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A TRIAXIAL ACCELEROMETER MODULE FOR VESTIBULAR APPLICATION

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13. ABSTRACT

A brief description is given of a 6-channel instrumentation module developed for collection of preliminary acceleration data for the a priori determination of optimal characteristics for transducers to be installed permanently on various aircraft and man-rated research devices for the measurement of vestibular-significant acceleration stimuli. The module utilizes three linear and three angular accelerometers, all of the standard, commercially available, servo type, to measure the triaxial linear and triaxial angular accelerations, along and about, respectively, the roll, pitch, and yaw axes of the test device or vehicle. Signal-conditioning amplifiers equipped with feedback circuitry to facilitate in-flight adjustment of gain and high-frequency rolloff characteristics are provided for optimal utilization of the dynamic range capabilities of magnetic tape data storage recorders. Though the instrument is used primarily to collect acceleration data in the 0-5 cps spectrum, the linear channels can also be used in determining vibration levels in the 0-100 cps range.

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A TRIAXIAL ACCELEROMETER MODULE FOR VESTIBULAR APPLICATION*

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SUMMARY PAGE

THE PROBLEM

The need for a priori acceleration data to establish optimal transducer characteristics for the measurement of the triaxial linear and angular acceleration parameters of selected force environments routinely encountered in vestibular research including those of fixed and rotary wing aircraft during flight, of seagoing naval vessels, and operation of motion-producing laboratory research devices or simulators.

FINDINGS

A six-channel instrumentation module was developed to measure the triaxial linear accelerations and the triaxial angular accelerations directed along and about, respectively, the roll, pitch and yaw axes of the vehicle or research device undergoing test. The module houses three orthogonally mounted linear accelerometers and three similarly mounted angular accelerometers, all of which are standard, commercially available, servo type transducers. Signal-conditioning for each accelerometer channel is provided by a chopper-stabilized DC operational amplifier with operator controls for selection of channel gain and high frequency rolloff. Though the instrument was developed primarily for evaluation of low-frequency vestibular stimuli in the 0-5 cps spectrum and below, the linear transducers allow vibration measurements extending to beyond 100 cps, while the frequency response of the angular accelerometers exceeds 50 cps.

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INTRODUCTION

This report presents a brief description of an acceleration measurement instrument which was developed as a vestibular research tool for evaluation of the low-frequency characteristics of the force environments encountered in fixed and rotary wing aircraft, seagoing naval vessels, land vehicles, and various man-rated laboratory motion devices and simulators. The instrument, identified as the Triaxial Accelerometer Module (TAM), provides an analog identification of its resultant linear acceleration and resultant angular acceleration in terms of three inertial linear acceleration components directed along the x, y, and z axes of a right-handed rectangular Cartesian coordinate reference frame, and in terms of three angular acceleration components directed about the same axes. The primary application of the device involves the selection of linear and angular motion transducers for permanent or long-term installation in the above environments so that motion measurements may be made on a continuing basis. Preliminary acceleration data pertaining to a given maneuver or test condition of interest are collected with the instrument and analysed in relation to peak level, rise times, and frequency content. The results of this analysis may then be used to select transducers which have technical characteristics optimal for the specific environment being investigated.

The instrument also finds application as a test and measurement device for setup and control of the various power servomechanism systems used to drive many of the large-scale rotating devices installed at the activity. The angular acceleration channels are particularly suited for adjustment of servo hunting stability and rise time characteristics since measurements can be made to frequencies extending from dc to 50 cps, a range far beyond the 0-5 cps spectrum of usual interest to vestibular studies. In the same manner, the 0-100 cps range of the linear accelerometers is of value to the investigation of low-frequency vibration levels in military helicopters.

GENERAL DESCRIPTION

A block diagram of the six acceleration measurement channels of the TAM is shown in Figure 1. In accordance with the kinematics nomenclature developed by this activity for the man-referenced identification of physiological acceleration stimuli (1), the three mutually orthogonal reference axes of the instrument are denoted as x, y, and z. The three linear acceleration channels, identified as A_x, A_y, and A_z, and the three angular acceleration channels, identified as α_x, α_y, and α_z, utilize standard, commercially available, force/torque balance accelerometers as the basic transduction elements. The output signal from each accelerometer is raised to record level by means of an associated signal-conditioning amplifier which features a "Scale" switch to allow operator selection of the acceleration level required to produce the rated 10-V output of the amplifier; and a "Filter" switch to select the high-frequency rolloff of the amplifier. A calibration network placed at the input of each amplifier permits a 10-V reference signal to be introduced into the system for establishment of the full-scale output level of each channel.

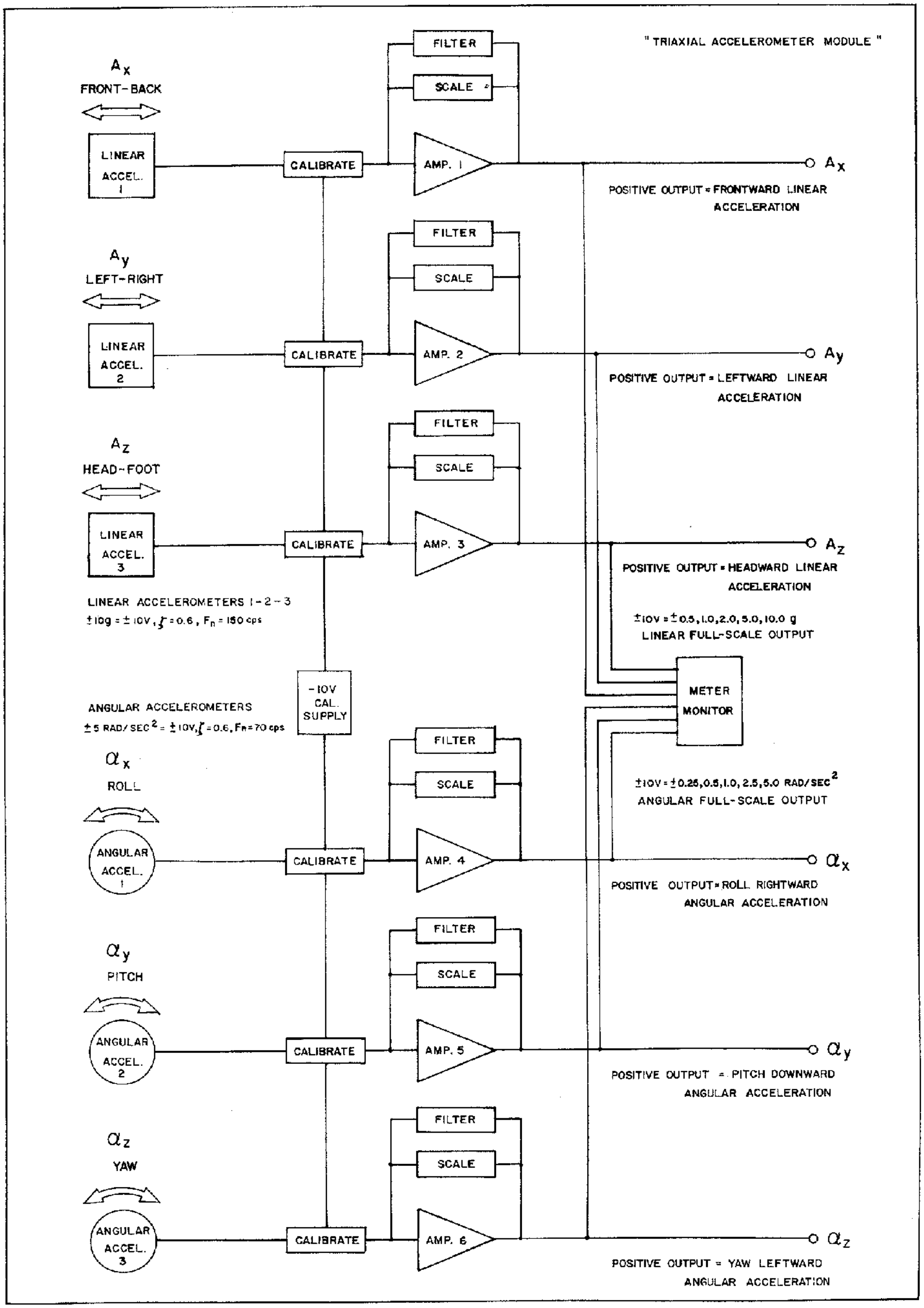

Figure 1

Block Diagram of Triaxial Accelerometer Module (TAM)

The linear accelerometers (Systron-Donner Corp. Model 4310) derive an analog measure of the inertial acceleration of the instrument case by sensing the resulting displacement of an internal seismic mass from a given reference or null point fixed to the case. Deviation of the mass from this reference is measured by a position-error detector whose output is amplified and directed to a restoring coil which drives the mass back to its original null position. With this feedback principle, the voltage across, or the current through, a precision resistor connected in series with the restoring coil then becomes an analog measure of the linear acceleration of the instrument case. The nominal ratings of the three linear accelerometers include a full-scale range of $\pm 10\,g$, a current sensitivity of 0.1000 mA output per g input, a natural frequency of approximately 150 cps, a damping ratio of 0.6 ± 0.1, a resolution of better than 0.001 % of full scale, a nonlinearity of less than 0.05% of full scale referenced to the best-fitted straight line, a temperature sensitivity of less than 0.01% of full scale, and a cross axis sensitivity of less than $0.002\,g$ per g of applied acceleration.

The three angular accelerometers (Systron-Donner Corp. Model 4525) operate on the same servo principle using the angular displacement of a torus-shaped sensing mass to derive an analog measure of the angular acceleration of the instrument case. The nominal ratings of these transducers include a full-scale range of ± 5 rad/sec^2, a current sensitivity of 0.200 mA output per rad/sec^2 input, a natural frequency of approximately 70 cps, a damping ratio of 0.6 ± 0.1, a nonlinearity of less than 0.1% of full scale, a resolution of better than 0.01% of full scale, a temperature sensitivity of less than 0.02% per degree F, and a linear acceleration sensitivity of less than 2.0% of full scale along any axis.

A simplified schematic drawing of the A_x channel, representative of the other five acceleration channels, is shown in Figure 2. External power to energize the module case is brought into the instrument via receptacle J2. The three-position "Mode" switch, S4, serves as a master on-off power control for all six channels while six individual switches, S3, allow independent energization of each channel. The current-output signal from the linear accelerometer is directed to the summing junction of the high-gain, chopper-stabilized, dc operational amplifier (Systron-Donner Corp. Model 3802), via the normally closed contacts of the Reset relay, RY1, associated with the given channel. Closed-loop amplifier gain, and thus the full-scale acceleration range required to produce the rated $\pm$ 10-V output of the channel, is controlled by the value of the feedback resistor, R1 through R5, that is selected by the A section of the six-position channel "Scale" switch S1. The EX position of S1A allows the connection of an external feedback resistor for selecting an intermediate full-scale g range when desired.

Operator adjustment of the corner frequency at which the amplifier gain falls off at a 6 db per octave rate is provided by the seven-position "Filter" switch, S2, which shunts one of six capacitors, C1 through C6, across the feedback resistor. The N position corresponds to no filter action from the circuit. Two 15-V back-to-back connected Zener diodes, D1 and D2, are wired in series with current-limiting resistor, R6, to apply over-voltage clipping action to the amplifier. When it is desired to

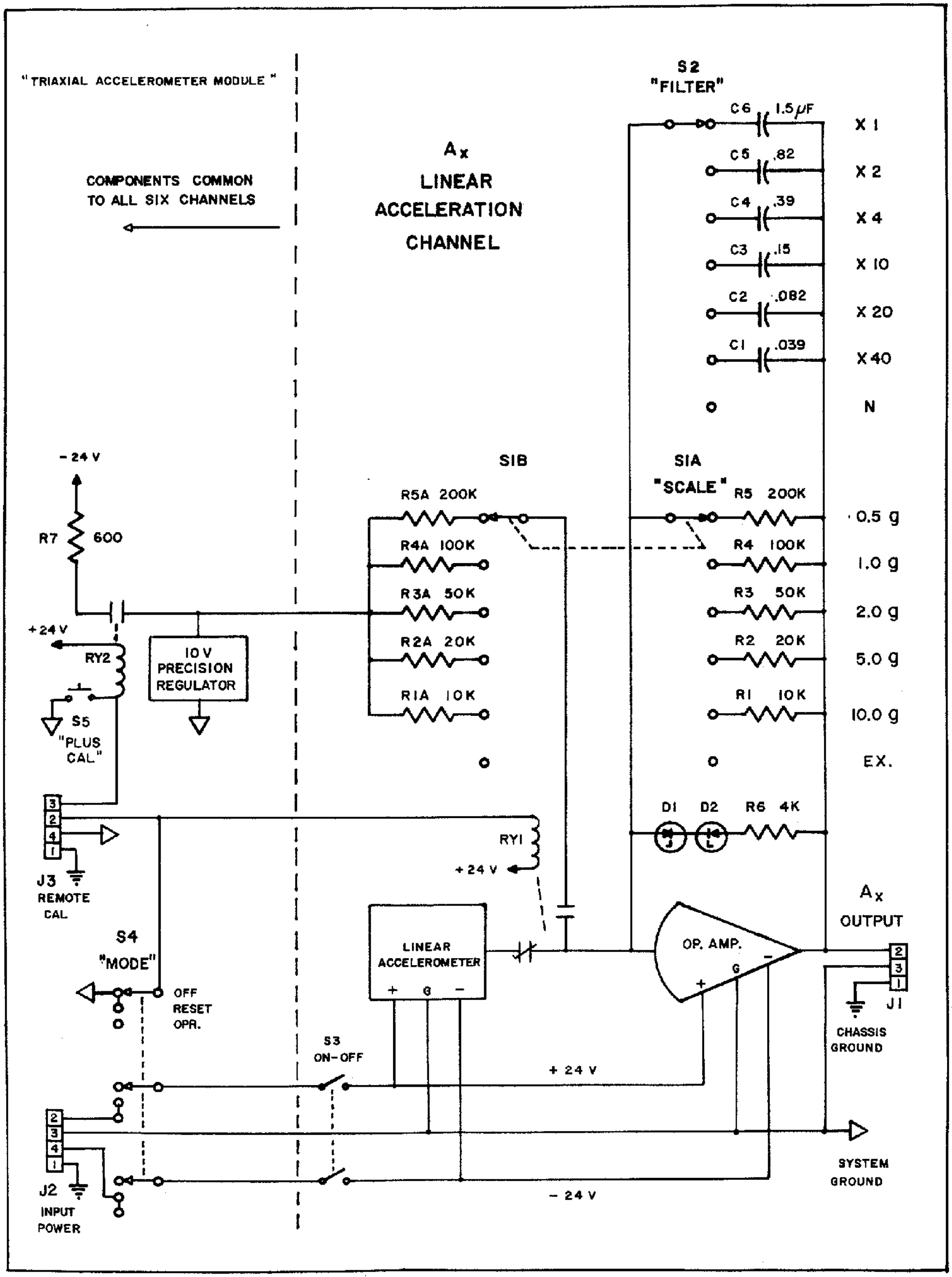

Figure 2

Simplified Schematic of a Single Acceleration Measurement Channel of the TAM.

establish the zero output signal level of the amplifiers, the "Mode" switch, S4, is placed in the "Reset" position which energizes the six Reset relays. When RY1 is turned on, the input to the amplifier summing junction is transferred from the output of the accelerometer to section S1B of the "Scale" switch. This section connects the amplifier input to a precision voltage regulator via one of the five input calibration resistors, R1A through R5A. When the 10-volt regulator is not energized, i.e., when the system Calibrate relay, RY2, is deenergized, its impedance level is sufficiently low to effectively return all of the amplifier inputs to ground potential. When the "Plus Cal" pushbutton, S5, is depressed, RY2 applies power to the voltage regulator which then furnishes - 10 V to the input of all six amplifiers. The calibration resistors R1A-R5A are selected so that the amplifier gain is unity regardless of the position of the " "Scale" switch S1. Accordingly, a +10-V calibration signal is developed at the output of each amplifier which then establishes the full-scale output level of the channel. Remote control of the Reset and Calibrate relays is provided via receptacle J3.

A front-view photograph of the completed module is shown in Figure 3. The approximate dimensions of the instrument are defined by a 11 in. by 11 in. control panel and an over-all height of 10 1/2 in. To minimize resonances of the case proper, the walls are constructed of 1/4-in.-thick aluminum plate. The total weight is 41 lb including all transducers and related signal-conditioning circuitry. The centrally located panel meter and the switch seen to its left are provided to allow the operator to monitor the output signal from each of the six acceleration channels as well as the voltage level of the external ±24-Vdc power sources and the internal 10-V regulator. The "Scale" switches associated with the three linear acceleration channels seen at the lower left of the module allow the operator to select full-scale acceleration ranges of ±0.5, 1.0, 2.0, 5.0, and 10.0 g. The upper corner frequency of the amplifier is determined by multiplying the numerical setting of the "Filter" switch by the g setting of the "Scale" switch. For example, if the ±2.0 g range is selected, the 40, 20, 10, 4, 2, and 1 positions of the "Filter" switch result in corner frequencies of 80, 40, 20, 8, 4, and 2 cps, respectively.

The "Scale" switches associated with the three angular acceleration channels seen at the lower right in Figure 3 provide full-scale ranges of ±0.25, 0.5, 1.0, 2.5, and 5.0 rad/sec^2. As with the linear channels, the high-frequency rolloff of the amplifier is determined as the product of the "Scale" and "Filter" settings. It should be obvious that the determination of the over-all frequency response of a given linear or angular channel must necessarily include consideration of the natural frequency of the related accelerometer at the higher settings of the "Filter" switch. It should also be observed that the basic accelerometer specifications are keyed to the rated full-scale ranges (±10g and ±5 rad/sec^2) of the transducers proper and not the setting selected by the "Scale" switch. However, since the data are usually stored on magnetic tape, the gain provided by each amplifier has the advantage of permitting a more optimal utilization of the limited dynamic range capability of each recording channel.

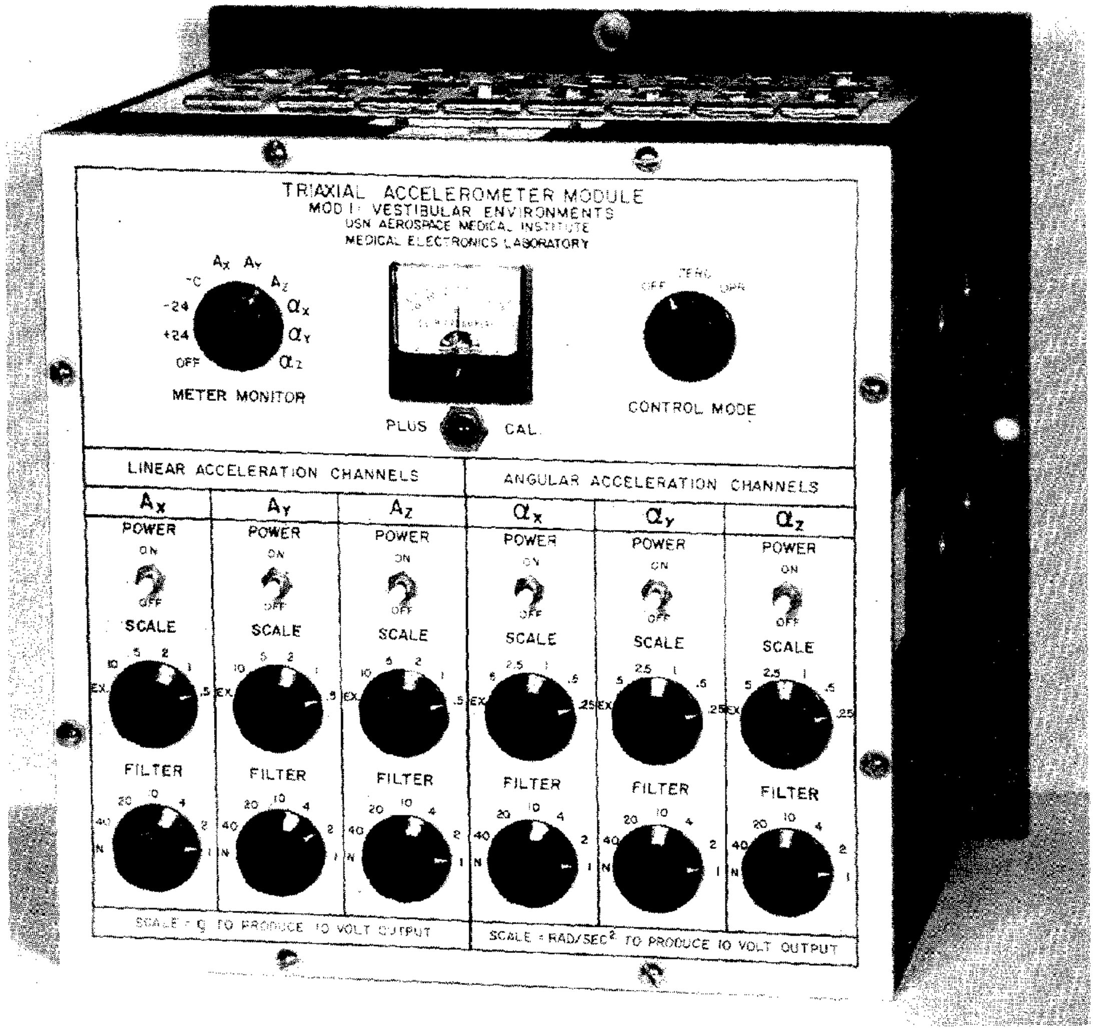

Figure 3

Photograph of Front Panel of TAM

APPLICATION NOTES

For the majority of research studies, the Triaxial Acceleration Module is installed in the test device or vehicle at a position, and in an orientation, which corresponds to that of a typical subject or crew member. As mentioned previously, the A_x, A_y, A_z, α_x, α_y, and α_z identification of the acceleration channels derives from the kinematics nomenclature developed for the mathematical description of vestibular stimuli. In brief, this nomenclature defines x, y, and z as three mutually orthogonal anatomical axes where x denotes the front-back axis, y the left-right axis, and z the head-foot axis of the subject; and where the $+x$, $+y$, and $+z$ directions are denoted by vectors drawn from the center of the subject and pointing toward the front, toward the left, and toward the head, respectively. Accordingly, positive values of the three linear acceleration components, i.e., $+A_x$, $+A_y$, and $+A_z$ describe linear accelerations of the subject in the frontward, leftward, and headward direction, all identified in the kinematics sense of motion. The A_x, A_y, and A_z output signals from the Triaxial Accelerometer Module would correspondingly be of positive polarity for linear accelerations occurring in the denoted directions.

With the common convention of describing the x, y, and z anatomical axes as the roll, pitch, and yaw axes, respectively, of a subject, $+\alpha_x$, $+\alpha_y$, and $+\alpha_z$ denote roll rightward, pitch downward, and yaw leftward angular accelerations following the conventions of the right-hand rule of rotation. The α_x, α_y, and α_z channels of the module provide output signals of positive polarity for these directions of angular acceleration and negative signals for their opposite. These conventions are separately stated for the linear and angular acceleration components in Figure 4. In all cases a plus or minus sign denotes a positive or negative output voltage, respectively, from the module whenever an acceleration occurs in the denoted direction.

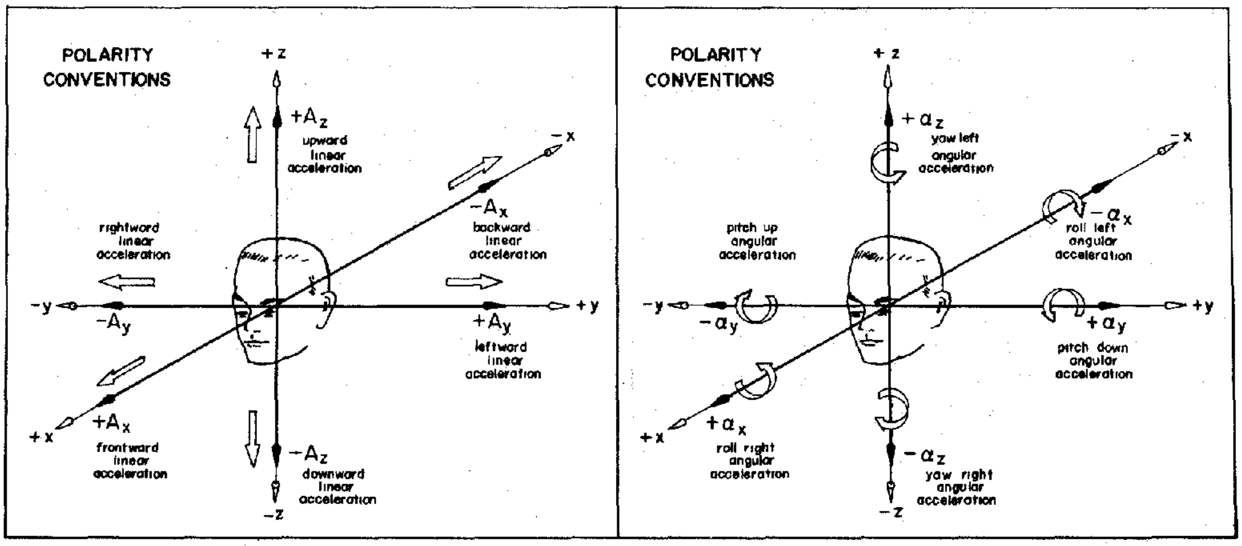

Figure 4

Pictorial Description of the Acceleration Directions Denoted by Positive and Negative Polarity Output Signals from the TAM. Linear Channels Depicted on Left and Angular Channels on Right.

Although this report is concerned with only the technical aspects of the TAM, a few sample records are presented in Figures 5 through 8 to illustrate typical measurement applications. The data presented in Figure 5 describes the linear and angular accelerations measured aboard a 55-ft liberty launch operating in a relatively rough sea state for this class of boat. The TAM was installed near the center of gravity and its x, y, and z axes aligned with the roll, pitch, and yaw axes of the vessel. The data seen in Figure 6 were collected on the Human Disorientation Device, a man-rated vestibular research motion device constructed in the form of a cylindrical capsule that can be rotated about its Earth-horizontal axis while undergoing simultaneous rotation about an Earth-vertical axis. For this application, the TAM was installed at the intersection of the two rotational axes and oriented so that its y axis was in alignment with the Earth-horizontal rotational axis. The device was then rotated at a constant velocity of 2.0 rad/sec about the horizontal axis and 0.5 rad sec about the vertical axis. The resulting cross-coupled angular acceleration, i.e., the angular Coriolis acceleration, is demonstrated by the α_x and α_z data which are sinusoidal in form and have a 90-deg phase difference.

In many research device applications of the TAM, it is necessary that the frequency response of the angular acceleration channels be extended to some relatively high frequency in the vicinity of 20 to 50 cps to minimize phase measurement errors. For most of these applications, the vibration levels of the device are sufficiently low so that usable angular acceleration data can be collected without the need for soft-mounting or vibration isolating the TAM. In aircraft applications, however, the structural vibrations are of such a level that some form of mechanical isolation is mandatory if overload of the angular accelerometers is to be prevented. The relatively high level of the linear accelerations due to vibration is illustrated at the top in Figure 7 for a fixed wing, propeller driven A-1E "Skyraider" aircraft and at the bottom for a rotary wing CH-34 "Choctaw" helicopter. These 0-100 cps data were collected during straight and level flight with the TAM hard-mounted to the deck of the aircraft. As before, x, y, and z correspond to the roll, pitch, and yaw axes of the vehicle. A sample record of the accelerations measured during a barrel roll of the A-1E aircraft is shown in Figure 8 where mechanical isolation in the form of neoprene was used to prevent vibration overload of the angular channels.

The next report will describe an airborne recording system developed for hard-mounted installation in helicopters and which approaches the vibration problem through a rate gyro measure of aircraft angular velocity.

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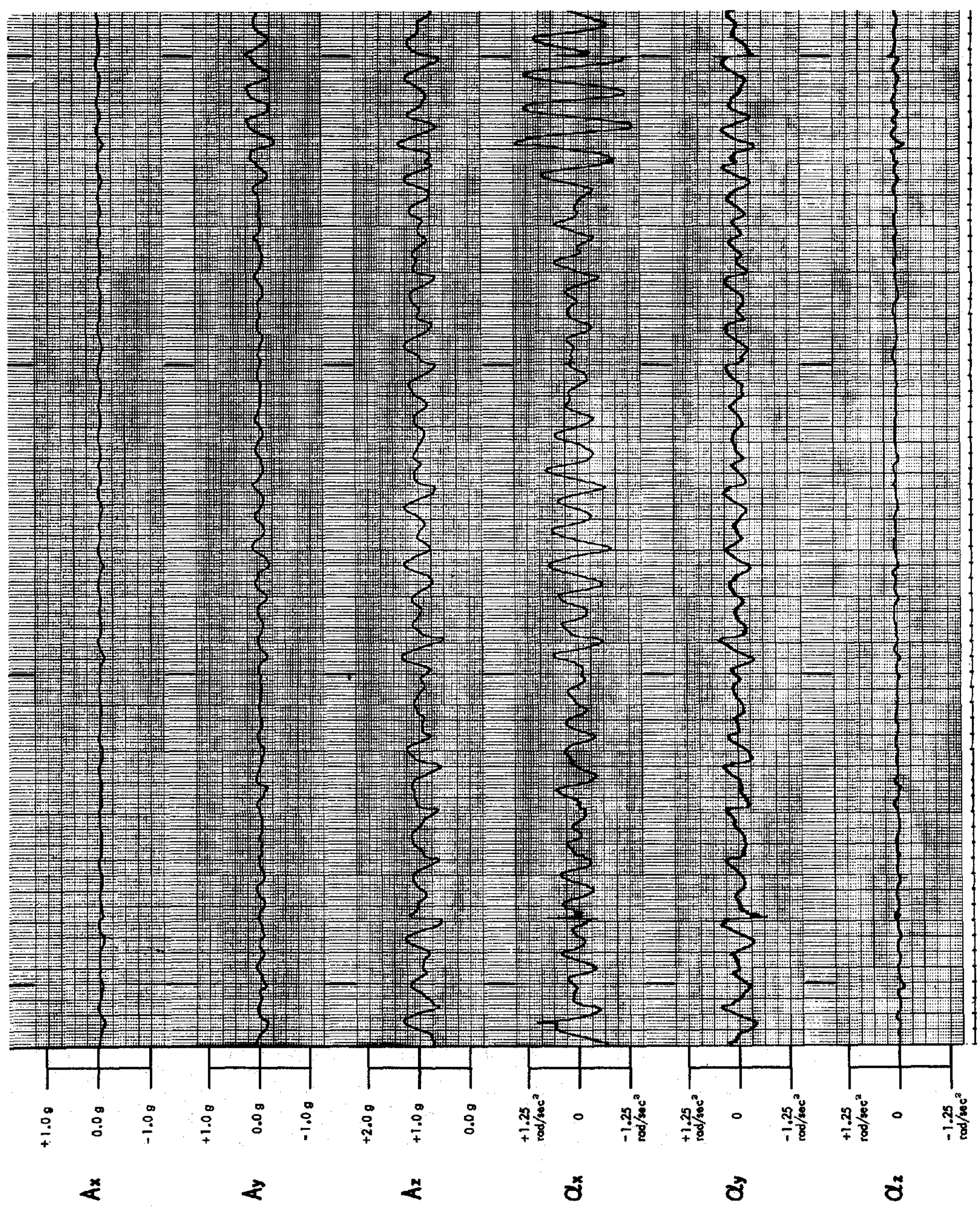


Figure 5

Linear and Angular Acceleration Measurements Made on a 55-ft Liberty Launch. One-second Timing Marks Shown at Bottom.

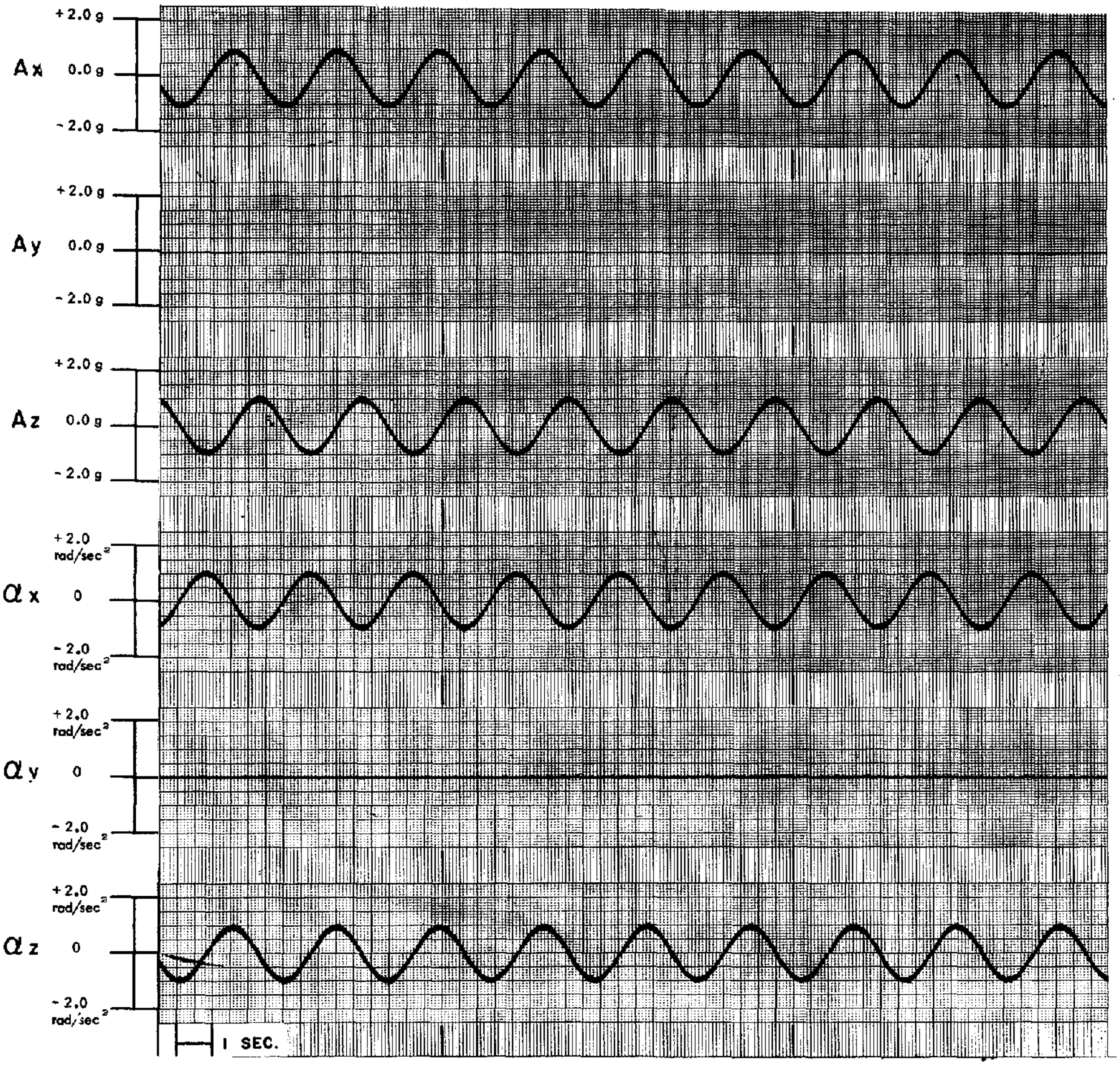
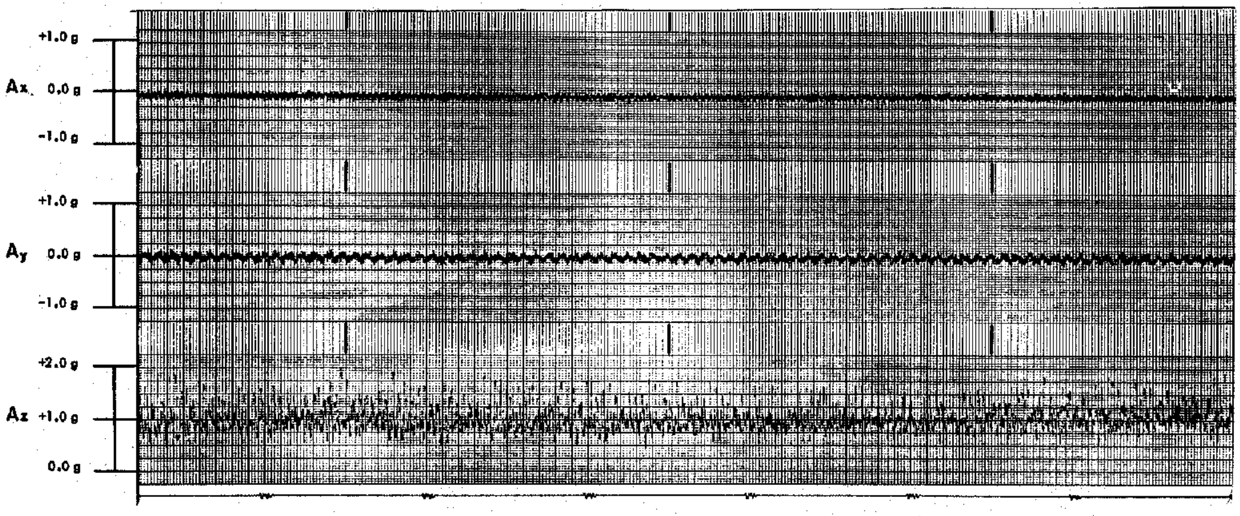


Figure 6

Linear and Angular Acceleration Measurements Made on Human Disorientation Device, a Two-Axis Man-Rated Rotating Device. (See text.)



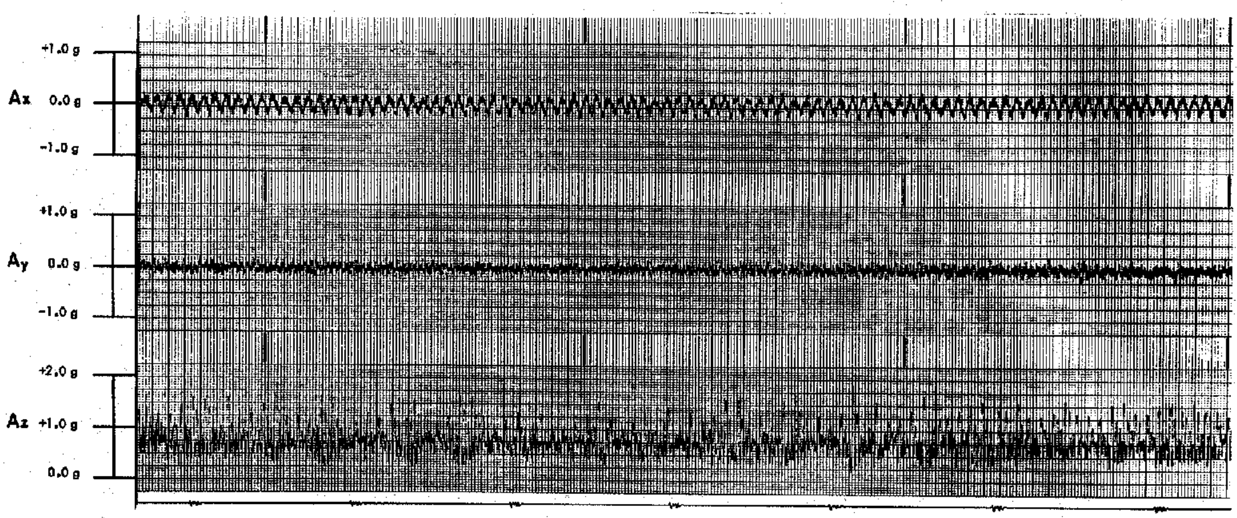


Figure 7

Linear Acceleration Data Collected During Straight and Level Flight of an A-1E Fixed-Wing Aircraft (top) and a CH-34 Rotary Wing Aircraft (bottom).

Figure 8

Linear and Angular Acceleration Measurements Made During a Barrel Roll of an A-1E Aircraft.