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IN-PLACE CALIBRATION OF

PIEZO-ELECTRIC CRYSTAL ACCELEROMETER AMPLIFIER SYSTEMS

(A Survey of Current Techniques and their Limitations)

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ABSTRACT

The requirement that instrumentation systems be calibrated immediately before and after use is more and more frequently encountered. The unique character of piezo-electric crystal accelerometers has produced considerable innovation in an attempt to provide in-place calibration of these devices. Several proposed techniques are discussed in some detail. In each case both the advantages and limitations of the method are considered. Further, an equation is developed for one category of techniques, based on a simple equivalent circuit, such that the utility of each technique is determined by evaluation of a single coefficient K. Examples of at least some of the currently available hardware are presented.

INTRODUCTION

The requirement that instrumentation systems can be calibrated immediately before (and after) use is commonly encountered, particulary in field testing. In those tests requiring high frequency acceleration (vibration) data, the need for dependable and accurate information normally dictates the use of piezo-electric crystal accelerometers. A few of the desirable characteristics of crystal accelerometers include a) wide, flat frequency response, b) small size and weight c) rugged, dependable construction, d) excellent linearity and e) self-generated output.

The only satisfactory method of calibration of these pickups, however, requires some type of mechanical excitation. The calibration lab usually employs a "shaker table" or vibration exciter whose force output can be accurately determined. Unfortunately, these machines are relatively large and heavy and require associated electronics. Even if a small, lightweight and self-contained shaker, suitable for field use were generally available, one major drawback still remains: the accelerometer must be calibrated while coupled to the force generator, rather than in place on the test specimen. Can such a calibration be considered still valid after removal of the accelerometer and reattachment to the specimen? If so, why not simply use the factory or calibration lab figures, which were obtained under much more desirable circumstances?

The problem, then, is this: to devise a method of in-place calibration of the accelerometer-amplifier system, preferably, as in missile test, just prior to launch (and possibly also during flight).

Several approaches have been considered, and can be grouped into three general categories: a) A means of providing an actual mechanical excitation to the transducer while in place, which would constitute a true calibration. b) Measurement of some passive electrical parameter of the accelerometer from which its condition can be inferred and which would provide, rather than calibration, go-no go information. c) Insertion into the system of an electrical signal which simulates a mechanical excitation and thus provides a calibration by simulation.

Let's, for a moment, take a more detailed look at a typical vibration instrument channel. See Figure 1. In normal operation this system provides, at the amplifier input, a voltage corresponding to the actual vibratory motion of the accelerometer. The amplitude of this signal is a function not only of the actual vibration amplitude, but also of the length of cable between transducer and amplifier *, as well as the basic accelerometer sensitivity. Signal waveform is controlled by the frequency response of the input circuitry. High frequency response is usually well above the limitation imposed by readout equipment, and can be disregarded as a limiting factor. Low frequency response is a function of the input circuit RC time constant *, where R is the amplifier input impedance and C is the sum of transducer capacitance and distributed cable capacitance. See Figure **2.** (It is also important that the accelerometer employed have a first resonance at least five times higher than the highest frequency to be measured. Otherwise signal waveform distortion due to spurious ringing is likely.)

IN PLACE MECHANICAL EXCITATION

Of the three alternatives mentioned above, true calibration would, of course, be the most desirable. The most feasible device so far proposed to achieve mechanical excitation of the in-place accelerometer is shown in Figure 3. To the basic accelerometer a) is added a second piezo-electric device b) which, when driven electrically, vibrates the accelerometer section. Thus, in theory, a precisely controlled signal fed to the calibrating section would produce a known acceleration at the transducer, which, in turn, would generate a signal allowing precise calibration of the entire vibration channel. Proposals of this general nature, however, fail to consider two major points: 1) impedance effects, and 2) calibrator reliability.

Successful prosecution of this technique is limited to these cases in which the mechanical impedance of the structure to which the transducer is affixed is much greater than the transducer impedance. Otherwise some portion of the energy generated in the calibrator will be dissipated in driving the structure itself and will produce faulty calibration figures. This effect is most serious, of course, with a resonant structure.

Let us examine, however, an even more powerful argument. The purpose of this device is to verify

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* Note: The conditions involving dependence on length of input cable and maintenance of high amplifier input impedance, do not apply when the system utilizes a charge amplifier. See below.

the crystal transducer calibration by provision of a reliable force input. Yet the force generator is itself a second crystal transducer with, at best, no greater reliability than the accelerometer in question. Thus, if a calibration input fails to produce the predetermined accelerometer signal, one can only decide with certainty that either the accelerometer has changed or the calibrator has changed (or perhaps both !), and must conclude that this is insufficient data upon which to establish new calibration points. Worse still, a failure of only the calibrator could lead to rejection of perfectly valid vibration data or, possibly, to an abort.

It appears, then, that such a device would yield neither calibration nor go-no go information, and could even be detrimental in adding another indeterminate source of failure.

MEASUREMENT OF PASSIVE CHARACTERISTICS

In order to design a satisfactory system of accelerometer checkout based on measurement of passive characteristics, we must answer the following questions:

1) What are the passive electrical characteristics of the pickup?

2) How can they best be measured?

3) What limitation can be imposed to establish the go-no go criterion?

Although the actual equivalent circuit of the piezo-electric crystal accelerometer is somewhat more complex, it is sufficient to consider the passive element as a capacitor of capacitance C_p whose dielectric possesses a leakage resistance R_p. See Figure 4. Measurement of this capacitance and resistance presents the surest known check of accelerometer condition, short of actual mechanical calibration techniques. Both parameters are measurable with the standard bridge, which is not only commercially available, but easily calibrated, as well as familiar to technician personnel.

Capacitance is easily measured with the normal bridge frequency of 1 KC. Leakage resistance is specified for an applied voltage of 100 Vdc. Insertion of a simple switching arrangement ahead of the amplifier would permit rapid sequential measurement of the two parameters over a series of pickups. See Figure 5.

Since both C_p and R_p may vary over a considerable range in any given group of pickups without any detrimental effect, setting a required value on these parameters would also require inclusion of a rather large tolerance range (as high as ± 30% in some cases). Where this is philosophically unsatisfactory, it is useful to set allowable minimums, below which the pickup is considered in the no-go state. For example, for the Endevco Model 2215 Accelerometer:

$$C_p \text{ (min)} = 6{,}000 \ \mu\mu\text{fd}$$
$$R_p \text{ (min)} = 1{,}000 \text{ megohm}$$

In actual practice, the following considerations must be applied:

1) The true capacitance, measured in the scheme of Figure 5 is $C = C_p + C_t$ where C_t, the cable capacitance, = (number feet of cable x 30) μμfd.

2) The true resistance measured will include any leakage paths due to contamination of cable connectors, etc. Since high R_p is needed only to maintain system low frequency response, the desired frequency spectrum should set the final allowable minimum leakage resistance. It should be reiterated that this method, while indicating transducer condition, does not provide a calibration. Neither does it permit a check of the remainder of the system, since the channel is broken ahead of the amplifier.

One adaptation of this measurement technique is used to ascertain accelerometer condition following installation on a solid propellant type rocket engine, but before connection into the amplifier and subsequent electronics. In order to eliminate the effect of cable capacitance which, for very long cable, could mask the true condition of the transducer, the scheme in Figure 6 is employed. A 500 cps square wave is introduced along line (a). The effect of the network composed of C_p, R, and the two diodes is to produce a (rectified) dc voltage at line (b), the amplitude of which is a measure of the value of C_p. (For preset value of R). There is, of course, no loss of DC due to capacitive effects over even a very long cable, thus permitting use of this method when calibration equipment is physically distant from the transducer under test.

Such a system is, as can be seen, not suitable for "count-down" type checkouts, being limited to early test and calibration phases.

CALIBRATION BY SIMULATION - VOLTAGE AMPLIFIERS

The simplest simulation method is illustrated in Figure 7. A known electrical signal, previously determined to correspond to a given acceleration at the transducer, is inserted at the amplifier input. This permits setting of gain levels throughout the system to produce the desired end output for a given mechanical input, as well as providing a continuity check from the amplifier on. The major drawback, of course, is that the elements ahead of the amplifier are not qualified. In order to include both accelerometer and connecting cable in the test, the method of Figure 8 is evolved. In this method, the ground side of the interconnecting cable is opened and the calibrating signal is applied across a series resistor. The signal travels down the ground line, through the pickup, acting here only as a coupling capacitor, and then back to the amplifier input. (Ground loops are prevented by use of an isolation mounting stud.) The simplified circuit of Figure 9 will permit examination of the salient features of this method. If C_p, the accelerometer internal capacity, is replaced by its effective reactive impedance (at the frequency of the calibrating signal) as in Figure 9 (b) and the circuit then redrawn as in (c), the value of this technique can be quickly determined. Application of Ohm's law yields:

$$\frac{E_{in}}{Z_p + Z_i} = \frac{E_{out}}{Z_i} \qquad \text{eq. 1}$$

$$E_{out} = E_{in} \frac{Z_i}{Z_p + Z_i} \qquad \text{eq. 2}$$

$$E_{out} = KE_{in} \quad \text{where} \qquad \text{eq. 3}$$

$$\boxed{K = \frac{Z_i}{Z_p + Z_i}} \qquad \text{eq. 4}$$

From eq. 3, we see that for a given calibration signal, E_{in}, the voltage developed at the amplifier input (E_{out}) is a function of K. If the system is in normal operating condition, the impedance of the accelerometer will be simply its capacitive reactance at the frequency (f) of the calibrating signal:

$$Z_p = X_c = \frac{1}{2\pi fC_p} \qquad \text{eq. 5}$$

which has some finite value. From eq. 4, as long as Z_p is finite, K is finite and lies between 0 and 1. In consequence, the voltage developed at the amplifier input will have some value less than E_{in}. If the transducer should become open, Z_p will become infinite and K will become zero. Thus E_{out} will also be zero; i.e., no signal reaches the amplifier if the circuit is opened. If, alternatively, the pickup should short, (or develop a low resistance path), Z_p would approach zero, causing K to approach unity, and the resultant output voltage to become essentially the same as the input voltage.

The three conditions above, plus their predicted consequences, can be tabulated as in Table 1.

CONDITION	PICKUP	Z_p	K	E_{out}	INDICATES
I	O K	$\frac{1}{2\pi fC_p}$	$0<K<1$	$0<E<E_{in}$	GO
II	OPEN	∞	0	0	NO - GO
III	SHORT	0	1	E_{in}	NO - GO

Table 1. Summary of expected indications in Calibration by Simulation using voltage amplifier.

Now let us assume typical values of the circuit parameters as might be found in the system of Figure 9 when operating normally (Condition I).

Let: $C_p = 500\ \mu\mu f$

$Z_i = 1000$ Megohm

$f = 1000$ cps

Then: $C_p = 5 \times 10^{-10}$

$Z_i = 10^9$

$f = 10^3$

And: $$K = \frac{Z_i}{Z_p + Z_i}$$

$$K = \frac{10^9}{10^9 + 2.9 \times 10^5}$$

$$K = \frac{100000}{100029}$$

$$\boxed{K = .9997}$$

Thus E_{out} (at the amplifier input) for the normal operating condition varies from that of the shorted condition (III) by only .03%. It would be rather difficult to attempt to resolve this small a difference in any practicable system. (Condition II, of course, is easily resolved since K = 0.)

As indicated by the foregoing calculations, better resolution requires smaller values of K (when in condition I).

From eq. 4:

$$K = \frac{Z_i}{Z_p + Z_i} \qquad \text{eq. 4}$$

or

$$\boxed{K = \frac{Z_i}{\frac{1}{2\pi f C_p} + Z_i}} \qquad \text{eq. 6}$$

Examination of eqs. 4 and 6 shows that smaller values of K can be obtained in three ways:

1) Decreasing the calibration frequency f

2) Decreasing the accelerometer capacity C_p

3) Decreasing the amplifier input impedance Z_i

However, consideration of the relative values involved shows that in order to make a significant difference, f would have to be reduced to a fraction of a cps – far below the low frequency limit of the a.c. amplifier. Also, accelerometer capacity must be kept as high as possible in order to reduce signal loss due to cable shunt capacitance. And finally, if the amplifier input impedance is reduced, system low frequency response is drastically curtailed. Thus better resolution between the operational and non-operational conditions appears to be blocked by several substantial problem areas. Before drawing conclusions, however, it should be recognized that the foregoing discussion has ignored the effect of significant lengths of interconnecting cable, and some examination of the nature and extent of such effects should be made.

Let us again consider the basic circuit in simplified form, but now with a finite length of cable between accelerometer and amplifier. If the ground side of the cable is opened at the amplifier and the calibration resistor inserted, the equivalent circuit is as shown in Figure 10. Since the cable possesses a significant distributed capacity, C_t, the definition of K is modified to:

$$K' = \frac{Z_i}{\frac{Z_p \; Z_t}{Z_p + Z_t} + Z_i} \qquad \text{eq. 7}$$

With this definition, let us re-examine the three possible conditions previously discussed, plus two new conditions: open and shorted cable. In tabular form:

CONDITION	PICKUP	CABLE	Z_p	Z_t	K'	E_{out}	INDICATES
I	OK	OK	$\frac{1}{2\pi f C_p}$	$\frac{1}{2\pi f C_t}$	$0 < K' < 1$	$0 < E_{out} < E_{in}$	GO
II	OPEN	OK	∞	$\frac{1}{2\pi f C_t}$	$\frac{Z_i}{Z_i + Z_t} \triangleq 1$	$\triangleq E_{in}$	NO GO
III	SHORT	OK	0	$\frac{1}{2\pi f C_t}$	$Z_i / Z_i = 1$	E_{in}	NO GO
IV	OK	OPEN				0	NO GO
V	OK	SHORT	$\frac{1}{2\pi f C_p}$	0	$Z_i / Z_i = 1$	E_{in}	NO GO

Table 2. Summary of expected indications in Calibration by Simulation using voltage amplifier - input at amplifier end.

As before, the usefulness of this system depends on the value of K' being significantly different from zero and from unity.

Assuming typical circuit values:

Let:

C_p = 500 uuf

Z_i = 1000 Megohm

f = 1000 cps

C_t = 300 uuf (10 foot length)

Then:

$C_p = 5 \times 10^{-10}$

$Z_i = 10^9$

$f = 10^3$

$C_t = 3 \times 10^{-10}$

And:

$$K' = \frac{Z_i}{\frac{Z_p \; Z_t}{Z_p + Z_t} + Z_i}$$

$$K' = \frac{Z_i}{Z_a + Z_i} \qquad \text{Where} \quad Z_a = \frac{Z_p\ Z_t}{Z_p + Z_t}$$

$$K' = \frac{10^9}{2 \times 10^5 + 10^9}$$

$$K' = \frac{10000}{10002}$$

$$\boxed{K' = .9998}$$

Thus, the difference in E_{out} between the GO conditionand 3 of the NO GO conditions is extremely small, of the order of .02%, and could easily be masked by other circuit variations. One NO GO condition is indicated; that of open cable. The condition of the accelerometer itself is not verified. A second possibility consists in opening the circuit at the transducer and inserting the simulation voltage at that point, as shown in Figure 12. Again we must re-define K:

$$\boxed{K'' = \frac{\dfrac{Z_t\ Z_i}{Z_t + Z_i}}{Z_p + \dfrac{Z_t\ Z_i}{Z_t + Z_i}}} \qquad \text{eq. 8}$$

As before, the expected indications are listed in tabular form.

CONDITION	PICKUP	CABLE	Z_p	Z_t	K"	E_{out}	INDICATES
I	OK	OK	$\frac{1}{2\pi fC_p}$	$\frac{1}{2\pi fC_t}$	$0 < K'' < 1$	$0 < E_{out} < E_{in}$	GO
II	OPEN	OK	∞	"	0	0	NO GO
III	SHORT	OK	0	"	1	E_{in}	NO GO
IV	OK	OPEN *				0	NO GO
V	OK	SHORT	$\frac{1}{2\pi fC_p}$	0	0	0	NO GO

Table 3. Summary of expected indications in Calibration by Simulation using voltage amplifier - input at transducer end.

Typical circuit values and normal operation yield (Condition I),

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* Inner conductor only

$$K'' = \frac{Z_a}{Z_p + Z_a} \qquad \text{Where } Z_a = \frac{Z_r \; Z_i}{Z_t + Z_i}$$

$$K'' = \frac{\frac{10^9}{1881}}{\frac{10^6}{3.14} + \frac{10^9}{1881}}$$

$$K'' \simeq 5/8$$

$$\boxed{K'' \simeq .625}$$

And for this value of K, each of the NO GO conditions is easily resolved from the normal GO condition. In effect, insertion of the simulation signal at the transducer accomplishes the desired result of reducing the value of K to a significant degree.

In the case of large rocket engines or vehicles, signal insertion at the pickup normally requires that a second cable of considerable length be extended to the area of the accelerometer, usually paralleling the signal cable. Simplicity of hardware and wiring suggests that the calibration cable also terminate at the amplifier. The calibration signal source can be either at the amplifier location (or even incorporated into the amplifier itself) or at some distant and more favorable location. In the latter case, the calibration signal circuitry can enter the main harness at the amplifier, along with the output signal, power line, etc. This type of approach permits retaining the calibration equipment external to the vehicle itself with a consequent reduction in weight penalty; calibration prior to launch being accomplished via the umbilical cable.

Although signal insertion at the transducer is obviously superior to all the previously discussed techniques, there are still drawbacks in the physical system which evolves. The necessity of running two, rather than one, somewhat delicate miniature coaxial cables adds to the mounting problem and doubles the amount of cable to be protected from the hazards of sharp corners, hot spots, etc. One method used is to bundle the coax in the middle of a large bunch of other cables. The fact, however, that the signal cable terminates in a 1000 Megohm resistor (voltage amplifier input impedance) makes the possibility of spurious pickup, or crosstalk from surrounding wiring more than remote. The effect of adding the second cable on system operational reliability must also be considered. From Figure 14 (b), if the calibration cable were to open, there would be no effect at all on the operational system. Should the calibration cable short, however, the effect would be to short out R_s. If R_s is small enough compared to other circuit parameters, there will be no consequent effect on operational integrity. Thus the value of R_s should be kept fairly low.

At this point it may well be asked: why is it necessary to have R_s physically at the transducer - couldn't it be placed elsewhere, for example in the amplifier package with attendant advantages? [Figure 14 (c).] For, if the resistor is at the amplifier, it would see a (normally) much less severe environment - thus improving reliability. Then it would be feasible to replace R_s with a variable resistor - a strong advantage in terms of versatility.

The normal approach has been to choose R_s such that a given current, i, flowing through R_s will produce a voltage drop e corresponding to a given mechanical input. For example: suppose the system incorporates an accelerometer whose sensitivity is 27.3 mv/g (unswamped sensitivity). The calibration specification states that a current of 10 ma flowing through the calibration circuit (and hence, through R_s) must produce a voltage drop across R_s equivalent to a 100 g input. The required voltage is then:

$$e = 100\text{ g} \times 27.3\text{ mv/g}$$

$$e = 2730\text{ mv}$$

$$e = 2.73\text{ v}$$

$$\text{But: } R_s = \frac{e}{i}$$

$$R_s = \frac{2.73\text{ v}}{.01\text{ v}}$$

$$\boxed{R_s = 273\ \Omega}$$

It is clearly simpler to utilize potentiometers which can be adjusted to match the sensitivity of any accelerometer than to maintain a stock of precision resistors in sufficient assortment to accomplish the same end.

It is clear, however, from Figure 14 (c) that calibration cable condition can affect system operation if R_s is not at the transducer itself. A short in the calibration cable, of course, has no effect on operation, as long as R_s is small. However, should the calibration cable open, the system cannot operate, since the ground return path is through the calibration cable.

CHARGE AMPLIFICATION

As has been pointed out, the foregoing discussion has been confined to calibration of accelerometer channels involving conventional voltage amplifiers. The recently introduced charge amplifier is sufficiently unique, operationally as well as calibration-wise, to deserve special attention.

Figure 15 shows both the actual and simplified equivalent circuits of a piezo-electric type transducer. The simplified circuit (b) will suffice for practical considerations and is described as a capacitor C_p which is also a coulomb generator, generating a specific charge q across its electrodes for any given mechanical input. The voltage E out of the transducer is equal to the generated charge divided by the transducer capacity or $E = q/C_p$. From the relation:

$$Q = CE \qquad \text{eq. 9}$$

we see in the system of Figure 15 (d), that the voltage appearing at the amplifier input is determined not only by the accelerometer output, but by the amount of shunt capacitance present (C_t). The amount of charge present, however, is unaffected by C_t. Therefore, if the amplifier senses charge rather than voltage, the system output is completely independent of shunt capacitance - and perhaps even more important, of changes in shunt capacity. This has several important consequences:

1) Cable length can be ignored in system output level calculation.

2) The system temperature characteristics are dependent only on the charge vs. temperature characteristics of the transducer and are not affected by changes in capacitance of the transducer or cable. In most cases this is a significant advantage because the crystal charge values change less with temperature than do capacitance values that are eliminated in this case.

Furthermore, direct measurement of instantaneous charge means there is no longer any requirement for long time constants to preserve the charge. Such a device has been developed by the Endevco Corporation.

The major advantages of the charge amplifier that concern us here are 1) the greatly lowered dynamic input impedance (less than one megohm) which materially reduces the effects of humidity and cable connector contamination, as well as lessening sensitivity to noise due to pickup from r.f. fields, 2) flat low frequency response to 10 cps or below is maintained without higher input impedances, 3) any length of cable, up to 300 feet or more, can be used between transducer and amplifier with no reduction in output.

A typical charge measuring system is shown in Figure 16. In normal operation this system provides, at the amplifier output, a voltage corresponding to the actual vibratory motion of the accelerometer. The amplitude of this signal is a function of the transducer charge sensitivity, the vibration amplitude and the amplifier gain setting. It is not affected by the length of interconnecting cable. Signal waveform is controlled by amplifier frequency response only - no RC time constant need be considered.

CALIBRATION BY SIMULATION - CHARGE AMPLIFIERS

As with voltage amplifiers, the simplest simulation method involves insertion at the amplifier input of a given electrical signal. There is, however, one important difference: the calibration voltage must be fed through a series capacitor (Figure 17) in order that the amplifier see a charge input. (The value of this charge is, as before, $q = C_c E$.)

Also, as with conventional amplifiers, the desirability of checking cable and transducer leads to the insertion of the calibrating signal in the ground side of the cable.

For the case of insertion at the transducer, refer to Figure 12 (a). Suppose the current flowing through the series resistor is such that the voltage developed across R_s corresponds to the voltage output of the accelerometer when undergoing 1 g of acceleration.* This voltage is fed through capacitor C_p thus generating a charge q. But from eq. 9, this value of charge is just that which the accelerometer itself would generate for 1 g. In other words, inserting the proper voltage (for a voltage calibration) in series with the pickup automatically yields the correct charge input for that acceleration level.

If the system is in normal operating condition, the amplifier output will be simply ($C_p E_{in}$ x Amplifier Gain).** If the pickup should open, no charge is generated and amplifier output is zero. For the case of a shorted pickup, again there is no charge input and the amplifier output is zero. Similarly, both open and shorted cable prevent the development of a charge input to the amplifier and the resultant output is zero.

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* Unswamped

** Charge amplifier gain is rated in millivolts out per micromicrocoulomb in (mv/μμcmb)

In tabular form:

CONDITION	PICKUP	CABLE	AMPLIFIER OUTPUT	INDICATES
I	OK	OK	$C_p E_{in}$ x Amp. Gain	GO
II	OPEN	OK	0	NO GO
III	SHORT	OK	0	NO GO
IV	OK	OPEN	0	NO GO
V	OK	SHORT	0	NO GO

Table 4. Expected indications in calibration by simulation using charge amplifier – input at transducer end.

The prime advantages of this method lie in that both system calibration and operation are completely independent of cable length, even though two cables are required per system. What about reliability? Examination of Figure 12 shows that neither a short nor an open in the calibrating cable affects the operational system. All of this, plus the clear differentiation between the go and no go conditions, recommends this particular method quite highly. Figure 18 shows a currently available system of this type. In this equipment, the calibrating resistor is located in the base of the accelerometer. It should also be feasible to fabricate an external adapter containing the calibration resistor, thus permitting the use of non-special accelerometers.

In the case of insertion at the amplifier (Figure 10), the situation is somewhat more complex. The voltage developed across R_s sees the shunt capacitance C_t of the cable in parallel with that of the accelerometer. Thus the charge appearing at the amplifier input is $q = (C_p + C_t) \times E_{in}$. In consequence, this technique requires <u>system</u> calibration – i.e., calibration is <u>not</u> independent of cable length, although normal operation remains unaffected by changes in cable.

If the system is in normal operating condition, the amplifier output will be $E_{in} \times (C_p + C_t) \times$ Amplifier Gain. For an open cable, output is zero; for a shorted cable, output is again zero. If the pickup opens, the output will be reduced by the factor

$$\frac{C_t}{(C_p + C_t)}$$

since only the cable capacitance remains in the circuit. If the pickup shorts, output is zero. In tabular form:

CONDITION	PICKUP	CABLE	AMPLIFIER OUTPUT	INDICATES
I	OK	OK	$E_{in} (C_p + C_t) \times$ Amp Gain	GO
II	OPEN	OK	$E_{in} C_t \times$ Amp Gain	NO GO
III	SHORT	OK	0	NO GO
IV	OK	OPEN	0	NO GO
V	OK	SHORT	0	NO GO

Table 5. Expected indications in calibration by simulation using charge amplifier – input at amplifier end.

The fact that this system requires but a single cable plus the utilization of standard transducers is its chief advantage over the previous method. Opposed to this is the necessity for system calibration – the same cable must be used for successive runs.

Currently available hardware using this technique is shown in Figure 19.

SUMMARY:

The major points upon which the several approaches to calibration by simulation can be judged are as follows:

Voltage Amplifier – Calibration Insertion at Amplifier

Insufficient resolution of GO – NO GO condition.

Voltage Amplifier – Calibration Insertion at Transducer

Good resolution of GO – NO GO condition.
Two cables required.
System sensitivity dependent on length of input cable.
Calibration accuracy independent of length of calibration cable.
Failure of calibration cable does not affect operational system.

Charge Amplifier – Calibration Insertion at Amplifier

Good resolution of GO – NO GO condition (except for very long cable coupled with low capacitance transducer).
One cable sufficient.
System sensitivity independent of cable length.
Calibration accuracy dependent on cable length.

Charge Amplifier – Calibration Insertion at Transducer

Good resolution of GO – NO GO condition.
Two cables required.

System sensitivity independent of cable length.
Calibration accuracy independent of cable length.
Failure of calibration cable does not affect operational system.

This paper is by no means an exhaustive one - other variations on the several calibration techniques have been omitted in the interests of brevity. It is intended only as a guide to the instrumentation engineer whose interest will lead him to further innovation and techniques.

Although these techniques are evolved from the suggestions of many contributors, special mention must be made of at least two whose ideas have been especially fruitful: Mr. A. F. Williams, Boeing Airplane Company, and Mr. Bernie Shoor, Endevco Corporation.

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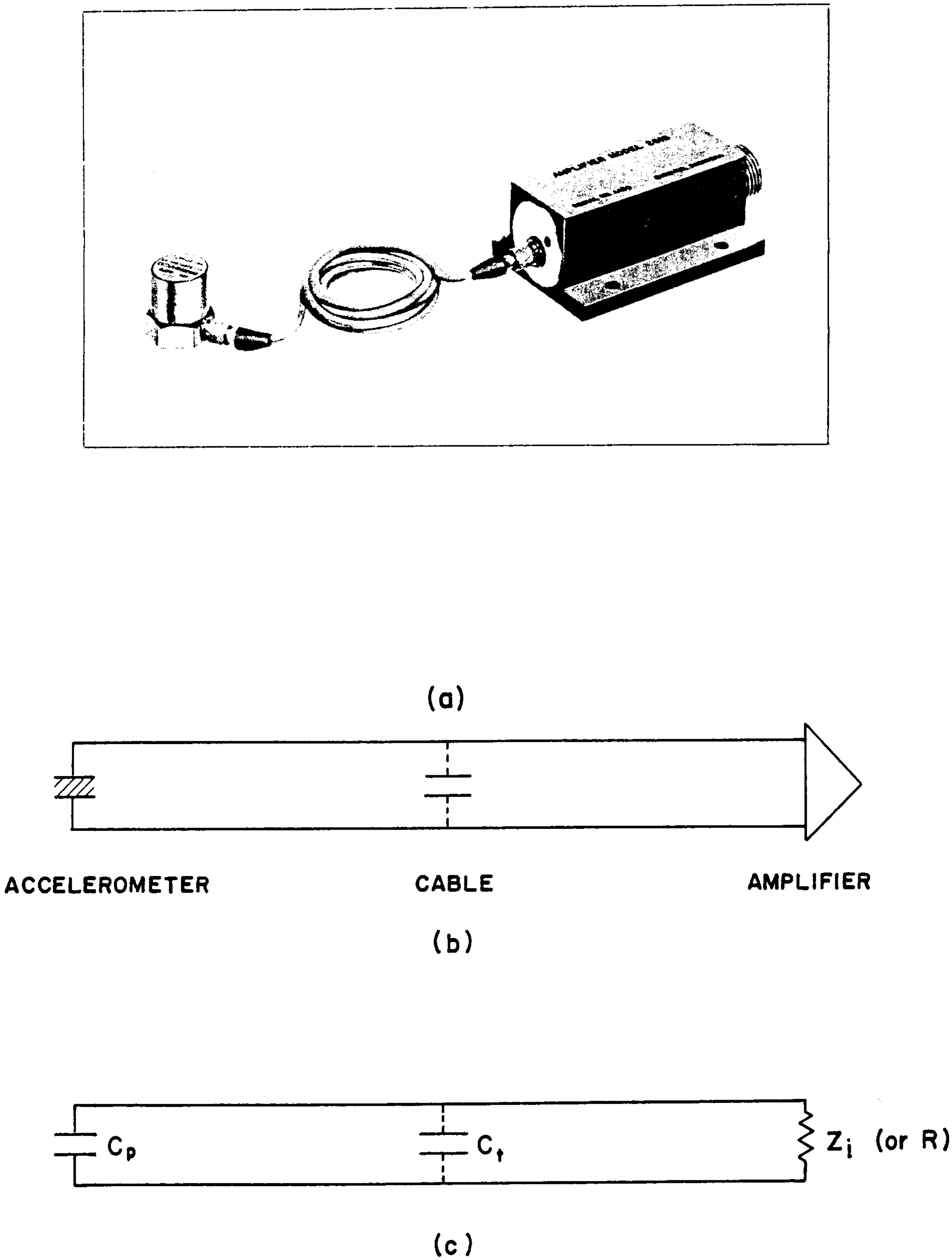
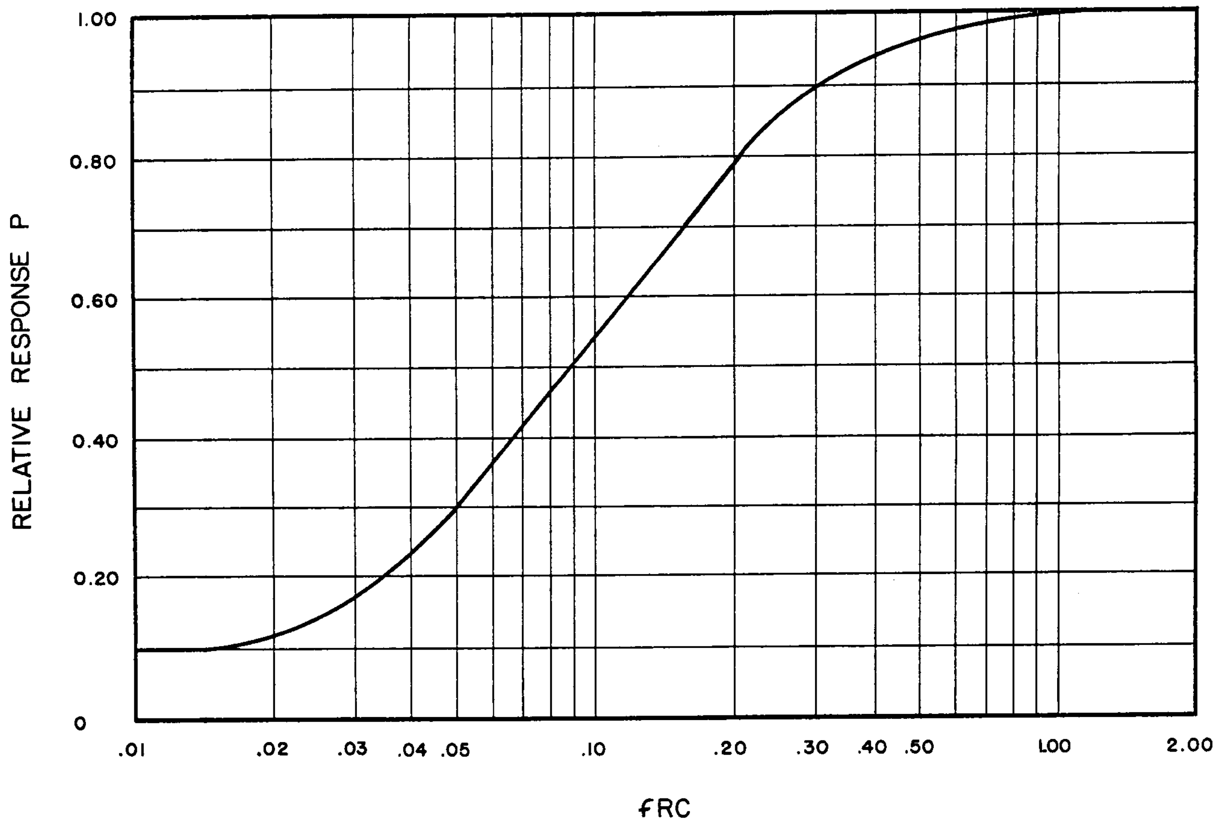


Figure 1 Typical Vibration Instrumentation System and Equivalent Circuit



LOW FREQUENCY RESPONSE . VS LOADING

Actual response at any frequency can be measured from figure 2 where f is the frequency in cps, R is the input impedance in ohms of the matching amplifier, C is the total capacitance in farads of the accelerometer, plus additional applied shunt capacity, if any.

Example: If frequency (f) of desired measurements is 10 cps, total capacitance (C) of accelerometer and cable is 500 mmfd, and amplifier input impedance (R) is 100 megohms (Endevco Cathode Follower), we can determine

$$f \times R \times C = 10 \times 100 \times 10^{6} \times 500 \times 10^{-12} = 0.50$$

Using Figure 2, we find relative response (p) corresponding to frc = 0.5 is 95% (indicating the signal at 10 cps will be down approximately 5%).

Using the same formula in the case of a Model 2215 accelerometer with an approximate capacity of 7,000 mmfd we can see that for frequency response to 10 cps and 10 megohms input impedance the following

$$f \times R \times C = 10 \times 10 \times 10^{6} \times 7{,}000 \times 10^{-12} = 0.70$$

Again using Figure 2, P = approximately 98% Or a 10 cps signal will be approximately 2% down

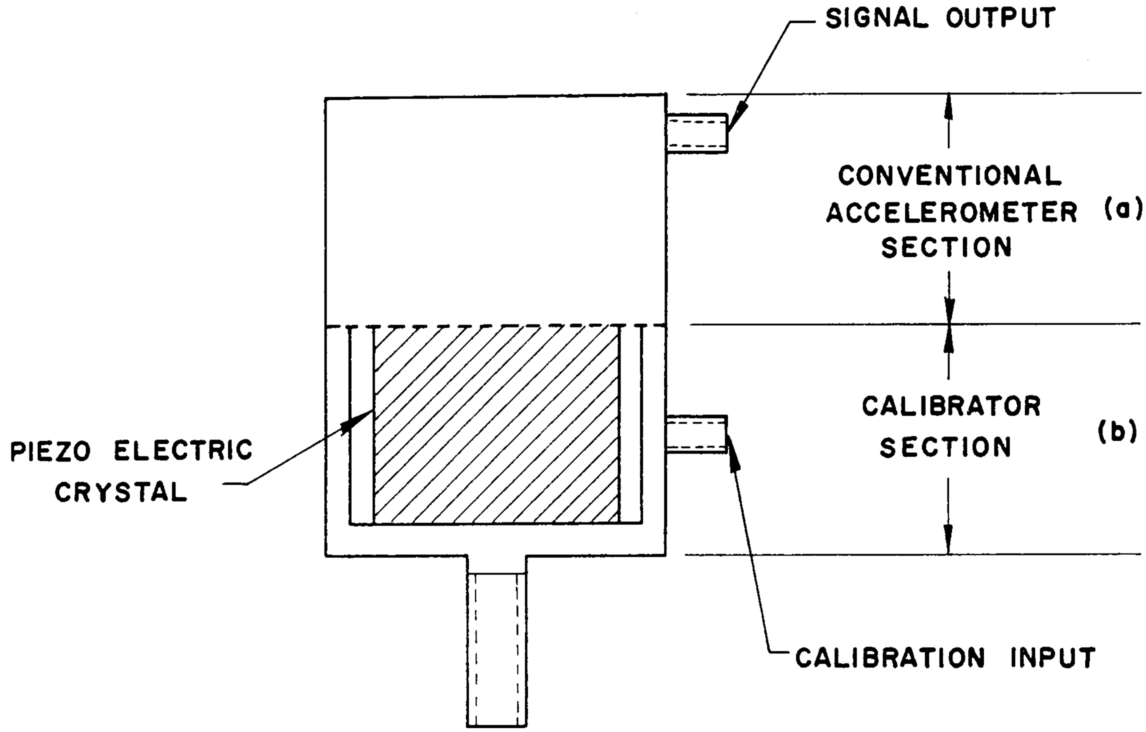


Figure 3 Method of In - Place Mechanical Excitation

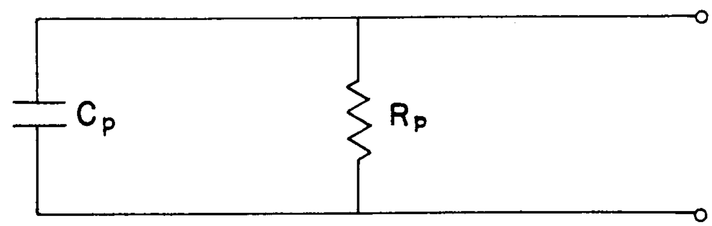


Figure 4 Electrical Equivalent of the passive Accelerometer

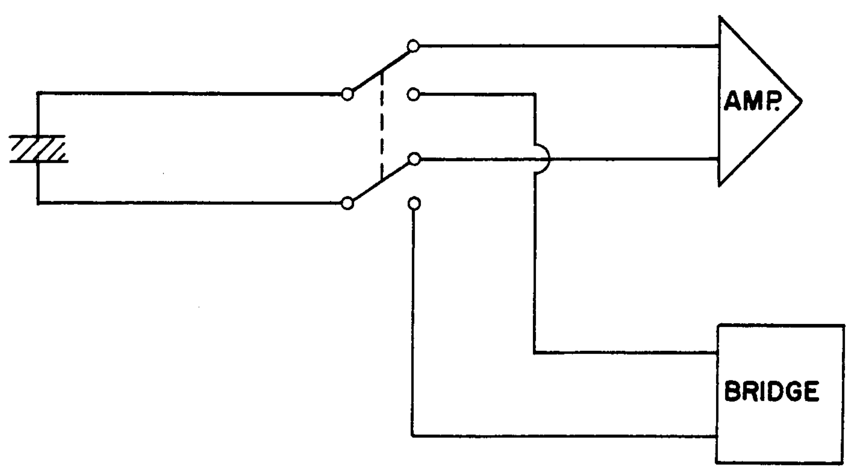


Figure 5 Measurement of Passive Parameters

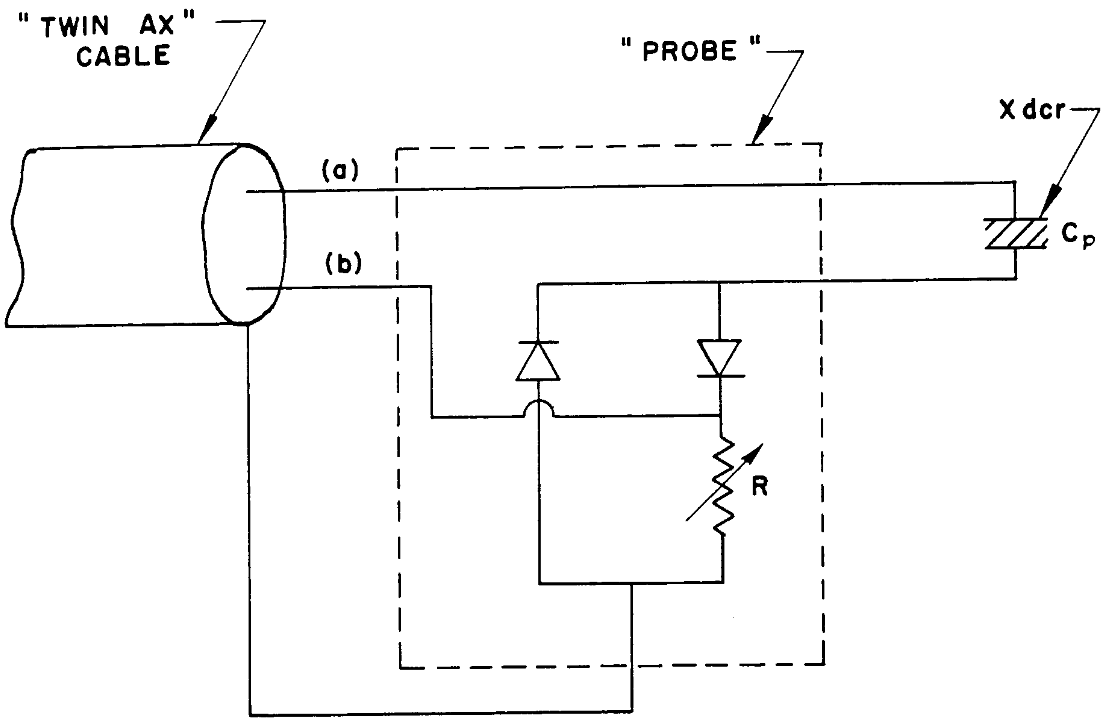


Figure 6 Alternate Method of Measurement - Passive Parameters

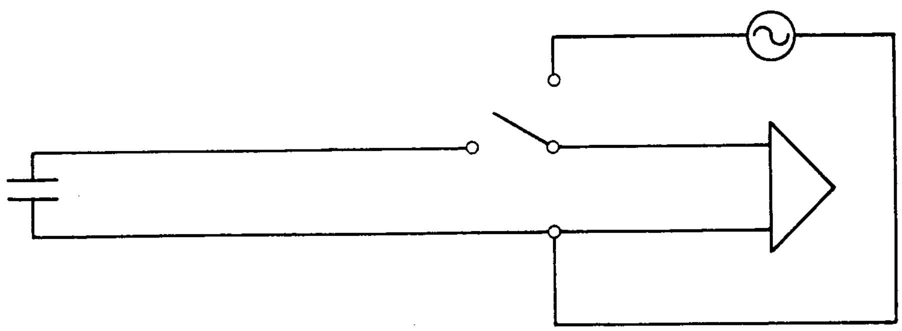


Figure 7 Simulation Method #1, Signal Insertion

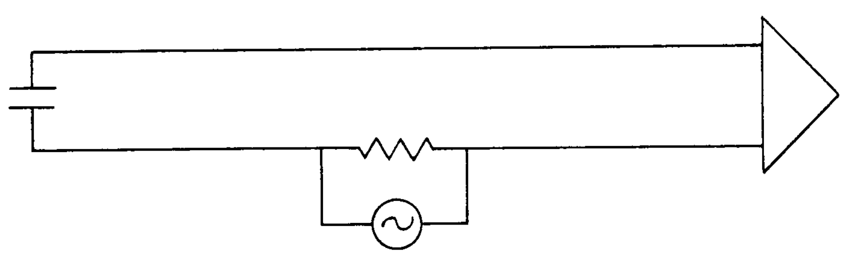
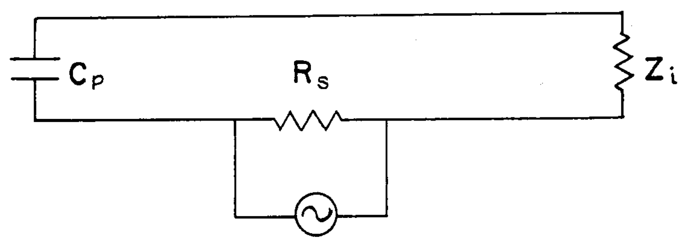
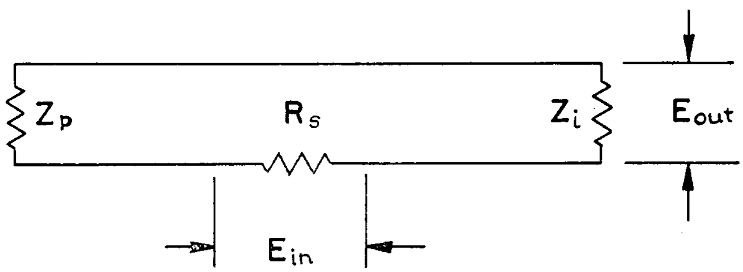


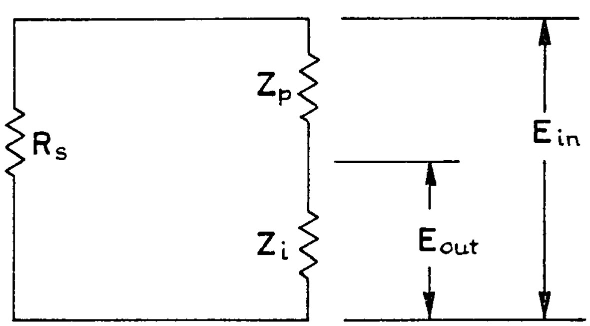
Figure 8 Simulation Method #2, Signal Insertion



(a)



(b)



(c)

Figure 9

Simulation Method #2, Equivalent Circuits

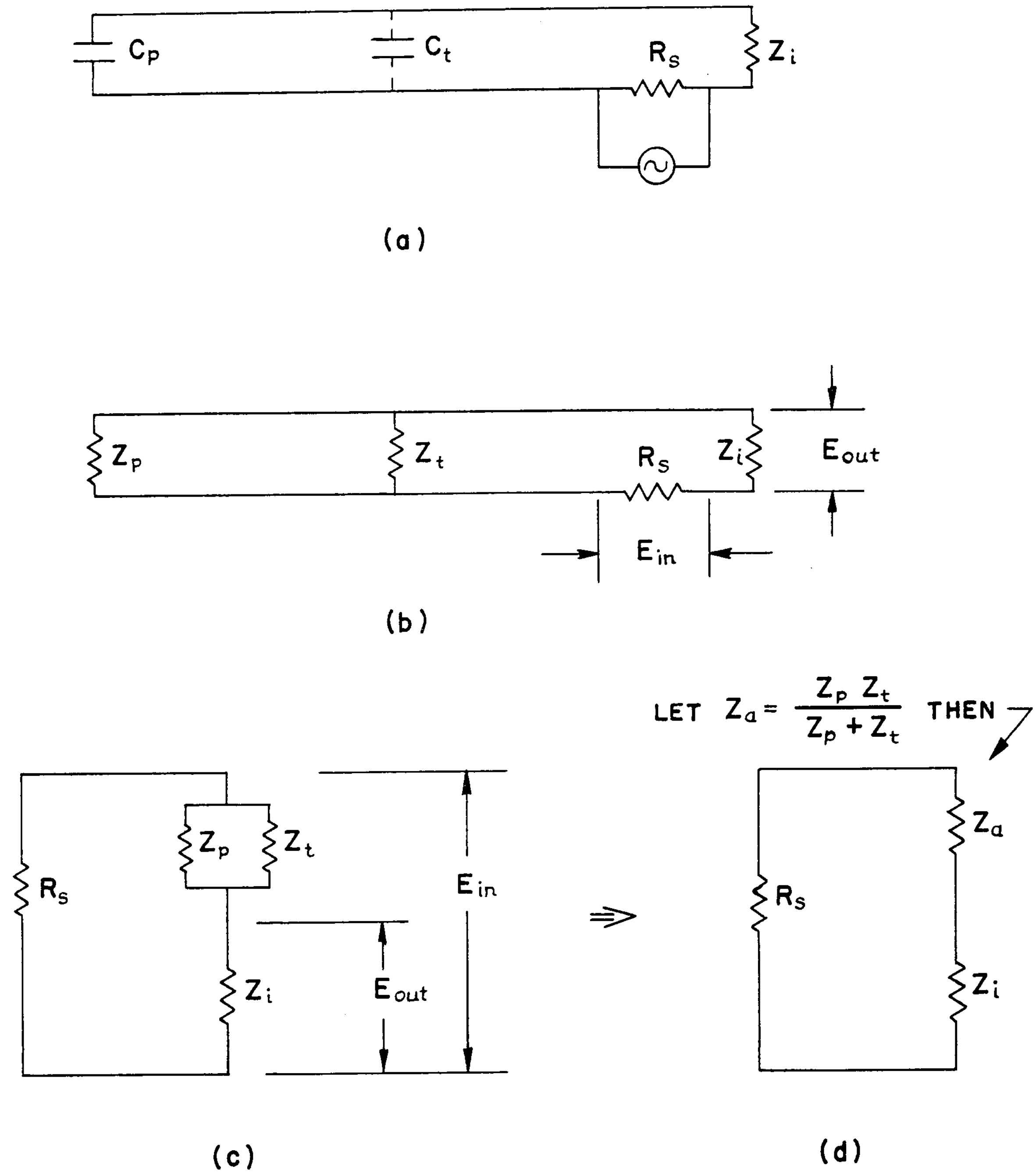


Figure 10

Simulation Method Equivalent Circuits - Insertion at Amplifier

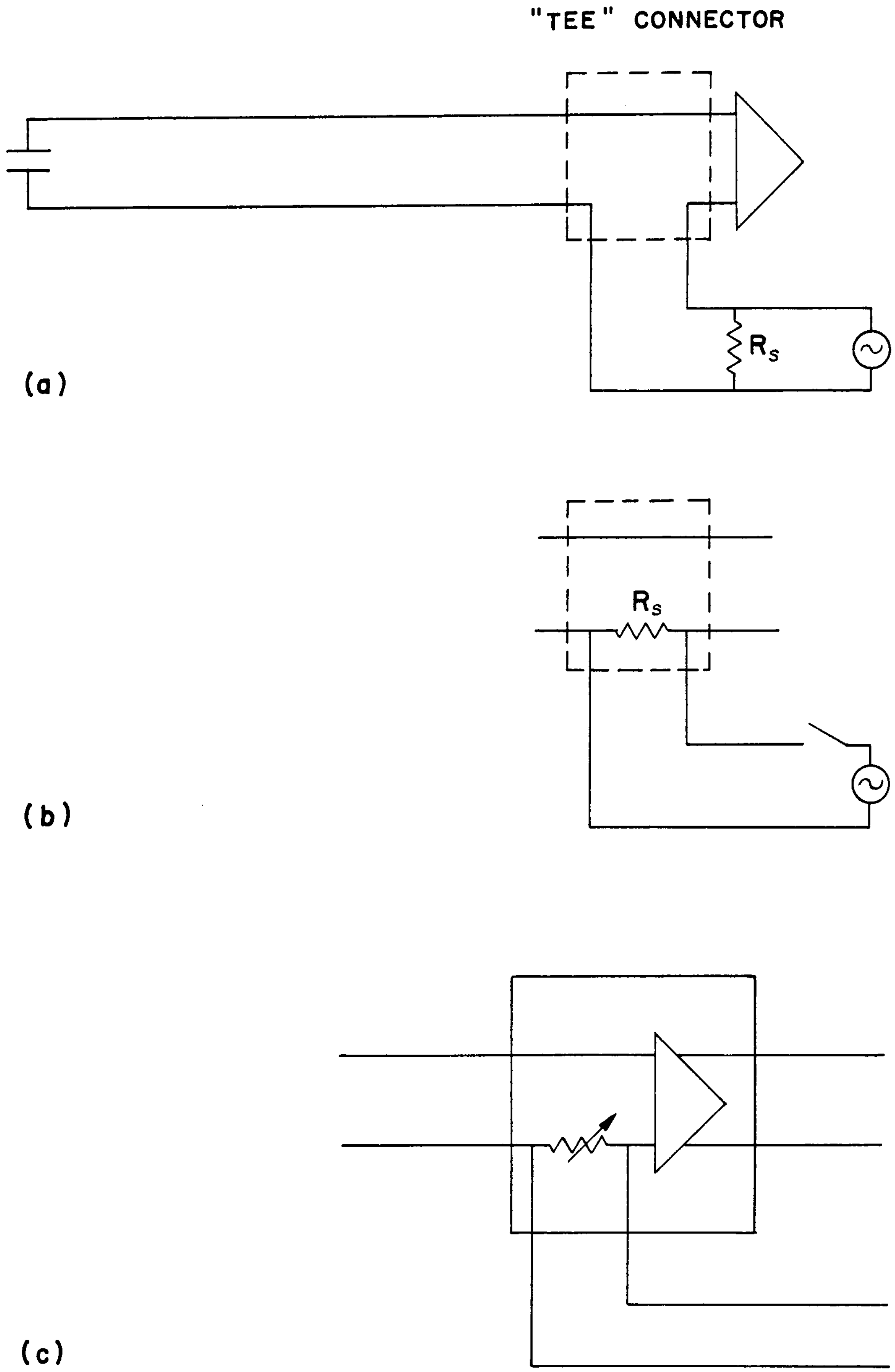


Figure 11 Simulation Techniques

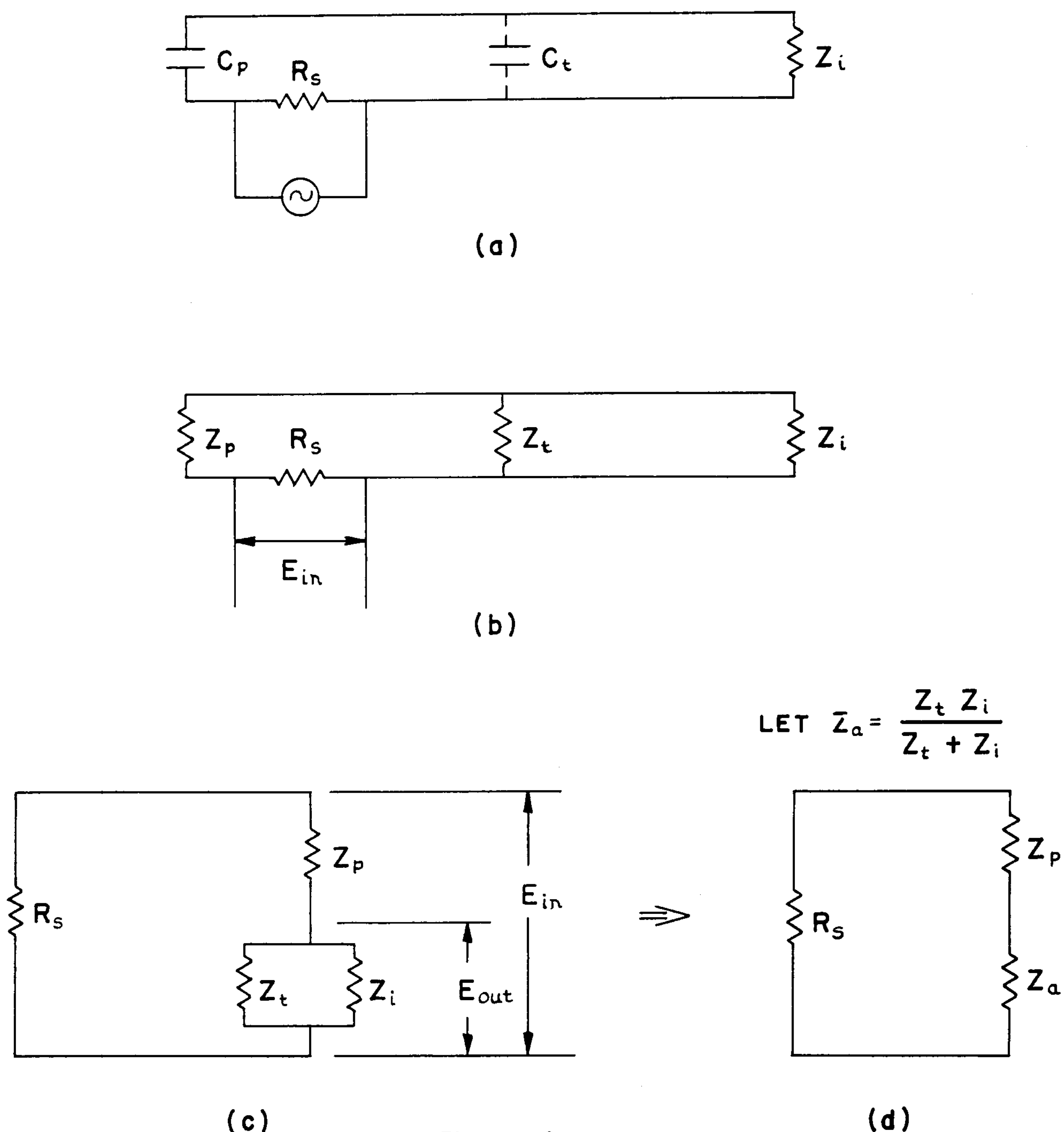


Figure 12

Simulation Method Equivalent Circuits – Insertion at Transducer

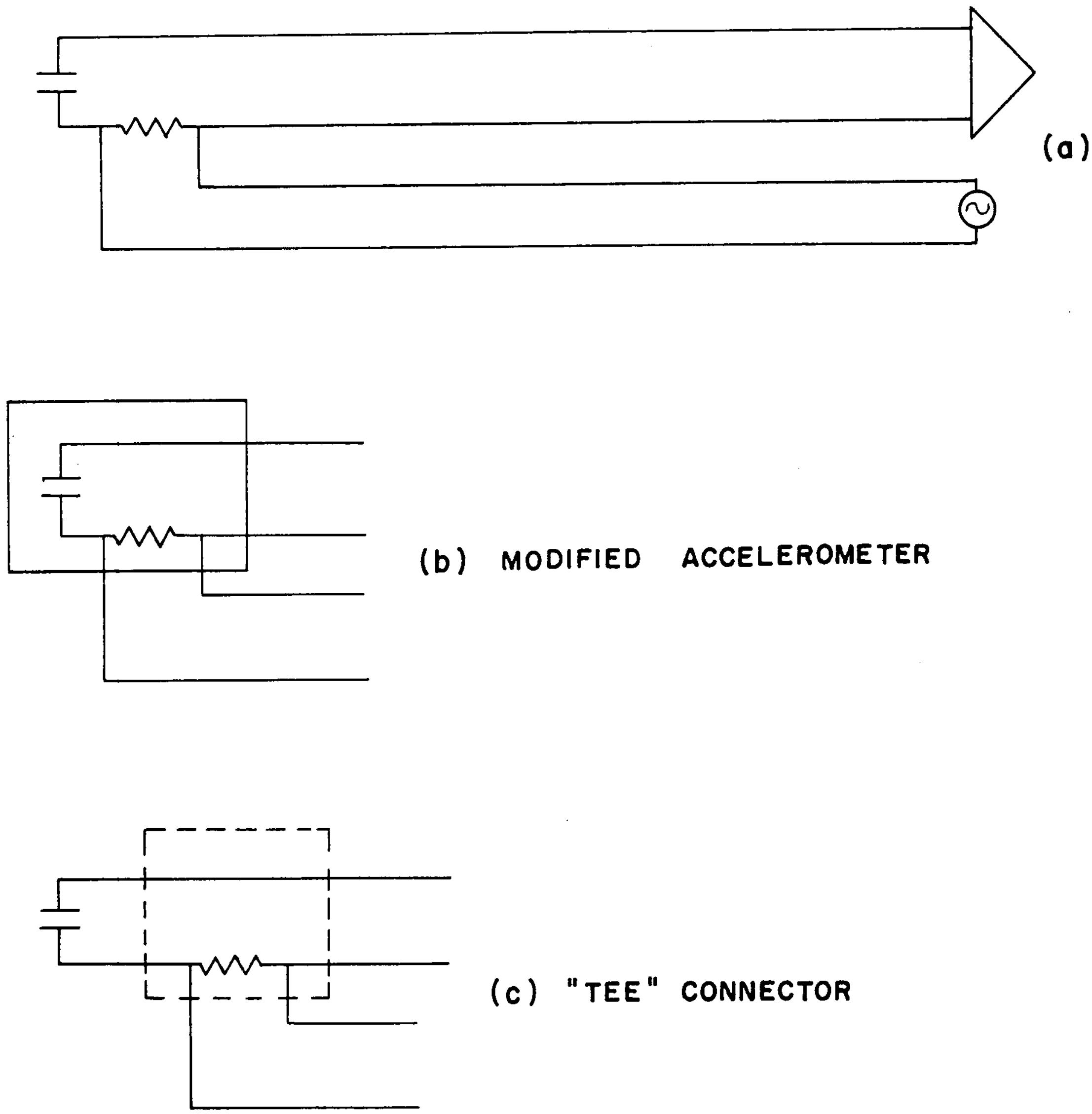


Figure 13 Simulation Techniques

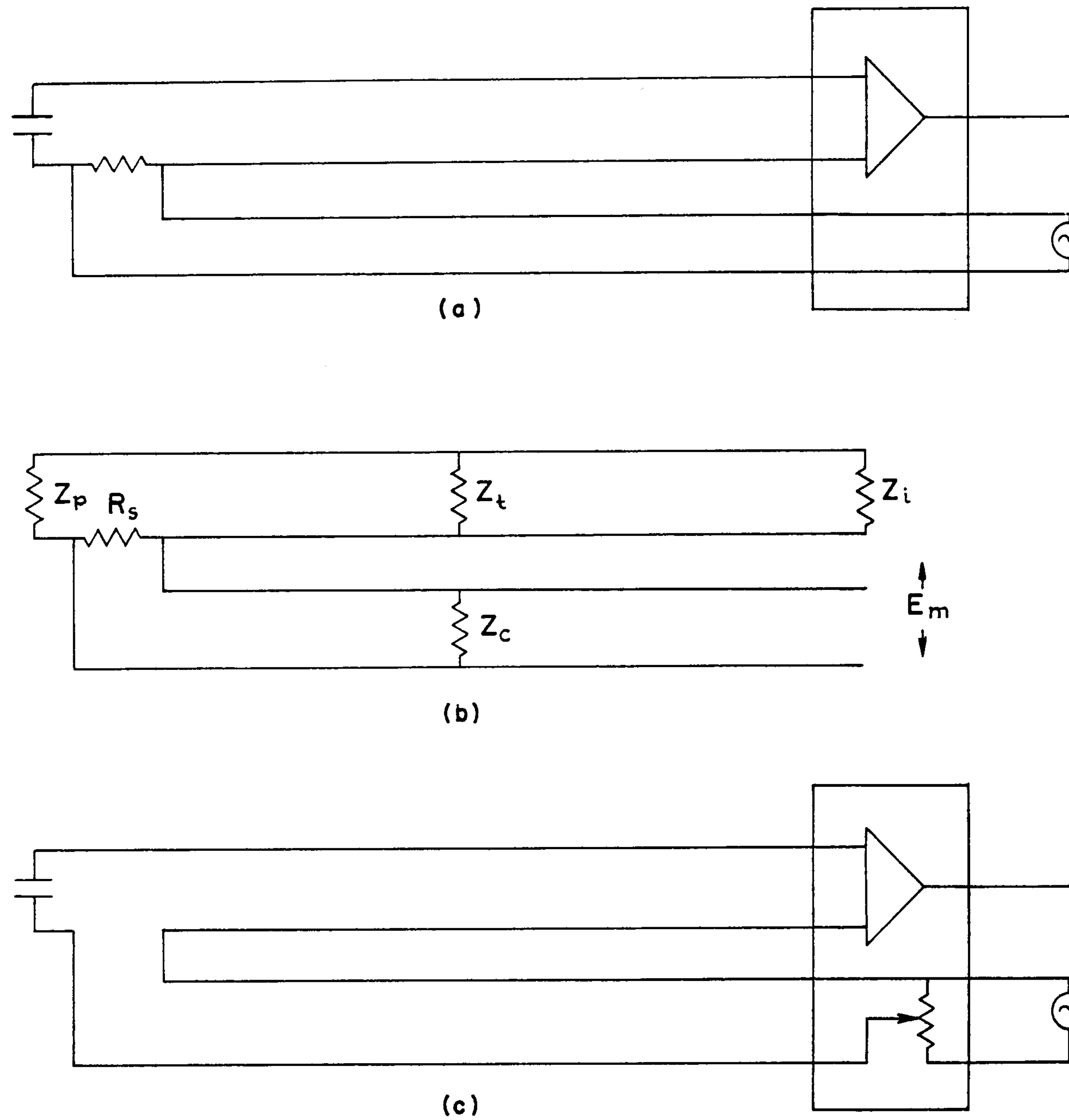
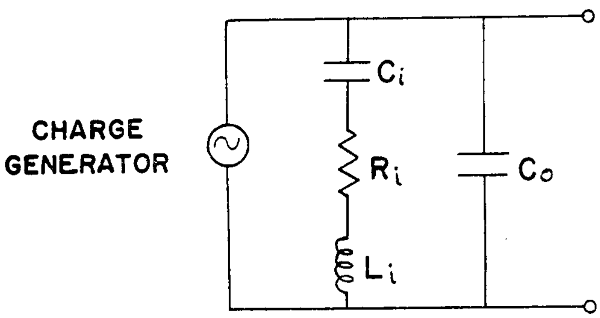


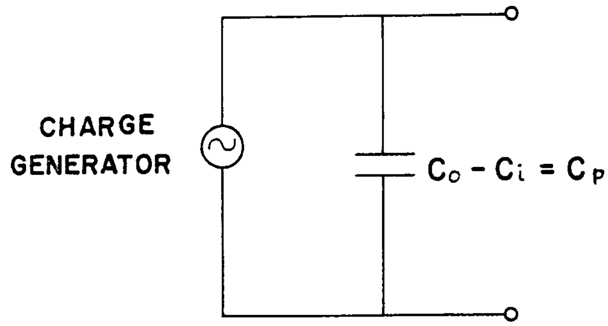
Figure 14

Simulation Method Equivalent Circuits - Effect of Second Cable



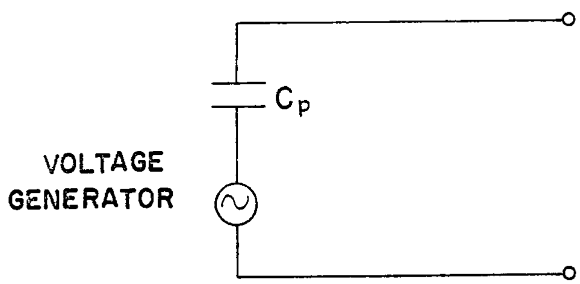
(a)

ACTUAL CIRCUIT



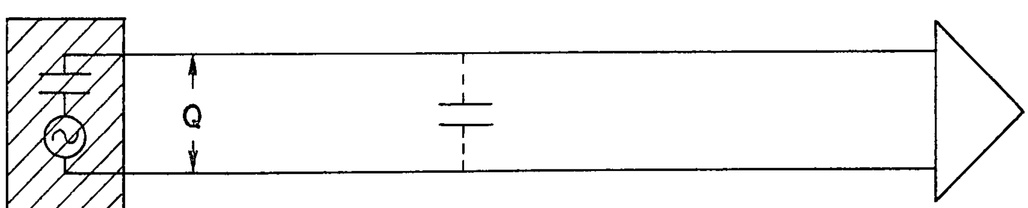
(b)

CHARGE GENERATOR EQUIVALENT



(c)

VOLTAGE GENERATOR EQUIVALENT



(d)

SYSTEM USING VOLTAGE GENERATOR EQUIVALENT
AND CHARGE SENSING AMPLIFIER

Figure 15
Charge Concepts

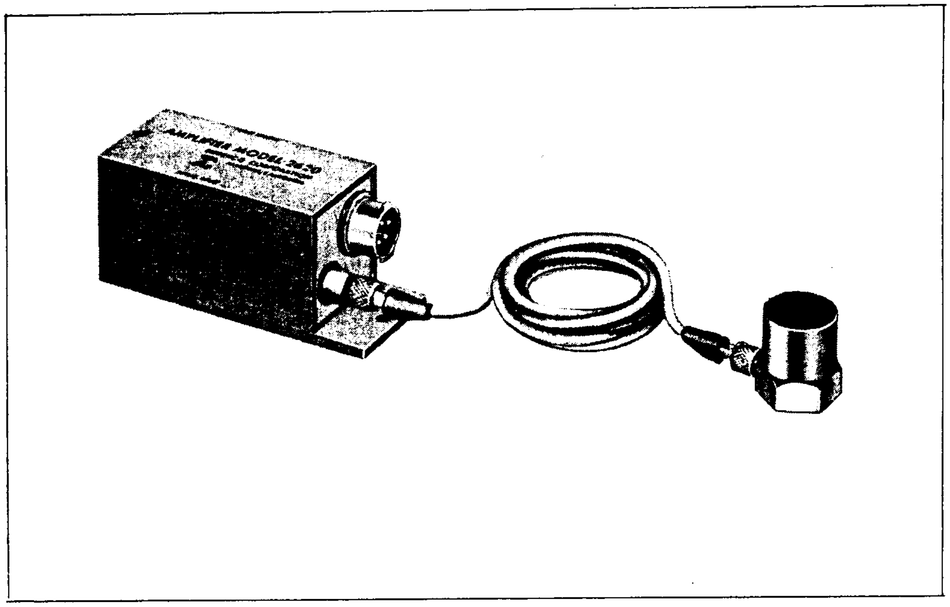


Figure 16

Endevco Model 2620 (Charge) Amplifier with Endevco Accelerometer

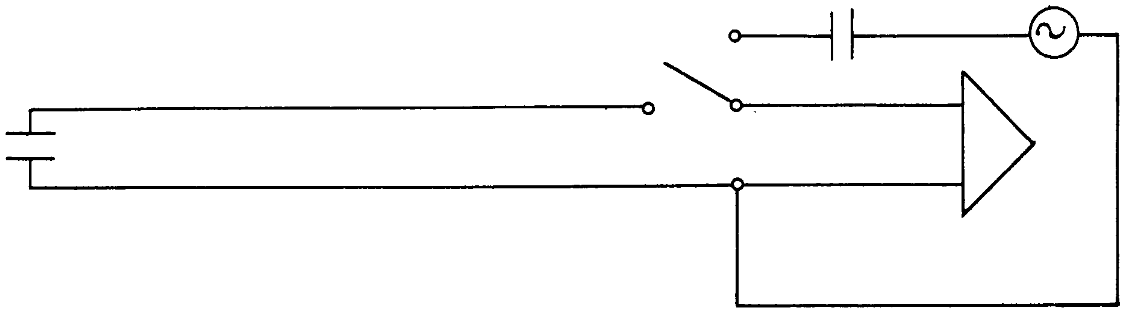


Figure 17

Simulation Method #1, Charge Amplifiers

Figure 18

Endevco Model 2633M2 Amplifier with Model 2242M5 Accelerometer (**resistor in base**)

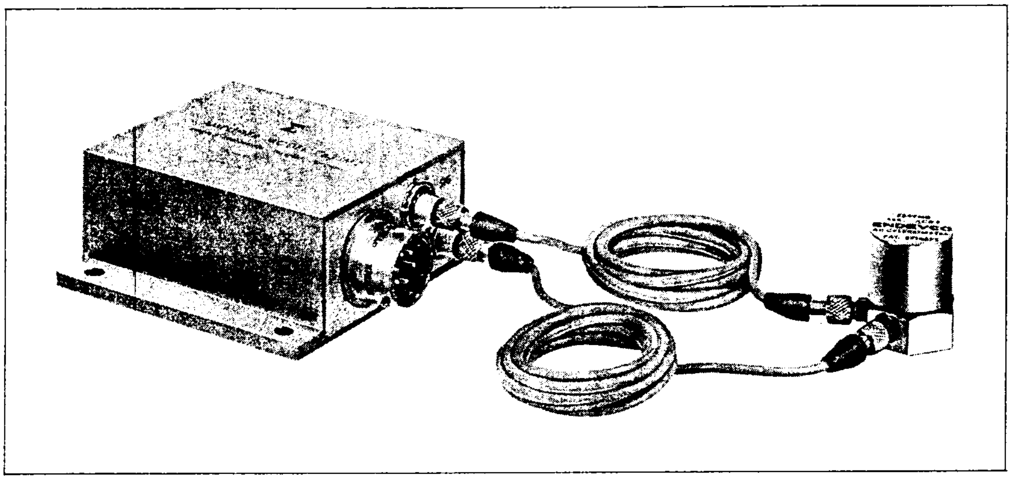


Figure 19

Endevco Model 2633M1 Amplifier with Endevco Accelerometer