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SPECIAL TEST AND EVALUATION METHODS USED FOR A NINE-AXIS ACCELEROMETER

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Abstract

The test methods used to characterize and evaluate the performance of a miniature nine-axis accelerometer are discussed. A special transducer containing nine separate linear accelerometers was examined. The intended application for this type of device is to derive angular acceleration data for dynamic-head motion measurements relating to automobile crash studies. The accelerometers, amplifiers, multiplexer, FM telemetry transmitter, and power supply are all to be molded into an athletic orthodontic mouthpiece and data will be obtained from measurements taken from boxer's head motions. The angular head motions of boxers is thought to be similar to those in automobile crashes. The transducer parameters tested include axial and transverse linear-vibration sensitivities, equivalent acceleration noise, effects of power supply voltage variations, and mouthpiece vibration transmissibility. Special test apparatus described includes a dual centrifuge and a dual spin-axis rate-table. Test philosophy and some test results are used to illustrate how apparently conflicting test results can be used to explain transducer performance under test conditions of combined environments.

1. INTRODUCTION

The need to perform car crash studies in order to develop appropriate safety regulations has generated technical requirements for the measurement of linear and angular accelerations during simulated and barrier crash studies. The kinematics of the human head, the limits of endurance and head injury criterion have been the subject of many discussions and many papers. Suitable instrumentation for experiments using anthropomorphic dummies has been well developed for linear acceleration using single, biaxial and triaxial accelerometers. To a limited extent, linear acceleration measurements on cadavers, human volunteers and primates have been successful. However, measurements of angular acceleration of the head has proven a much more difficult task, largely because of the lack of suitable angular sensing instrumentation. Proposals and attempts have been made to sense angular acceleration directly, however those instruments performed with only limited success.

In a period from 1967 to 1973, Metz, [1] Clarke, et al., [2] and Ewing, et al., [3] demonstrated that angular acceleration and angular velocity data could be obtained by using four linear acceleration measurements in one plane. In 1974 Alem [4] showed that three dimensional rigid-body motion could be kinematically described by the use of six linear acceleration measurements at three separate orthogonal locations. However, the computations were difficult and round-off errors could seriously effect the accuracy of the angular velocity computation.

In 1975, Padgaonkar, et al., [5] proposed the use of nine linear accelerometers at four locations (i.e., one triaxial-cluster and three biaxial-clusters) to provide sufficient information from which angular motion measurements could be derived. With this special arrangement, angular acceleration computations were greatly simplified to algebraic operations. Angular velocity can be derived from the integral of the angular acceleration. Chou and Sinha [6] in 1976 demonstrated the feasibility of this scheme.

Based on this approach, a special nine-axis accelerometer meeting the Euleran alignment criteria was designed and fabricated by Konigsberg Instruments[1] under Department of Transportation contract. This miniature sensor along with the necessary electronic amplifiers, multiplexer and FM telemetry transmitter will ultimately be packaged such that it would fit within the palate region of the mouth when molded into a mouthpiece. It is thus anticipated that such a system can transmit data from which dynamic linear and angular head motions can be derived.

This paper briefly describes the transducer and gives descriptions of the tests and methods used to characterize the dynamic performance of the accelerometers and system. The sensitivity factor for each of the nine accelerometer sensors is the most

[1] This report is intended to be an initial effort in developing test procedures for evaluating nine-axis accelerometers and not to judge the performance of any one device by any manufacturer for a specific application.

important parameter to be determined over a frequency range from a few hertz to 600 Hz. Axial sensitivity was measured by two methods described herein. The transverse sensitivity is likewise important, especially in this application. When measured by these two methods, radically different results were observed. This led to the careful examination of the accelerometer design and indicated that the different response to the two methods was likely due to a twisting mode of the accelerometer sensor. The effect of power supply voltage variations on the system response was measured. Mouthpiece transmissibility was measured over the temperature range from laboratory ambient to 100 °F to ensure high-frequency response up to 2000 Hz.

2. DESCRIPTION OF EQUIPMENT

The purpose of this paper is to describe the tests and methods used to evaluate and characterize the performance of a special miniature nine-axis accelerometer. A short discussion describing the accelerometer design is given before the tests are discussed, since it is necessary to understand the design and operation of the sensing elements within the accelerometer as well as the constraints of the environments to which the unit will be exposed. The test results were selected to illustrate the test method and not necessarily the quality of the transducer performance.

2.1 Description of the Transducer

The design of the transducer is such that the nine accelerometers are arranged as shown schematically in Fig. 1. At the origin, a cluster of three accelerometers are arranged in a triaxial configuration, while at the remaining three locations, the accelerometers are arranged in a biaxial configuration. The arrows indicate the direction of the sensitive axis for each of the nine accelerometers. The distance between the sensing centers for each of the in-plane accelerometers is given by d_{ij} where i and j are subscripts denoting the sensing planes and the locations 1, 2, or 3 as shown in Fig. 1. With such an arrangement, it is possible to compute the angular acceleration about three orthogonal axes as:

$$\alpha_x = (A_{z1} - A_{z0})/2d_{y1} - (A_{y3} - A_{y0})/2d_{z3}, \tag{1}$$

$$\alpha_y = (A_{x3} - A_{x0})/2d_{z3} - (A_{z2} - A_{z0})/2d_{x2}, \tag{2}$$

and

$$\alpha_z = (A_{y2} - A_{y0})/2d_{x2} - (A_{x1} - A_{x0})/2d_{y1}, \tag{3}$$

where x, y and z denote directions, α denotes angular acceleration, A denotes linear acceleration, and d denotes the distance between accelerometers.

The derivation of these relationships and a more complete discussion may be found in refs. [5] and [6]. As can be seen from the above three equations, the angular acceleration is a function of the linear accelerations and the distances between pairs of accelerometers. More specifically, the angular acceleration depends on the difference of vectorial differences of acceleration pairs.

The vector acceleration can be derived from a basic relationship

$$A_{ij} = (E_{ij}/S_{ij}), \tag{4}$$

where A is the linear acceleration, E is the accelerometer output signal (usually a voltage), S is the accelerometer sensitivity factor, and i and j are as previously described.

Thus the angular acceleration can be obtained from measurements of the individual accelerometer output signals and their individual sensitivity factors.

The physical arrangement of the nine-axis accelerometer follows that shown schematically in Fig. 1. Figures 2 and 3 show the unit, without the cover and fully assembled. Each of the acceleration sensing elements consists of a forked cantilever beam with two semiconductor strain gages bonded onto each side of the two forks. The free ends of each forked beam are connected together with a concentrated mass to increase the strain for a given input acceleration thus increasing the sensitivity factor. The forked feature allows the individual accelerometers to be nested at each of the corners of a tetrahedron. This is especially important at the origin where the triaxial cluster is located because, there, the sensing axes of each of the three accelerometers must intersect at a common point.

With this novel design each of the accelerometers has a common angle of 54.75 degrees to the base of the tetrahedron. This shape minimizes the volume of the unit and allows it to fit into the athletic type orthodontic mouthpiece. After assembly, the unit is filled with a silicone fluid having a viscosity of 1000 centistrokes which is intended to provide viscous damping.

2.2 Transducer System Electronics

The transducer system electronics consisted of nine channels of amplifiers, a multiplexer, a pulse-width modulator, a regulated battery power supply, and an FM telemetry transmitter. This part of the system was intended to be placed in an orthodontic mouthpiece. The FM receiver and electronics consisted of a diversity antenna system, FM receiver, demodulator, a nine-channel amplifier, tape formatter, and tape recorder. The system tested did not have the RF-link, but rather fed the modulator output directly to the demodulator input. This simplified certain of the tests inasmuch as the RF electronics did not have to be considered.

The demodulator has two switch-selected, full-scale ranges, 50- and 125-g full scale. The multiplexer switches between channels such that each channel is sampled at a nominal rate of 1200 times per second. Therefore, the maximum usable input frequency to any one accelerometer channel is 600 Hz in order to satisfy the Shannon sampling theorem. [7] The accelerometer amplifiers have a high-pass filter set to about 0.1 Hz to block dc components resulting from unbalance of the strain-gage circuitry, and a low-pass filter which begins to roll off at about 400 Hz to minimize aliasing errors for frequencies greater than 600 Hz (half the multiplexing rate per channel).

The final version will have custom electronic "chips" which will incorporate these features into very small packages. The mouthpiece system will be powered by replaceable batteries. The units tested and described herein were powered by a regulated dc power supply. Tests were made to ensure that power supply noise, regulation, and impedance were not affecting the system adversely.

3. TESTS PERFORMED

3.1 Transducer System Tests

For any mechanical-to-electrical transducer, the gage factor or sensitivity factor is the single most important parameter which characterizes the transducer. This transfer function (i.e., the ratio of electrical output to mechanical input) is a complex ratio having both a magnitude and phase angle. Most calibrations of accelerometers seek only the magnitude. For many applications this is sufficient, however, when the vector voltage (or acceleration) is required, as in this case for the determination of angular acceleration, then the phase response of the accelerometers can become very important. When amplifiers and filters are incorporated into the system, their phase lags add to that of the transducer. It is therefore important and necessary to perform a "system calibration" which encompasses all components which will add phase shift and amplitude changes to the overall transfer function.

As in the case of many transducer calibrations, special fixtures are required to properly mount and orient the transducer. The nine-axis accelerometer has three sensors per plane, thus once one plane is properly oriented, three sensors can be evaluated; then the transducer can be reoriented to the next plane, etc. A multipurpose fixture was designed to hold the transducer and provide for convenient and precise rotations so that each of the three planes can be made perpendicular or parallel to the input acceleration vector. The fixture is shown in Fig. 4. It is made of 2024-ST aluminum alloy except for the three "finger" clamps which are made of type 301 stainless steel. It provides balanced moments about the two vertical axes and a known location of the center of gravity. (The latter is important when it will be used on the centrifuge and dual spin-axis rate-table). Once the transducer is mounted to the rotatable cylindrical adaptor, it can be precisely rotated in 60° steps to provide accurate and quick alignments for each of the X-Y-Z planes of the nine accelerometers.

3.2 Noise Level and Spectra

Tests were made to determine the noise level and spectrum from each transducer and demodulator channel. Because a line-operated power supply was used on the modulating electronics and to provide excitation voltage for the transducers, it was essential to verify that the power supply was not contributing additional noise to the system, especially at harmonics of the power-line frequency.

The noise was measured using a digitizing oscilloscope, and the power spectral density (PSD) determined. An ensemble average of 20 measurements were made for each channel and each range to arrive at a suitable result. Figure 5 is a typical PSD plot of the system output noise. It is relatively flat over a frequency range from near zero hertz to about 400 Hz at which frequency, a filter in the system attenuates the response to a "null" at about 600 Hz (one-half of the channel-to-channel multiplexing frequency). No evidence of 60-Hz related signals was detected in the noise output with the ac-operated power supply. The rms-noise level over bandwidth of 0 to 600 Hz was about 2.15-mV rms for the 125-g range and about 4.2-mV rms for the 50-g range (less than 0.2 equivalent g). These noise levels are about -55 dB below full range output.

3.3 System Sensitivity and Resonance

The transducer and accompanying electronics, including the demodulator, were configured as a system for all the tests performed. The sensitivity were determined by two methods. The first method employed an air-bearing electrodynamic vibration exciter under the control of a minicomputer. All data were computer collected and analyzed. The second method used a dual centrifuge to generate a dynamic sinusoidal acceleration at low frequencies. The Dimoff Vibration Standards [8] were used for the first set of sinusoidal tests. The accelerometer base was mounted to an adaptor in such a way as to equally excite each of the nine channels. The output was reduced by a factor of cos 54.75° (approximately 42% reduction) and a transverse input component was intentionally introduced into each accelerometer. The "reduced" sensitivity was measured on each channel of each unit over a frequency range from 10 to 600 Hz. The nominal values were about 8 mV/g on the 125-g range and about 17 mV/g on the 50-g range. This corresponds to a nominal "in-axis" sensitivity of 13 mV/g and 29 mV/g, respectively, where the 54.75° angle is taken into account.

The resonance frequency of each of the nine accelerometers on each unit was determined by measuring maximum output response for a constant input acceleration.

These values were slightly less than 2 kHz for all channels.

In-axis (axial) sensitivity measurements were performed. The test frequencies selected were performed at 21 frequencies between 10 and 600 Hz. The acceleration amplitudes were 2-g peak at 10 and 14 Hz and 5-g peak at the remaining frequencies. The axial sensitivities measured about 24 – 30 mV/g for the 50-g range and about 12 – 14 mV/g for the 125-g range. Figure 6 shows a typical sensitivity plot. The response is relatively flat from about 10 to 400 Hz; thereafter, the response rolls off sharply because of a system filter inserted to attenuate higher frequency signals.

The test matrix becomes very large if multichannel devices are tested at various frequencies on two different gain ranges. Additionally, two runs were made on each unit thus doubling the required data. In numbers of required measurements for each transducer system, (9 channels each) × (2 gain ranges) × (21 test frequencies) × (2 runs per gain range per instrument) = 756 measurements. When this amount of quality data is needed, automation is very helpful.

Tables 1 and 2 give the results of the sensitivity measurements at 100 Hz. Channel-to-channel variations are evident; however, each channel was relatively stable and repeatable.

Table 1. Linear vibration test data, unit no. 1 (test frequency is 100 Hz at an acceleration of 5-g peak)

	System Sensitivity, mV/g								
	Ch 1	Ch 2	Ch 3	Ch 4	Ch 5	Ch 6	Ch 7	Ch 8	Ch 9
50-g range	27.67	29.48	27.71	28.48	27.34	24.18	–	27.52	25.71
125-g range	13.66	14.67	13.66	14.19	13.34	11.92	–	13.51	12.89

Table 2. Linear vibration test data, unit no. 2 (test frequency is 100 Hz at an acceleration of 5-g peak)

	System Sensitivity, mV/g								
	Ch 1	Ch 2	Ch 3	Ch 4	Ch 5	Ch 6	Ch 7	Ch 8	Ch 9
50-g range	25.31	26.88	25.41	25.97	27.54	12.85	25.77	26.95	25.94
125-g range	12.42	13.27	12.62	12.89	14.01	6.28	12.96	13.39	12.99

The second sinusoidal test method employed a dual centrifuge. Because the transducer system amplifiers have a low-frequency cutoff at about 0.1 Hz, normal centrifuge techniques (0 Hz operation) would not work. The dual centrifuge is capable of generating relatively large sinusoidal accelerations at low frequencies. For example, with a radius of nominally 25 cm, it is possible to generate 0.25-g peak at 0.5 Hz and 125-g peak at 11 Hz. Figure 7 shows the capabilities of the particular dual centrifuge used for these tests. The relationship used to derive the sinusoidal acceleration as a function of dual centrifuge speed is

$$a = R_0 \omega_0^2 \cos d_0 t \tag{5}$$

where a is sinusoidal acceleration, R is distance from the center of the main table to the center of gravity of the accelerometer seismic element, ω_0 is the angular velocity of the main and satellite table, rad/s, and t is generalized time variable in seconds.

A number of assumptions have gone into the above equation. These and a description of the dual centrifuge are given in reference [9]. When the angular velocity is given in revolutions per minute (rpm) and the distance in inches, then Eq 5 reduces to

$$a = 2.8403 \times 10^{-5} S_0^2 R_0 \ \text{g peak} \tag{6}$$

where a is acceleration in units of g peak, S_0 is the angular velocity of centrifuge in units of rpm, and R_0 is as described in Eq 5 in units of inches.

Fixturing and balancing counter weights were designed and fabricated for use on the dual centrifuge. The same rotatable accelerometer mounting block was used as for the linear vibration tests.

Figure 8 shows the main and satellite tables of the dual centrifuge. The satellite table is driven such that it completes one revolution for each revolution of the main table.

The transducer and electronics were mounted on the centrifuge with channels 1, 2 and 3 in-axis with the acceleration vector of the dual centrifuge. The centrifuge satellite table was adjusted so that the radius, R, was 6.817 inches. The amplitude linearity was checked for input accelerations from nominally 10 to 75-g peak. (The frequency varied from nominally 3.7 to 10.4 Hz). Figure 9 shows the results of the tests. Channel 1 showed an increased sensitivity of about 15% over the range of input accelerations of 10- to 75-g peak while channels 2 and 3 showed a decrease of about 2% and 4% over the same ranges. A figure of non-linearity can be calculated by using a regressional single degree of freedom fit to the linearity data. Notice the sudden increase of sensitivity for channel 1 in Fig. 9 above 40-g peak. The cause for this increase in unknown. If the resulting coefficients are used such that the ratio of the slope to the ordinate intercept is computed, this ratio can be used to describe the quality of "flatness" of the sensitivity factor as a function of vibration amplitude. The values computed for channels 2 and 3 of unit 2 were +0.275%/g and −0.086%/g, respectively. As can be seen, channel 1 exhibited a gross nonlinearity as compared to channels 2 and 3. In fact, the two lower values for channels 2 and 3 are high as compared to, for example, piezoelectric accelerometers (PZT shear-type design) whose nonlinearity is generally less than +0.00025%/g.

Because of the "jump" in sensitivity in channel 1, only limited dual-centrifuge work was completed for the remaining channels. Tests were made at 20-g peak at a nominal frequency of 4.5 Hz. The differences between the sensitivity data from the electrodynamic tests done earlier and the dual centrifuge tests were about −3 percent. Waveform distortion was evident in several of the channels and is attributed to the nonlinearities of the accelerometer.

3.4 Transverse Sensitivity

The transverse sensitivity ratio was measured by two methods. The first method utilized the dual centrifuge and the second employed an electrodynamic vibration exciter. In both methods, the transducer was oriented such that the input acceleration vector was in a direction perpendicular to the accelerometer's sensitive axis. A transverse sensitivity, in units of mV/g, was computed by dividing the output signal by the acceleration. The TSR was then obtained as the ratio of the transverse sensitivity to the axial sensitivity. This latter ratio is expressed as a percentage of the axial sensitivity. When using the dual centrifuge, the input acceleration vector "sweeps" through all the angles of the accelerometer's transverse plane in each revolution of the centrifuge tables. As such, "100% transverse motion" was applied to the accelerometer's transverse input plane. This was an important difference from usual methods of measuring transverse sensitivity. With this method, it was not necessary to rotate the accelerometer to "search" for the maximum transverse output; the maximum output occurred automatically.

When using the electrodynamic vibration exciter, the transducer was mounted such that the accelerometer's sensitive axis was perpendicular to the motion. Two measurements were necessary, one at an arbitrary rotational angle about the sensitive axis, and a second at a rotational angle of 90° to the first. The square root of the sum-of-the-squares of the two outputs then yields the maximum transverse output (at least in theory). [10, 11, 12]

The tests on the dual centrifuge were performed at a frequency of 3.7 Hz at an acceleration of about 14-g peak. The tests on the electrodynamic vibration exciter were performed at a frequency of 100 Hz at an acceleration of 20-g peak. Table 3 gives the results of these tests. The only channels tested were 7, 8 and 9; no other data were obtained.

Table 3. Transverse sensitivity ratio (TSR) tests, unit 2, channels 7, 8 and 9 (50-g range)

	TSR value, % of axial sensitivity	
	Dual Centrifuge	Electrodynamic Exciter
Channel 7	13.1	7.8
Channel 8	7.2	3.1
Channel 9	17.6	2.5

The centrifuge TSR tests indicated significantly greater transverse response than did the electrodynamic exciter tests. It was noted that significant waveform distortion existed in the outputs for these tests, especially for the dual centrifuge tests. Causes for such distortion are currently unexplained, but the most probable cause is thought to be a torsional vibration mode of the accelerometer beam caused by nonsymmetrical geometry and fabrication. Other causes may exist; however, when discussing them with the accelerometer's designer, [13] they seemed remote.

The values of TSR given in Table 3 should have more reasonable agreement between the two test methods. It might be that each value is indeed valid for each method since the two methods are substantially different. Without further tests, one cannot state with certainty just what the TSR values typically are. It is impossible to know the transverse response or what the total response means under unknown motion conditions such as those of human head dynamics. If the electrodynamic exciter-test values of TSR were to be accepted, then they appear reasonably small and probably acceptable for the intended application. The test results discrepancies certainty demonstrate the value of evaluating devices by independent methods. Generally, the TSR measurements would have been made only by the electrodynamic exciter method. In this case, the results appeared reasonably acceptable, but without the centrifuge tests, the probable beam twisting would not have been discovered. These apparently conflicting test data led to the discovery of a design problem which, in all likelihood, would have led to errors in the measurements of angular acceleration that this device was designed to make.

3.5 Power Supply Voltage

The effect of a decreasing power supply voltage was assessed which, to some extent, simulated a discharging battery in the real application of this system. The accelerometer was mounted on the dual centrifuge and operated at a nominal speed of 180 rpm to produce an acceleration of nominally 4.3-g peak at frequency of 3 Hz. Output signals were recorded for unit no. 2, channel 8 which was selected because of the fidelity of its sinusoidal output. Figure 10 shows the results. The sensitivity remained approximately constant down to 85% of rated voltage at which point it increased by about 2.3%. The next 2.5% voltage decrease produced a further increase of sensitivity to about 3.3%; further voltage decreases produced decreasing output until at 72.5% (2.175 volts) signal "drop-out" occurred and the system ceased to operate. There is a hysteresis inherent in the system. If, once drop-out has occurred, the voltage is slowly increased, operation is not regained until a voltage of about 80% (2.400 volts) is reached. Thereafter, system operation appears normal.

3.6 Test Results Summary

Because of the test results and findings regarding amplitude linearity, waveform distortion and transverse sensitivity, further testing was suspended. The use of four semiconductor strain-gage elements on the forked beams rather than two should provide a more symmetrical system and reduce the beam's tendency to twist under certain motion conditions. Also, the use of "U-shaped" gages would eliminate a gage lead near the center of the beam.

3.7 Angular Acceleration

A major and important test that was not performed was the input angular acceleration to the transducer. This test could not successfully be done because several of the accelerometer channels had failed. However, the test and method will be discussed here without the benefit of test results.

The central apparatus that will be used to evaluate the angular characteristics of the nine-axis accelerometer system is the dual spin-axis rate-table and is shown in Fig. 11. It consists of two separate electrical-drive systems whose rotational axes are horizontal and vertical and at right angles to each other. The large, lower table rotates about a vertical axes. This table carries a smaller drive system that rotates about a horizontal axis. When both tables are driven, sinusoidal angular acceleration is generated about the vertical axis. The angular acceleration about the vertical axis is computed from

$$\alpha = \omega_v \omega_x sin \omega_h t, \qquad (7)$$

where α is the angular acceleration in radians per second squared, ω_v is the angular velocity about the vertical axis in units of radians per second, ω_h is the angular velocity about the horizontal axis in units of radians per second, and t is a general time variable.

From Eq 7, it can be seen that the angular acceleration amplitude is simply the product of the two angular velocities, each of which can be measured very accurately. The possible amplitudes of angular acceleration that can be generated with this device range from a few radians per second squared to $8000 \mathrm{rad/s}^2$. The frequency of the angular acceleration about the vertical axis is determined by the satellite-table drive speed and ranges from about 1 to 100 Hz. When the nine-axis accelerometer is mounted on the dual spin-axis rate-table, several choices of orientation are available. The simplest mounting orientation is when one of the three transducer axes is parallel to the table's vertical axis. Referring to Eqs 1, 2, and 3, it is seen that the acceleration about the X axis is sensed by pairs of Z and Y axis accelerometers, about the Y axis is sensed by pairs of X and Z accelerometers, and about the Z axis is sensed by pairs of Y and X axis accelerometers. Therefore, in order to derive the angular acceleration about any one axis, four accelerometer outputs must be measured simultaneously and the vector differences obtained. These differences scaled by the distance between the accelerometer pairs are used to calculate the angular acceleration. Also, the proper accelerometer sensitivity must be taken into account as previously discussed. If a general solution for the angular acceleration about all three axes is to be obtained, then all nine accelerometer outputs must be recorded at one time.

3.8 Mouthpiece Transmissibility Tests

The purpose of the mouthpiece transmissibility tests is to ensure that the mechanical stiffness of the mouthpiece is sufficiently high so that shock spectra up to several hundred hertz are transmitted from the jaw/tooth interface to and through the mouthpiece to the nine-axis accelerometer package. The mouthpiece is cast from an acrylate material which was polymerized at 74 °C for a minimum of five hours. The material is pliable at room temperature which indicates that the glass transition temperature is lower than ambient temperature. At 37.8 °C (nominal body temperature), the material feels soft and is very pliable.

The mouthpiece geometry is such that there is a thin, U-shaped portion between the inside tooth perimeter and large mass of the palate region which contains the transducer and electronics module. Figure 12 shows the cast mouthpiece containing a transducer mockup module. There was concern that the high compliance of this thin section and the relative large mass of the palate region would yield a spring-mass resonant system having a resonance frequency within the overall operating range of 0.1 to 600 Hz. Should the mouthpiece have a resonance in this range, it could significantly distort the data near resonance and attenuate the data at frequencies greater than resonance. It is, therefore, highly desirable to have the resonance at a frequency greater than 600 Hz.

A "stone" dental casting was used to mold the mouthpiece and was also used in the fixturing to clamp the mouthpiece. The stone cast "mouth" was obtained from an adult male and had the following dimensions:

Width: 44 mm,
Length (front-to-back): 48 mm, and
Palate depth (at maximum location): 22 mm.

This represents a larger than average mouth for an adult male. It was assumed that a mouthpiece for a large mouth would be a worse-case condition, i.e., having the lowest resonance because of the maximum palate region mass.

The vibration test fixture is shown in Figures 13 and 14. The circular plates are medium-hard aluminum alloy and the bolts are stainless steel. The lower plate is attached to an electrodynamic vibration exciter through five cone-shaped ceramic standoff insulators. These are necessary to achieve the desired thermal conditions for the mouthpiece. Without the ceramic insulators, the heat loss through the exciter becomes sufficiently large that the lower plate cannot obtain the desired temperature of 37.8 °C. A thermal chamber was placed over the fixture and the internal air temperature adjusted so that the mouthpiece temperature was 37.8 °C. Thermocouples were placed inside the mockup module, on both the upper and the lower aluminum plate. The top of the mockup module was instrumented with a small piezoelectric accelerometer. This accelerometer sensing axis was in the vertical direction.

Prior to performing the transmissibility measurements, the fixture was evaluated for resonances. The stone castings were not yet mounted onto the aluminum. Figure 15 shows the major resonances from each of the three circular plates and two other minor resonances. The frequency was swept from 100 to 5000 Hz and the input acceleration amplitude servo controlled to a constant acceleration level of 1-g peak. The vertical response of an accelerometer mounted on the top plate was plotted as shown in Fig. 15. As can be seen, the response shows no resonances below 1000 Hz.

The mouthpiece was lubricated with petroleum jelly and heated to about 120 °F, then clamped into the fixture. The pull-down bolts were used to seat the teeth and then the pressure released. The remaining six bolts were used to adjust for a tooth clearance of nominally 0.020 inch. The pull-down bolts were then tightened against the 'jack' bolts.

The vibration transmissibility results are shown in Fig. 16 for three temperatures, 23.3 °C, 29.3 °C, and 37.1 °C. These temperatures are the average of measurements made simultaneously at three locations on the apparatus: top plate, bottom plate, and bottom of mouthpiece. The maximum difference between any two locations did not exceed 2 °C. As can be seen, a major peak in the transmissibility occurs at a frequency of 2500 Hz. Further tests showed that this resonance was a fixture resonance and not a resonance of the mouthpiece. The frequency of this fixture resonance remained approximately constant with varying temperature; however, the mechanical Q decreased with a temperature increase. There is nothing in the fixture which would change the mechanical Q by a measurable amount over the temperature range of the tests; therefore, it is a reasonable assumption that the energy loss in the mouthpiece material increases with a temperature and was an indication of increased damping within the mouthpiece material. In any instance, there was no resonance in the mouthpiece under these test conditions below 600 Hz. In fact, the mouthpiece resonance appears to be at a frequency greater than 5 kHz. This was not the expected result because both the pliability of the elastic acrylic resin of the mouthpiece and the geometry suggest a resonance at a much lower frequency. A brief investigation into the physical properties of acrylic materials disclosed that it is not uncommon that the dynamic bulk modulus can be very high at high-rates of strain-change when the material is at a temperature greater than its glass-transition temperature.

4. SUMMARY

Test methods used to characterize and evaluate the performance of two miniature nine-axis accelerometers were discussed. Performance parameters tested included axial and transverse linear-vibration sensitivities, acceleration-amplitude linearity, equivalent-acceleration noise spectra, effects of power supply voltage variations, and mouthpiece-vibration transmissibility. Special test hardware and fixturing were also described.

The linear vibration sensitivities of each of the nine accelerometers in each of the two units tested was measured by two methods. The first method employed a linear electrodynamic vibration exciter and the second used a dual centrifuge. The vibration-sensitivity factors ranged from about 24 to 30 mV/g on the 50-g range, and about 8 to 12 mV/g on the 125-g range. Agreement of about 3% between the results from the two test methods was observed. The equivalent noise on the 50-g range was approximately 0.2 g rms (-55 dB below full-scale range) over a bandwidth of 0 to 600 Hz. There was no measurable amounts of hum at frequencies of 60 Hz or related harmonics.

Acceleration amplitude linearity was measured on three channels of one unit. Two of the channels showed relatively large nonlinearity of about 5%, while one channel indicated a very large nonlinearity of about 15%. Acceptable values normally would be expected to be a small fraction of 1%. Substantial waveform distortion was also noted during the measurement process, that is, nonsinusoidal signal output voltages when sinusoidal input accelerations were being applied.

The transverse sensitivity ratios (TSR) were determined for three channels by two methods. When measured on a linear electrodynamic vibration exciter, values for the three channels ranged between 2 to 8%, while on a dual centrifuge, the values ranged from 7 to 18% for the same three channels. The apparent discrepancy is thought to be the result of a torsional vibration mode being excited when using the dual centrifuge.

The vibration measuring system was tested for its sensitivity to power supply voltage variations. The system continued to operate for a supply voltage drop of 15% of the rated voltage. Below that value, the system simply ceased to operate and no outputs were obtainable.

It is essential that the orthodontic mouthpiece into which the accelerometer package was intended to be mounted have a sufficiently high mechanical stiffness so that head motion vibrations can be faithfully transmitted from the jaw/tooth interface into the pliable mouthpiece. Mechanical transmissibility tests performed at temperatures of 23.3 °C, 29.3 °C, and 37.1 °C indicated no mechanical resonances over a frequency range up to 600 Hz. In fact, the first resonance was probably greater than 5 kHz.

As previously discussed, the solution for angular acceleration data requires that difference of differences be calculated from linear vibration data. This places extra rigid requirements on each of the nine accelerometers in the units. The present design of the nine-axis accelerometer units probably will not provide suitable results for boxer head motion studies for the following reasons:

- Each of the individual accelerometers measured had rather high and unequal acceleration amplitude nonlinearities.

- The transverse sensitivity of each of the individual accelerometers measured was much greater than what would be acceptable values.

- Suspected torsional vibration modes can be excited in the accelerometers leading to undesired outputs and waveform distortions.

The calculation of angular acceleration also requires that the mechanical separation of certain pairs of accelerometers be known, as previously discussed. These distances must be known very accurately and it is thought that the design dimensions and fabrication methods are not known sufficiently well to be able to predict these distances. The distances will have to measured. Although this report did not cover a method for determining these distances, a method to measure the effective distance between accelerometer sensing axes will have to be developed and evaluated.

5. ACKNOWLEDGMENTS

This work at the National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards, NBS) was supported by the U. S. Department of Transportation, National Highway Traffic Safety Administration under an Interagency Agreement D0T-HS-9-02193IA. Thanks is also due B. F. Payne of NIST who made many of the measurements, and to Ed Parry of the Dental Materials Group of NIST who fabricated the mouthpiece.

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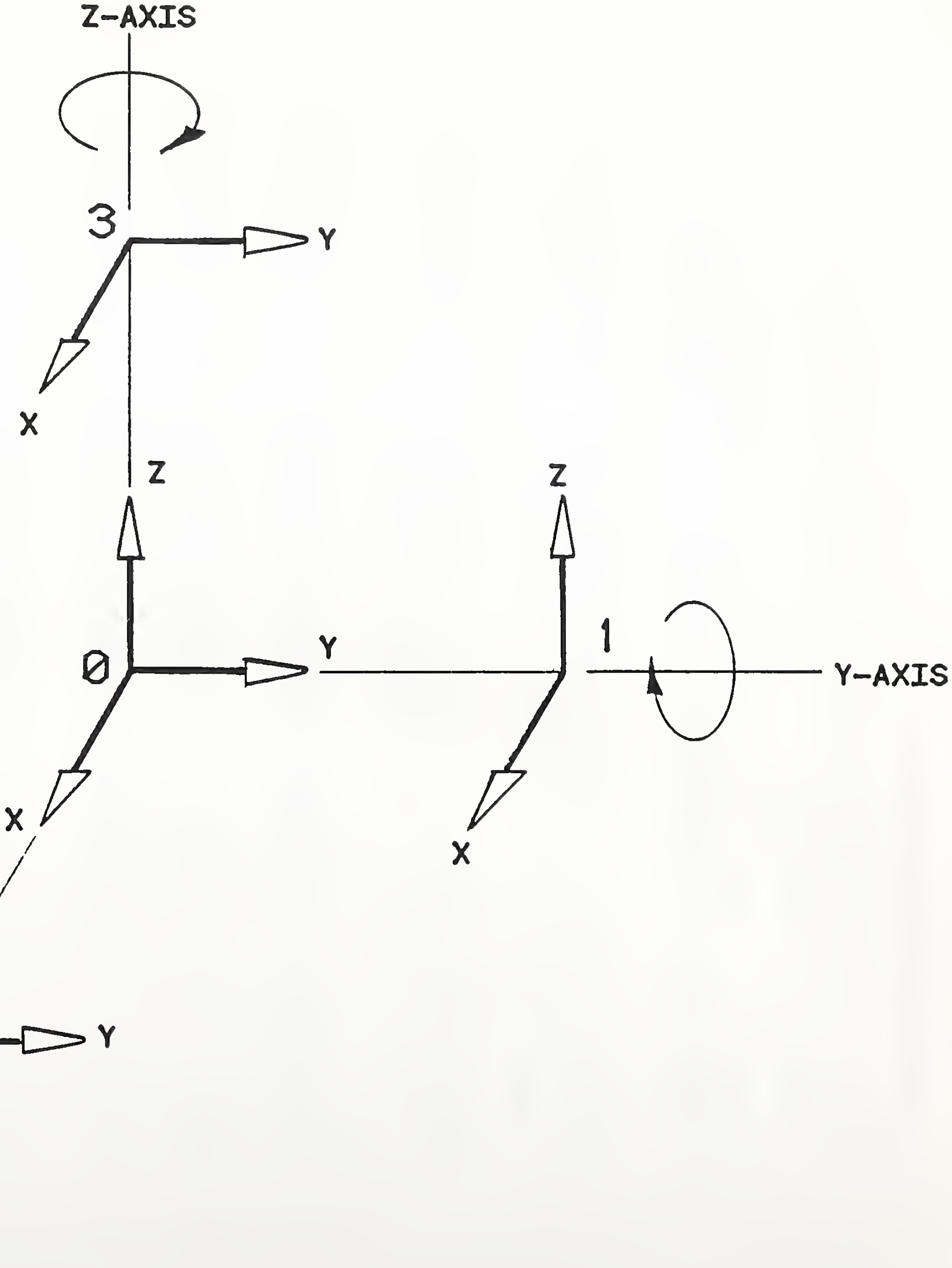

Fig. 1. Accelerometer sensor locations and directions for the nine-axis accelerometer.

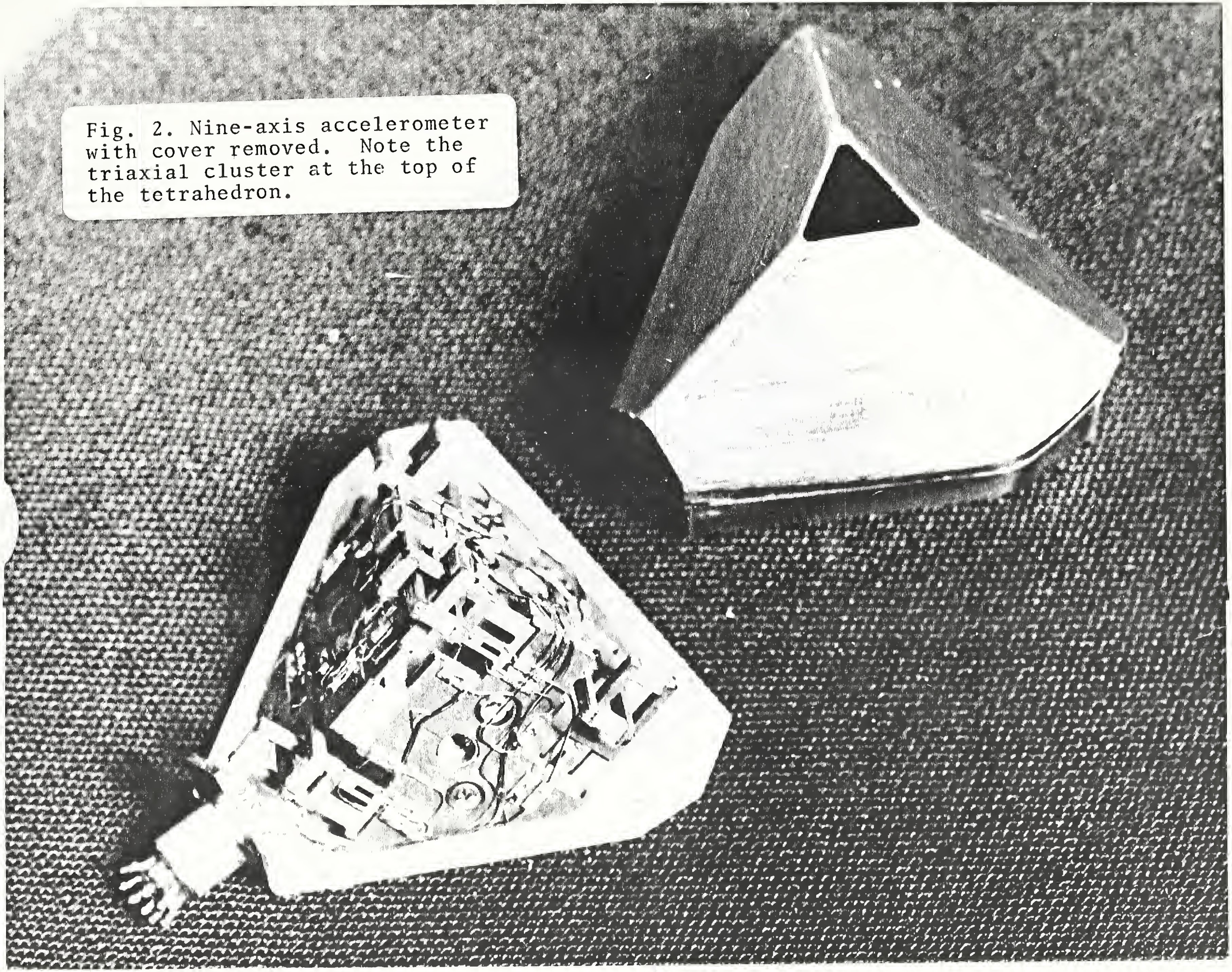

Fig. 2. Nine-axis accelerometer with cover removed. Note the triaxial cluster at the top of the tetrahedron.

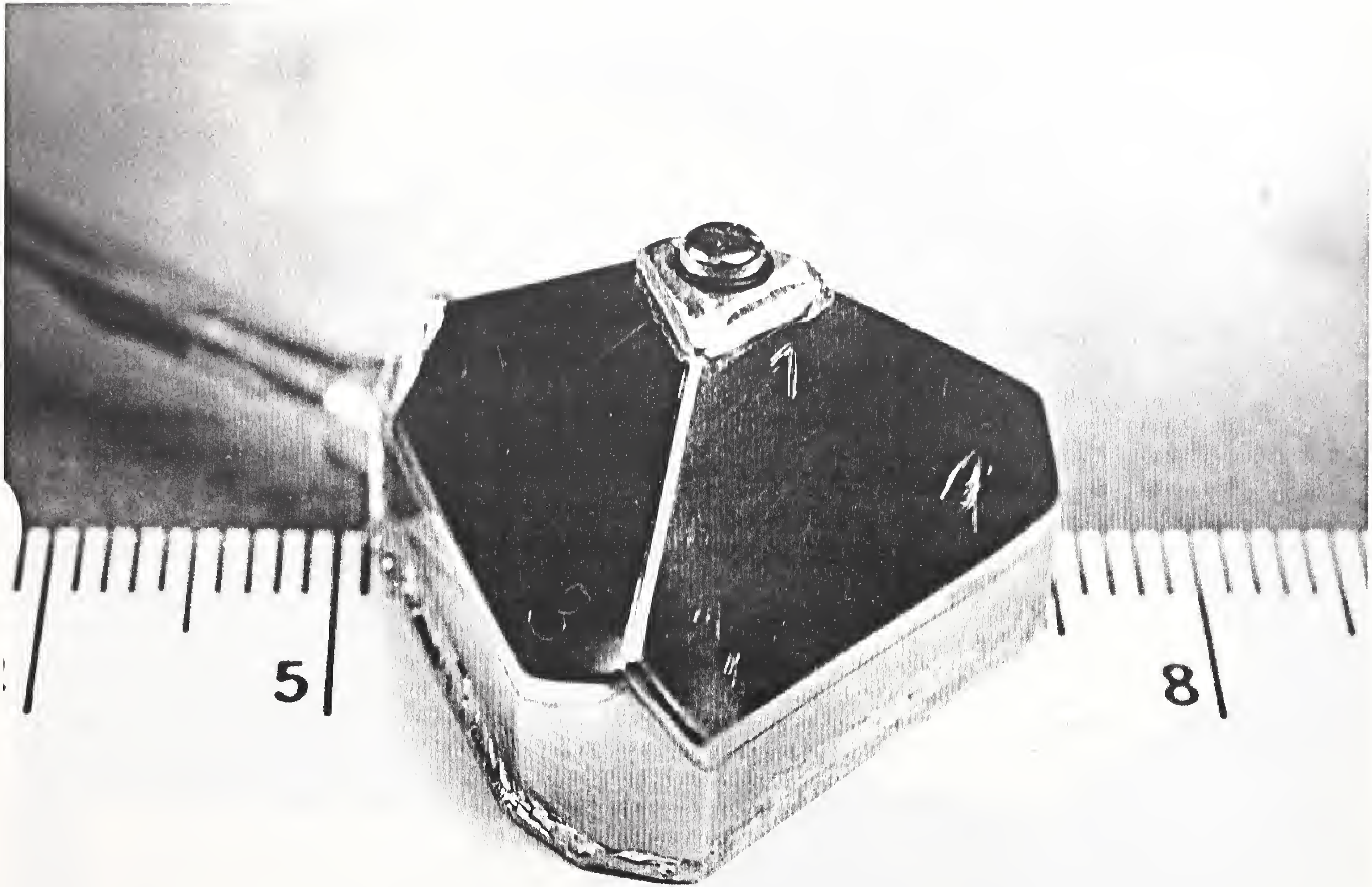

Fig. 3. Nine-axis accelerometer assembled. (Scale beneath the unit is in centimeters.)

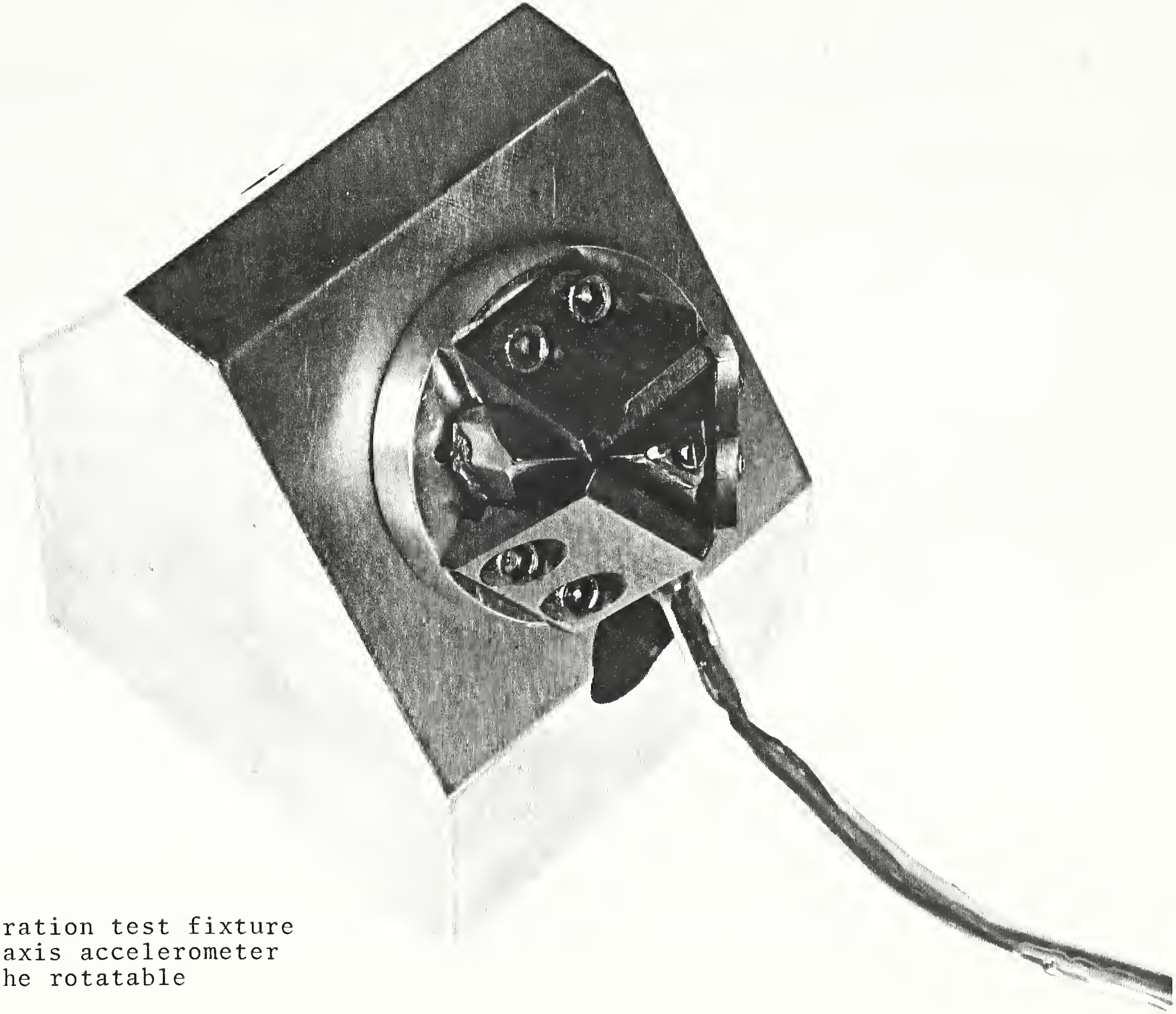

Fig. 4. Vibration test fixture with a nine-axis accelerometer mounted on the rotatable adaptor.

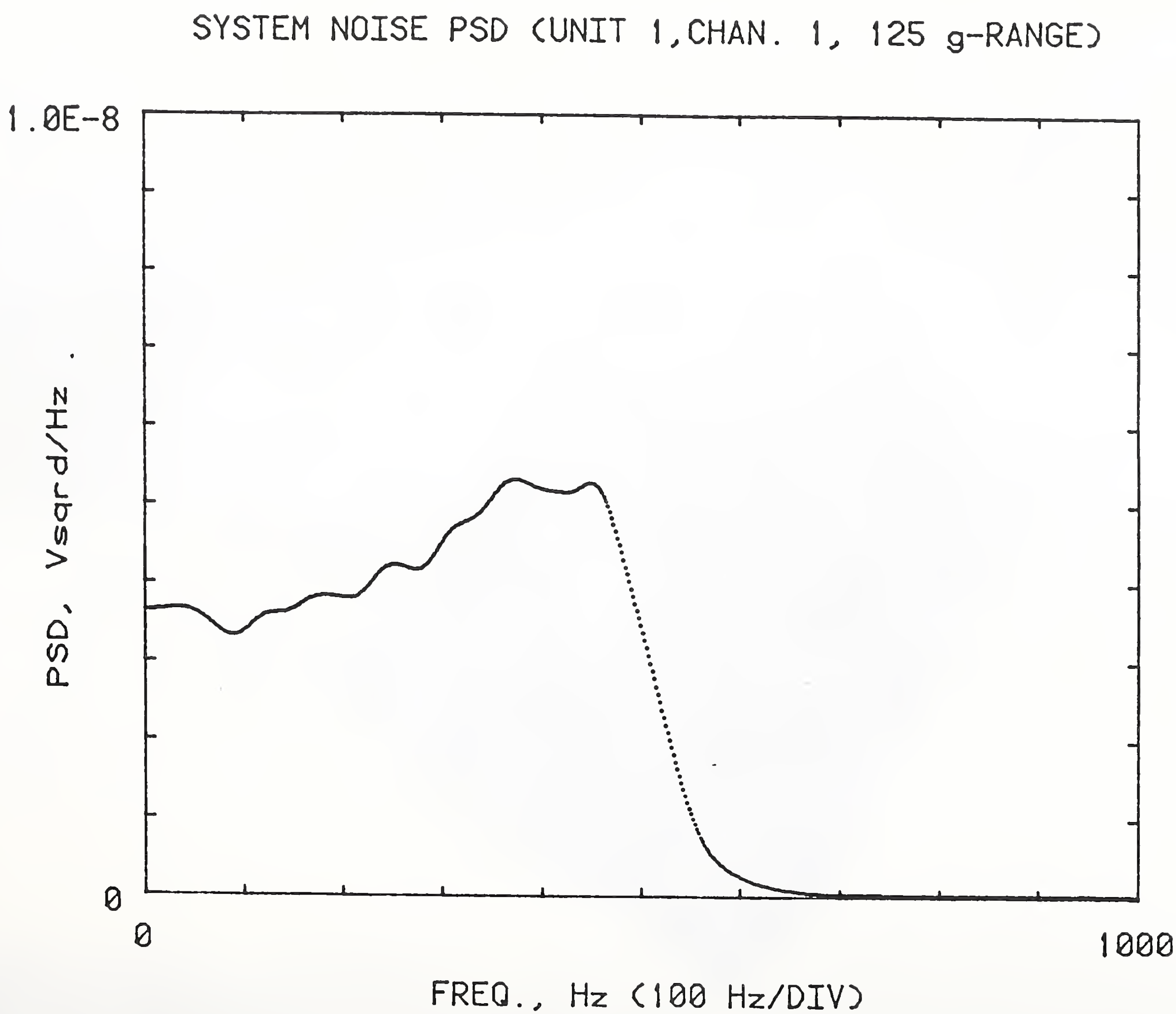

Fig. 5. Typical noise spectra from NAPELX, 125 g-range.

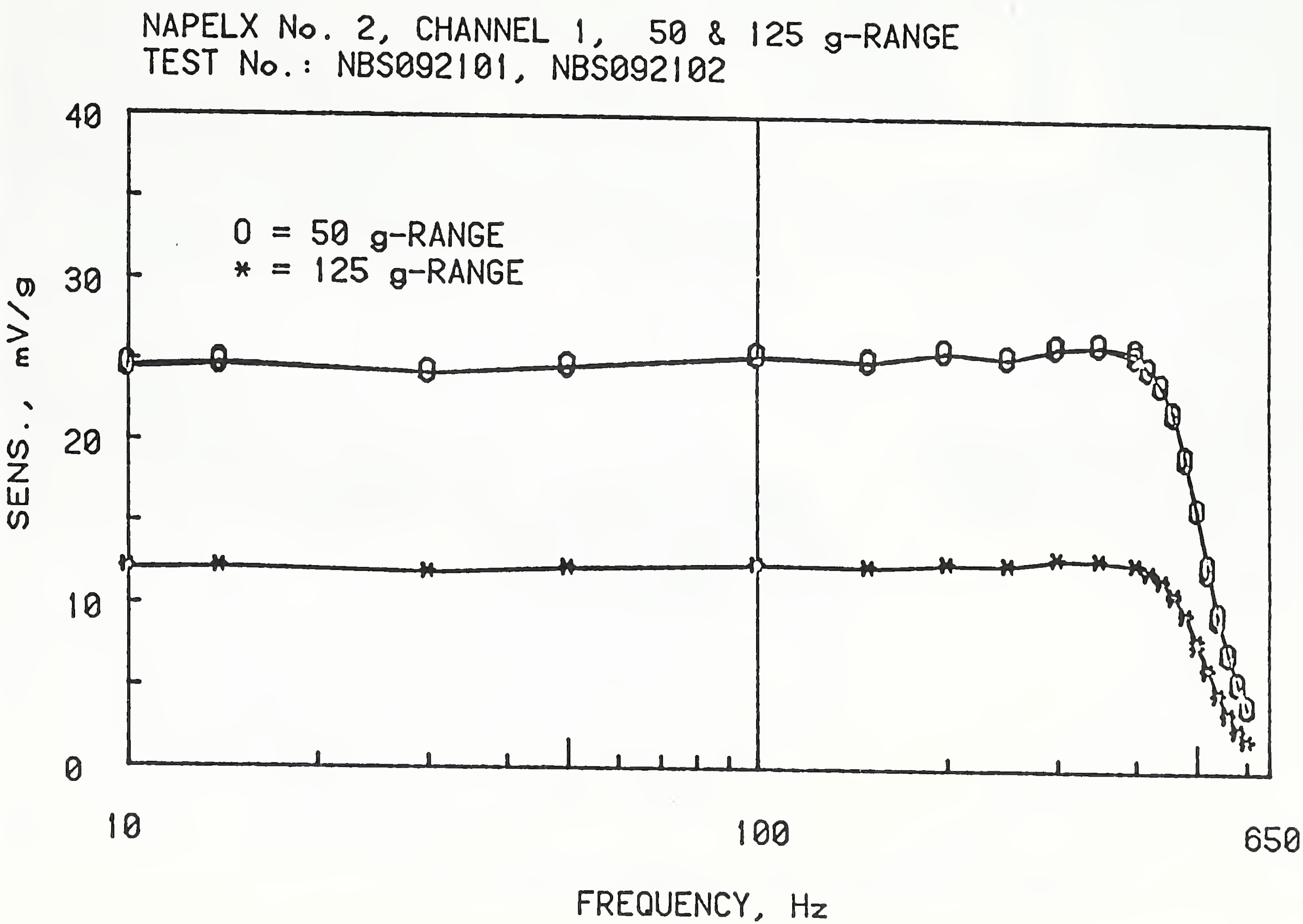

FIGURE 6. Typical axial sensitivity for one channel of the nine axis accelerometer.

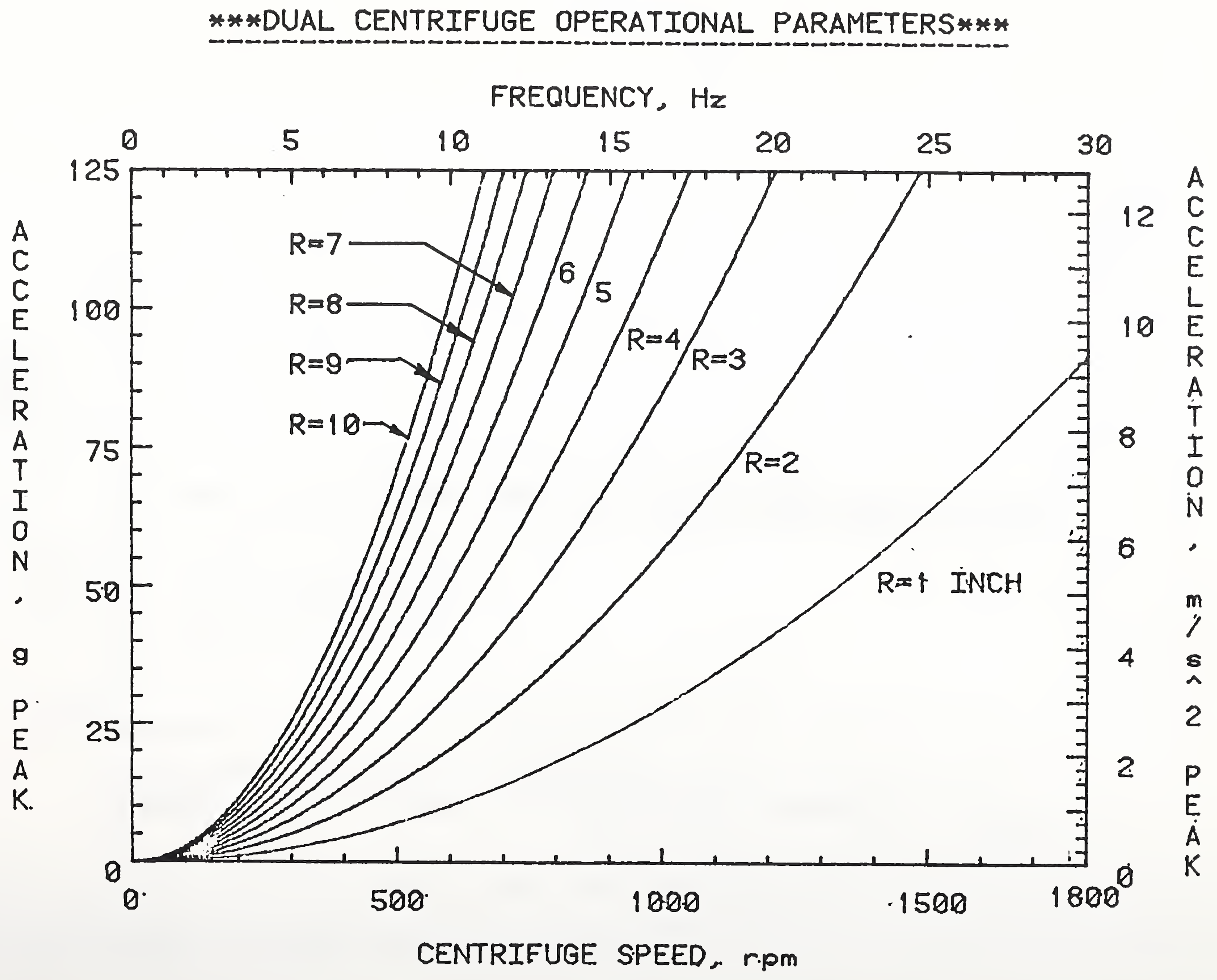

Fig. 7. Dual centrifuge operating parameters and ranges.

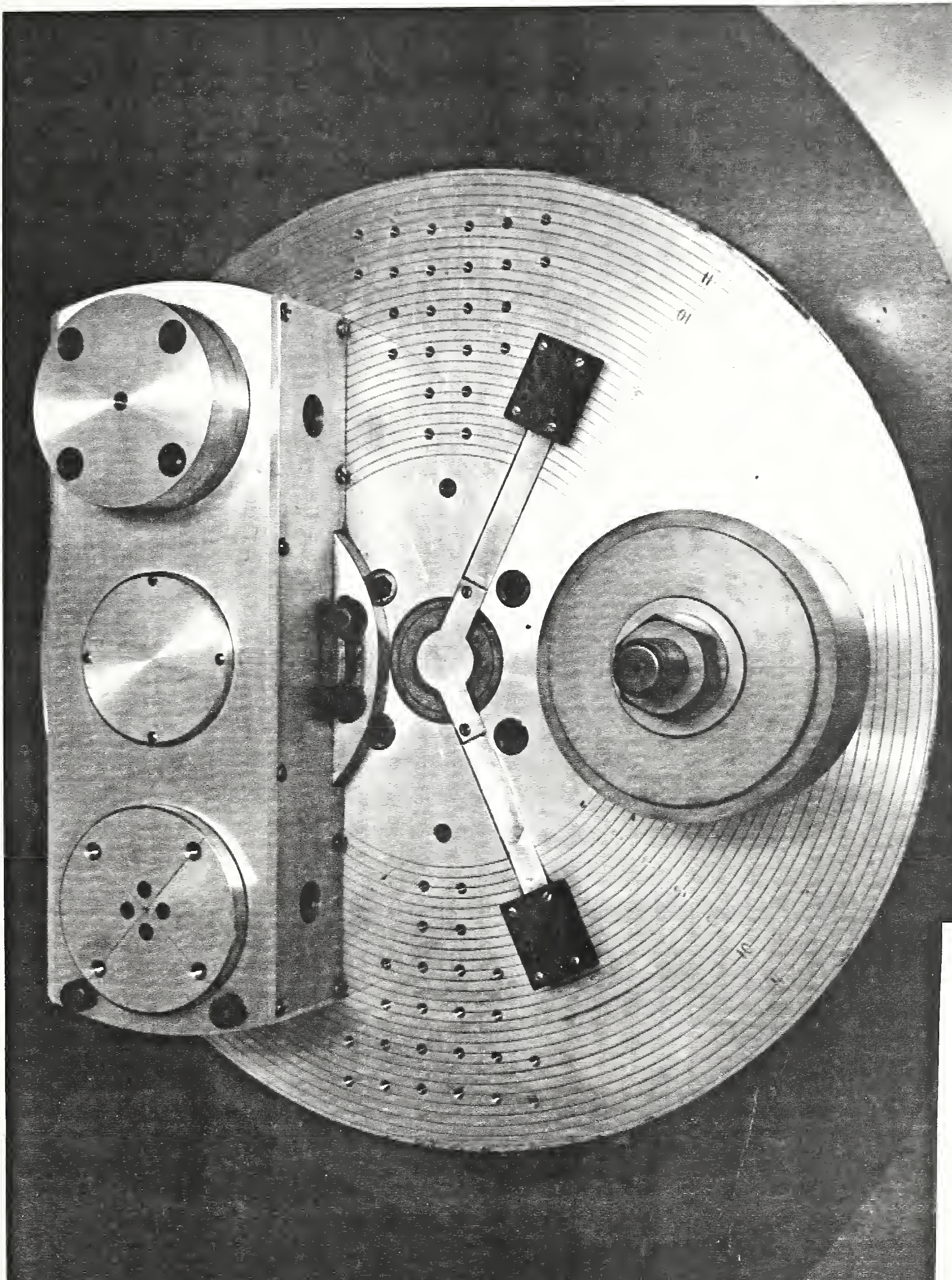

Fig. 8. Dual centrifuge.

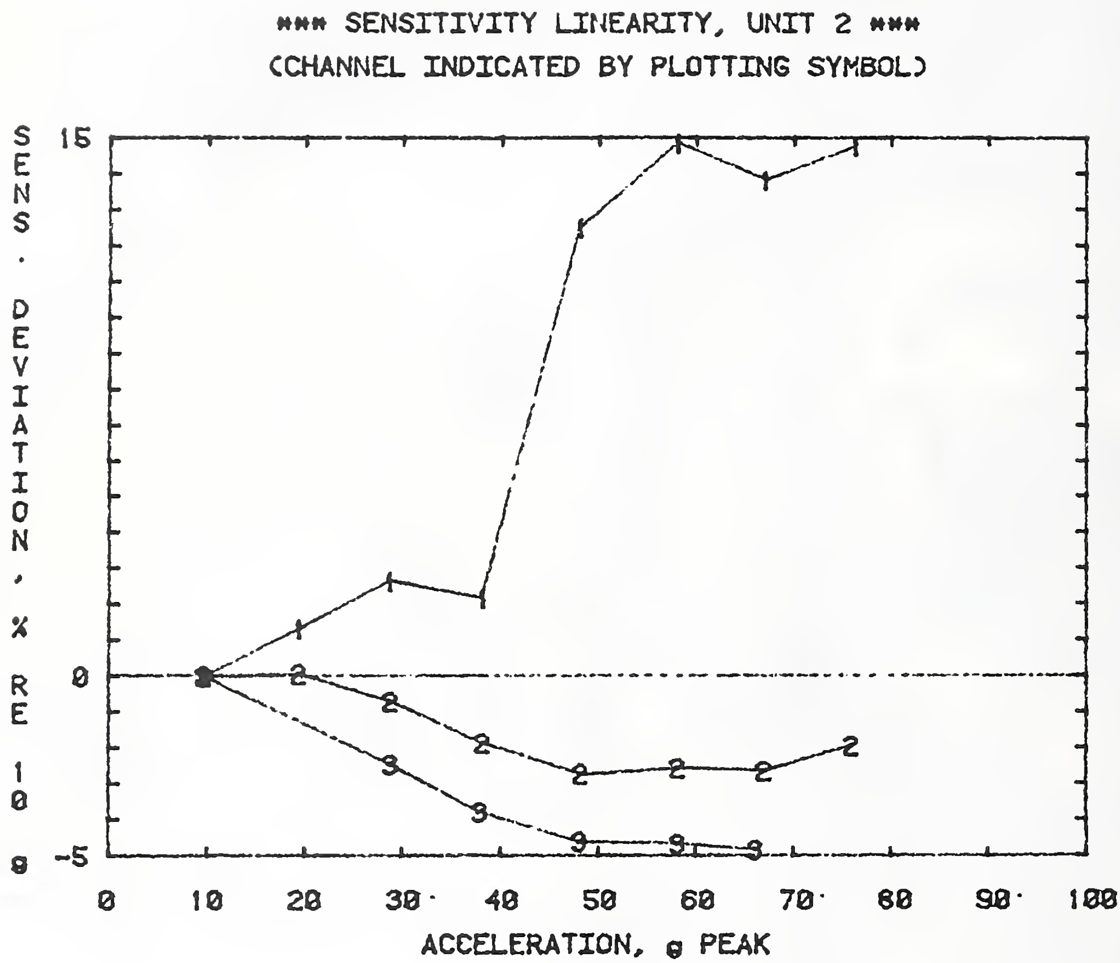

Fig. 9. Acceleration amplitude linearity test results.

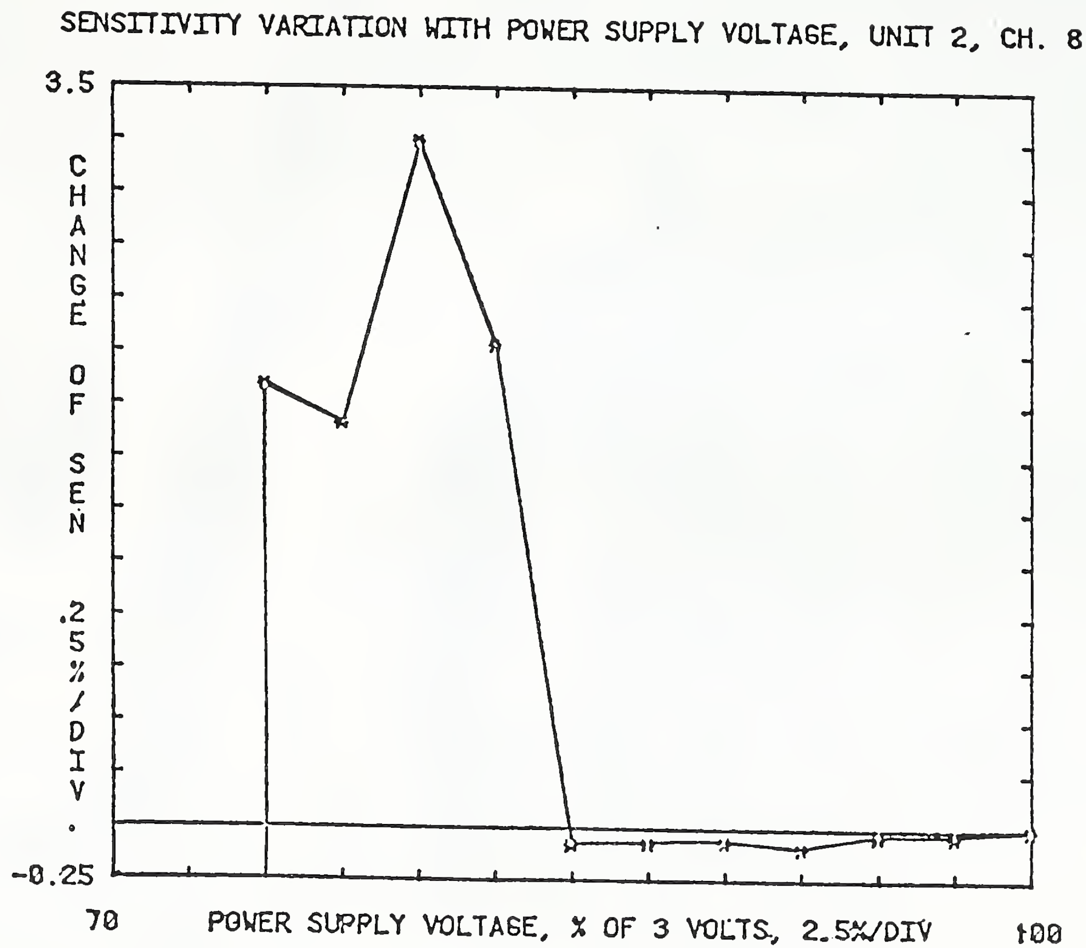

FIGURE 10. Sensitivity variation as a function of power supply voltage, percent change in sensitivity vs. percent of power supply full scale voltage (3 volts). Unit 2, channel 8, 50-g range.

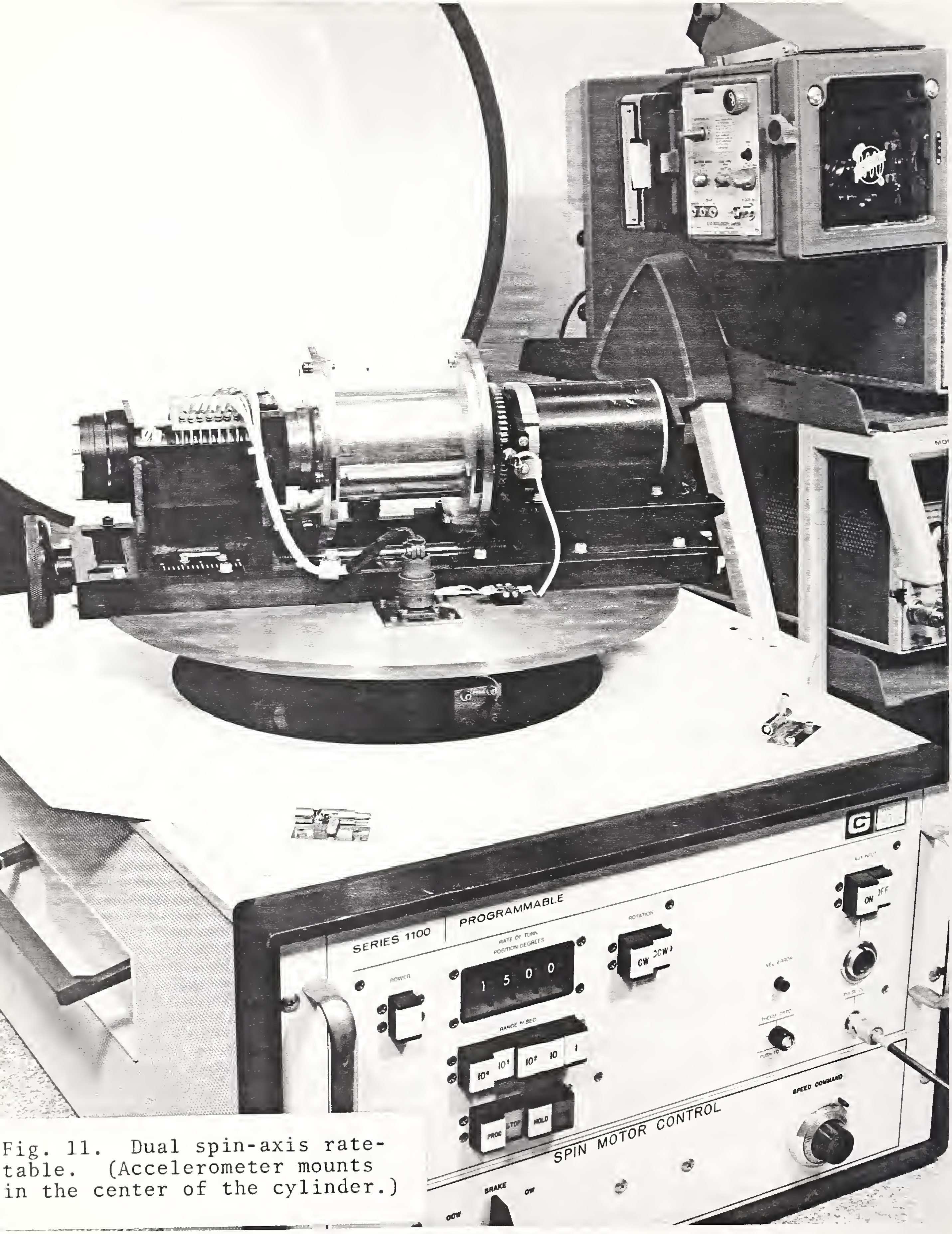

Fig. 11. Dual spin-axis rate-table. (Accelerometer mounts in the center of the cylinder.)

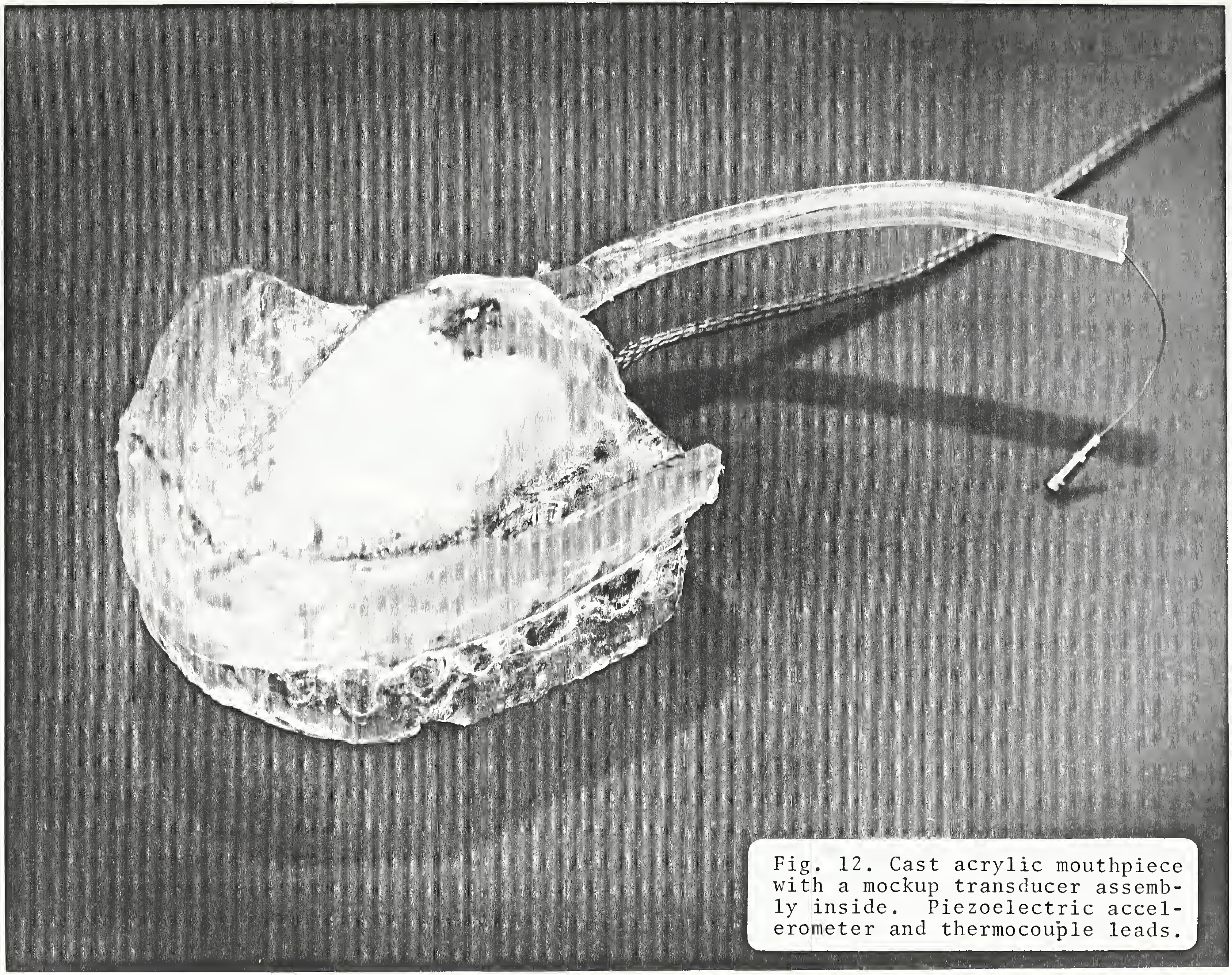

Fig. 12. Cast acrylic mouthpiece with a mockup transducer assembly inside. Piezoelectric accelerometer and thermocouple leads.

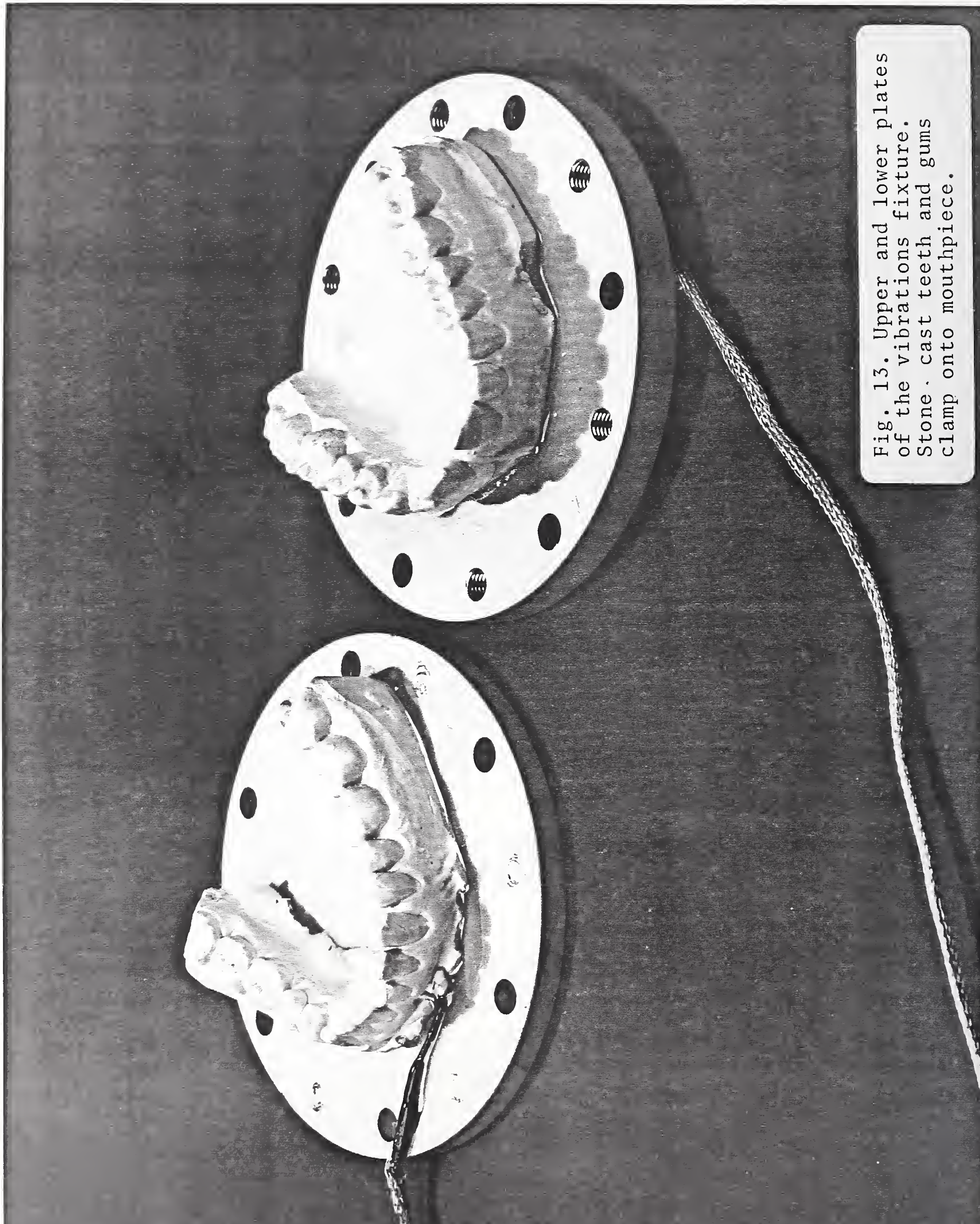

Fig. 13. Upper and lower plates of the vibrations fixture. Stone cast teeth and gums clamp onto mouthpiece.

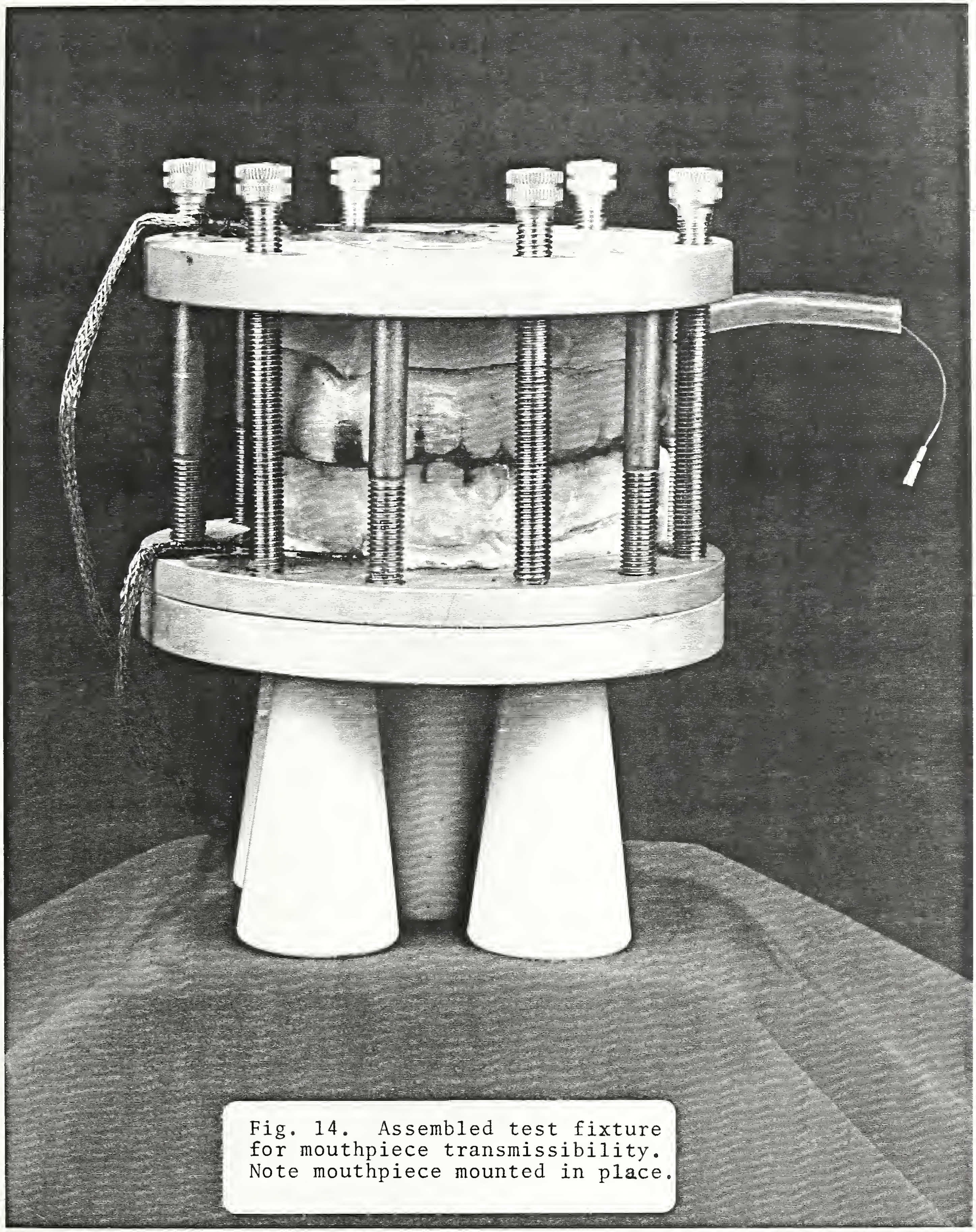

Fig. 14. Assembled test fixture for mouthpiece transmissibility. Note mouthpiece mounted in place.

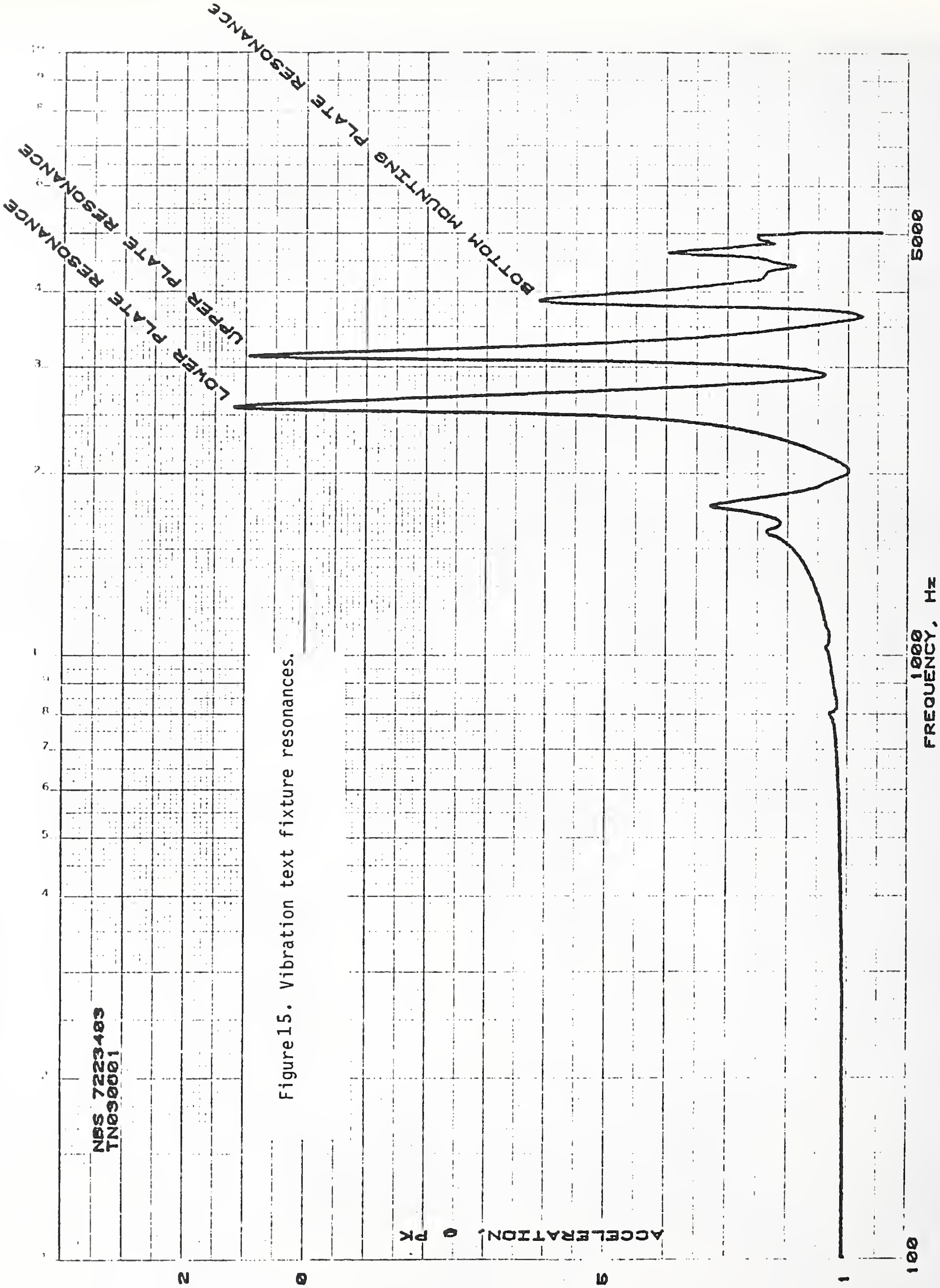

Figure 15. Vibration text fixture resonances.

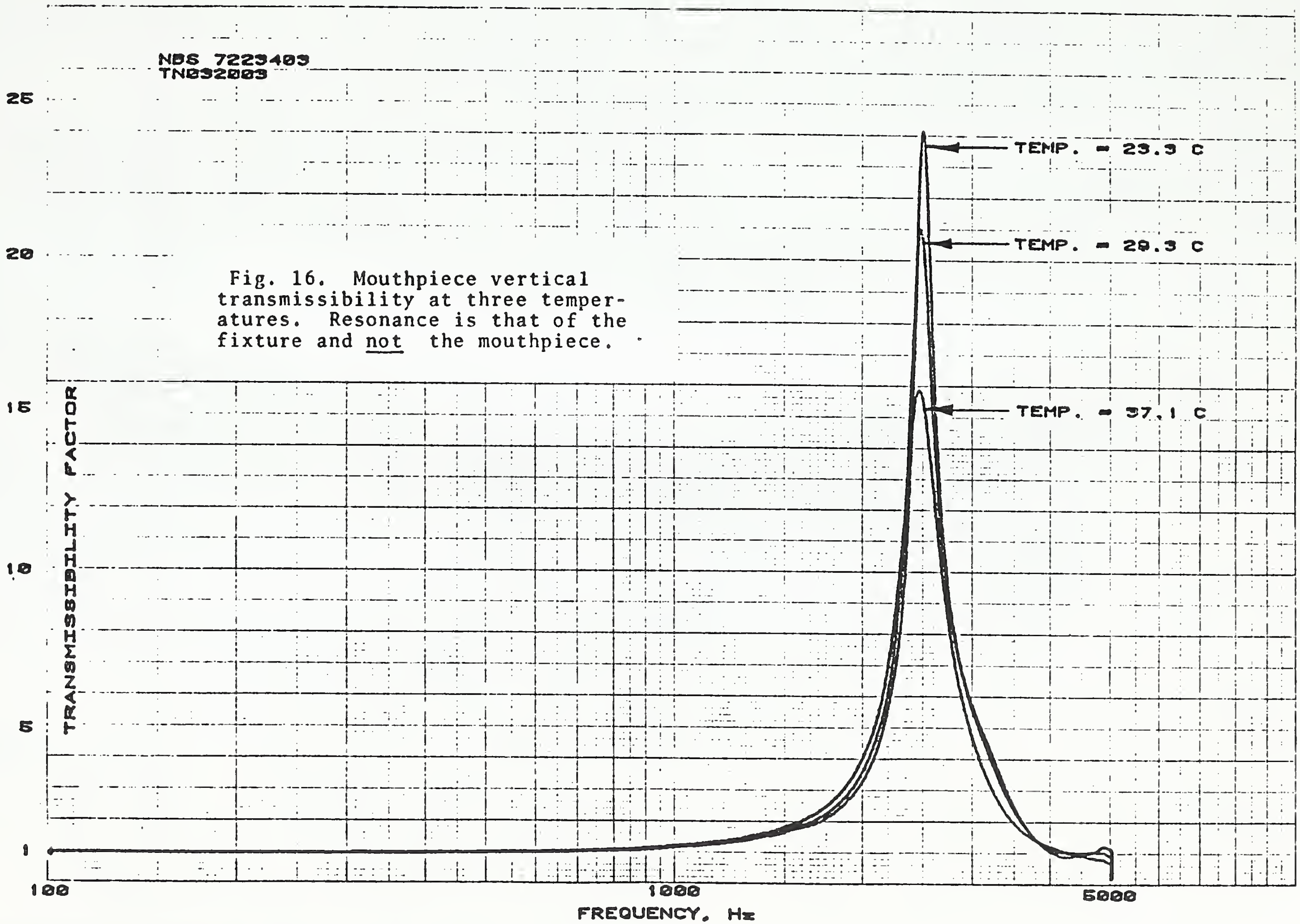

Fig. 16. Mouthpiece vertical transmissibility at three temperatures. Resonance is that of the fixture and <u>not</u> the mouthpiece.

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

The test methods used to characterize and evaluate the performance of a miniature nine-axis accelerometer are discussed. A special transducer containing nine separate linear accelerometers was examined. The intended application for this type of device is to derive angular acceleration data for dynamic head motion measurements relating to automobile crash studies. The accelerometers, amplifiers, multiplexer, FM telemetry transmitter and power supply are all to be molded into an athletic orthodontic mouthpiece and data will be obtained from measurements taken from boxer's head motions. The transducer parameters tested include axial and trasverse linear vibration sensitivities, equivalent acceleration noise, effects of power supply voltage variations, and mouthpiece vibration transmissibility. Special test apparatus described includes a dual centrifuge and a dual spin-axis rate-table. Test philosophy and some test results are used to illustrate how apparently conflicting test results can be used to explain transducer performance under test conditions of combined environments.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

angular acceleration measurement; angular accelerometer; calibration; head motion measurement; measurement methods; vibration

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