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Piezoelectric Accelerometer Low-Frequency Response by Signal Insertion Methods

Robert S. Koyanagi, James D. Pollard

Vibration Section, Mechanics Division
Institute for Basic Standards
National Bureau of Standards
Washington, D. C. 20234

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Final Report

Prepared for
Department of Defense
Calibration Coordination Group
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U.S. DEPARTMENT OF COMMERCE, Rogers C.B. Morton, Secretary
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

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FOREWARD

The evaluation of the piezoelectric accelerometers discussed in this report was sponsored by the Department of Defense Calibration Coordination Group (DOD/CCG), Subgroup for Shock and Vibration, consisting of: the Metrology Engineering Center, Bureau of Naval Weapons Representative, Pomona, California 91766; the Aerospace Guidance and Metrology Center, Newark Air Force Station, Newark, Ohio 43055; and the Metrology Calibration Center, Redstone Arsenal, Alabama 35809. The Atomic Energy Commission was represented by an observer from Sandia Laboratories, Albuquerque, New Mexico 87115.

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PIEZOELECTRIC ACCELEROMETER LOW-FREQUENCY RESPONSE BY SIGNAL INSERTION METHODS

by

Robert S. Koyanagi
James D. Pollard

ABSTRACT

The purpose of this study was to compare the frequency response of selected piezoelectric accelerometers using a signal insertion method to the response using traditional mechanical vibration tests. Signal insertion methods included "voltage insertion" and "charge insertion" techniques. The signal is inserted in series with the electrical low-side of the accelerometer by means of a suitable series resistance. Commercially available insertion devices were used. Confidence in the use of insertion methods is increased where there is agreement between the results from insertion tests and mechanically excited tests.

UNITS OF MEASURE

SI units were used throughout this report with one exception. To facilitate communication with the intended readers "g" was used for the acceleration of gravity. The SI units can be obtained by use of the relationship: 1 g = 9.80665 m/s^2.

KEY WORDS

Accelerometer, calibration, vibration, low frequency, signal insertion.

1. INTRODUCTION

The report describes the investigation of signal insertion methods of calibrating piezoelectric accelerometers at low frequencies. This method may be particularly useful to laboratories which do not have the facilities to mechanically produce a suitable, sinusoidal low-frequency waveform. For purposes of comparison, each accelerometer was calibrated mechanically on an electrodynamic exciter [1] and by insertion techniques [2, 3, 4].

Tests were conducted from 1.5 to 50 Hz. A total of 11 accelerometers of eight different models were tested. Where possible, each accelerometer was tested with a voltage amplifier and a charge amplifier used as signal conditioners.

2. SIGNAL INSERTION METHOD

Figure 1 illustrates the signal insertion technique. The calibration voltage is inserted in series with the accelerometer on the ground side. This is facilitated by use of commercially available insertion devices [5, 6]. The accelerometer must be electrically isolated from ground.

The frequency response of the accelerometer-amplifier system is obtained by measuring the voltage output of the amplifier (V_o), and the calibration voltage (V_{cal}). The variation in the ratio V_o/V_{cal} with frequency is the frequency response of the system.

3. MECHANICAL VIBRATION TESTS

NBS electrodynamic Vibration Standard LF-1 was used to calibrate the accelerometer-amplifier systems mechanically. Sensitivity factors were determined by comparing the voltage output of the amplifier used with the accelerometer with the output of the Standard.

Varying degrees of difficulty were encountered in measuring the voltage output of the accelerometer-amplifier systems at very low frequencies. Vibration Standard LF-1 has a maximum double amplitude of 4.45 cm [1]. At low frequencies this limits the maximum attainable acceleration. For example, at 2 hertz the maximum acceleration is 0.36g peak. These low acceleration levels coupled with the low sensitivity of some of the accelerometers result in very low signals and poor signal-to-noise ratios.

Figure 2 shows the level of mechanical test acceleration versus frequency. The ordinates on the right side of the graph gives the voltage output at these acceleration levels for various system sensitivities. The intersection of this curve with the 7 mV output point of the various systems gives the approximate lowest frequency at which reliable voltage measurements were made (column 2 of tables 2 and 3).

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[1] Numerals in brackets refer to references found at the end of this paper.

4. VOLTAGE MEASURING SYSTEMS

Low-frequency voltage measurement is a difficult problem. In these tests, the quantities sought were voltage ratios and therefore, some of the errors tend to cancel. The following voltage measuring systems were used:

1. The voltages were measured with two true rms differential voltmeters, or
2. The voltages were fed directly into two voltage-to-frequency converters; the ratios of the converter frequencies were measured on a counter and are proportional to the voltage ratios.

A principal problem of this study is the result of limitations of voltage measurements at low frequencies and low amplitudes. Voltmeters, in general, do not provide accurate measurements at frequencies below about 5-10 Hz, and at 1.5 to 5 Hz, their uncertainties are often large. It was a principal goal of this study to compare signal insertion results to mechanically excited results. Because of the limitations discussed in Section 3 above, (i.e. low voltage signal amplitudes due to low acceleration amplitudes) it was also necessary to perform the signal insertion tests at nominally the same low signal amplitudes. Otherwise, ranging errors in the voltmeters could be as large as the effects being studied.

Voltmeter errors due to roll-off at low-frequencies could be taken into account by using the same voltmeter on the same range when measuring by both the insertion and mechanically excited methods. By keeping the voltmeter range the same, only differences were being sought between the two methods, even though voltmeter roll-off with decreasing frequency might have been present. So long as the voltmeter error remained the same between the two methods, this source of error ideally subtracts to zero in the difference between the methods.

In addition to the kinds of problems discussed above in making voltage measurements, it was discovered that the true rms differential voltmeters exhibited a strange increase in uncertainty when certain combinations of voltage and frequency were being used. For example, the voltmeter would exhibit a rather normal and somewhat predictable roll-off at low frequencies when the voltage amplitude was maintained at reasonably high levels (i.e., in the tens of millivolts or greater). However, when the voltage amplitude reached about 7 mV or less, the roll-off occurred at a very much greater rate; this happening only at low frequencies. At higher frequencies, this effect does not occur and low level voltages less than 7 mV could be measured.

When using voltage-to-frequency converters to measure low frequency voltages, any dc levels present in the signal can create errors in their readings. Some of the signal conditioners (i.e., voltage or charge amplifiers) used in this study did produce small dc voltage offsets. The zero stability of the balancing circuits would not remain sufficiently stable to permit meaningful measurements to be made. Furthermore, slowly changing voltage levels from such causes as the pyroelectric effect in some of the accelerometers would cause large and unmanageable errors.

The inability to measure low-level, low-frequency voltages limited the lowest frequencies at which meaningful tests could be performed. These are shown and discussed in section 6 of this report.

5. DISCUSSION OF RESULTS

5.1 Accelerometers Tested

Some of the accelerometers tested were not compatible with the voltage or charge amplifiers used. Table 1 indicates which systems were tested and gives the nominal system sensitivity for the accelerometer and amplifier combination used.

Table 1. Accelerometer Systems Tested. Values in Parenthesis are Nominal Sensitivities in Units of mV/g.

Accelerometer Code*	Design Type	Charge Amplifier		Voltage Amplifier	
			Fig. No.		Fig. No.
[ERK14]	Compression	X (10)	3	-	-
[ERK18]	Compression	X (10)	4	-	-
[ERK19]	Compression	X (10)	5	-	-
[C05D7]	Compression	X (1400)	6	X (40)	13
[C05D1]	Compression	X (1500)	7	X (40)	14
COM28	Compression	X (110)	8	X (20)	15
C0151	Compression	X (140)	9	X (10)	16
C07C5	Compression	X (290)	10	X (150)	17
C07E0	Compression	X (390)	11	X (200)	18
C04C8	Shear	X (130)	12	X (40)	19
C0253	Shear	-	-	X (15)	20

*Bracketed codes indicate accelerometers of the same make and model.

5.2 Plotted Data

Plots were made to facilitate the comparison of the results of the signal insertion method and the mechanical vibration testing. Each plot shows the frequency response in percent referenced to the 10 Hz point. The first set of curves present the results using a charge amplifier as a signal conditioner. The second set presents the results using a voltage amplifier.

Tables 2 and 3 emphasize the more pertinent results obtained from the data presented in the plots. The columns for both tables present the following:

Column 2 gives the lowest frequency at which reliable voltage measurements were made.

Column 3 gives the lowest frequency at which the insertion and mechanical methods checked each other to within one percent.

Column 4 indicates which method tends to yield a higher accelerometer sensitivity at lower frequencies. A "VI" indicates that the signal insertion tends to be higher; a "MV" indicates that mechanical vibration tends to be higher; and a "C" indicates that the two methods check each other to within the accuracies of the tests. Only data above the low frequency cut off of column 2 were considered in making these judgements. Other data with unreasonable deviations from the trends of the majority of data were not considered.

Table 2. Results of Tests with a Charge Amplifier as a Signal Conditioner

Accelerometer Code	Lowest Reliable Frequency, Hz	Lowest Frequency Check, Hz	Higher Sensitivity
ERK14	5	5	C
ERK18	5	5	C
ERK19	4	4	VI
CO5D7	1.5*	4	MV
CO5D1	1.5*	3	MV
COM28	1.5*	4	VI
CO151	4*	4	VI
CO7C5	2*	2	C
CO7EO	1.5	4	MV
CO4C8	1.5	1.5	C

*Excessive dc voltage prohibited use of voltage-to-frequency converters; measurements use rms differential voltmeters only.

Table 3. Results of Tests with Voltage Amplifier as a Signal Conditioner.

Accelerometer Code	Lowest Reliable Frequency Hz	Insert Frequency Check Hz	Higher Sensitivity
C05D7	2*	2	C
C05D1	3*	3	C
COM28	3	4	VI
C0151	2	5	VI
C07C5	2**	8**	VI
C07E0	2**	8**	VI
C04C8	2**	5**	VI
C0253	4	4	C

*Excessive dc voltage prohibited use of voltage-to-frequency converters; measurements use rms differential voltmeters only.
**Large roll-off in sensitivity occurred.

6. CONCLUSIONS

Some of the accelerometers tested are not suitable for low-frequency vibration measurements. Two requirements for low-frequency accelerometers are low sensitivity to case strain and high sensitivity to acceleration. Discontinuity or irratic points in the frequency response curves may be due to case strain or low signal-to-noise ratios. These problems are especially prevalent below 4 or 5 Hz.

The low acceleration sensitivities (approximately 10 mV/g) of accelerometers ERK18, ERK19 and C0151 limited their lowest calibration frequency to approximately 5 Hz. It should be noted that signal insertion methods could be employed when the voltage or charge insertion amplitudes would be maintained at some relatively high level, say 100 mV (or equivalent charge) or so. In this instance, good signal-to-noise ratios could be maintained and the noise would be no major problem.[1] However, direct comparison with mechanically excited results could not be realistically made, as discussed in section 4 above. Difficulties were encountered in attempting to calibrate accelerometer C0253 with a charge amplifier. This system has low acceleration sensitivity (approximately 8.5 mV/g) and is very temperature sensitive.

It should be emphasized that the primary objective of this project was to test the feasibility of the signal insertion method to calibrate various models of accelerometers.

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[1] In separate tests where signal levels were maintained well above the noise levels using signal insertion methods, the frequency response appears flat to within the ability to measure the low frequency voltages. This is in general agreement with results reported by other experimenters.

In general, there is reasonable agreement between the two methods. At lower frequencies, in the instances where the two methods did not check each other, the voltage insertion method tends to be higher than the mechanical vibration method; especially for voltage sensing systems.[2] The only instances where the mechanical vibration method tended to be higher were when accelerometers C05D7, C05D1 and C07E0 were tested with a charge amplifier. It was noticed that these accelerometers are all of similar construction and have the same type of piezoelectric material.

If it is assumed that the results of the mechanical method represent the "right" response, correction factors might be useful for some of the models of accelerometers tested. However, caution must be exercised by placing a large enough uncertainty on signal insertion measurements. A three percent estimated uncertainty down to the frequencies where a one percent check was made (column 3 in tables 2 and 3) seems reasonable. Additional conservatism is necessary due to the small number of accelerometers tested.

7. ACKNOWLEDGEMENTS

John D. Ramboz of NBS, and Michael J. Luwe and Dale W. Rockwell of MEC Pomona contributed guidance and shared their expertise on these measurement methods.

---

[2] This effect was also noted by test results reported by private correspondence with D. E. Upton, and later by M. J. Luwe of the Metrology Engineering Center in Pomona Calif. See references 7 and 8.

8. REFERENCES

1. Koyanagi, R. S., "Development of a Low Frequency Vibration Calibration System," Nat. Bur. Stds. Report 10 529, Jan. 1971.

2. Rhodes, J. E. "Piezoelectric Transducer Calibration Simulation Method Using Series Voltage Insertion," Environmental Quarterly, April, 1962. (Reprinted by the Endevco Corporation as publication TP 216).

3. Pennington, D., *Piezoelectric Accelerometer Manual*, Endevco Corporation, San Juan Capistrono, Calif., 1965; pp. 71-72.

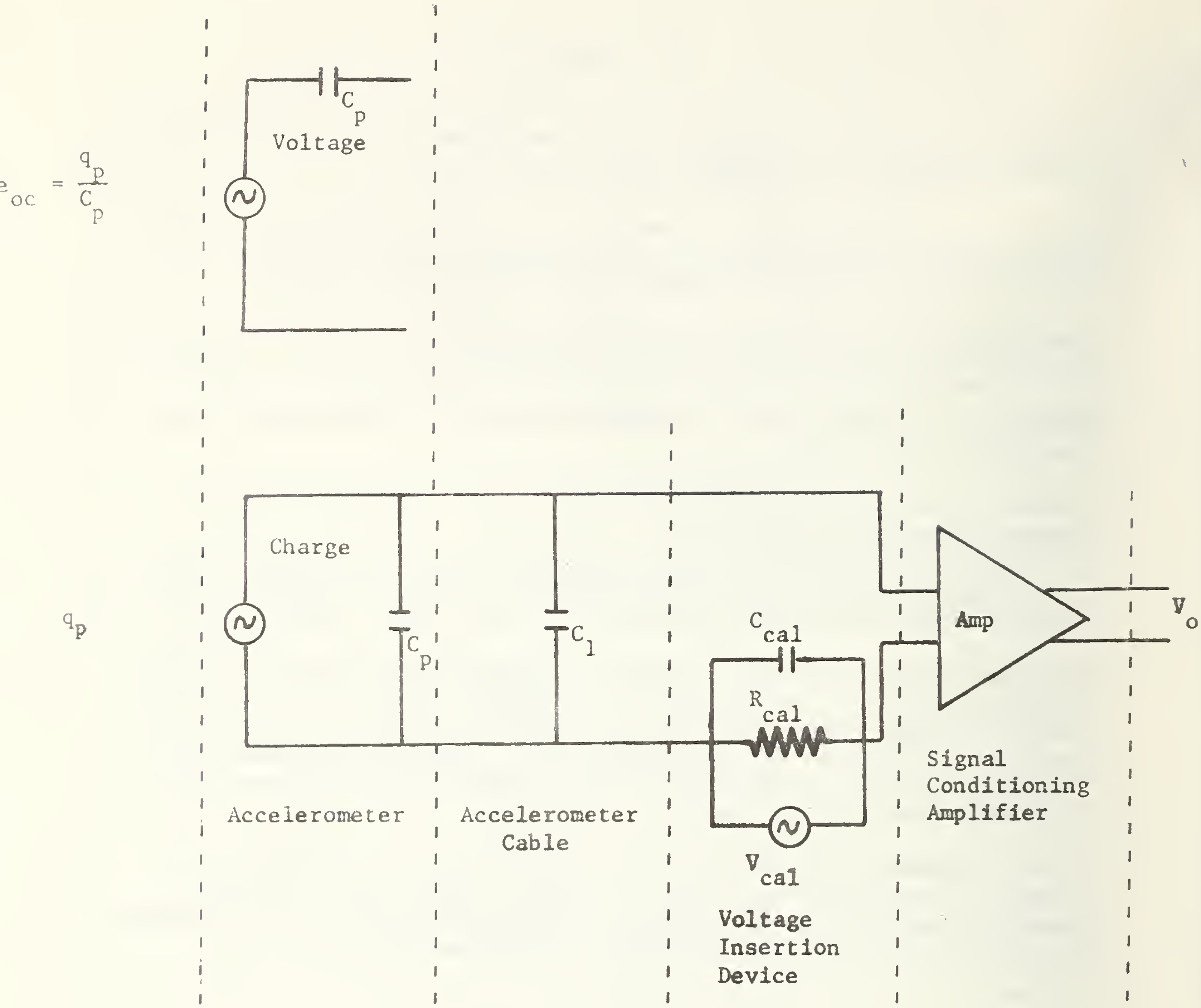
4. Keast, D. N., *Measurements in Mechanical Dynamics*, McGraw-Hill, New York, 1967; pp. 133-134.

5. "Endevco Specification Sheet for Model 2944.1 T-Junction Calibrator," Endevco Corporation, May, 1968.

6. Insert Voltage Adapter, UA 0322, Bruel and Kjaer specification sheet for Type 8305 Accelerometer Reference, p. 165, Master Catalog, 1971.

7. Private communication, D. E. Upton of the Metrology Engineering Center, Pomona, California; Jan. 20, 1972. Vibration tests from 1.5 to 30 Hz, insertion tests from 0.5 to 15 Hz. High level voltage measurements at approximately 1000 mV for insertion tests. Maximum displacement for vibration tests was about 1 cm. Voltage insertion results were higher than mechanical excited results.

8. Private communication, M. J. Luwe of the Metrology Engineering Center, Pomona, California; May 6, 1974. Vibration tests from 5 to 200 Hz, insertion tests from 1 Hz to 200 Hz. Insertion results were consistently higher than those obtained by mechanical excited tests.



Legend: e_{oc} = Accelerometer generated open circuit voltage
q_p = Accelerometer generated charge
c_p = Accelerometer capacitance
C_1 = Cable capacitance
C_{cal} = Calibration voltage source capacitance
R_{cal} = Voltage insertion resistor
V_{cal} = Calibration voltage
V_o = Amplifier output voltage

Fig. 1. Signal Insertion Schematic

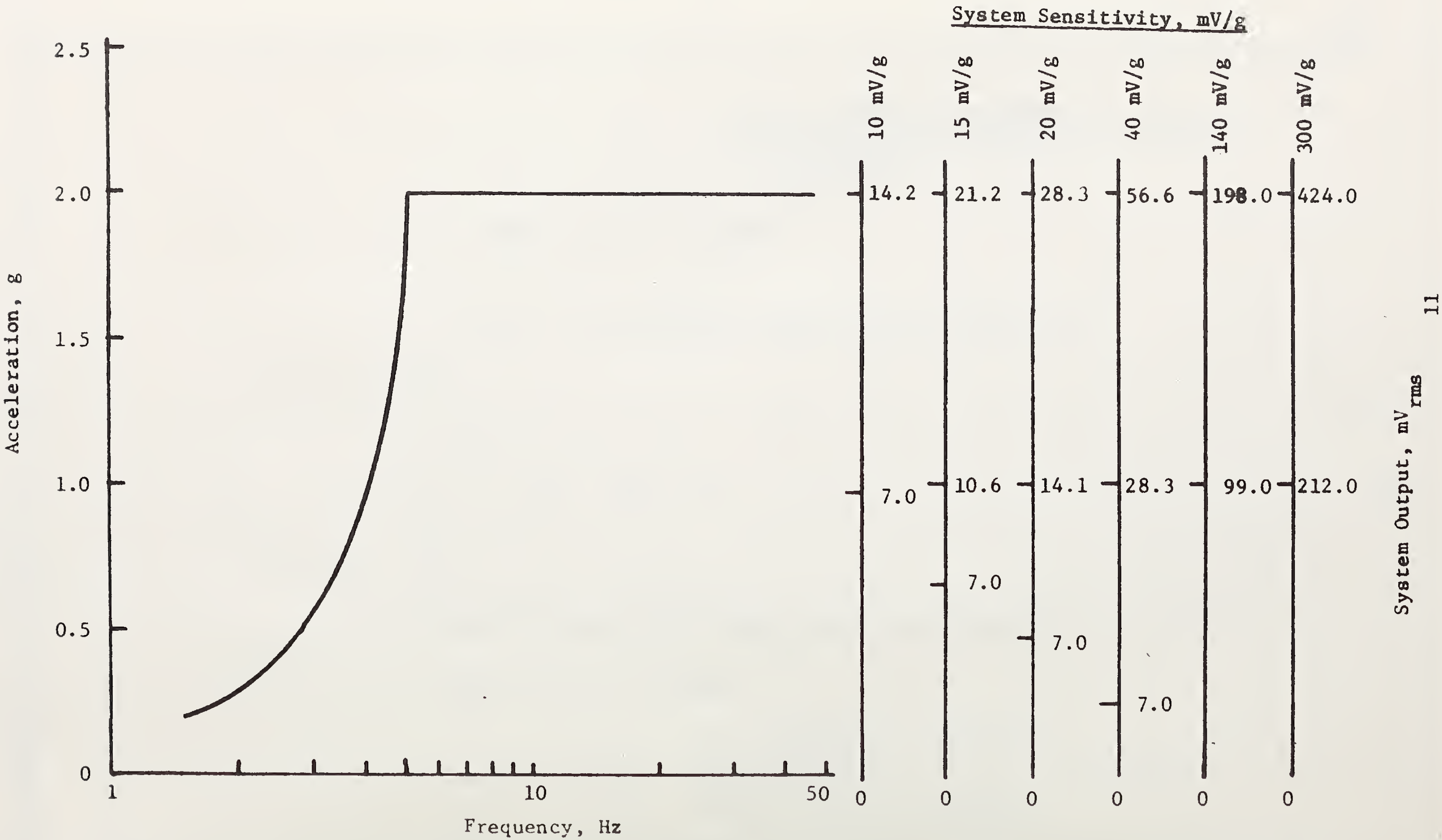


Fig 2. Acceleration and system outputs versus frequency. The intersection of this curve with the 7 mV output point given on the ordinates on the right gives the approximate lowest frequency at which reliable voltage measurements were made.

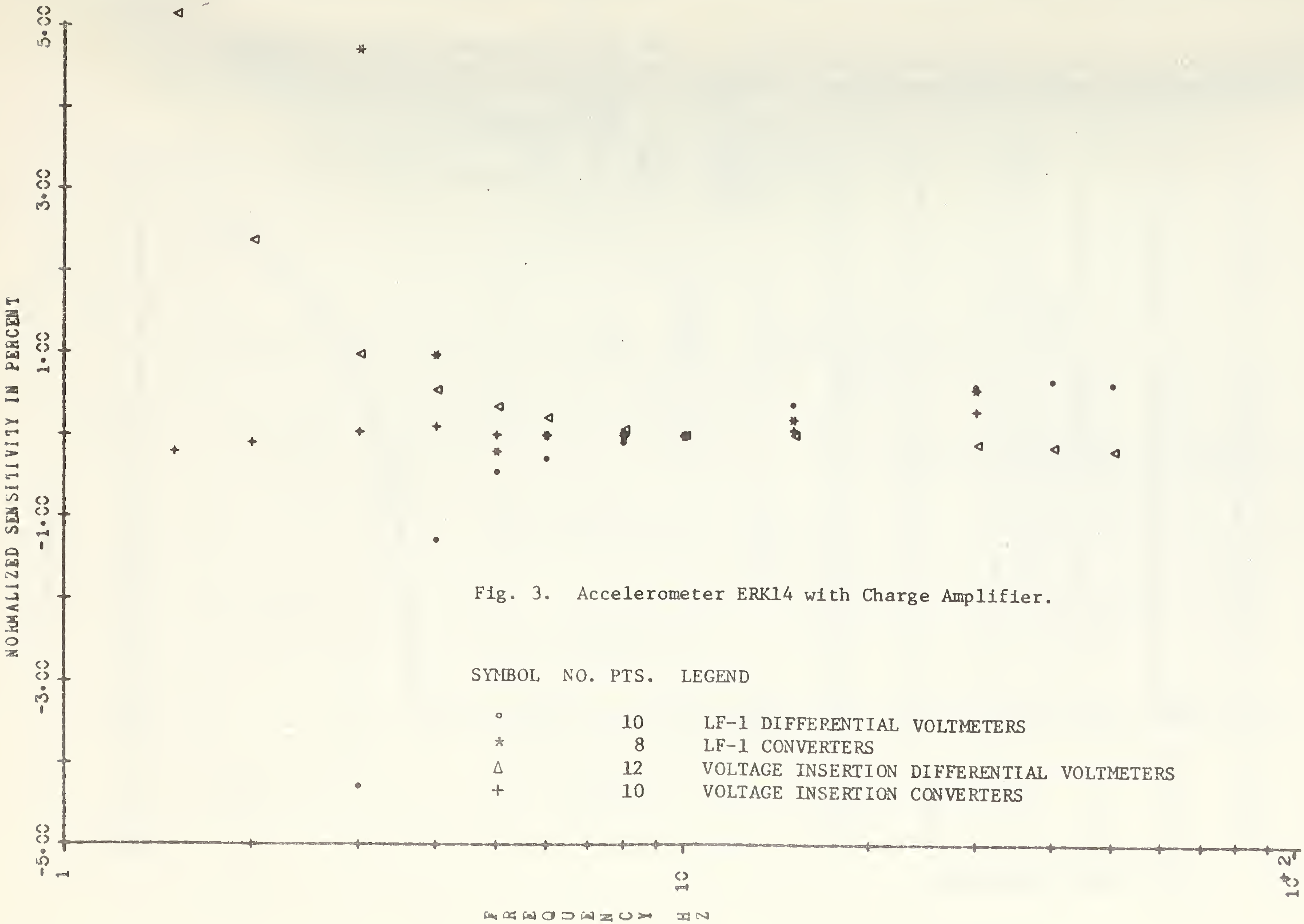


Fig. 3. Accelerometer ERK14 with Charge Amplifier.

SYMBOL	NO. PTS.	LEGEND
∘	10	LF-1 DIFFERENTIAL VOLTMETERS
*	8	LF-1 CONVERTERS
Δ	12	VOLTAGE INSERTION DIFFERENTIAL VOLTMETERS
+	10	VOLTAGE INSERTION CONVERTERS

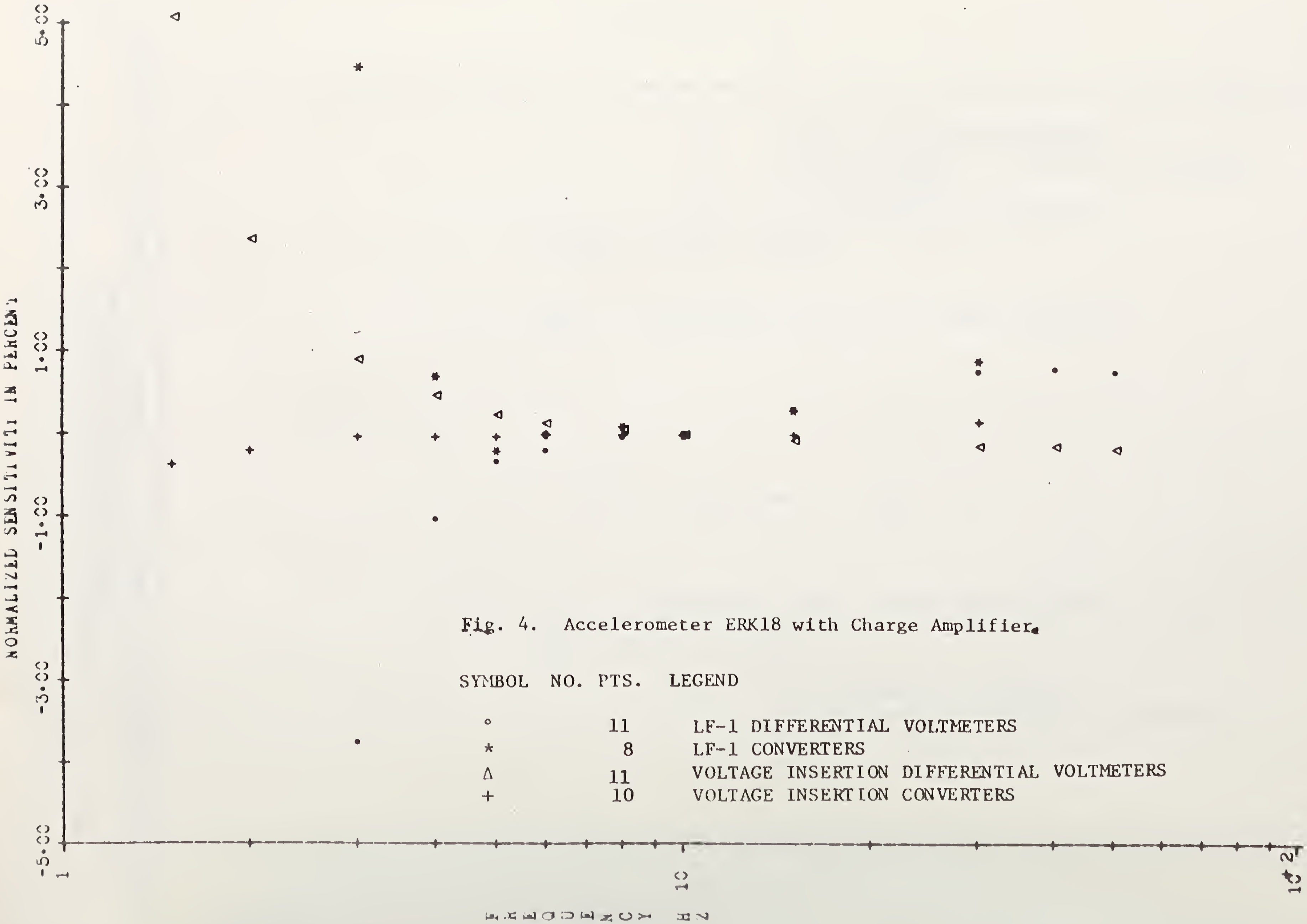


Fig. 4. Accelerometer ERK18 with Charge Amplifier.

SYMBOL	NO. PTS.	LEGEND
°	11	LF-1 DIFFERENTIAL VOLTMETERS
*	8	LF-1 CONVERTERS
Δ	11	VOLTAGE INSERTION DIFFERENTIAL VOLTMETERS
+	10	VOLTAGE INSERTION CONVERTERS

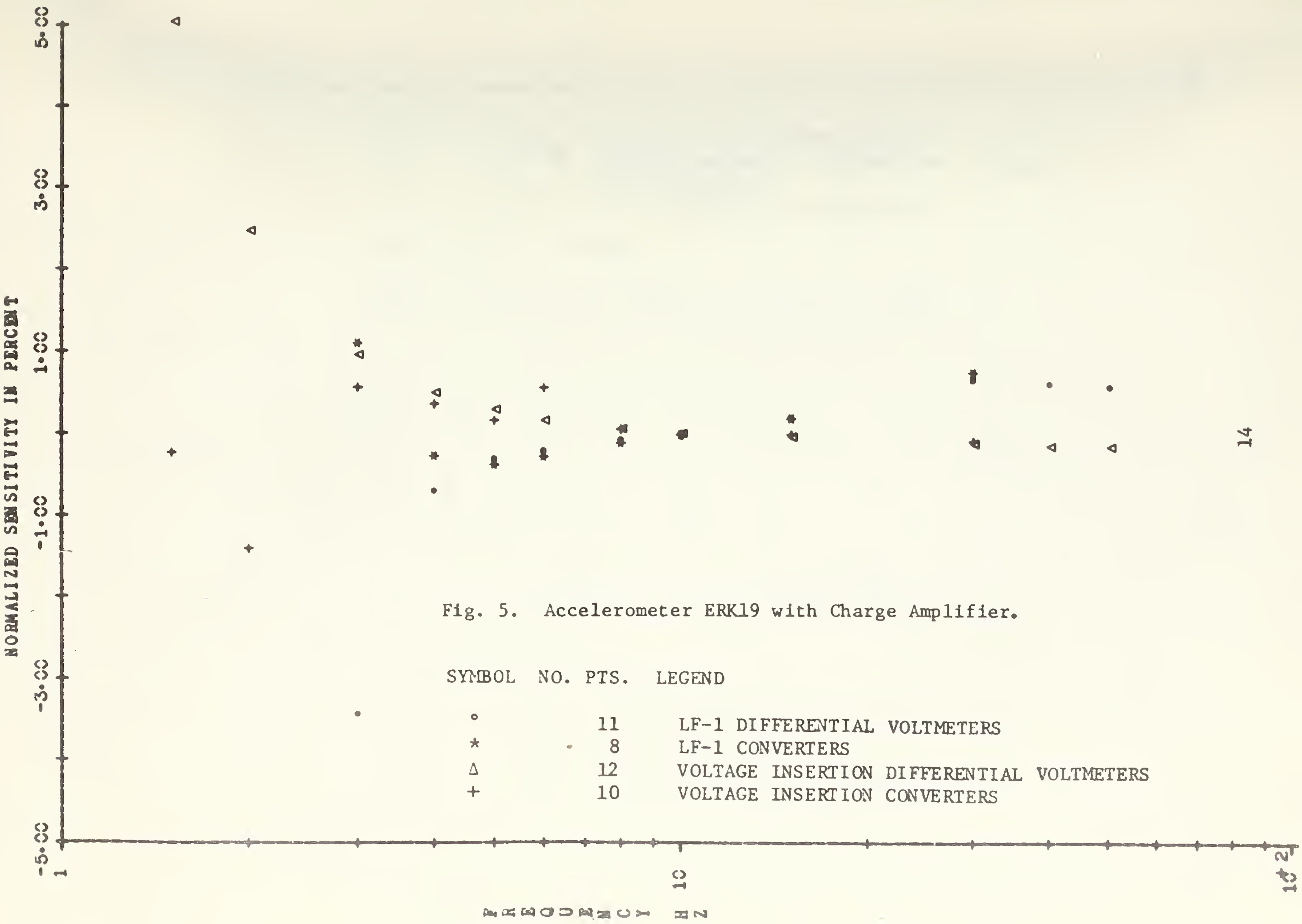


Fig. 5. Accelerometer ERK19 with Charge Amplifier.

SYMBOL	NO. PTS.	LEGEND
∘	11	LF-1 DIFFERENTIAL VOLTMETERS
*	8	LF-1 CONVERTERS
Δ	12	VOLTAGE INSERTION DIFFERENTIAL VOLTMETERS
+	10	VOLTAGE INSERTION CONVERTERS

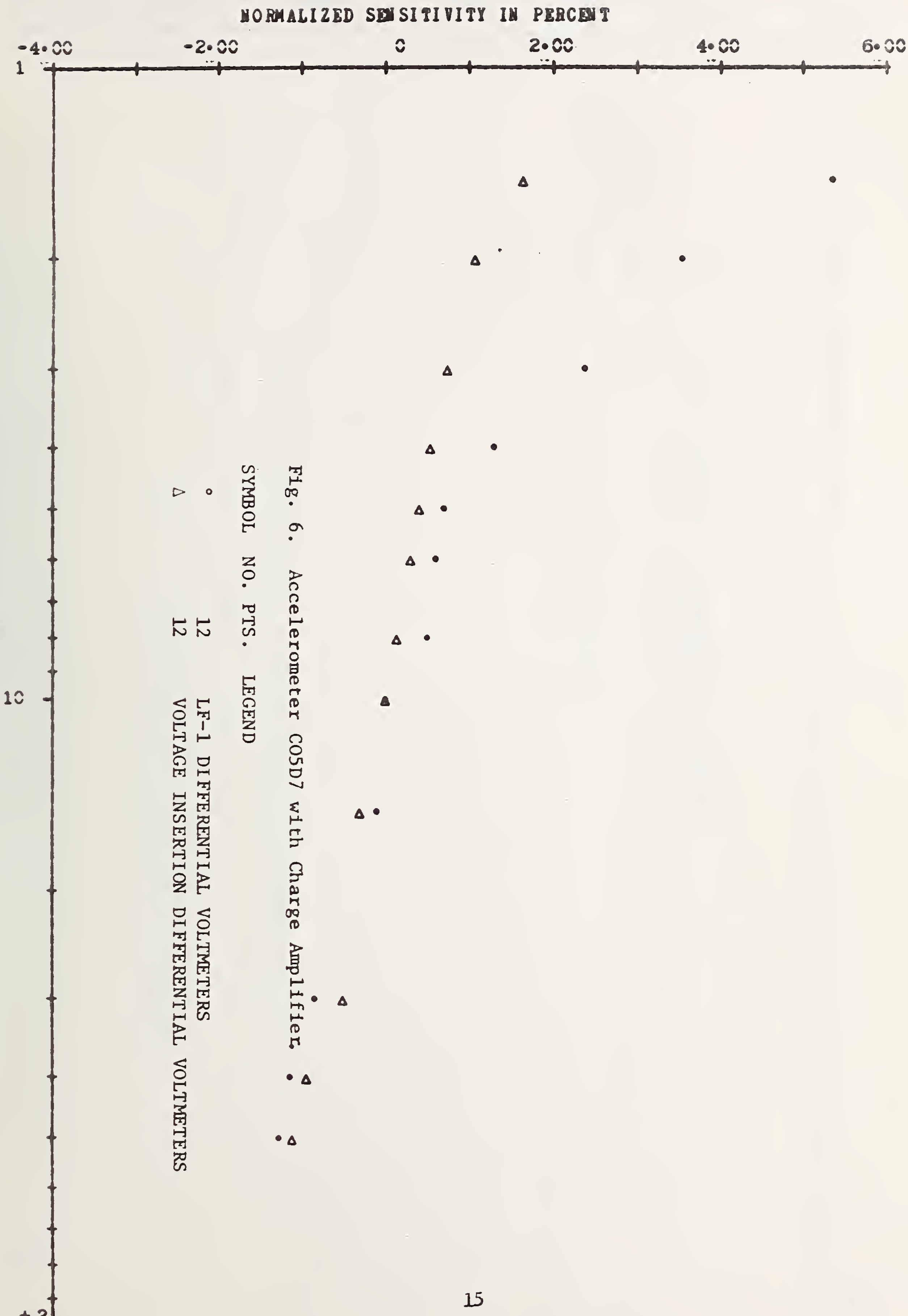


Fig. 6. Accelerometer C05D7 with Charge Amplifier.

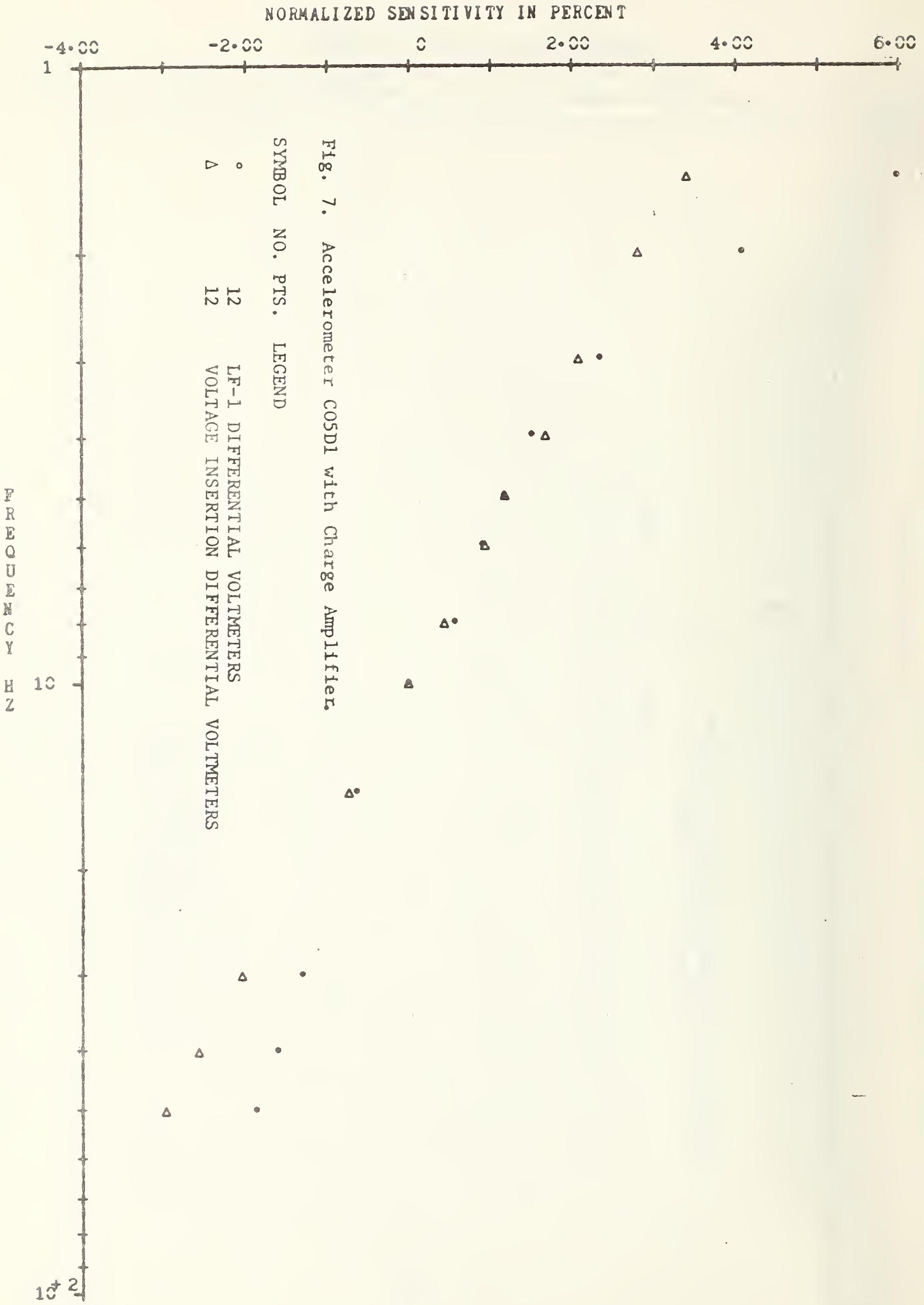


Fig. 7. Accelerometer C05D1 with Charge Amplifier

SYMBOL	NO. PTS.	LEGEND
∘	12	LF-1 DIFFERENTIAL VOLTMETERS
Δ	12	VOLTAGE INSERTION DIFFERENTIAL VOLTMETERS

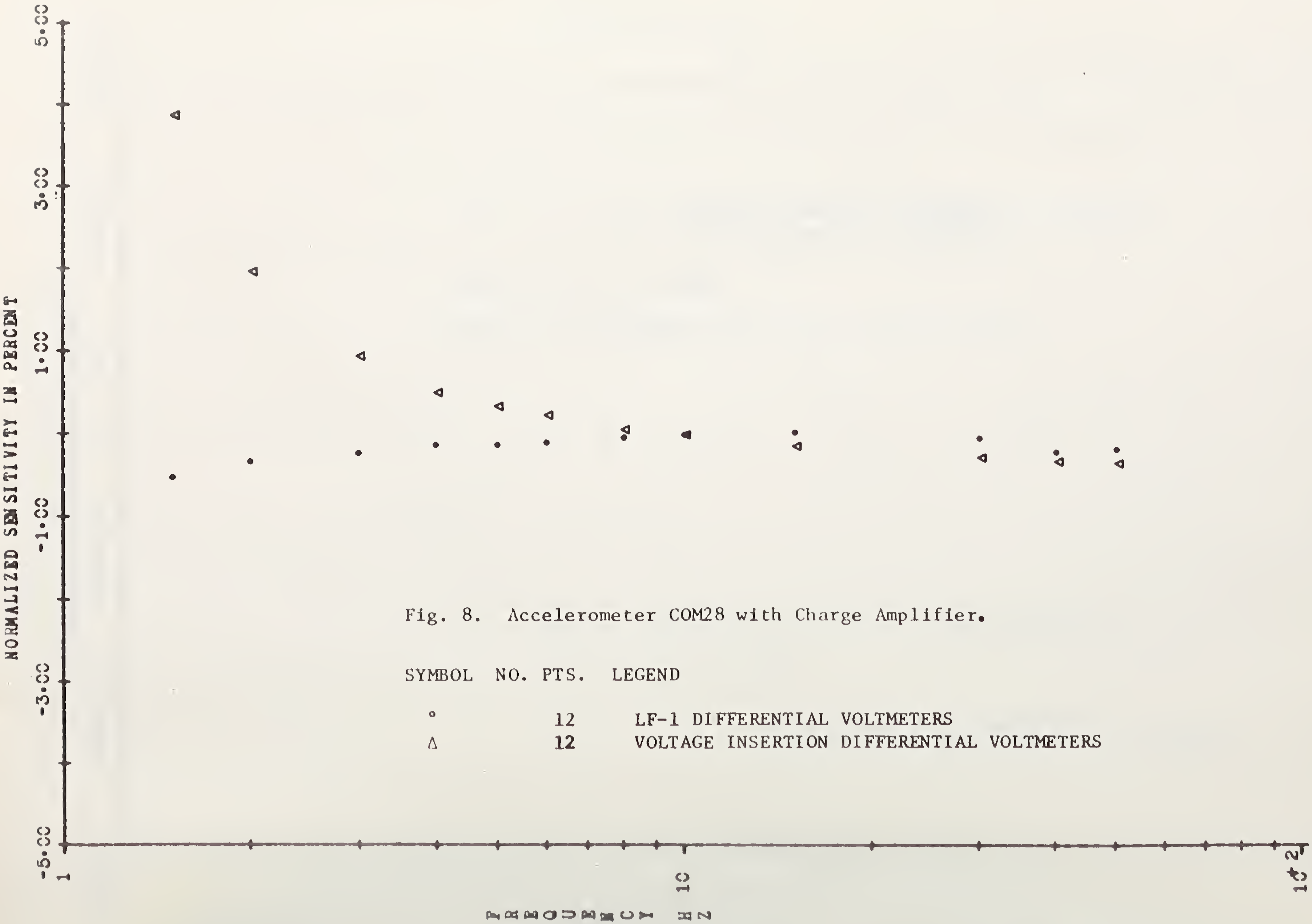


Fig. 8. Accelerometer COM28 with Charge Amplifier.

SYMBOL	NO. PTS.	LEGEND
°	12	LF-1 DIFFERENTIAL VOLTMETERS
Δ	12	VOLTAGE INSERTION DIFFERENTIAL VOLTMETERS

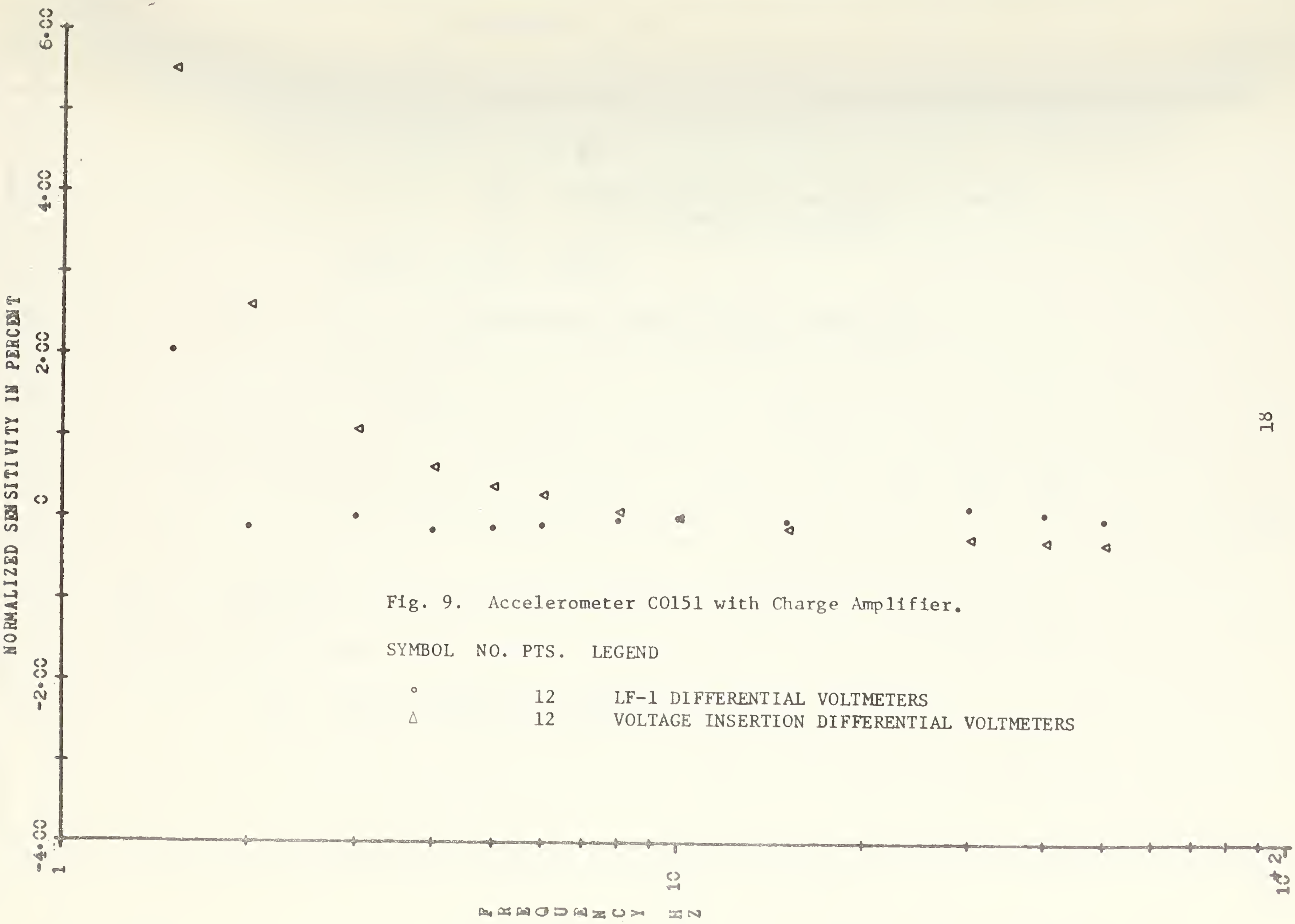


Fig. 9. Accelerometer C0151 with Charge Amplifier.

SYMBOL	NO. PTS.	LEGEND
∘	12	LF-1 DIFFERENTIAL VOLTMETERS
△	12	VOLTAGE INSERTION DIFFERENTIAL VOLTMETERS

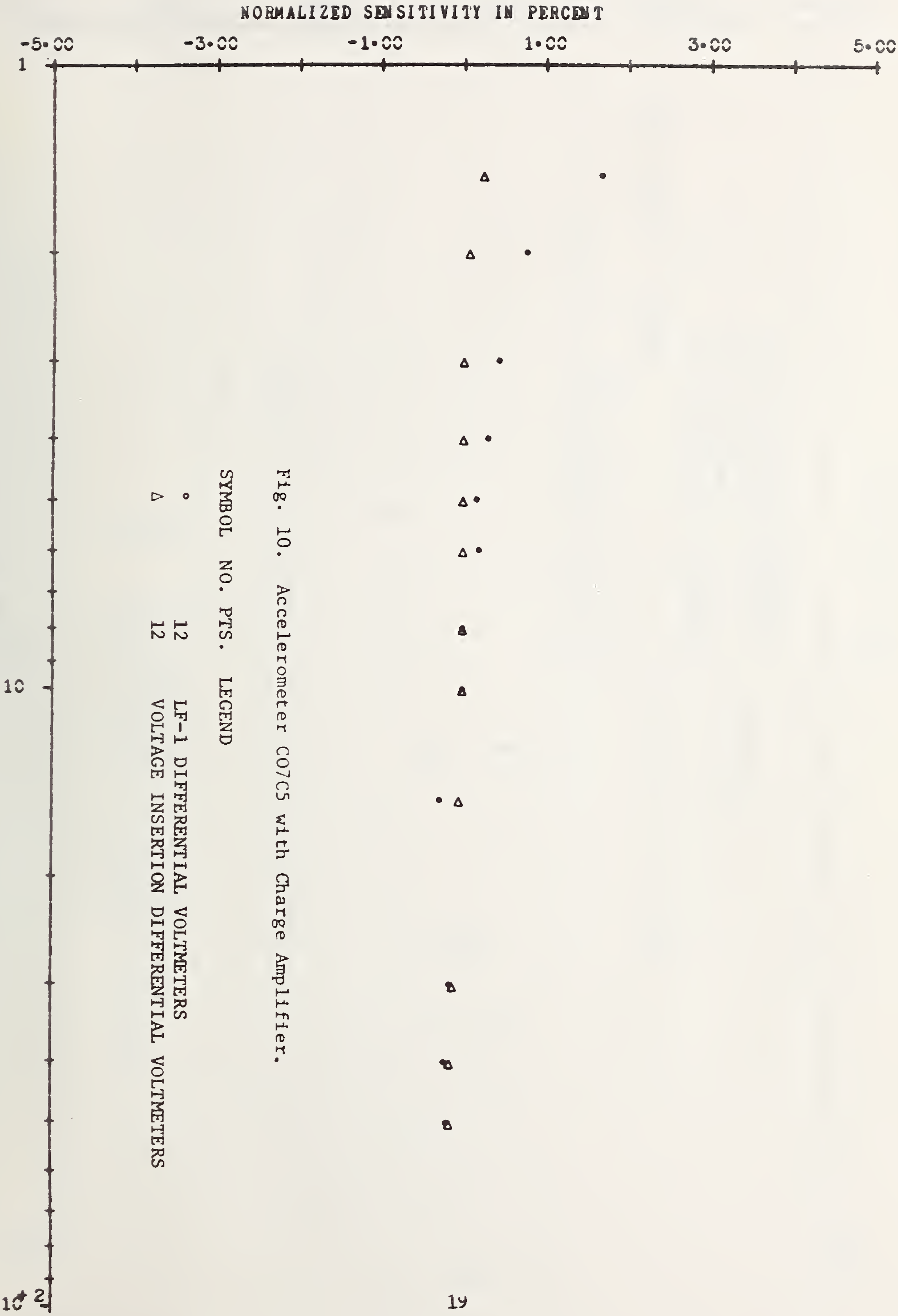


Fig. 10. Accelerometer C07C5 with Charge Amplifier.

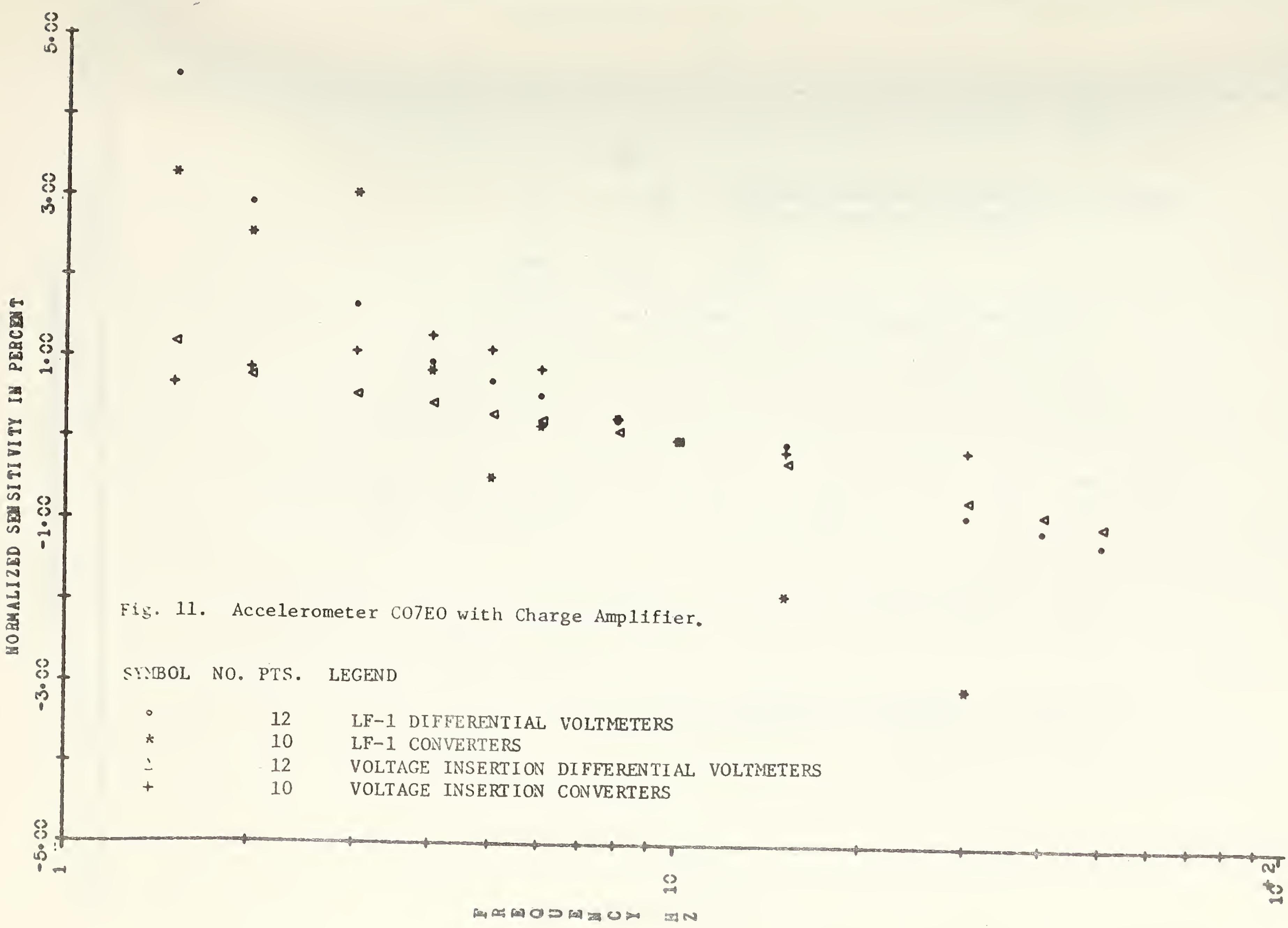


Fig. 11. Accelerometer C07E0 with Charge Amplifier.

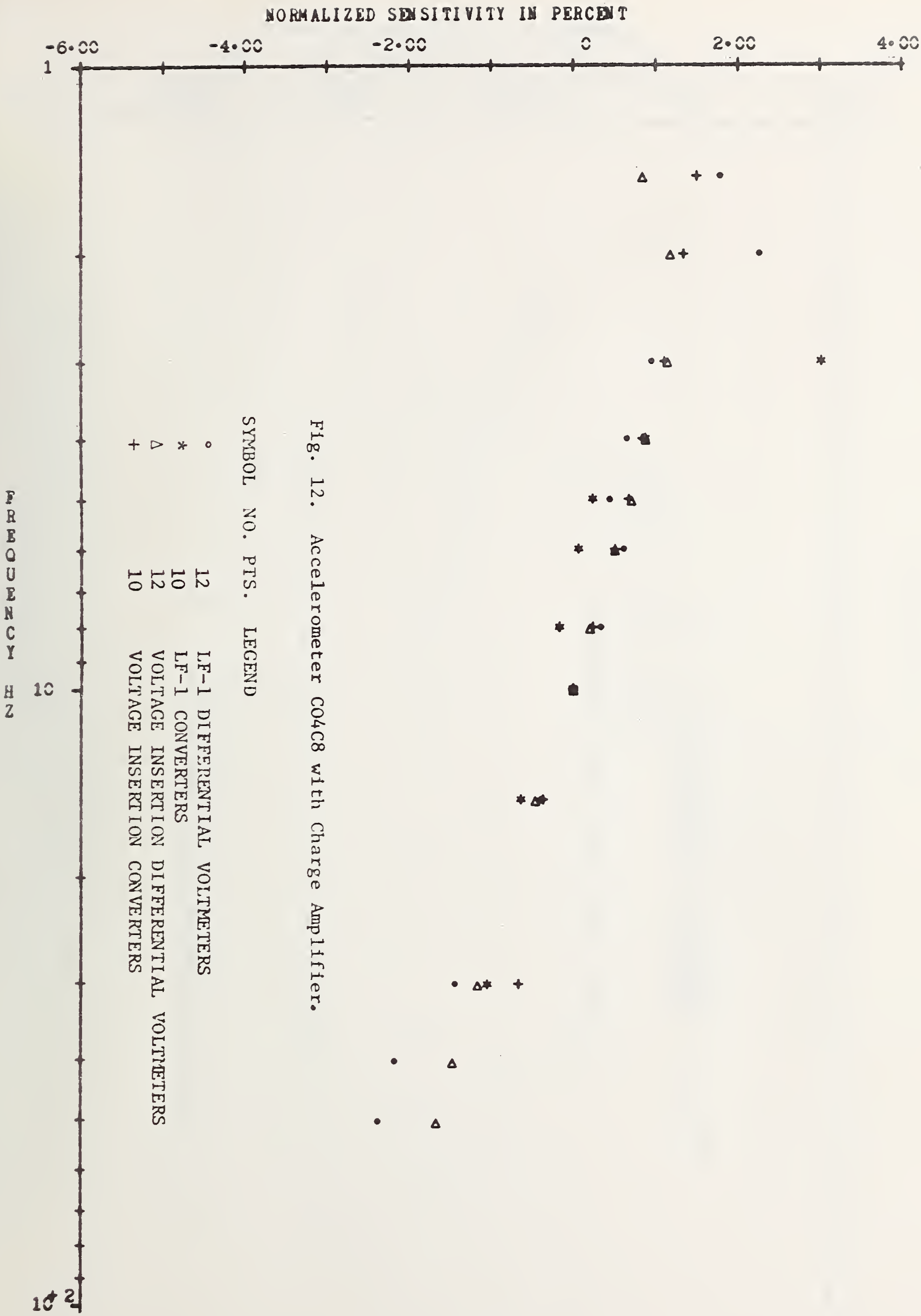


Fig. 12. Accelerometer CO4C8 with Charge Amplifier.

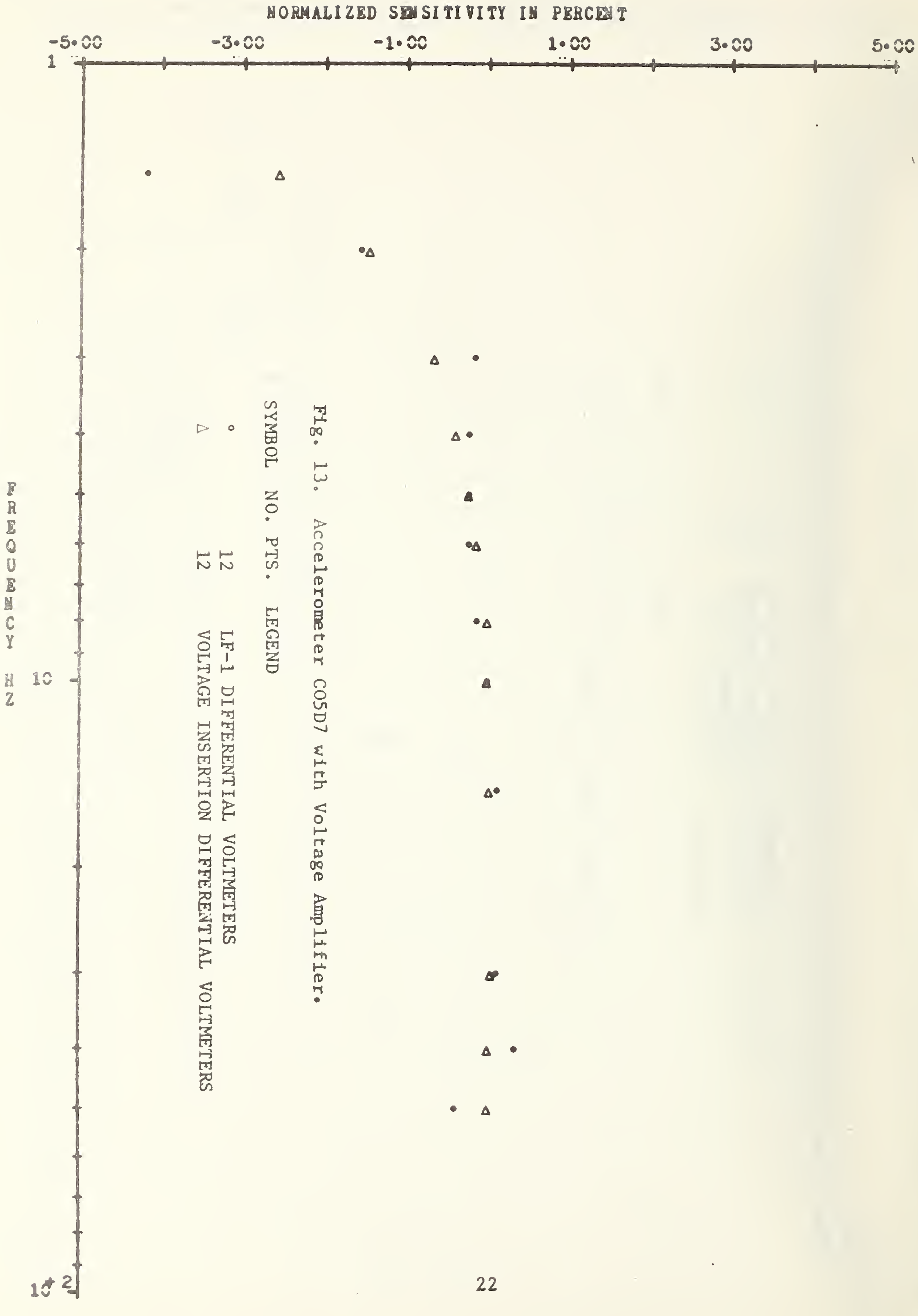


Fig. 13. Accelerometer CO5D7 with Voltage Amplifier.

SYMBOL	NO. PTS.	LEGEND
°	12	LF-1 DIFFERENTIAL VOLTMETERS
△	12	VOLTAGE INSERTION DIFFERENTIAL VOLTMETERS

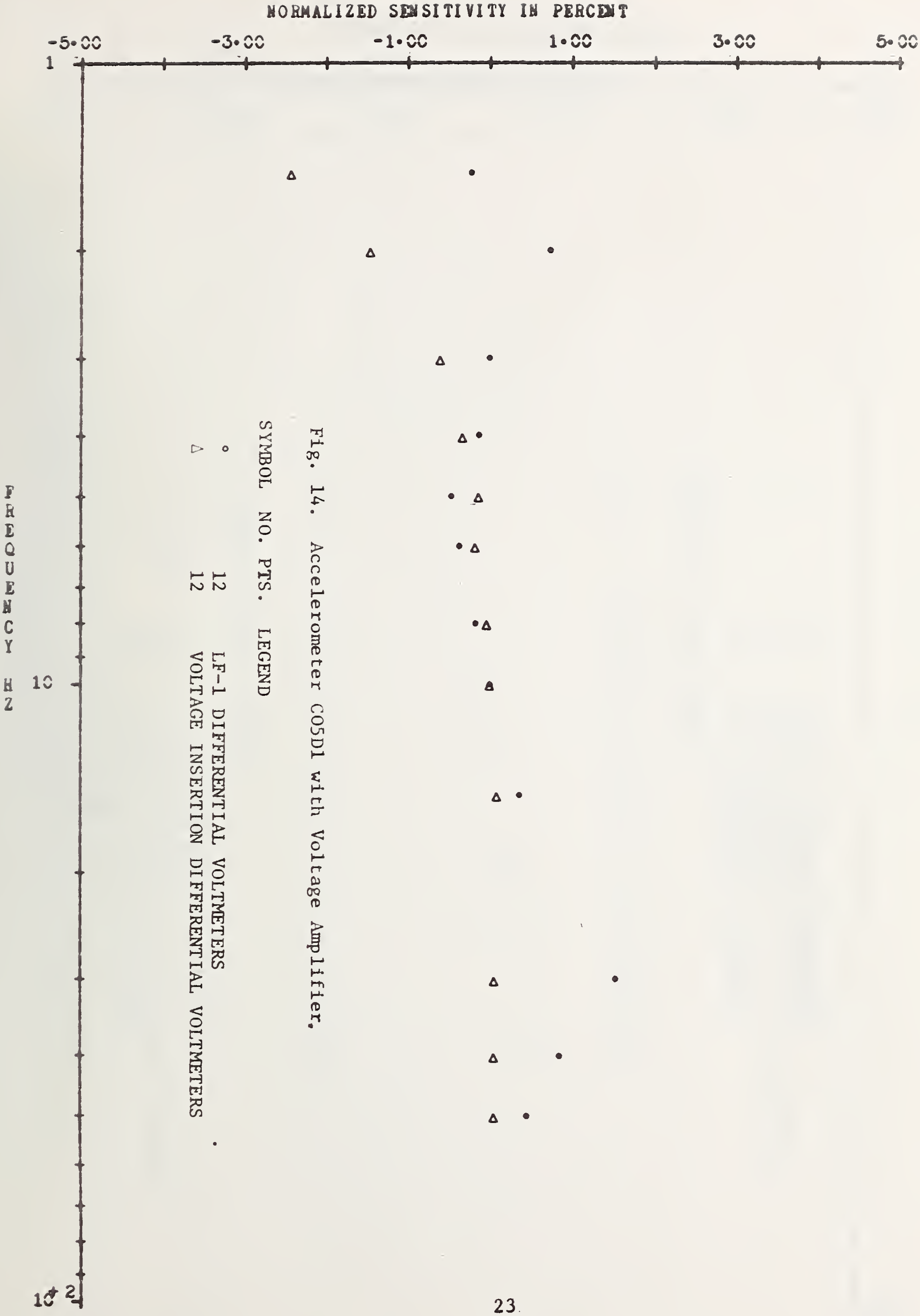


Fig. 14. Accelerometer CO5D1 with Voltage Amplifier.

SYMBOL	NO. PTS.	LEGEND
∘	12	LF-1 DIFFERENTIAL VOLTMETERS
△	12	VOLTAGE INSERTION DIFFERENTIAL VOLTMETERS

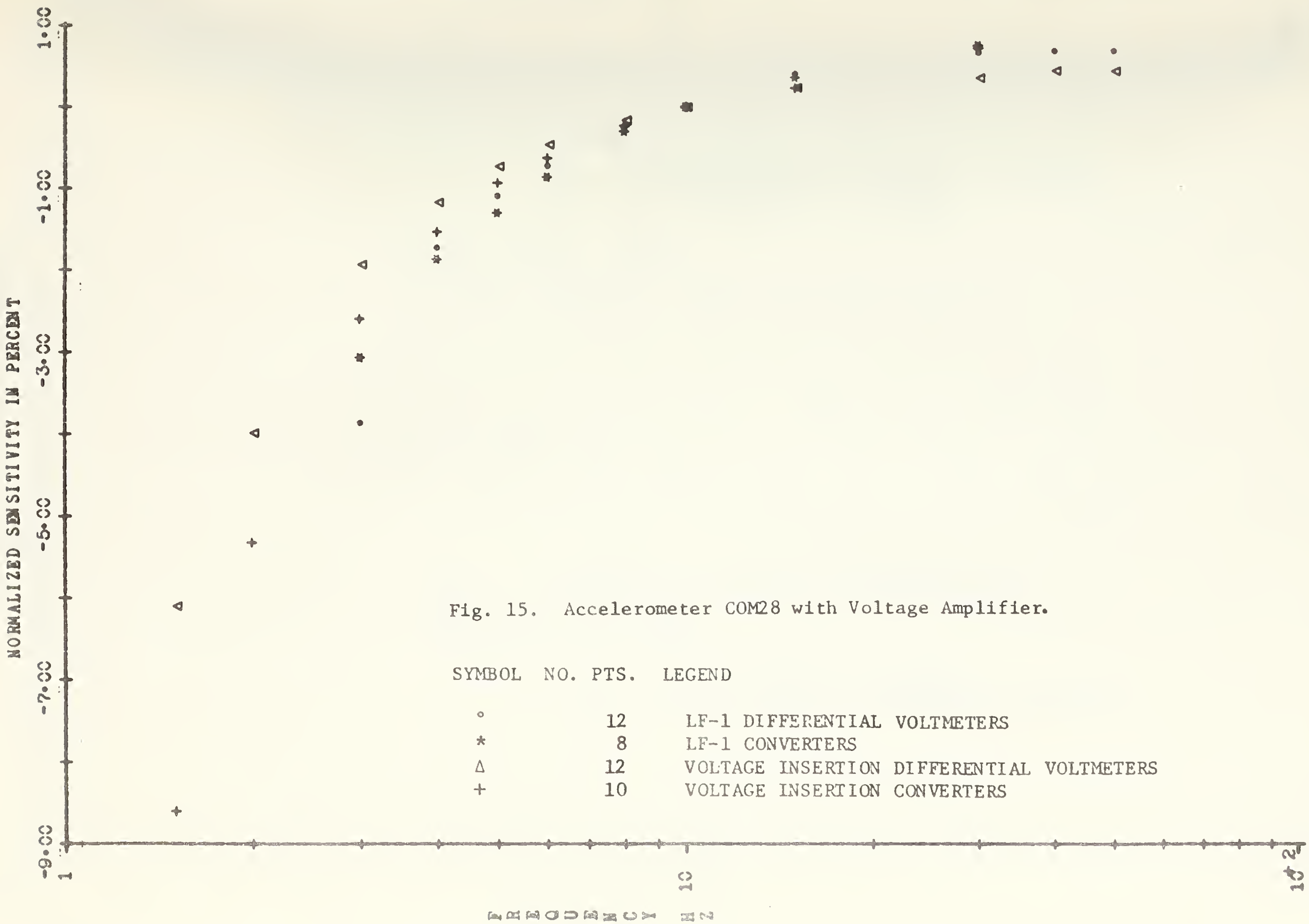


Fig. 15. Accelerometer COM28 with Voltage Amplifier.

SYMBOL	NO. PTS.	LEGEND
∘	12	LF-1 DIFFERENTIAL VOLTMETERS
*	8	LF-1 CONVERTERS
Δ	12	VOLTAGE INSERTION DIFFERENTIAL VOLTMETERS
+	10	VOLTAGE INSERTION CONVERTERS

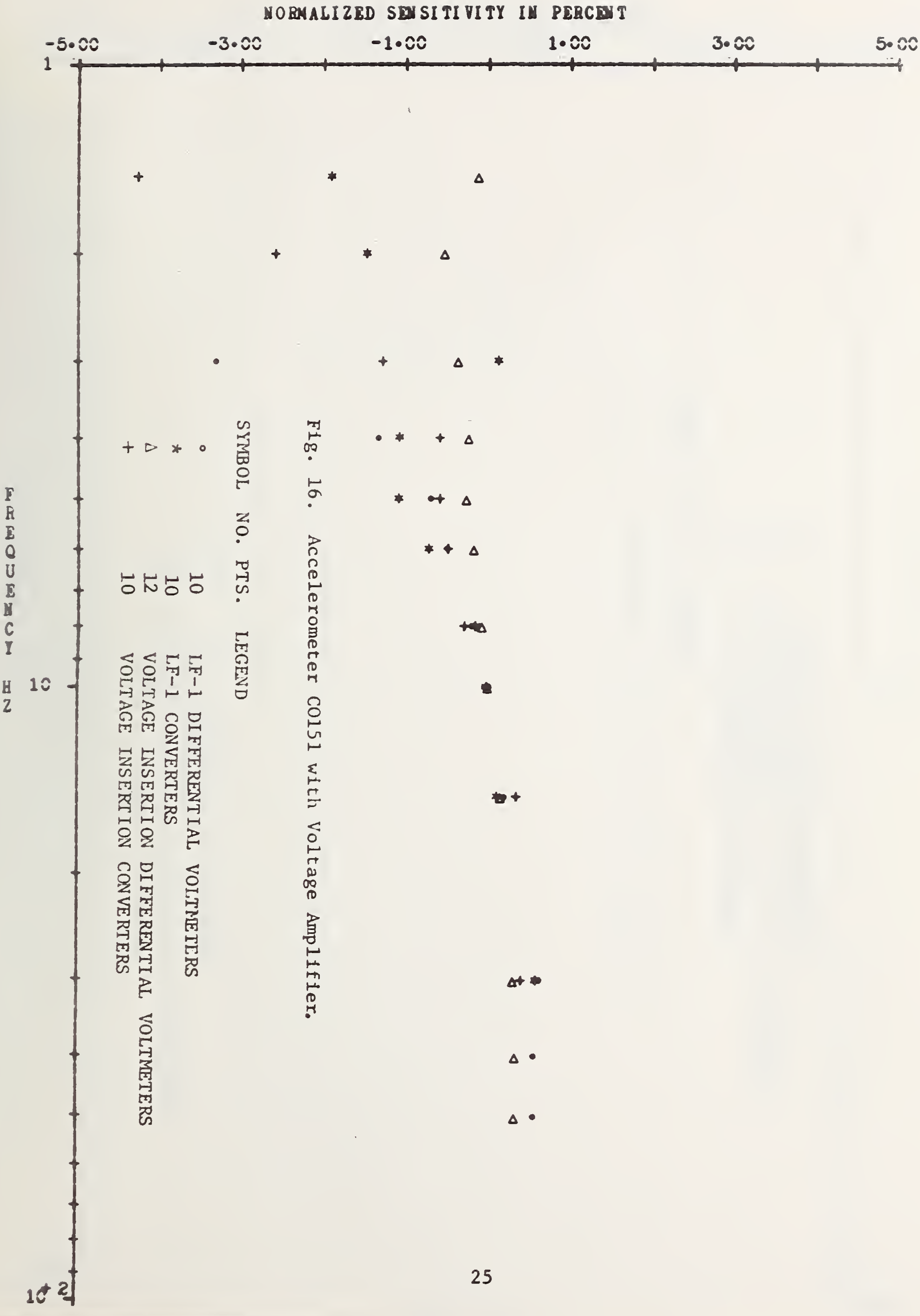


Fig. 16. Accelerometer C0151 with Voltage Amplifier.

SYMBOL	NO. PTS.	LEGEND
∘	10	LF-1 DIFFERENTIAL VOLTMETERS
*	10	LF-1 CONVERTERS
Δ	12	VOLTAGE INSERTION DIFFERENTIAL VOLTMETERS
+	10	VOLTAGE INSERTION CONVERTERS

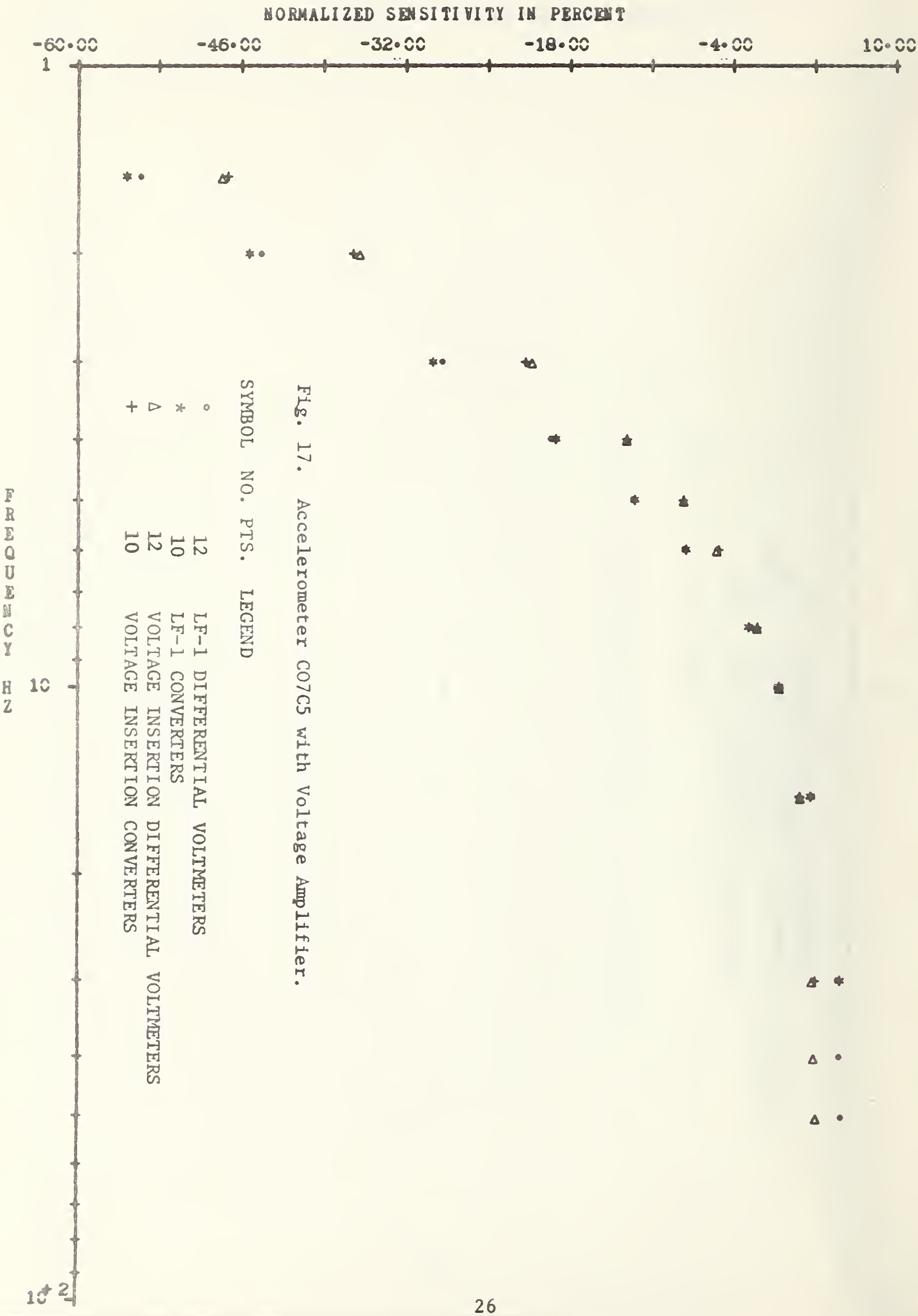


Fig. 17. Accelerometer C07C5 with Voltage Amplifier.

SYMBOL	NO. PTS.	LEGEND
∘	12	LF-1 DIFFERENTIAL VOLTMETERS
*	10	LF-1 CONVERTERS
Δ	12	VOLTAGE INSERTION DIFFERENTIAL VOLTMETERS
+	10	VOLTAGE INSERTION CONVERTERS

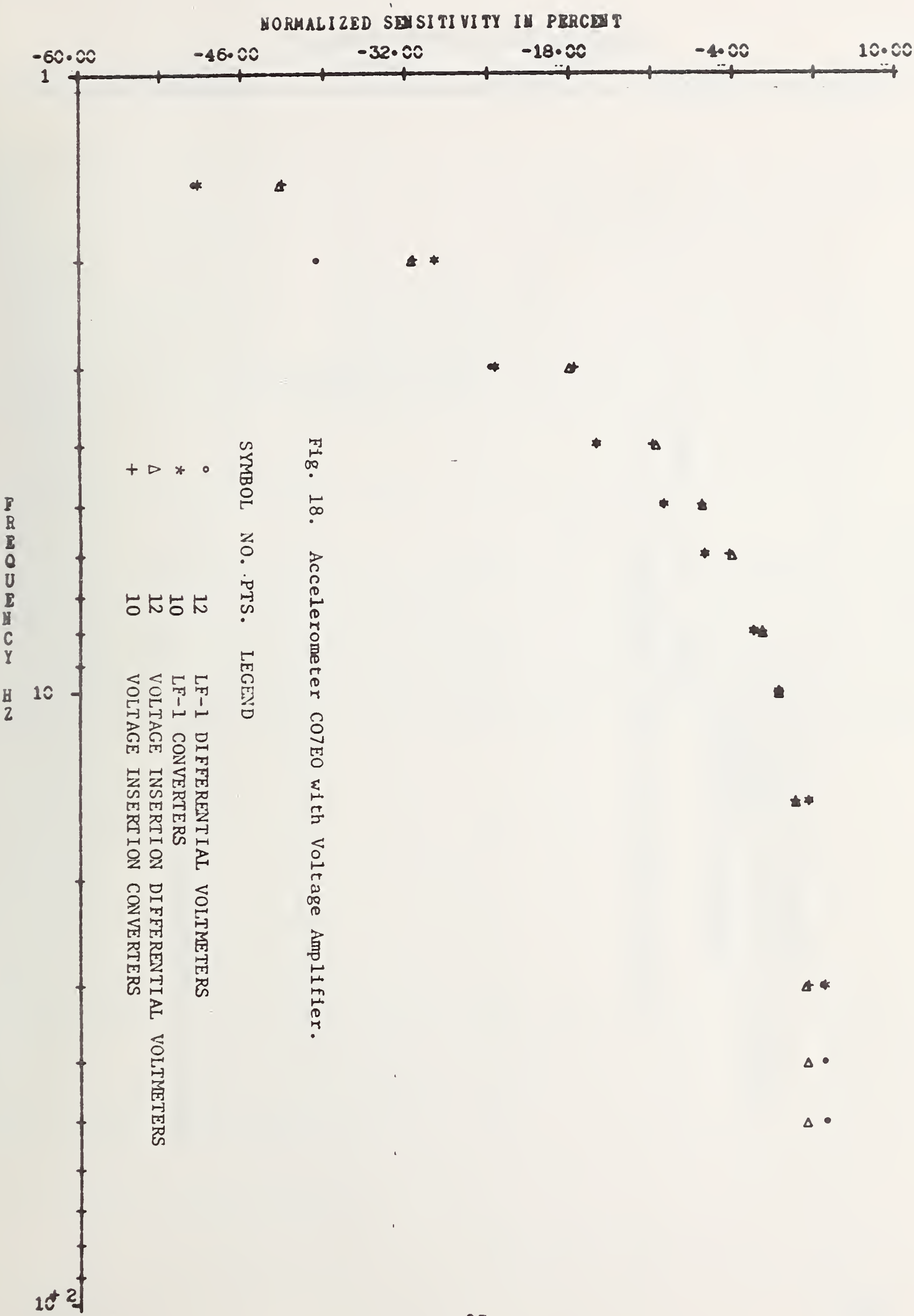


Fig. 18. Accelerometer CO7EO with Voltage Amplifier.

SYMBOL	NO. PTS.	LEGEND
o	12	LF-1 DIFFERENTIAL VOLTMETERS
*	10	LF-1 CONVERTERS
Δ	12	VOLTAGE INSERTION DIFFERENTIAL VOLTMETERS
+	10	VOLTAGE INSERTION CONVERTERS

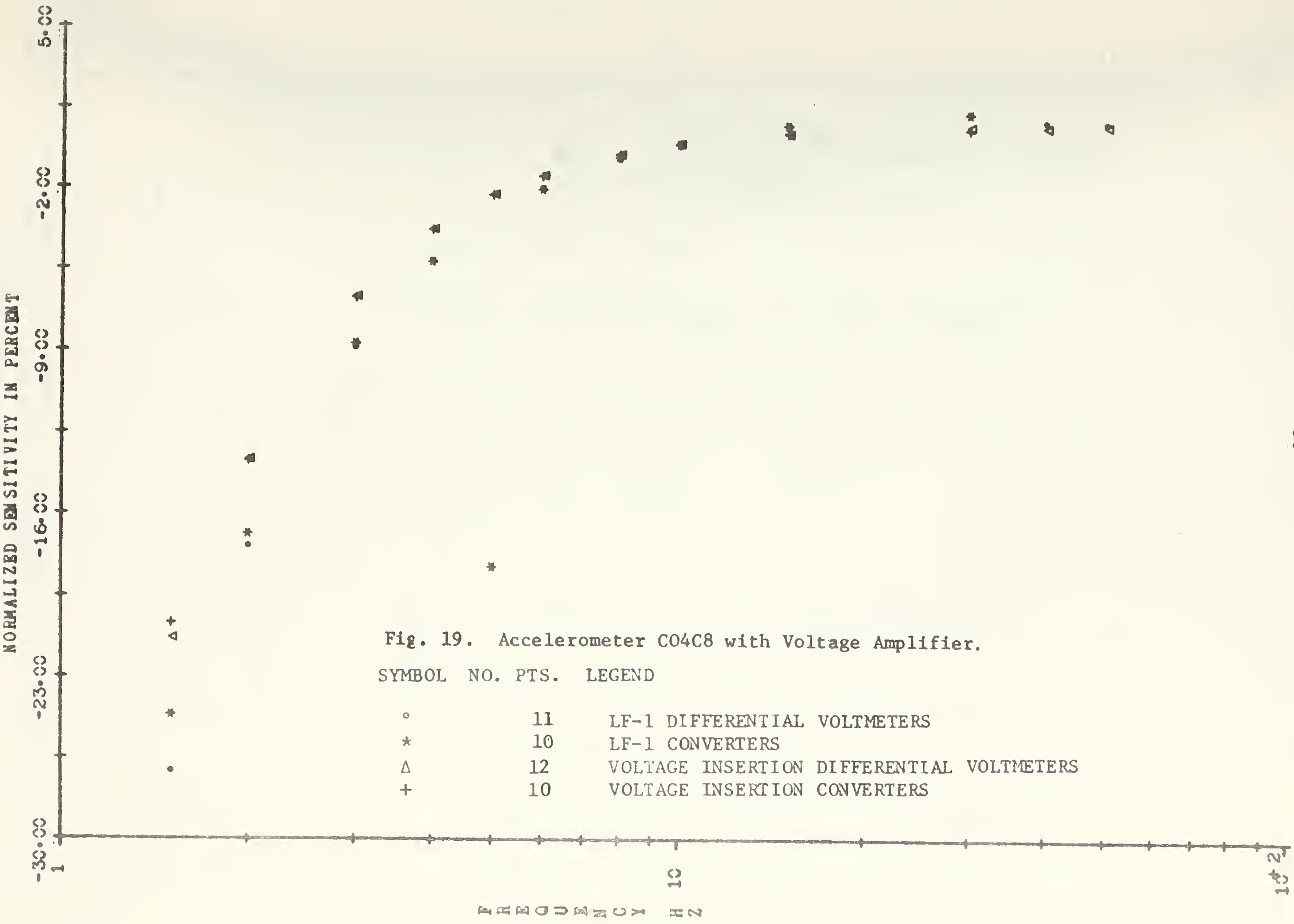


Fig. 19. Accelerometer C04C8 with Voltage Amplifier.

SYMBOL	NO. PTS.	LEGEND
∘	11	LF-1 DIFFERENTIAL VOLTMETERS
⋆	10	LF-1 CONVERTERS
Δ	12	VOLTAGE INSERTION DIFFERENTIAL VOLTMETERS
+	10	VOLTAGE INSERTION CONVERTERS

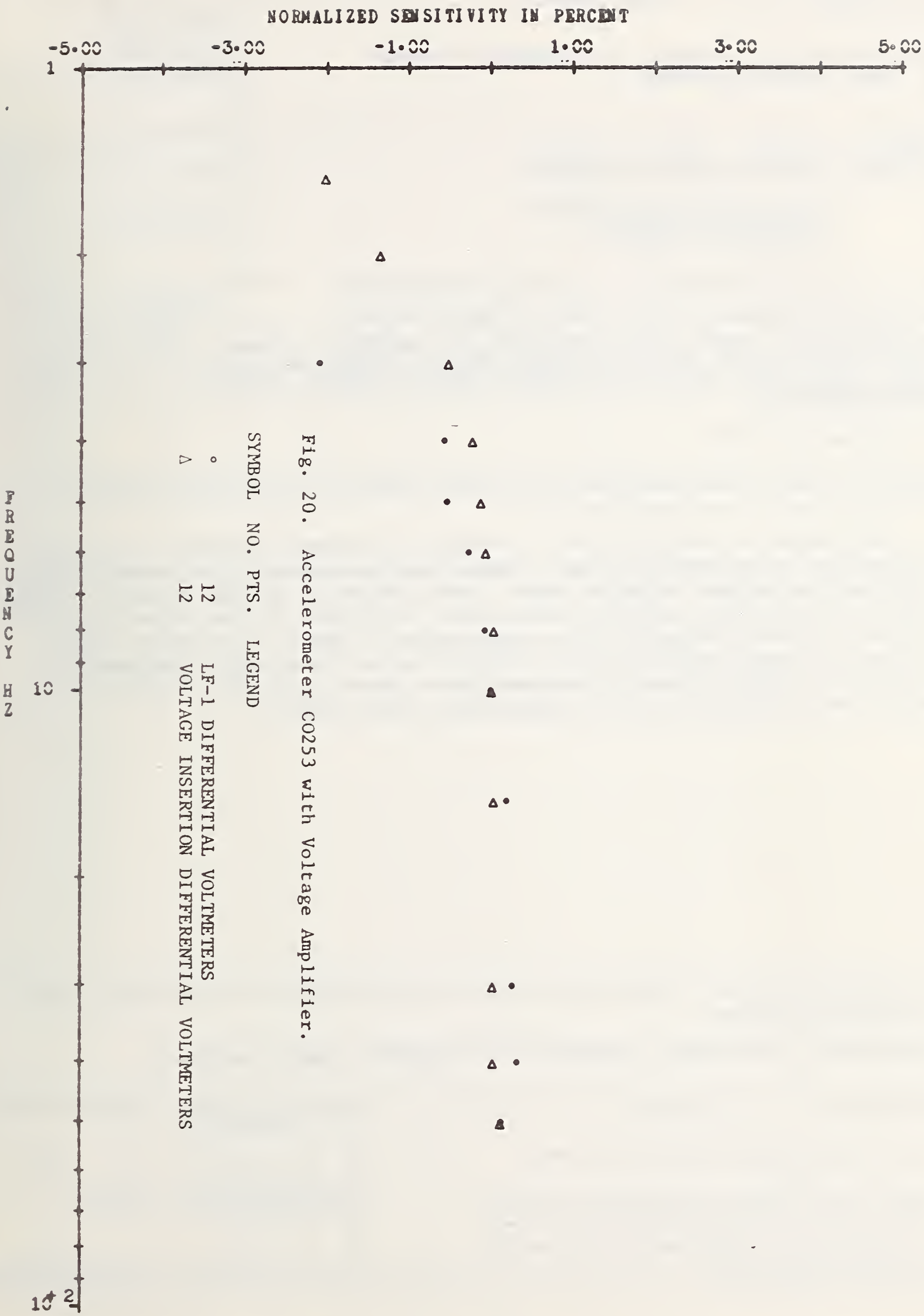


Fig. 20. Accelerometer C0253 with Voltage Amplifier.

SYMBOL	NO. PTS.	LEGEND
°	12	LF-1 DIFFERENTIAL VOLTMETERS
Δ	12	VOLTAGE INSERTION DIFFERENTIAL VOLTMETERS

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16. 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 purpose of this study was to compare the frequency response of selected piezoelectric accelerometers using a signal insertion method to the response using traditional mechanical vibration tests. Signal insertion methods included "voltage insertion" and "charge insertion" techniques. The signal is inserted in series with the electrical low-side of the accelerometer by means of a suitable series resistance. Commercially available insertion devices were used. Confidence in the use of insertion methods is increased where there is agreement between the results from insertion tests and mechanically excited tests.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Accelerometer; calibration; vibration; low frequency; signal insertion.

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