating hub shears—vertical, lateral, and fore/aft—and an oscillating lateral load applied near the tail rotor gearbox (referred to as tail rotor load) representing the effect of aerodynamic interaction between the 2P main rotor downwash and the empennage. The loads did not represent a specific flight condition. The M/R hub applied shears were selected to be within their constant mobility range; however, in a few cases (runs 49 thru 53), at least one shear was selected to be outside its constant mobility range to determine the effect on the accuracy of the calculated loads. The magnitude of the tail rotor (T/R) lateral shear used was an estimate and its suitability was judged by the response it produced at various points on the airframe; all T/R lateral shears were within the constant mobility range. Prior to applying all four loads, various combinations of two simulated flight loads—and then three simulated flight loads—were applied at a time (i.e., M/R hub vertical and lateral shears, M/R hub vertical and T/R lateral shears, M/R hub lateral and T/R lateral shears, etc.) using different phase angles. This test procedure allowed a quantitative assessment of the interaction of the applied loads; the results obtained and shown in the appendix include information related to the effects of phase shift changes and boundary conditions on airframe calibration mobilities and, in turn, their effect on the accuracy of calculated loads. As part of the sensitivity study, airframe calibration mobilities were obtained by (a) exciting the airframe with one attached shaker/actuator at a time and (b) attaching all exciters—as many as required for a specific load combination—but activating only one at a time. The rationale for doing this was to account for the stiffness and inertia effects that the exciters may have on the airframe response. The calibration mobilities are referred to as “free” (only one exciter attached) and “constrained” (all exciters attached) mobilities, respectively. In the results shown in the appendix, the type of calibration mobilities used to obtain the calculated loads is specified in each run. The buildup of load sets employed in this task was conservative. Calibration mobilities for single load cases were obtained, and various single load cases were tested and loads calculated by FD. For the two-load cases, a new calibration matrix was developed for each two-load combination and used during all relevant sensitivity studies, i.e., variations of load magnitudes and phases. Again, for the three-load case, a new calibration matrix was developed and used for the sensitivity studies. The same process was used for all load cases, and the magnitudes of excitation load(s) used to develop respective calibration mobilities were in the respective constant mobility range. As a reminder to the reader, development of constrained calibration mobilities will not be necessary when flight accelerations are available. In the constrained cases, a cross-talk between actuators was observed. Specifically, when the M/R hub vertical and lateral actuators were attached, with the lateral actuator being active, a vertical excitation of approximately 35 pounds was measured by the load cell of the vertical actuator. The reverse action induced a 5-pound reaction load on the lateral actuator. This cross-talk was attributed to the airframe/isolation system pendulum motion.

The two factors that had a substantial negative effect on the accuracy of calculated loads were the use of free mobilities and the 90- and 180-degree phase shifts. In general, in the two-load configurations, use of free or constrained mobilities produced basically the same results, i.e., the error between calculated and applied loads remained low and consistent. However, the accuracy generally deteriorated as more loads were applied in conjunction with free calibration mobilities. Use of free mobilities with a three-load configuration produced error as high as 35%, which is totally unacceptable. Use of constrained calibration mobilities generally produced satisfactory results except in configurations where the phase between the reference load and any other applied loads was at or near 90 or 180 degrees; the errors produced were rather high, approximately 16%, affecting primarily the calculated M/R hub vertical shears. Throughout this study, phase shifts in lateral and fore/aft hub shears and the calculated M/R vertical shear remained sensitive. The 90- and 180-degree phase shifts and M/R hub vertical shear discrepancies cannot be explained. Overall, the accuracy obtained from the remaining configurations was quite satisfactory. The results of error percentages are summarized in Figures 13 and 14.

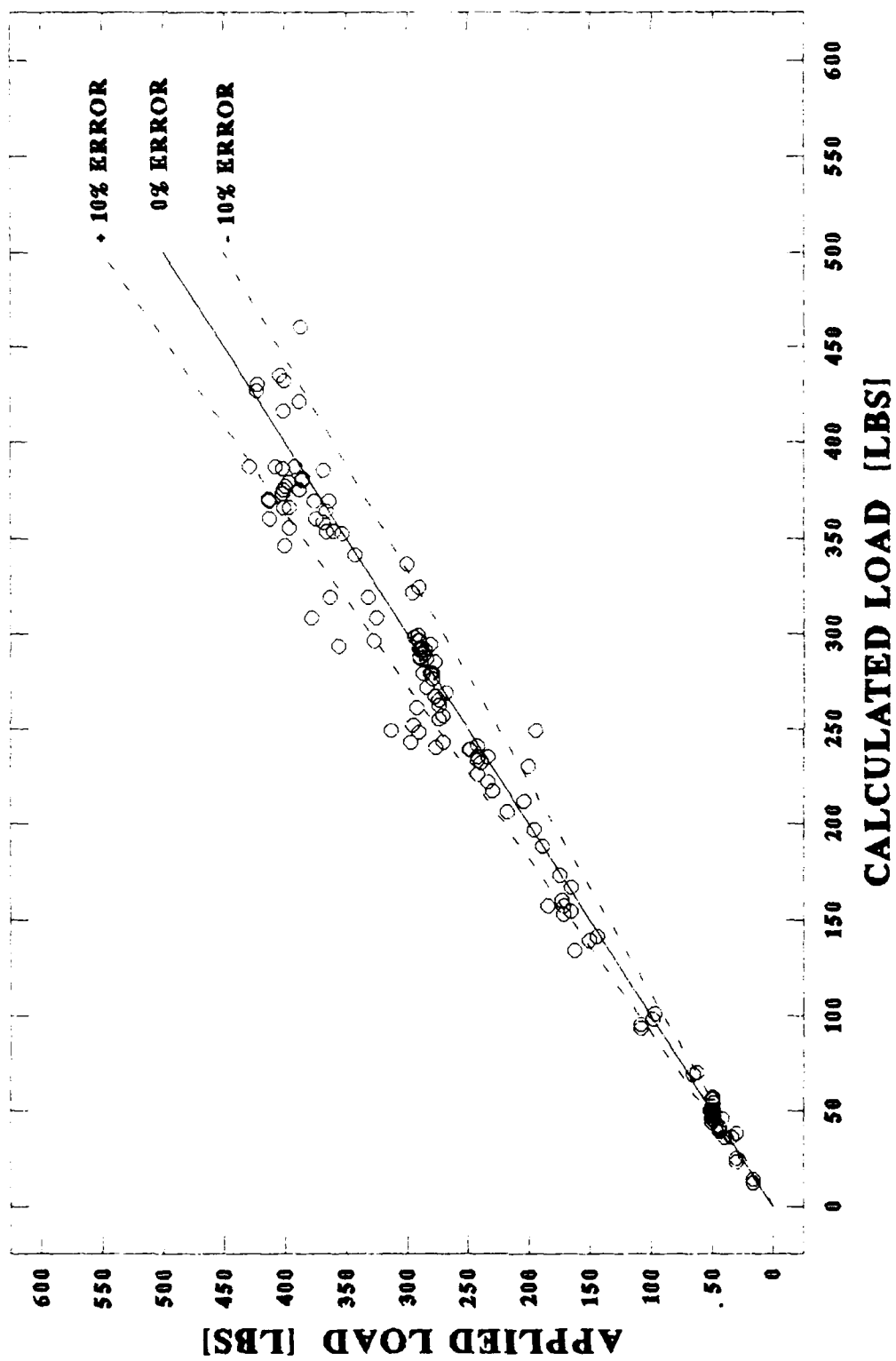


Figure 13. Calculated load error with constrained calibration mobilities.

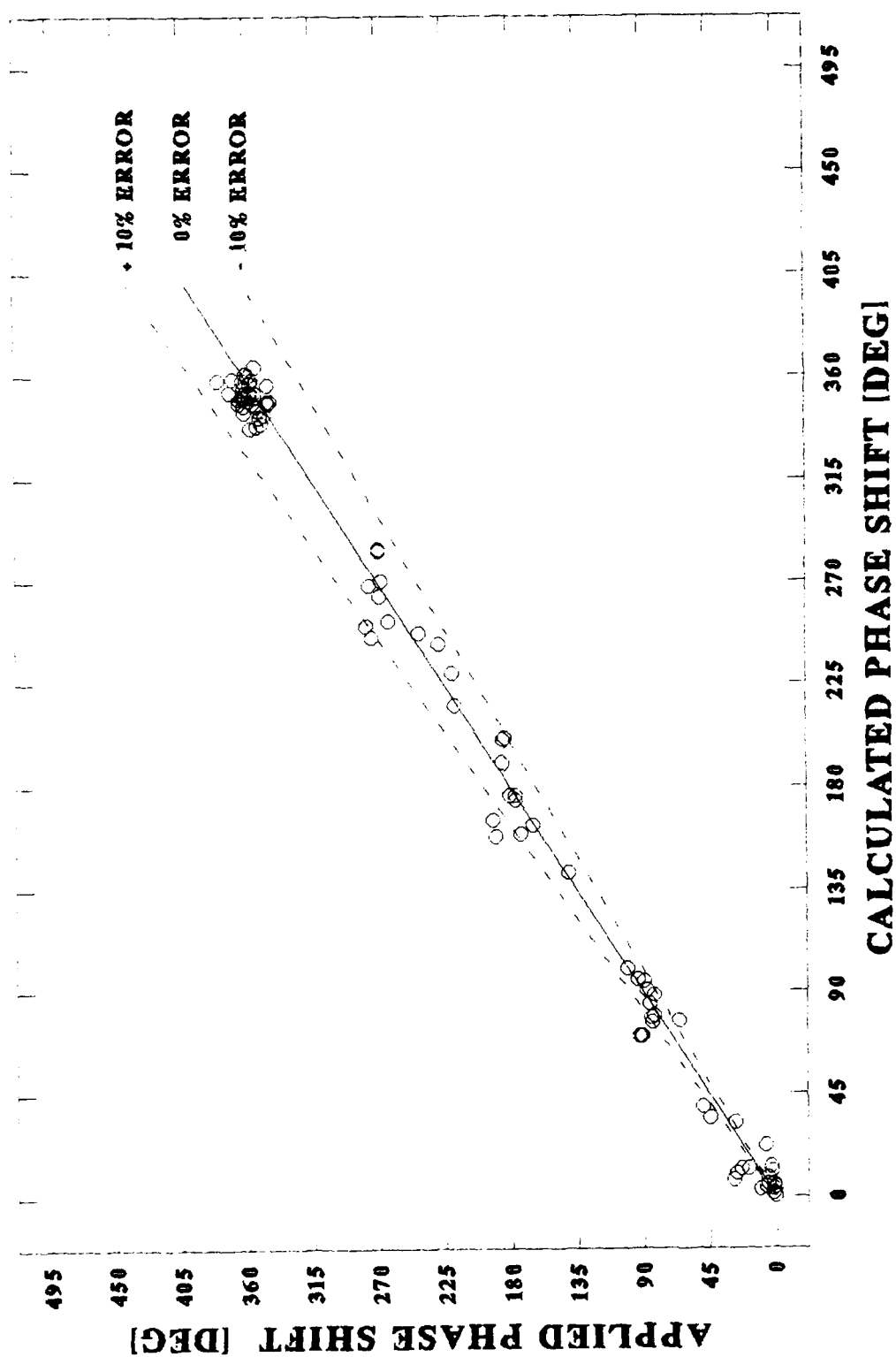


Figure 14. Calculated load phase error with constrained calibration mobilities.

CONCLUSIONS AND RECOMMENDATIONS

The application of the FD method described in this report focused on determining the accuracy with which the methodology could predict major vibratory loads. This was accomplished through a controlled laboratory experiment in which the points where the simulated flight loads applied to the aircraft were preselected, and in most cases, their magnitudes were chosen to be within a range that produced acceleration mobilities that were essentially independent of excitation force levels.

Application of the methodology, as performed in this program, is a relatively easy process, and the accuracy of the results obtained was, for the most part, quite satisfactory.

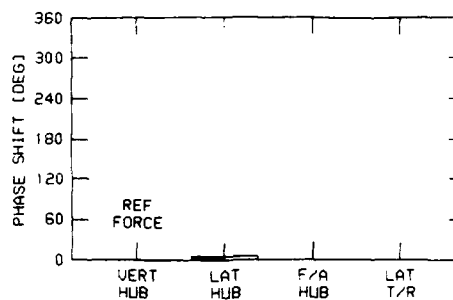
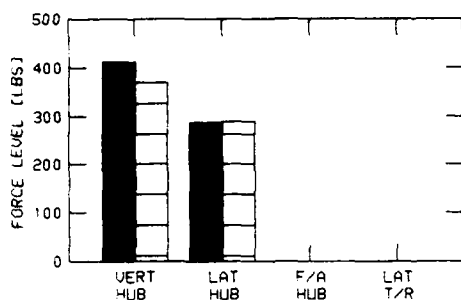
Additional research would be required to extend the methodology to the case where vibratory loads produce structural responses outside the constant mobility range.

REFERENCES

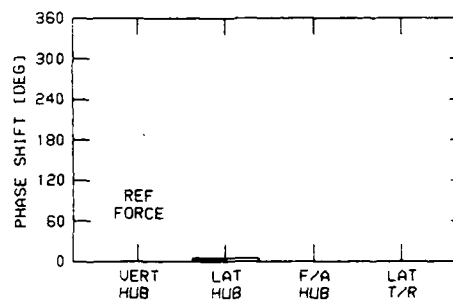
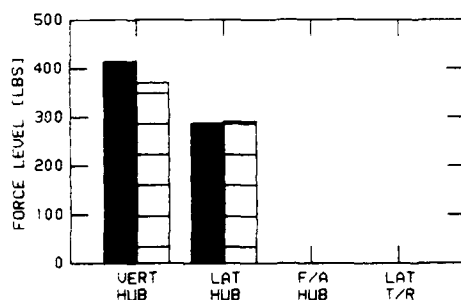
- [1] Flannelly, W. G., Bartlett, F. D., Jr., and Forsberg, T. W., Laboratory Verification of Force Determination, a Potential Tool for Reliability Testing, Kaman Aerospace Corporation, USAAMRDL-TR-76-38, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, AD A035960.
- [2] Flannelly, W. G., Jones, R., Nagy, E. J., and Fabunmi, J. A., Experimental Verification of Force Determination and Ground Flying on a Full-Scale Helicopter, Kaman Aerospace Corporation, USAAVRADCOTR 81-D-11, Applied Technology Laboratory, U.S. Army Research and Development Laboratories (AVRADCOT), Fort Eustis, Virginia, AD A100182.
- [3] Calopados, N. J., "AATD's Vibration Testing Facility", Army Research and Development Acquisition Magazine, March 1986.

APPENDIX APPLIED AND CALCULATED LOAD COMPARISON

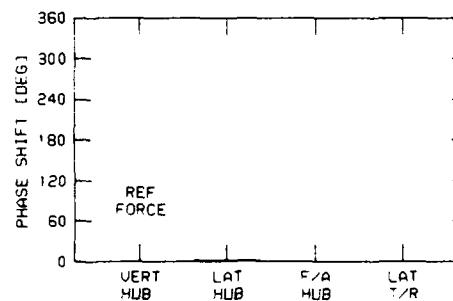
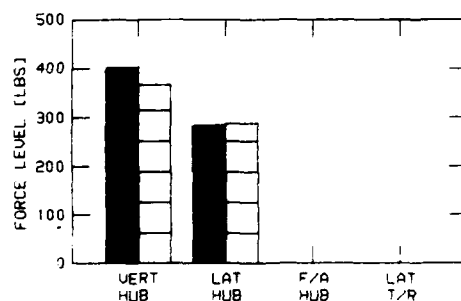
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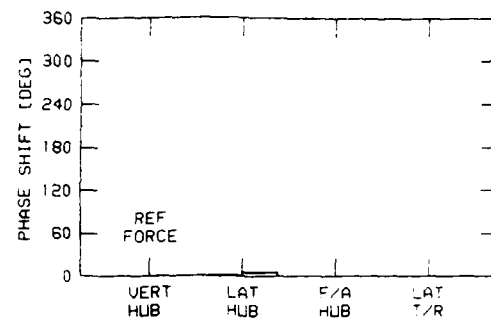
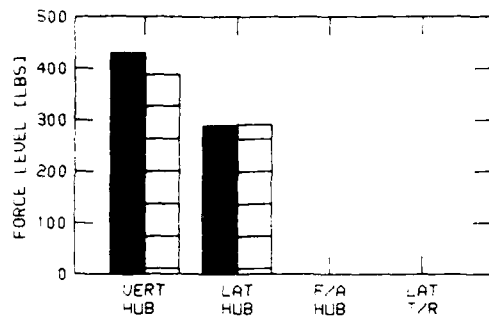
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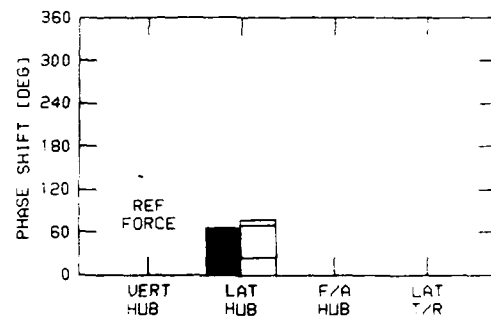
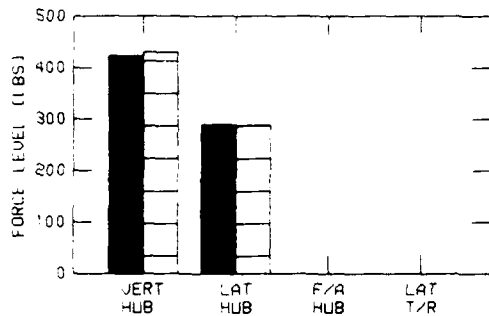
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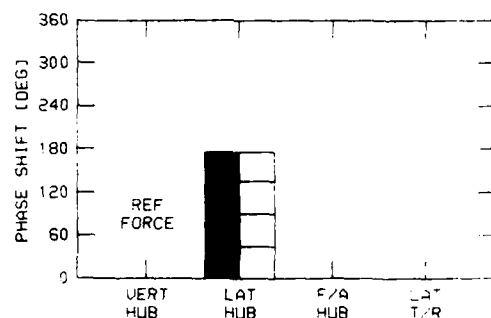
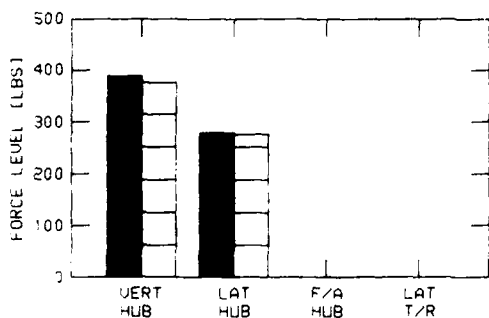
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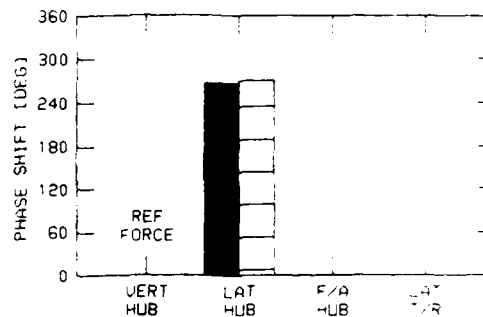
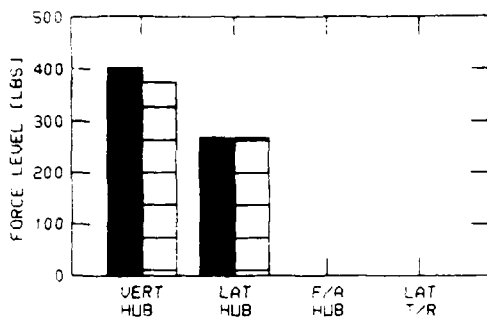
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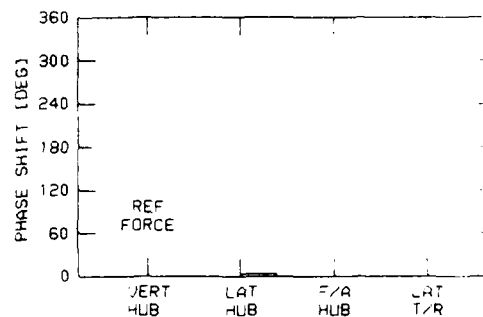
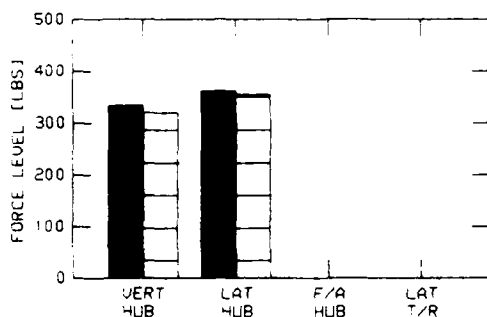
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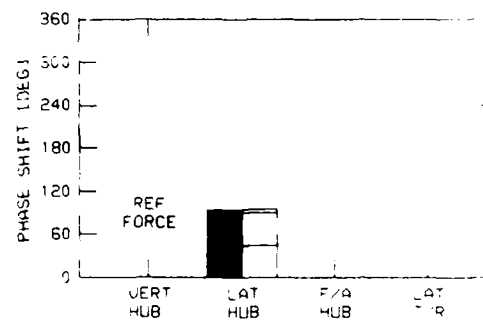
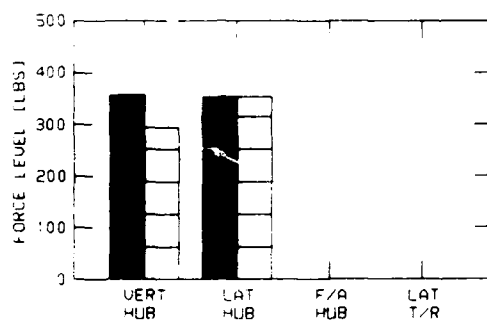
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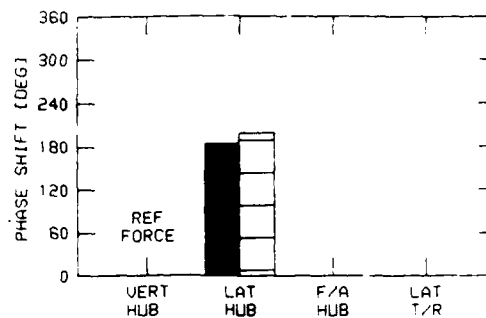
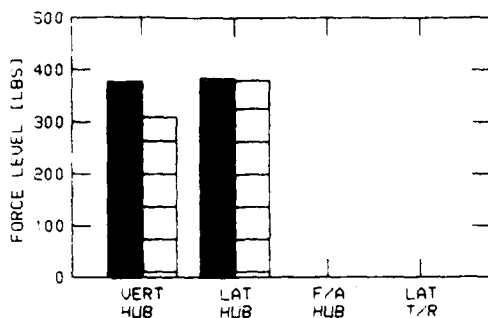


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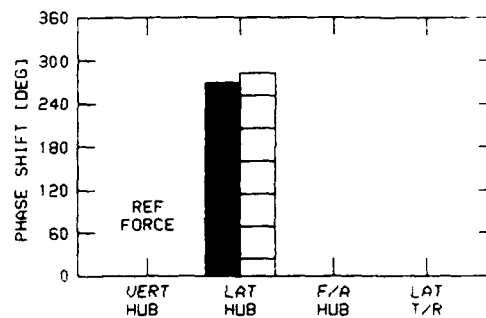
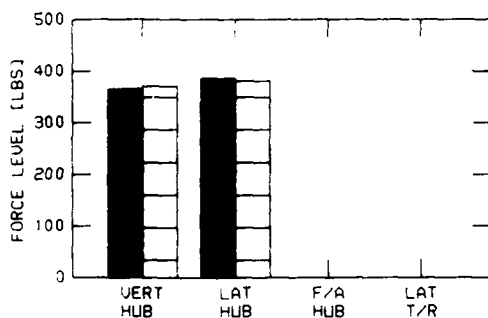


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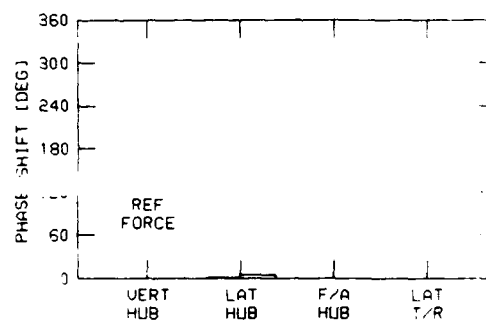
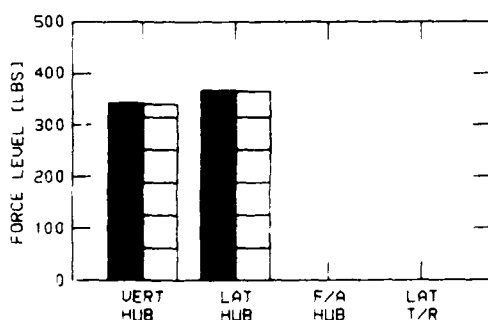
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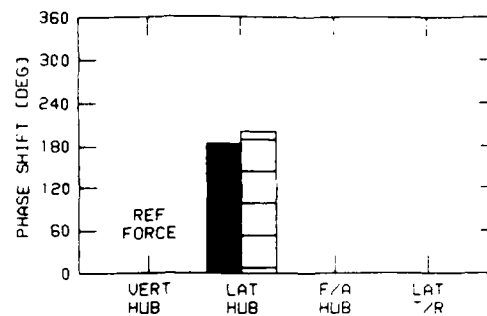
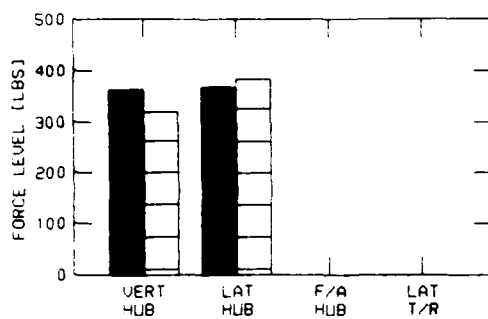


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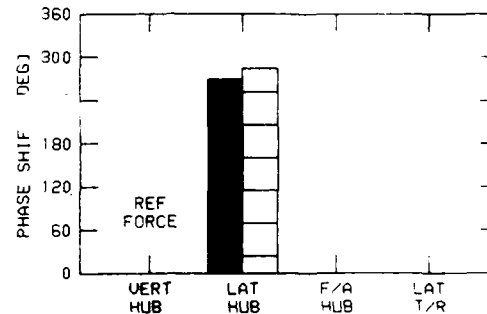
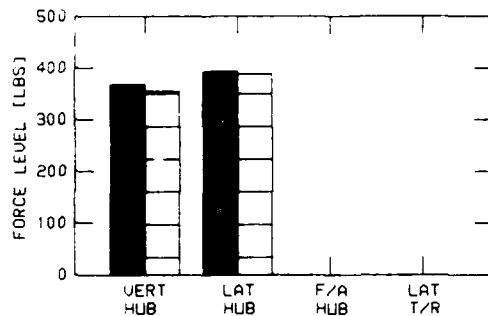


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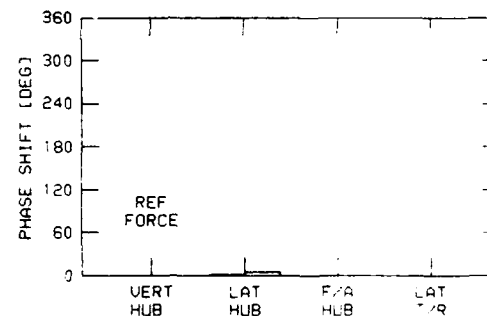
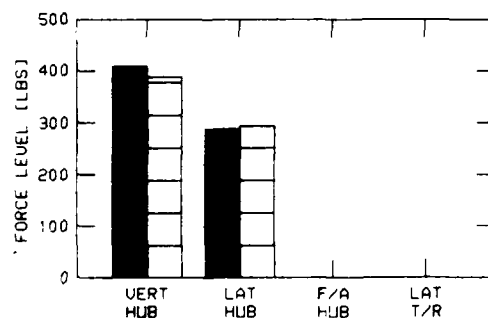
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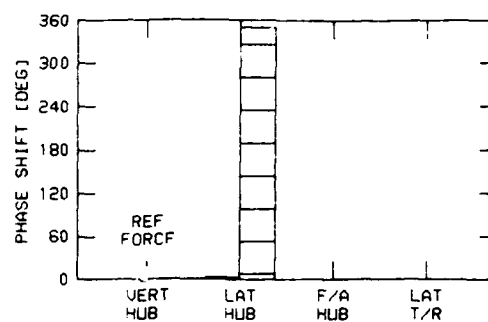
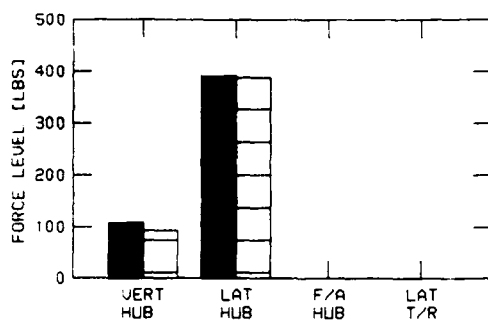
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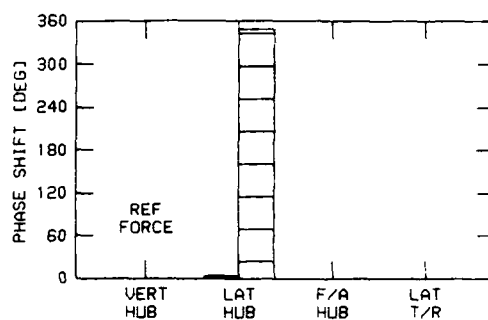
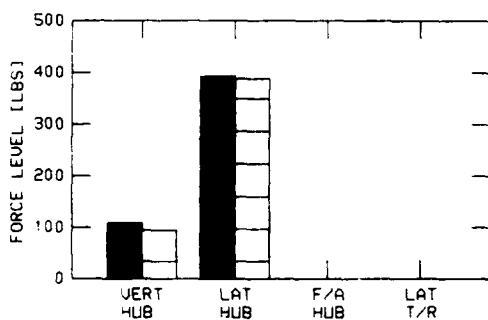
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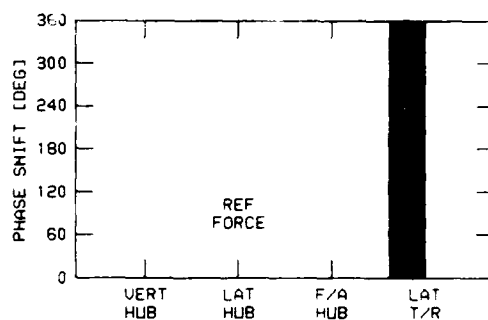
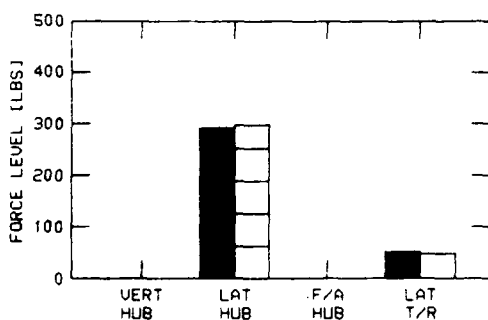
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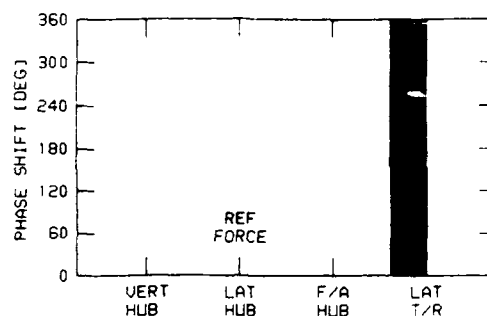
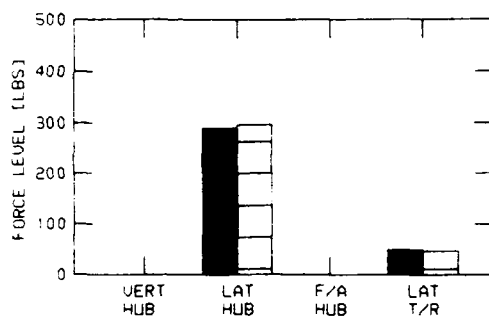


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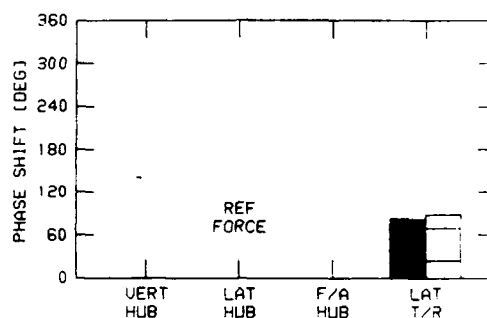
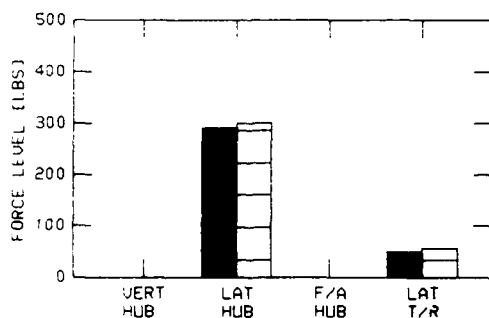


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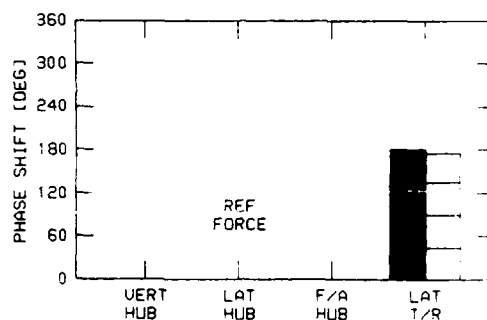
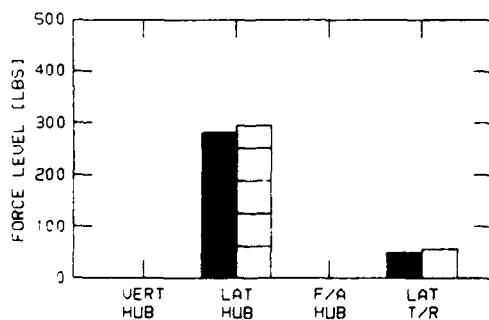
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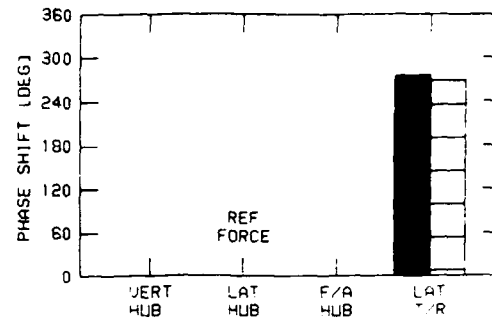
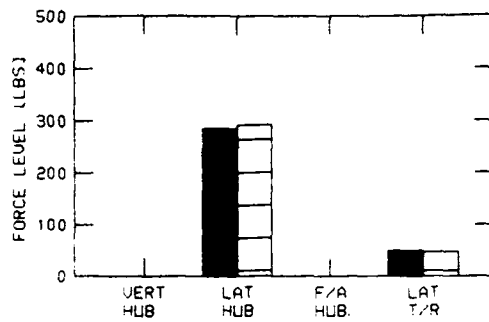
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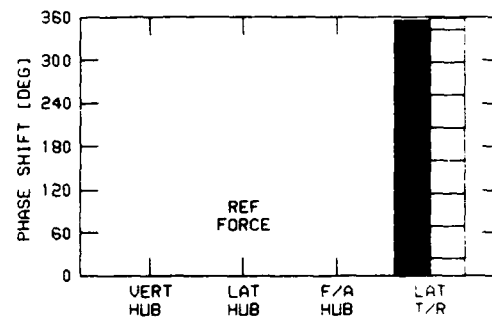
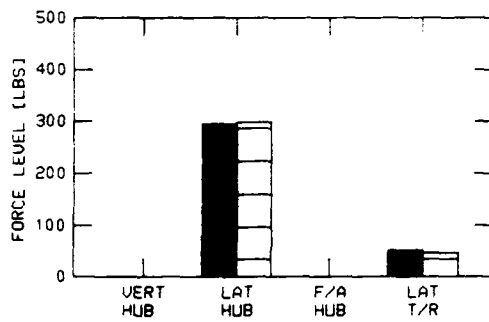
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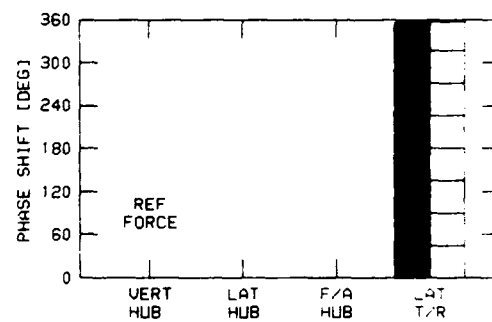
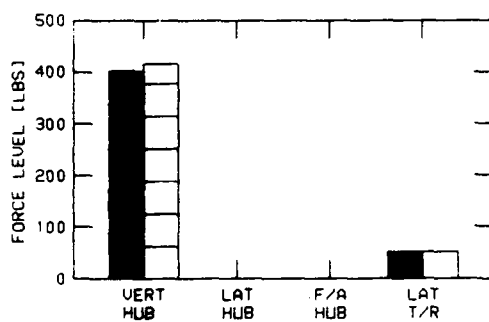
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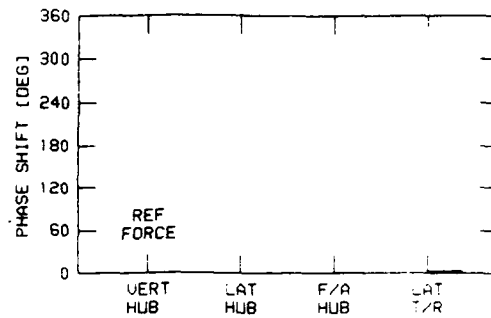
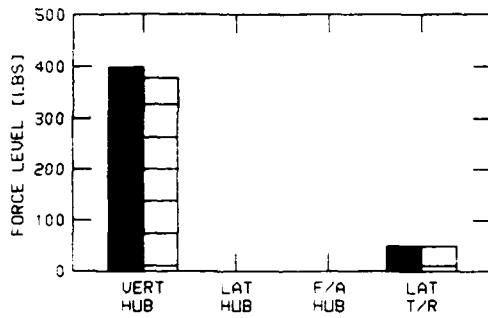
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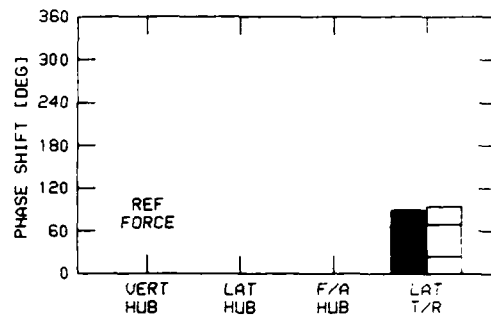
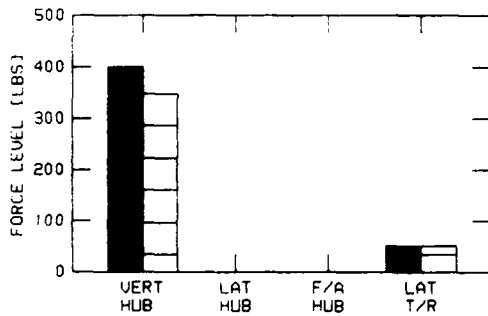
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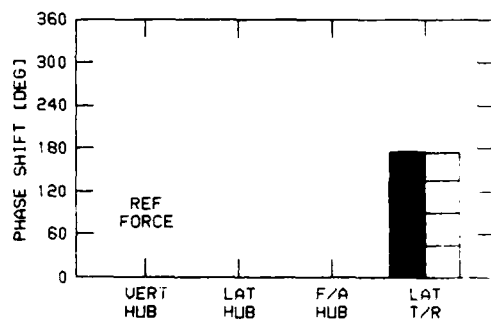
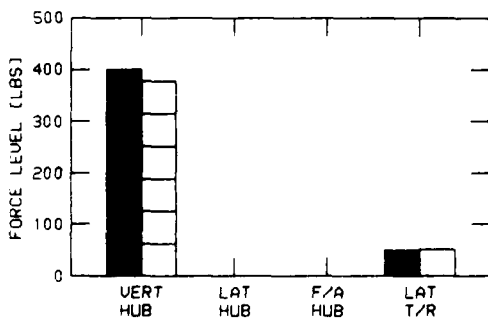
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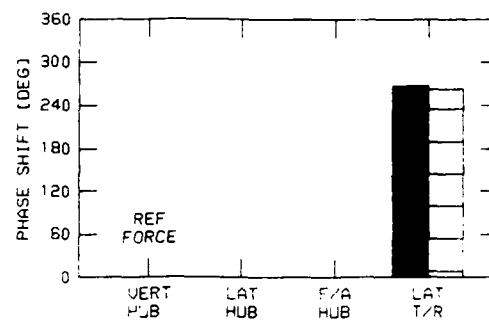
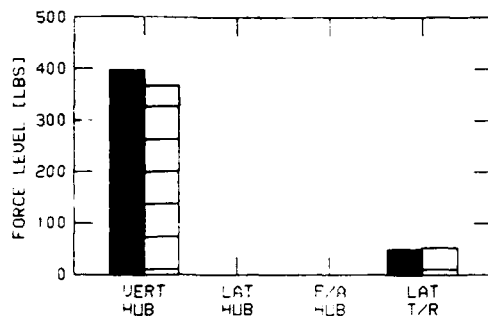


TEST - APPLIED

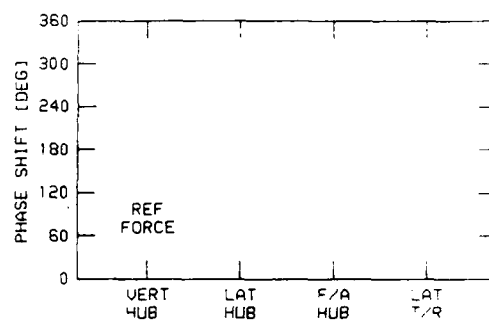
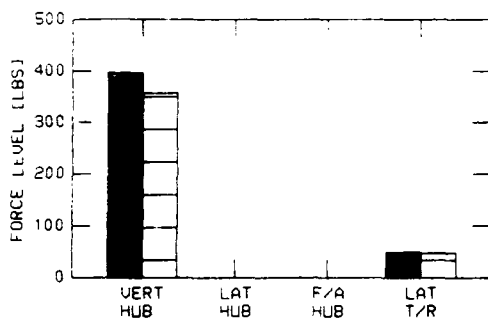


FD - CALCULATED

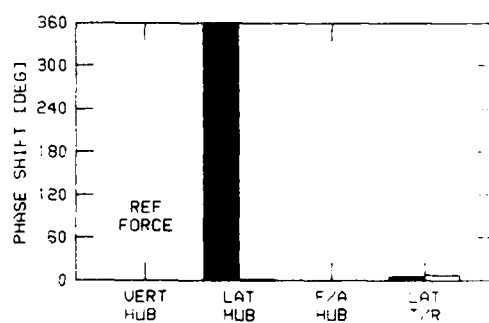
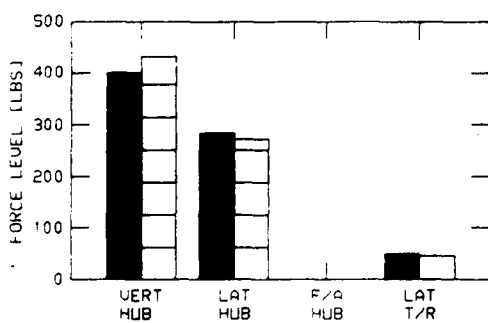
RUN NO.: 28
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



RUN NO.: 29
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



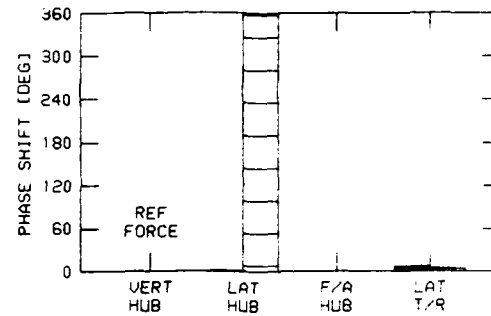
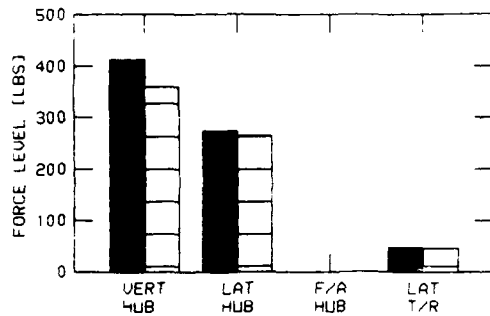
RUN NO.: 30
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



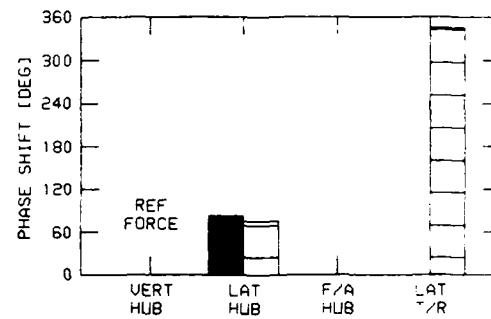
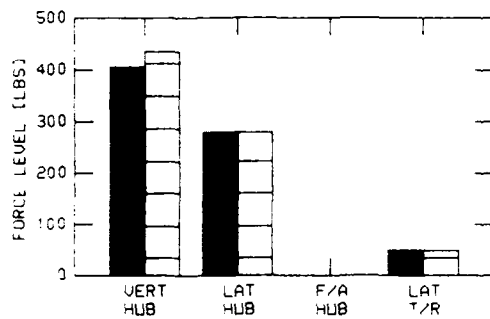
TEST - APPLIED

FD - CALCULATED

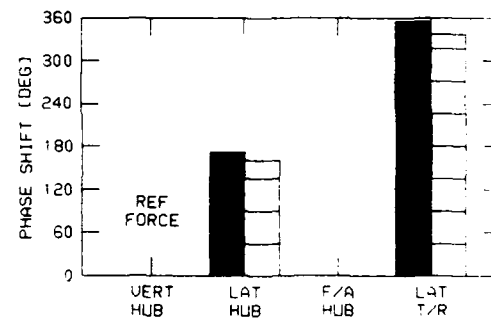
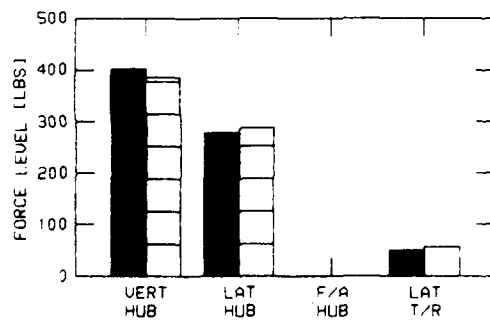
RUN NO.: 31
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



RUN NO.: 32
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



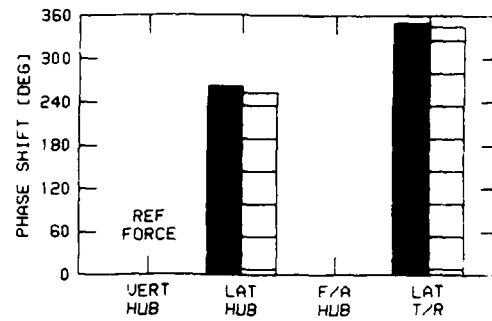
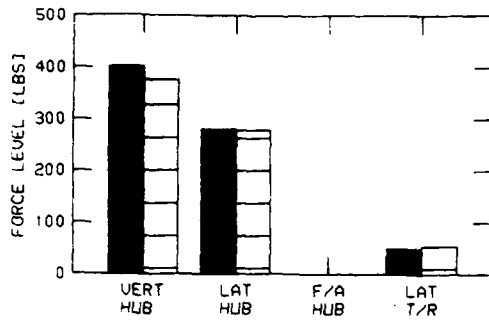
RUN NO.: 33
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



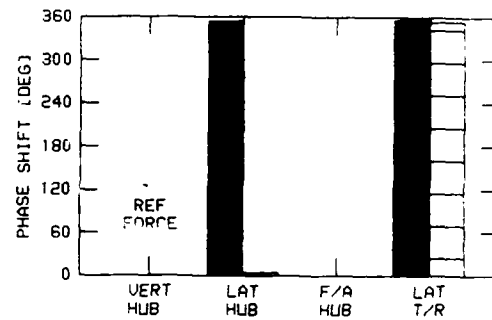
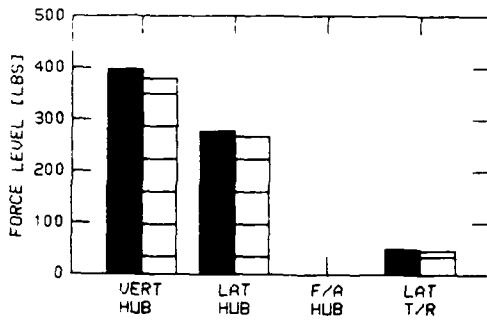
TEST - APPLIED

FD - CALCULATED

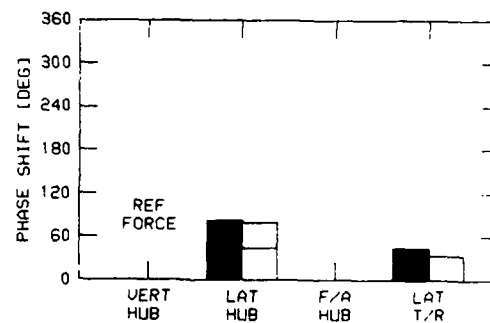
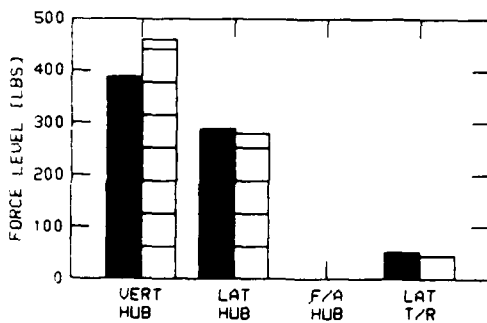
RUN NO.: 34
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



RUN NO.: 35
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



RUN NO.: 36
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL

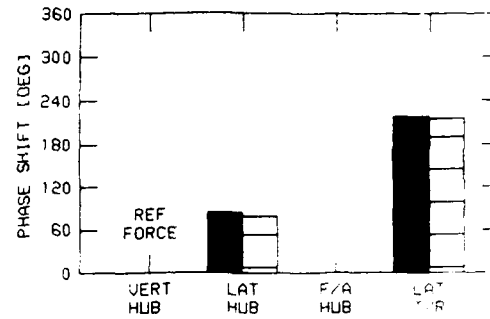
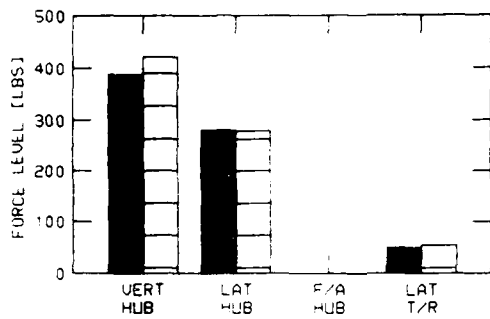


TEST - APPLIED

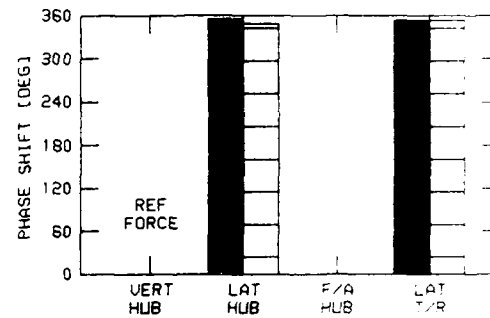
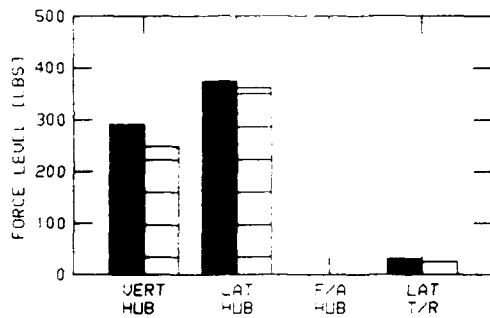


FD - CALCULATED

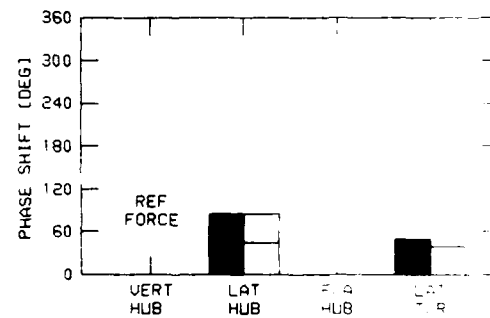
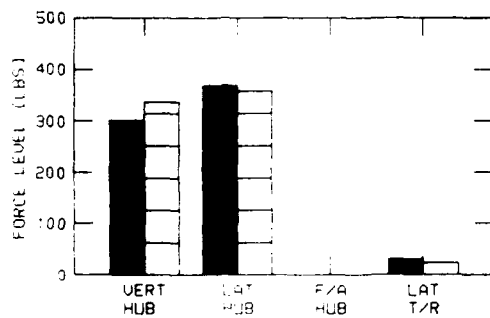
RUN NO.: 37
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



RUN NO.: 38
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



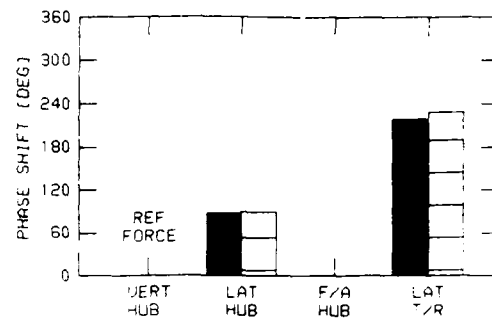
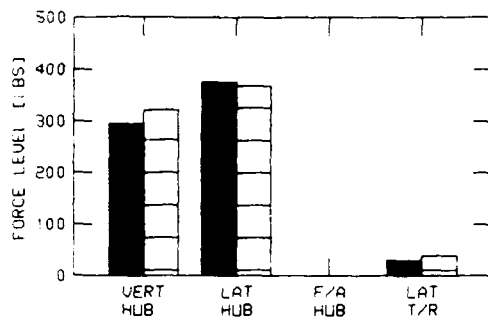
RUN NO.: 39
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



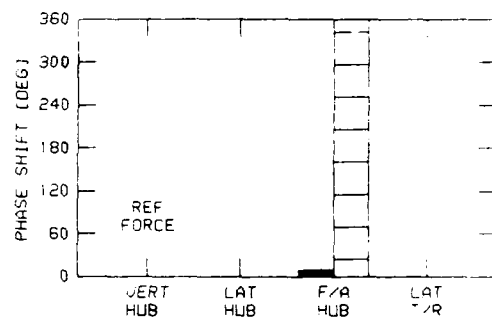
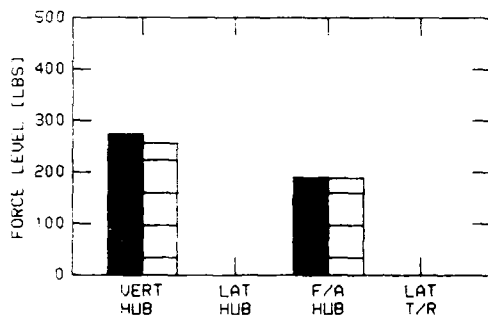
TEST - APPLIED

FD - CALCULATED

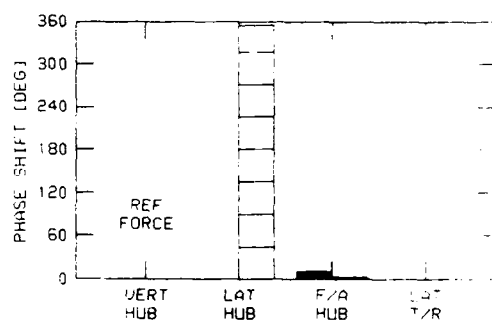
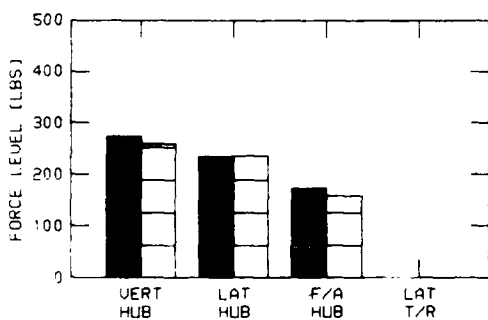
RUN NO.: 40
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



RUN NO.: 41
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



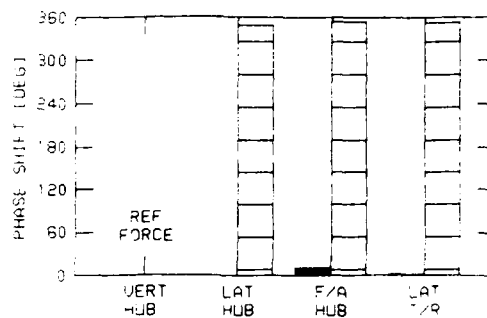
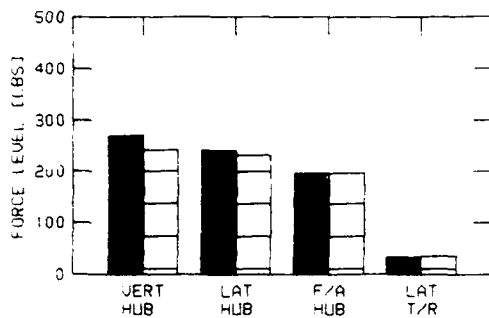
RUN NO.: 42
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



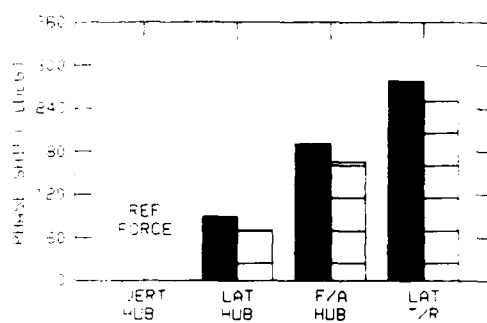
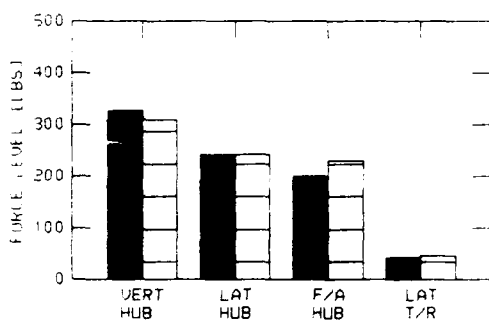
TEST - APPLIED

FD - CALCULATED

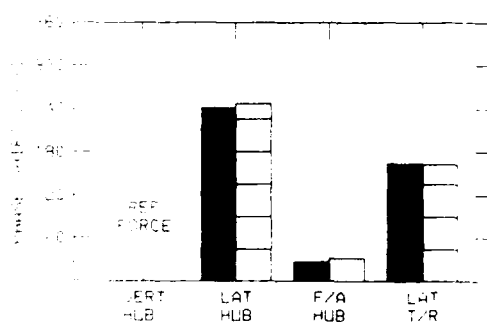
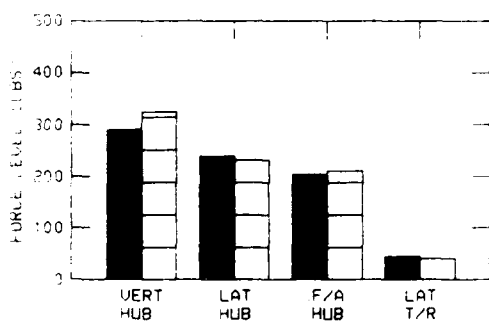
RUN NO. 43
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



RUN NO. 44
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



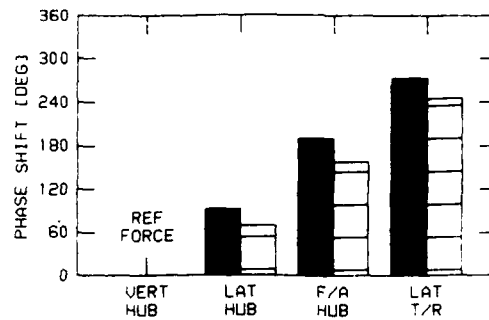
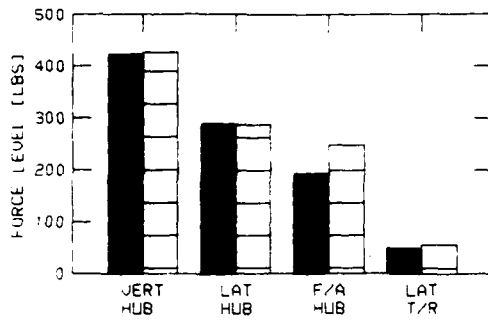
RUN NO. 45
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



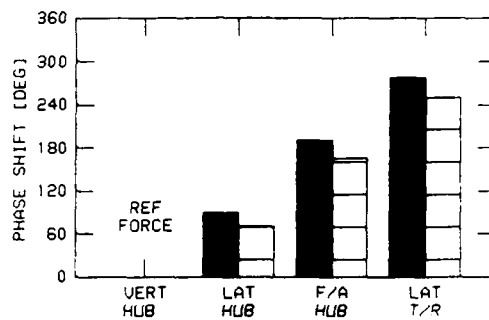
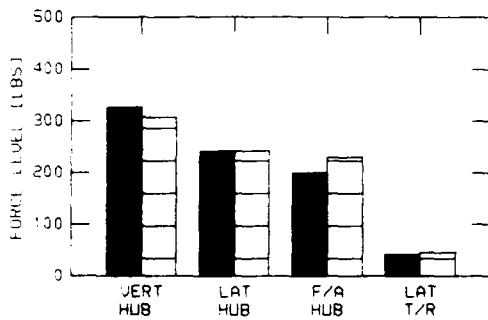
TEST - APPLIED

APPLIED - CALCULATED

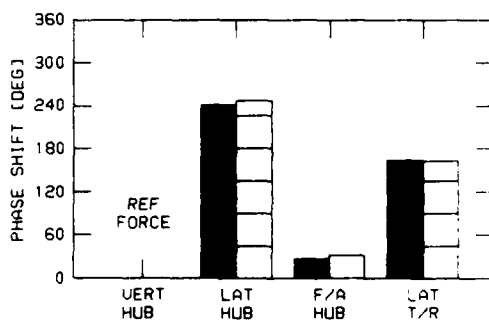
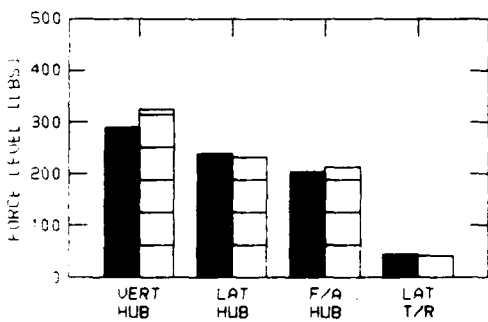
RUN NO.: 46
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



RUN NO.: 47
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



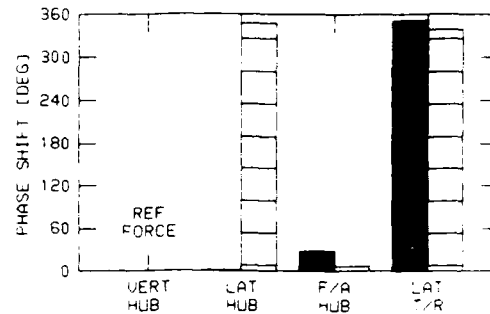
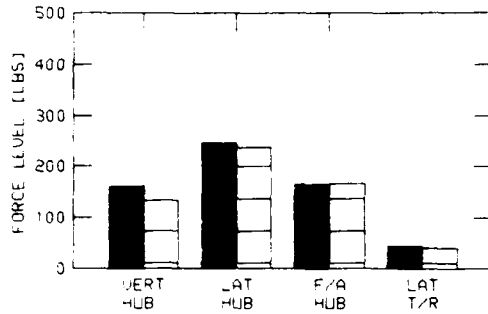
RUN NO.: 48
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



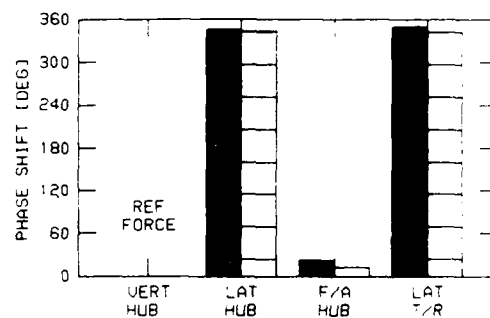
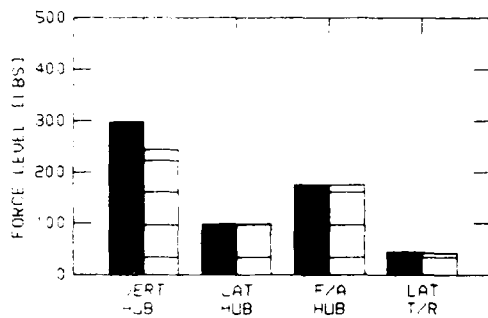
■ TEST - APPLIED

▨ FD - CALCULATED

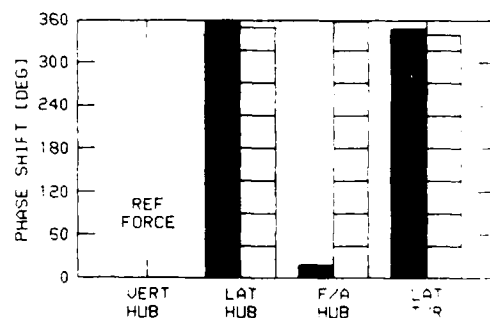
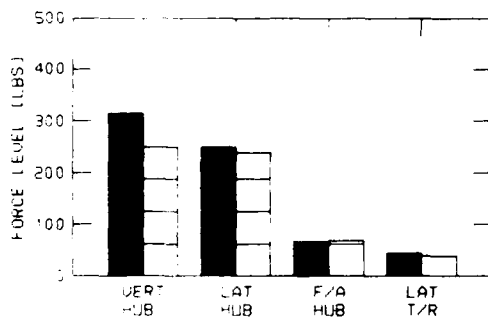
RUN NO. 49
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



RUN NO. 50
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



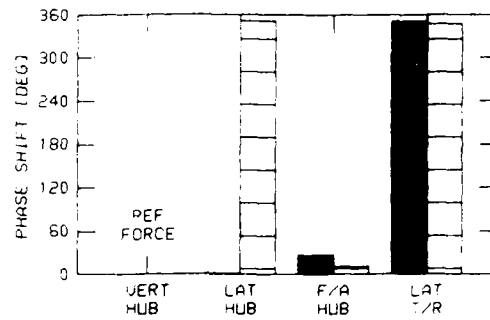
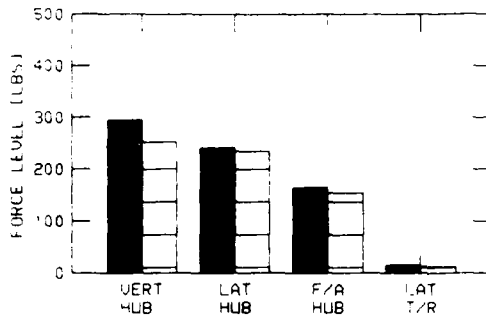
RUN NO. 51
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



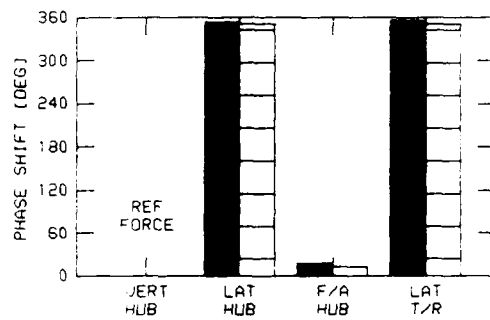
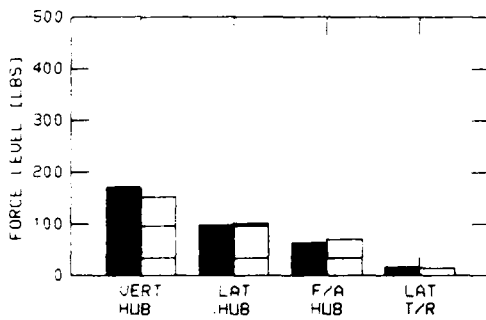
TEST - APPLIED

FD - CALCULATED

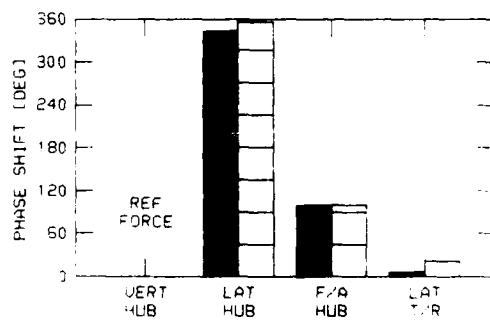
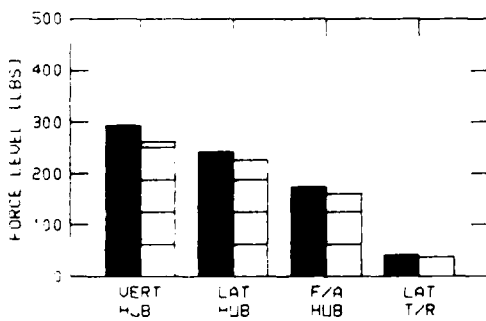
RUN NO.: 52
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



RUN NO.: 53
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



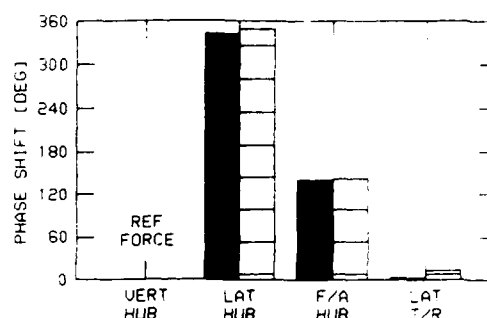
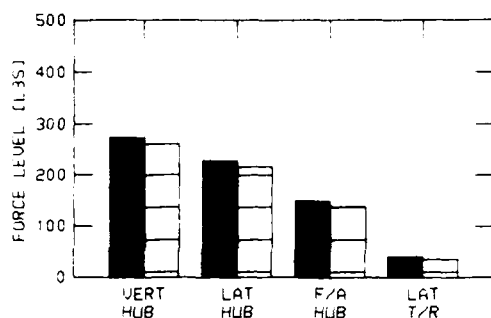
RUN NO.: 54
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



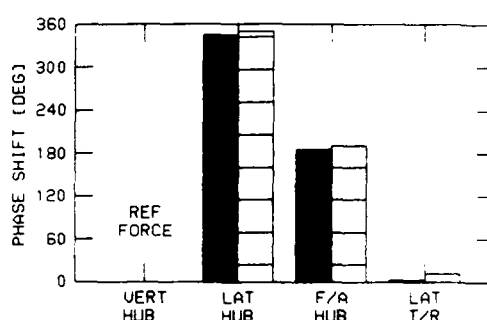
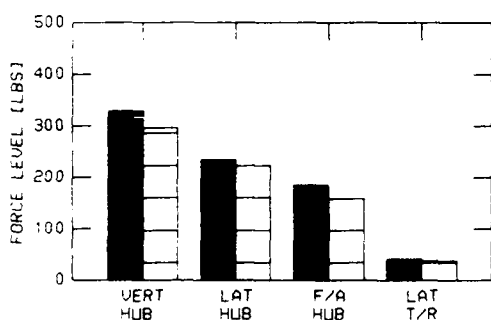
TEST - APPLIED

FD - CALCULATED

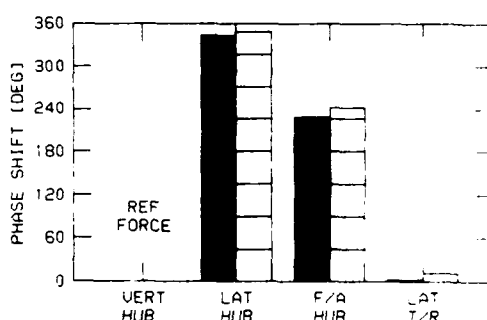
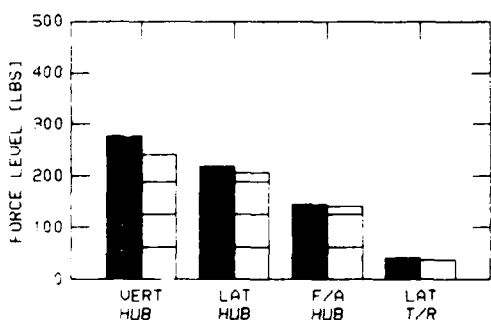
RUN NO. 55
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



RUN NO. 56
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



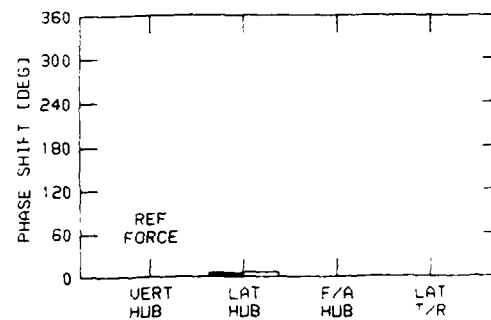
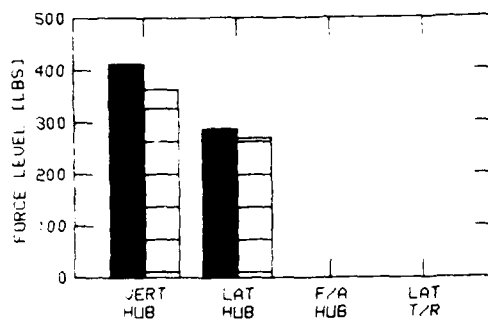
RUN NO. 57
 CALIBRATION MOBILITIES: CONSTRAINED
 REFERENCE ACCELEROMETER: T/R GEAR BOX, LATERAL



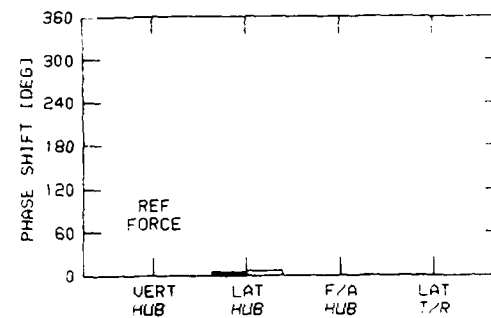
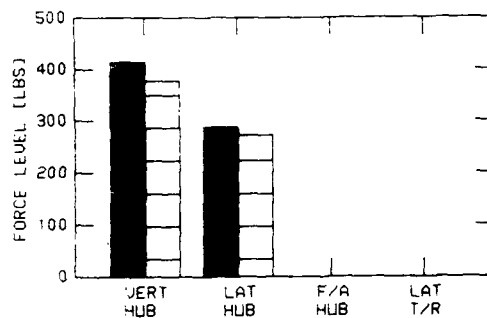
TEST - APPLIED

FD - CALCULATED

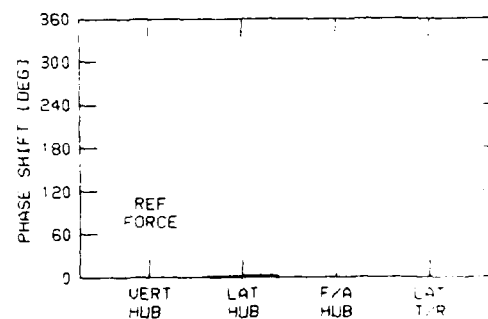
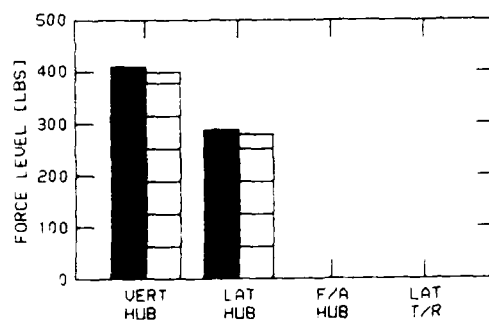
RUN NO.: 58
 CALIBRATION MOBILITIES: FREE
 REFERENCE ACCELEROMETER: TAIL FIN, VERTICAL



RUN NO.: 59
 CALIBRATION MOBILITIES: FREE
 REFERENCE ACCELEROMETER: TAIL FIN, LATERAL



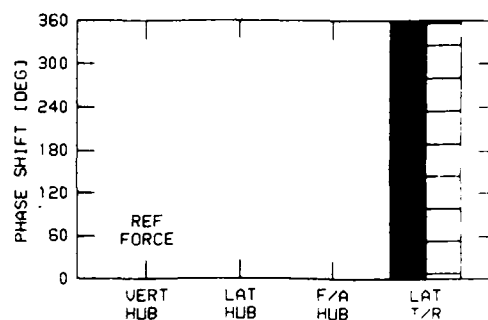
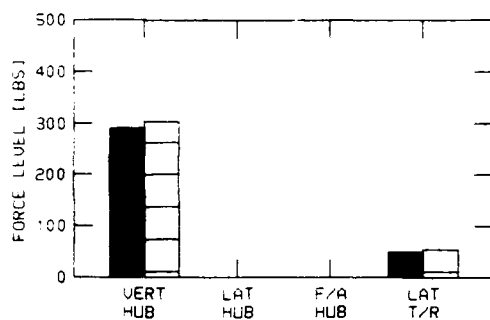
RUN NO.: 60
 CALIBRATION MOBILITIES: FREE
 REFERENCE ACCELEROMETER: TAIL FIN, LATERAL



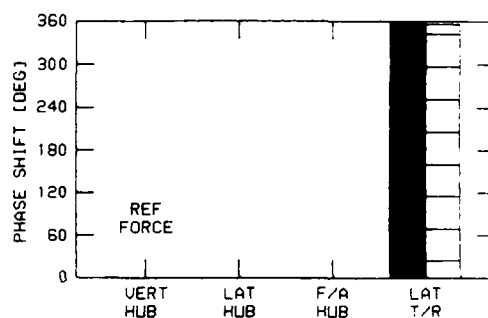
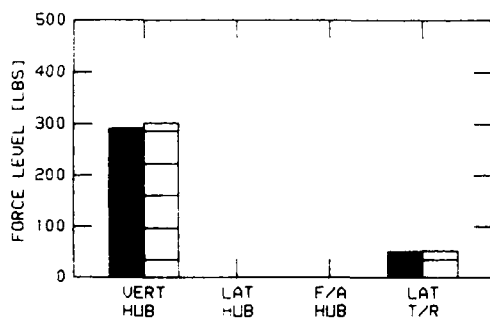
TEST - APPLIED

FD - CALCULATED

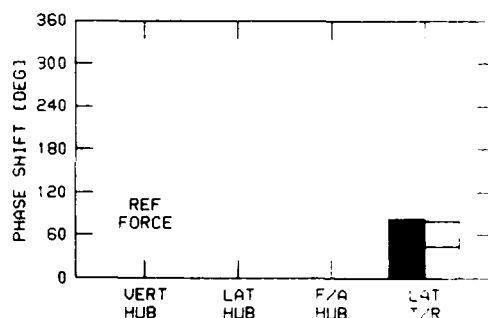
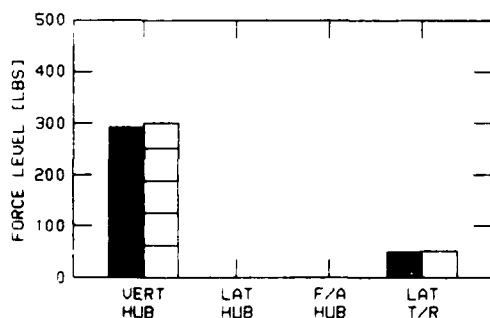
RUN NO.: 61
 CALIBRATION MOBILITIES: FREE
 REFERENCE ACCELEROMETER: TAIL FIN, LATERAL



RUN NO.: 62
 CALIBRATION MOBILITIES: FREE
 REFERENCE ACCELEROMETER: TAIL FIN, LATERAL



RUN NO.: 63
 CALIBRATION MOBILITIES: FREE
 REFERENCE ACCELEROMETER: TAIL FIN, LATERAL

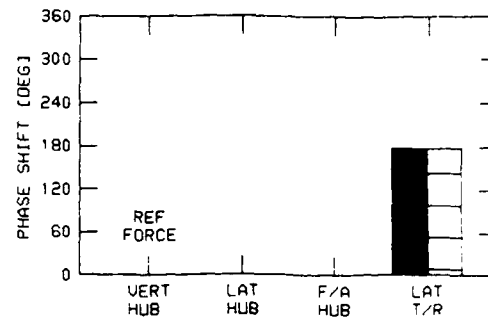
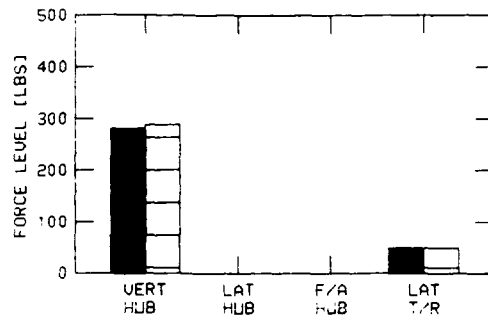


TEST - APPLIED

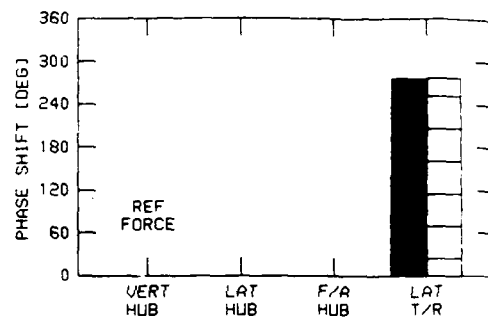
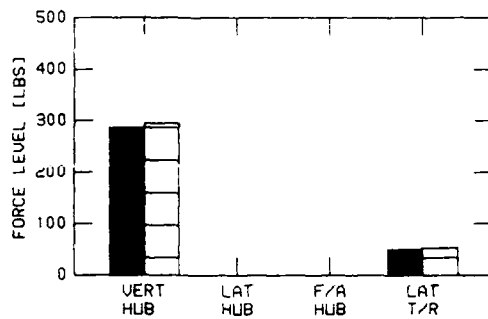


FD - CALCULATED

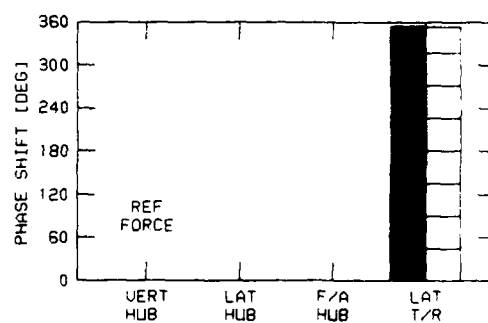
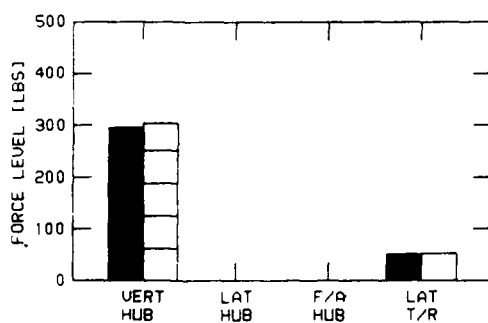
RUN NO.: 64
 CALIBRATION MOBILITIES: FREE
 REFERENCE ACCELEROMETER: TAIL FIN, LATERAL



RUN NO.: 65
 CALIBRATION MOBILITIES: FREE
 REFERENCE ACCELEROMETER: TAIL FIN, LATERAL



RUN NO.: 66
 CALIBRATION MOBILITIES: FREE
 REFERENCE ACCELEROMETER: TAIL FIN, LATERAL



TEST - APPLIED



FD - CALCULATED

	Load - Pounds				Phase - Degrees		
	Applied	Calculated	Difference	Percent Error	Applied	Calculated	Difference
Run No. 14							
Vertical Hub	366.3	353.1	-13.2	-3.6	Reference		
Lateral Hub	391.5	386.7	-4.8	-1.2	269.4	283.9	14.5
Run No. 15							
Vertical Hub	407.9	386.6	-21.3	-5.2	Reference		
Lateral Hub	288.2	391.5	3.3	1.1	1.0	4.9	3.9
Run No. 16							
Vertical Hub	108.4	93.1	-15.3	-14.12	Reference		
Lateral Hub	392.0	386.6	-5.4	-1.4	3.0	349.5	-13.5
Run No. 17							
Vertical Hub	108.4	94.7	-13.7	-12.6	Reference		
Lateral Hub	392.0	387.2	-4.8	-1.2	3.0	347.6	-15.4
Run No. 18							
Lateral Hub	290.5	296.3	5.8	2.0	Reference		
Lateral T/R	49.8	47.1	-2.7	-5.4	357.03	0.4	3.37
Run No. 19							
Lateral Hub	289.6	296.1	6.5	2.3	Reference		
Lateral T/R	49.5	45.8	-3.7	-7.3	357.01	0.4	
Run No. 20							
Lateral Hub	290.6	299.3	8.7	3.0	Reference		
Lateral T/R	49.4	55.9	6.5	13.2	81.9	88.3	6.4
Run No. 21							
Lateral Hub	280.7	294.0	13.3	4.7	Reference		
Lateral T/R	49.4	57.0	7.6	15.4	180.3	175.5	-4.8
Run No. 22							
Lateral Hub	284.9	291.4	6.5	2.3	Reference		
Lateral T/R	49.4	48.0	-1.4	2.8	274.8	267.8	-7.0
Run No. 23							
Lateral Hub	293.8	298.1	4.3	1.5	Reference		
Lateral T/R	49.5	45.9	-3.6	-7.3	355.3	358.2	2.9
Run No. 24							
Vertical Hub	401.2	415.9	14.7	3.7	Reference		
Lateral T/R	49.6	49.7	0.1	0.2	356	357	1.0
Run No. 25							
Vertical Hub	399.4	377.4	-22	-5.5	Reference		
Lateral T/R	49.0	48.8	-0.2	-0.4	0.7	2.9	2.2
Run No. 26							
Vertical Hub	400.3	346.2	-54.1	-13.5	Reference		
Lateral T/R	50.5	49.7	-0.8	-1.6	88.9	94.4	5.5
Run No. 27							
Vertical Hub	398.7	377.0	-21.7	-5.4	Reference		
Lateral T/R	49.4	49.7	0.3	0.6	176.0	174.4	-1.7

	Load - Pounds				Phase - Degrees		
	Applied	Calculated	Difference	Percent Error	Applied	Calculated	Difference
Run No. 28							
Vertical Hub	396.1	365.9	-30.2	-7.6	Reference		
Lateral T/R	49.9	51.5	1.6	3.2	268.2	262.6	-5.6
Run No. 29							
Vertical Hub	395.7	354.9	-40.8	-10.3	Reference		
Lateral T/R	49.3	47.4	-1.9	-3.9	0	0.4	0.4
Run No. 30							
Vertical Hub	400.3	432.4	32.1	8.0	Reference		
Lateral Hub	284.0	271.8	-12.2	-4.3	358.6	1.1	2.5
Lateral T/R	49.4	46.0	-3.4	-6.9	4.7	7.9	3.2
Run No. 31							
Vertical Hub	411.5	359.8	-51.7	-12.6	Reference		
Lateral Hub	274.3	264.5	-9.8	-3.6	0.9	357.8	-3.1
Lateral T/R	48.4	44.9	-3.5	-7.2	6.2	3.6	-2.6
Run No. 32							
Vertical Hub	404.2	435.4	31.2	7.7	Reference		
Lateral Hub	278.8	278.7	-0.1	-0.3	82.6	76.1	-6.5
Lateral T/R	49.2	48.1	-1.1	-2.2	0	343.6	-16.4
Run No. 33							
Vertical Hub	401.7	385.5	-16.2	-4.0	Reference		
Lateral Hub	276.5	284.9	8.4	3.0	172.3	159.0	-13.3
Lateral T/R	49.1	55.6	6.5	13.2	354.9	337.1	-17.8
Run No. 34							
Vertical Hub	400.9	374.6	-26.3	-6.6	Reference		
Lateral Hub	279.6	278.6	-1.0	-0.4	261.9	251.6	-10.3
Lateral T/R	49.1	53.6	4.5	9.2	350.1	344.9	-5.2
Run No. 35							
Vertical Hub	396.2	378.6	-17.6	-4.4	Reference		
Lateral Hub	276.9	266.5	-10.4	-3.8	353.4	360+	-11.88
Lateral T/R	49.2	46.0	-3.2	-6.52	355.5	352.6	-2.9
Run No. 36							
Vertical Hub	386.7	459.3	72.6	18.8	References		
Lateral Hub	287.0	279.0	8.0	2.8	81.5	79.0	-2.5
Lateral T/R	50.1	44.4	5.7	11.42	43.7	34.2	9.5
Run No. 37							
Vertical Hub	387.6	421.0	33.4	8.6	Reference		
Lateral Hub	280.7	279.1	-1.6	0.6	84.4	78.4	-6.0
Lateral T/R	49.1	53.9	4.8	9.8	217.0	214.8	-2.2
Run No. 38							
Vertical Hub	290.1	248.2	-41.9	-14.4	Reference		
Lateral Hub	374.3	359.7	-14.6	-3.9	353.6	347.8	5.8
Lateral T/R	30.4	24.6	-5.8	-19.0	352.7	352.9	0.2
Run No. 39							
Vertical Hub	300.3	335.6	35.3	11.8	Reference		
Lateral Hub	367.8	357.9	-9.9	-2.7	85.1	84.1	-1.0
Lateral T/R	30.4	23.0	-7.4	-24.5	48.6	38.9	9.7

	Load - Pounds				Phase - Degrees		
	Applied	Calculated	Differences	Percent Error	Applied	Calculated	Difference
Run No. 40							
Vertical Hub	295.0	320.8	25.8	8.7	Reference		
Lateral Hub	375.9	368.9	-7.0	-1.9	87.2	89.6	2.4
Lateral T/R	30.3	37.8	7.5	24.8	219.4	228.9	9.5
Run No. 41							
Vertical Hub	273.59	255.1	-18.49	-6.76	Reference		
Fore/Aft Hub	188.9	188.42	-0.48	-0.25	8.38	358.98	-9.4
Run No. 42							
Vertical Hub	270.98	257.1	-13.86	-5.13	Reference		
Lateral Hub	233.75	234.85	1.1	0.47	0.26	354.97	-5.29
Fore/Aft Hub	171.45	157.08	-14.37	-8.39	9.99	2.9	-7.09
Run No. 43							
Vertical Hub	269.67	242.6	-27.07	-10.04	Reference		
Lateral Hub	241.64	232.67	-8.97	-3.71	0.24	349.37	-10.87
Fore/Aft Hub	196.03	196.93	0.90	0.4	10.12	353.4	-16.73
Lateral T/R	34.49	35.87	1.38	3.63	0.92	352.07	-8.85
Run No. 44							
Vertical Hub	324.67	307.85	-16.82	-5.18	Reference		
Lateral Hub	241.80	241.31	-0.49	-0.2	90.8	70.16	-20.64
Fore/Aft Hub	200.10	230.45	30.35	15.16	190.6	165.13	-25.47
Lateral T/R	40.97	46.01	5.04	12.27	276.58	249.76	-26.82
Run No. 45							
Vertical Hub	290.23	324.30	34.07	11.74	Reference		
Lateral Hub	238.57	231.73	-6.84	-2.87	240.77	246.69	5.92
Fore/Aft Hub	204.21	211.83	7.62	3.73	27.14	32.24	5.10
Lateral T/R	44.19	41.09	-3.10	-7.01	164.25	163.02	-1.23
Run No. 46							
Vertical Hub	423.16	427.41	4.25	1.0	Reference		
Lateral Hub	288.99	286.66	-2.33	-0.81	91.81	70.05	-21.76
Fore/Aft Hub	193.59	248.64	55.05	28.44	189.32	158.43	-30.89
Lateral T/R	50.23	56.02	5.79	11.55	272.64	245.49	-27.15
Run No. 47							
Vertical Hub	324.67	307.85	-16.82	-5.18	Reference		
Lateral Hub	241.80	241.31	-0.49	-0.20	90.0	70.16	-19.84
Fore/Aft Hub	200.10	230.44	30.34	15.16	190.6	165.13	-25.47
Lateral T/R	40.97	46.00	5.03	12.27	276.58	249.76	-26.82
Run No. 48							
Vertical Hub	290.23	324.30	34.07	11.74	Reference		
Lateral Hub	238.57	231.78	-6.84	-2.87	240.77	246.70	5.93
Fore/Aft Hub	204.21	211.83	7.62	7.62	27.14	32.24	5.10
Lateral T/R	44.19	41.03	-3.16	-7.01	164.25	163.02	-1.23
Run No. 49							
Vertical Hub	162.40	134.18	-28.22	-17.37	Reference		
Lateral Hub	248.14	238.54	-9.6	-3.87	1.03	347.07	-13.96
Fore/Aft Hub	164.61	166.56	1.95	1.19	27.65	6.85	-20.78
Lateral T/R	44.13	39.66	-4.47	-10.12	351.38	338.37	-13.01

	Load - Pounds				Phase - Degrees		
	Applied	Calculated	Difference	Percent Error	Applied	Calculated	Difference
Run No. 50							
Vertical Hub	296.82	242.88	-53.94	-18.17	Reference		
Lateral Hub	97.86	97.69	-0.17	-0.17	346.29	343.02	-3.27
Fore/Aft Hub	173.89	173.39	-0.50	-0.29	23.30	12.18	-11.12
Lateral T/R	44.08	42.33	-1.75	-3.96	348.75	342.02	-6.73
Run No. 51							
Vertical Hub	313.06	249.41	-63.65	-20.33	Reference		
Lateral Hub	248.57	238.99	-9.58	-3.86	359.29	350.61	-8.68
Fore/Aft Hub	66.08	68.64	2.56	3.87	17.51	358.05	-19.46
Lateral T/R	44.13	39.18	-4.95	-11.21	348.47	339.04	-9.43
Run No. 52							
Vertical Hub	294.75	251.15	-43.24	-14.67	Reference		
Lateral Hub	241.53	234.52	-7.01	-2.90	1.09	350.68	-10.41
Fore/Aft Hub	164.57	154.33	-10.24	-6.22	25.75	9.62	-16.13
Lateral T/R	15.90	11.80	-4.10	-25.79	351.22	346.67	-4.55
Run No. 53							
Vertical Hub	171.42	152.99	-18.43	-10.75	Reference		
Lateral Hub	97.02	101.33	4.31	4.45	352.65	351.00	-1.65
Fore/Aft Hub	63.44	70.43	6.99	11.03	17.52	11.67	-5.85
Lateral T/R	15.89	14.28	-1.51	-10.10	355.64	351.08	-4.56
Run No. 54							
Vertical Hub	292.24	260.68	-31.56	-10.8	Reference		
Lateral Hub	242.23	225.97	-16.26	-6.71	343.80	355.79	12.0
Fore/Aft Hub	172.50	160.17	-12.33	-7.15	99.53	99.55	0.02
Lateral T/R	39.90	35.93	-3.97	-9.95	6.26	21.55	15.3
Run No. 55							
Vertical Hub	273.96	261.86	-12.11	-4.42	Reference		
Lateral Hub	229.99	216.86	-13.13	-5.71	341.82	349.39	7.58
Fore/Aft Hub	150.40	138.67	-11.74	-7.80	140.47	142.40	1.92
Lateral T/R	39.93	35.71	-4.22	-10.57	3.08	13.15	10.07
Run No. 56							
Vertical Hub	326.63	295.78	-30.85	-9.45	Reference		
Lateral Hub	233.67	221.94	-11.72	-5.02	344.48	348.67	4.19
Fore/Aft Hub	124.00	157.30	26.70	14.51	184.57	189.96	5.39
Lateral T/R	39.92	36.29	-3.63	-9.09	1.84	10.55	8.72
Run No. 57							
Vertical Hub	276.26	240.24	-36.03	-13.04	Reference		
Lateral Hub	218.43	206.49	-11.94	-5.47	342.99	348.26	5.26
Fore/Aft Hub	144.22	141.05	-3.17	-2.20	228.03	242.44	14.40
Lateral T/R	39.93	36.37	-3.56	-8.91	1.86	10.59	8.73

Calibration Mobilities: Free

	Load - Pounds				Phase - Degrees		
	Applied	Calculated	Difference	Percent Error	Applied	Calculated	Difference
Run No. 58							
Vertical Hub	412.71	363.0	-49.71	-12.1	Reference		
Lateral Hub	287.2	270.6	-16.6	-5.7	4.7	5.7	2.0
Run No. 59							
Vertical Hub	412.71	377.2	-35.51	-8.6	Reference		
Lateral Hub	287.2	270.8	-16.4	-5.7	4.7	6.0	1.3
Run No. 60							
Vertical Hub	407.9	397.9	-10.0	-2.4	Reference		
Lateral Hub	288.2	278.7	-9.5	-3.3	1.0	2.0	1.0
Run No. 61							
Vertical Hub	290.5	302.8	12.3	4.2	Reference		
Lateral T/R	49.8	53.5	3.7	7.4	357.3	355.7	-1.5
Run No. 62							
Vertical Hub	289.6	300.9	11.3	3.9	Reference		
Lateral T/R	49.5	52.4	2.9	5.9	357.1	355.6	-1.5
Run No. 63							
Vertical Hub	290.6	300.7	10.1	3.5	Reference		
Lateral T/R	49.4	51.1	1.7	1.8	81.9	79.4	2.6
Run No. 64							
Vertical Hub	280.7	288.2	7.5	2.7	Reference		
Lateral T/R	49.4	50.0	0.6	1.3	180.3	179.1	-1.1
Run No. 65							
Vertical Hub	284.9	294.0	9.1	3.2	Reference		
Lateral T/R	49.4	52.0	2.6	5.5	274.8	275.8	1.0
Run No. 66							
Vertical Hub	293.8	304.3	10.5	3.6	Reference		
Lateral T/R	49.5	52.5	3.0	6.2	355.3	354.0	-1.4
Run No. 67							
Lateral Hub	401.2	243.1	-158.1	39.4	Reference		
Lateral T/R	49.6	38.4	-11.2	22.5	355.8	333.2	-22.6
Run No. 68							
Vertical Hub	400.3	256.7	-143.6	35.9	Reference		
Lateral Hub	284.0	265.9	-18.1	6.4	358.6	343.4	-15.2
Lateral T/R	49.4	47.0	-2.4	5.0	4.7	346.3	-18.4