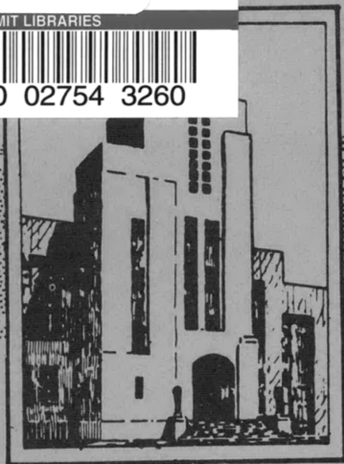

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A DYNAMIC CALIBRATION TECHNIQUE FOR UNDERWATER EXPLOSION PRESSURE GAGES

by

Joseph Gesswein and George Chertock, Ph.D.

STRUCTURAL MECHANICS LABORATORY
RESEARCH AND DEVELOPMENT REPORT

September 1959

Report 1328

PRNC-TMB-648 (Rev. 3-58)

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September 1959

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ABSTRACT

An apparatus and technique are described for the laboratory calibration of pressure gages used in underwater explosion measurements. The method can be used with completed gages mounted on electrical cables. It measures the dynamic sensitivity of the gage, and it employs a null-method measuring circuit which is independent of the amplifier and detector characteristics and does not require photographic recording. Experience indicates that the relative sensitivity of a test gage can be measured in terms of the sensitivity of some reference gage by this method with a precision approaching 1 percent, which is about the same precision as obtained by other methods.

INTRODUCTION

Methods of calibration of piezoelectric gages used for the measurement of underwater explosion pressures have been given considerable study since 1940. As a result several somewhat different methods have been evolved.[1] In connection with a project requiring the use of piezoelectric gages,[2] a method has been developed at the David Taylor Model Basin where it has been in intermittent use since 1956. The method can be used with waterproofed gages mounted on electrical cables. It measures the dynamic sensitivity of the gage, employs a null-method measuring circuit which is independent of amplifier and detector characteristics, and does not require photographic recording.

This method is the subject of this report. After a survey and discussion of other calibration techniques, the apparatus and procedures of the TMB method are described and the operations are analyzed. Finally the results of actual gage calibrations are presented, and the precision and accuracy of the results are discussed.

SURVEY OF OTHER CALIBRATION TECHNIQUES

Since piezoelectric pressure gages operate into finite resistance, they ordinarily show poor low-frequency response and cannot be calibrated by exposure to known static pressures. In one standard method of calibration, an unmounted gage is sealed in a small chamber which is pumped up to a high static pressure which is measured with a precision static pressure gage. Then the pressure is released quickly, either with a quick-opening valve or a bursting diaphragm, and the peak electrical signal due to the pressure change is measured with an appropriate circuit. With sufficient care, this method gives results reproducible to about 1 percent which is adequate for most underwater explosion work.

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[1]References are listed on page 20.

The above method is ordinarily used only with crystals which have not yet been mounted on an electrical cable or covered with thick coats of insulation, because it is difficult to provide a stuffing tube for the cable which would operate properly at the high initial static pressure (about 2000 psi) in the chamber. However, there is substantial experimental evidence that the sensitivities of mounted and waterproofed gages can differ from the sensitivities of the unmounted gages by as much as ± 10 percent. Another defect of the usual calibration scheme is that it gives a poor indication of the dynamic response of the gage. There can be undisclosed resonance frequencies, particularly in the larger size gages, and there may be hysteresis effects in the insulation coating of the gage which will not show up in the standard calibration.

A calibration technique which can be used with mounted piezoelectric gages and which gives some indication of the dynamic properties of the gage has been described in a report of the Underwater Explosion Research Division at the Norfolk Naval Shipyard.[3] In this technique, the test gage and a standard reference gage are both sealed into a pressure chamber with a freely moving and close-fitting piston at the top. A falling weight impinges on the top of the piston and gives a pressure pulse to the chamber with a duration of about 5 msec and a peak amplitude of the order of 2500 psi depending upon the height of fall. The signals from the two gages are separately and simultaneously recorded with appropriate circuits, and the peak voltages are then compared to give the calibration of the test gage in terms of the assumed calibration of the reference gage. The reference gage used was a Rutishauser condenser-type pressure gage. As described in Reference 3, the Rutishauser gage was nonlinear in response and had only been calibrated statically. The accumulated error in reading two oscillograms and in calibrating two amplifier and recording systems would probably exceed the errors in the standard method. The analysis assumes that the pressures seen by the two gages are identical. As is discussed below, differences of a few percent may occur.

Another common calibration technique, and one which also tests a mounted gage with a dynamic pressure, is to expose the test gage together with a "standard" piezoelectric gage to an underwater explosion, record both signals separately, and then calculate the sensitivity of the test gage. The difficulty here is that this is inherently a field technique and cannot be carried out with the precision possible in the laboratory. Furthermore, the signals from two separate gages exposed to underwater explosions rarely show the same detailed pattern, particularly at the time of the initial peak.

DESCRIPTION AND ANALYSIS OF METHOD

In the calibration technique described here, the method is similar to the drop test method[3] in that the test gage and a reference gage are exposed simultaneously in a chamber to the pressure pulse resulting from the impact of a weight on a piston. However, instead of measuring the signals from the two gages separately, the gages are connected in the same circuit with a single detector to measure the difference in the signals. Then, by varying the circuit parameters between successive impacts, the voltage difference is made null, and the relative sensitivities of the two gages can be calculated from the circuit parameters.

PRESSURE CHAMBER

The pressure chamber used in the calibration is shown in Figure 1. The fluid in the chamber may be either water or oil and has a volume of about 20 cu in. The wall is thick enough to allow stuffing tubes to be built into the sides. There are five ports in the chamber in addition to the piston opening. One, in the top bonnet, is a hole to bleed any trapped air; a second hole in the bottom is for the attachment of a hand pump if desired; a third hole in the center takes a ½-in.-diameter, flush-mounted, diaphragm pressure gage, and the remaining two holes are threaded as stuffing tubes for ½-in. electrical cable on which piezoelectric gages can be mounted to project into the chamber. If the gage width is greater than 5/8 in., the cables can be threaded through the holes from the inside of the chamber by removing the top bonnet. The piston, placed at the top, weighs 0.5 lb.

The chamber can easily be adapted for calibrations by the standard procedures. For this purpose, the piston is replaced by a plug which seals the opening, pressure is applied with a hand pump, and pressure is released with a hand valve or by bursting a diaphragm in one of the side openings. (Or an adapter can easily be made for the piston opening to accommodate either a quick-opening valve or a bursting diaphragm.) In this method of operation the maximum static pressure for which the stuffing tube will seal the electrical cable is not greater than 1000 psi. If the gage is mounted on a solid bushing instead of an electrical cable, the

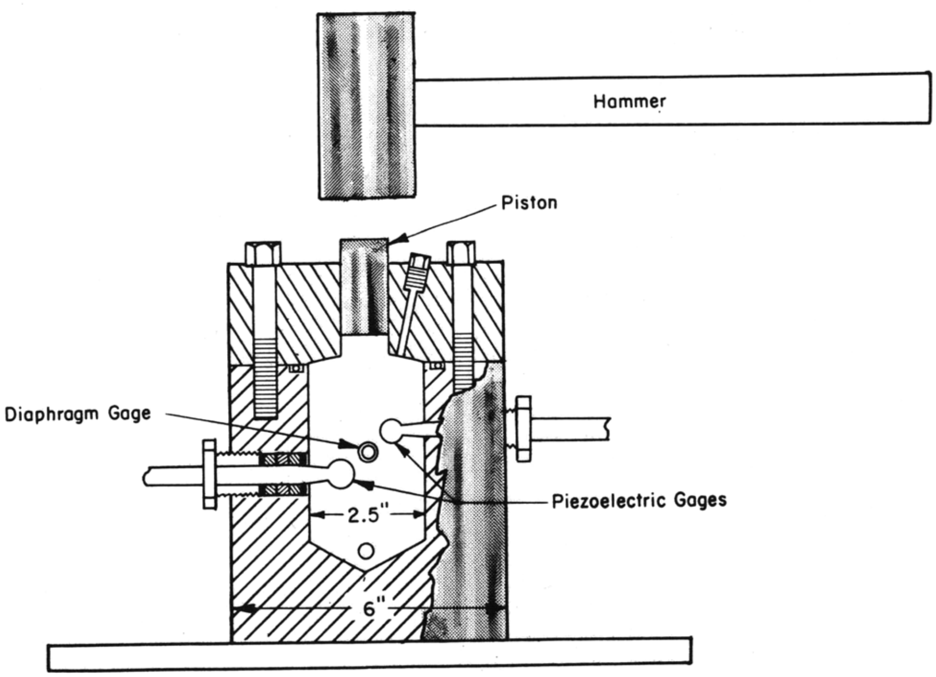

Figure 1 – Chamber for Calibration of Pressure Gages

pressure seal will probably be adequate even above 5000 psi. The chamber can also be used in the same way as in Reference 3 because tracks are attached to the frame along which a falling weight can drop and impinge on the piston. Ordinarily, the pressure pulse is obtained simply by hitting the piston with a 5-lb lead hammer. When the pressure is applied as a pulse rather than statically, the stuffing tubes should operate satisfactorily at pressures of 5000 psi or more, even with rubber cables.

PRESSURE VARIATIONS IN CHAMBER

To make a reliable gage calibration with a transient pressure pulse, the variation of pressure with time and also with position in the chamber must be understood. For it turns out that two gages in the chamber are exposed to pressures which can differ by several percent, and any assumption to the contrary may lead to an erroneous calibration.

The gross features of the pressure-time curve can easily be calculated with the simplifying assumptions (1) that immediately after the impact, the weight, or hammer, and the piston move together with a common initial velocity which is reduced to zero as the initial kinetic energy is converted into compressional energy of the liquid, and (2) that the fluid in the chamber acts as a uniformly compressed system of negligible mass which resists the motion of the piston with a force proportional to the amount of compression.

Let M be the total mass of piston and hammer,
$x(t)$ be the displacement of piston and hammer,
v be the initial velocity of piston and hammer,
A be the piston area,
V be the volume of liquid,
$L = \rho V$ be the mass of liquid, and
ρc^2 be the bulk modulus of liquid.

Then the resisting force due to the compression of the liquid is

$$A(\rho c^2)\frac{Ax}{V} = \frac{\rho^2 c^2 A^2 x}{L}$$

and the equation of motion is

$$M\ddot{x} + \frac{\rho^2 c^2 A^2 x}{L} = 0 \qquad [1]$$

The solution which gives $x = 0$ and $\dot{x} = v$ at $t = 0$ is

$$x = \frac{v}{\rho c A}\sqrt{ML}\cdot\sin\left(\frac{\rho\, cAt}{\sqrt{ML}}\right)$$

from which the pressure $P = \dfrac{\rho^2 c^2 A x}{L}$ is $P = \rho c v \sqrt{\dfrac{M}{L}} \sin\left(\dfrac{\rho c A t}{\sqrt{ML}}\right)$ [2]

For this chamber, using a 5.7-lb hammer, the duration of the pressure pulse (half period) is $\dfrac{\pi\sqrt{ML}}{\rho c A} = 3.9$ msec and the amplitude is about 1000 psi if the hammer falls through a distance of about 1 ft.

In reality the fluid in the chamber is not a lumped massless spring but has distributed mass and elasticity, with a whole series of normal modes. The impact excites all the modes, and each pressure gage experiences pressures due to all the modes acting simultaneously in proportions which depend upon the position of the gage. The geometry of the piston, chamber, and gages is too complicated to make it feasible to calculate the exact mode shapes and contributions, but they can be calculated for a somewhat simpler geometry.

In Appendix A, a calculation is made for a chamber which is a simple cylinder with a free piston at one end and a rigid wall at the other. The analysis of Appendix A shows that this simple system responds predominantly in the lowest mode with an amplitude and frequency which are very close to those given by Equation [2]. Even this lowest mode does not have a uniform pressure in the chamber. The pressure is a maximum at the closed end and decreases towards the piston as $\cos\sqrt{\dfrac{L}{M}}\dfrac{x}{a}$. (See Equation [17] in Appendix A.) A small pressure difference, of the order of 2 percent, is expected at the two locations for the piezoelectric gages. The higher modes are almost harmonics of the lowest. They have planes of zero pressure and large pressure gradients throughout the chamber, but they are not greatly excited relative to the fundamental. Thus the maximum amplitude of the second mode should be about 6.5 percent of the fundamental.

This analysis of the pressure in the chamber is verified by the pressure oscillogram shown in Figure 2. The upper trace is a record from a piezoelectric gage in the upper gage position (See Figure 1) due to an impact, and the lower trace is a record from a gage in the lower position due to a second impact of about the same strength as the first. The third trace is a 1000-cps square-wave voltage calibration signal. Both pressure records show a pulse with a half period in good agreement with Equation [2]. Both traces also show high-frequency components with amplitudes of a few percent of the fundamental. Furthermore, although it is difficult to see on this record, it is apparent with careful measurements that the next higher mode is out of phase on the two traces.

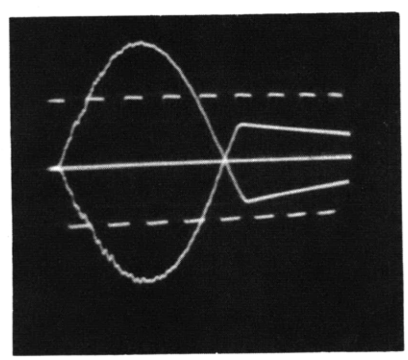

Figure 2 – Oscillogram of Two Pressure Pulses in Test Chamber

Hence, if a pressure pulse is to be used to make an accurate comparison of the sensitivities of two gages, certain precautions should be taken to minimize the pressure differences at the two locations. Ideally, the two gages should be of the same size and placed in the same horizontal plane below the piston. In that way the pressure difference would be negligible at all times. If, in addition, the plane is at middepth, half of the harmonics disappear from the record. If the two gages are placed one above the other as in Figure 1, then the comparison should be made at the time of peak pressure amplitude in the fundamental, for, at that time, the contributions of the harmonics are neglibible. Even when the comparison is based only on the amplitudes of the fundamental mode, the gage positions should be reversed and a new sensitivity comparison should be made to assess the effect of possible pressure differences in the fundamental mode at the two locations. If the apparent sensitivity ratio of the two gages does have different values when the gage positions are interchanged, then the proper value is the geometric mean of the two ratios.

CIRCUITS AND TECHNIQUES

One feature of this calibration method is that the comparison between the sensitivities of the two gages is made by a null method and can be made independent of the characteristics of amplifiers and recorders. Three circuits to accomplish this are suggested below. All circuits using piezoelectric gages are high-impedance circuits which must be protected from stray voltages. All cables should be completely shielded and grounded at only one point to avoid ground loops.

Figure 3 shows a circuit for the calibration of one pressure gage in terms of another of approximately the same sensitivity. Each gage is connected to a terminal capacitor, one of which is variable, and to separate inputs of a push-pull cathode-ray oscilloscope, such as the Tektronix Model 512. The cathode-ray oscilloscope is connected to measure the voltage *difference* between the two inputs and the gains of the two sides are adjusted to be equal (which can be done within 0.01 percent). The sweep circuit triggers when the hammer hits the piston and closes a circuit. The sweep speed is adjusted so that the peak of the pressure pulse occurs when the cathode-ray trace crosses the center of the tube face. Then the piston is repeatedly hit with the hammer, and the capacitor C_{11} is adjusted until a null voltage occurs at the time of the peak in the pressure pulse. This is done by visual observation of the oscilloscope screen, and no photographic record is necessary. In practice C_{11} can be brought to its balancing value in a few minutes. Then the input capacities to each amplifier are measured with a capacitance bridge, e.g., a General Radio Type 650-A, by disconnecting the inputs to the cathode-ray oscilloscope and connecting them separately to the bridge. The relative sensitivities of the two gages can then be calculated from the equation

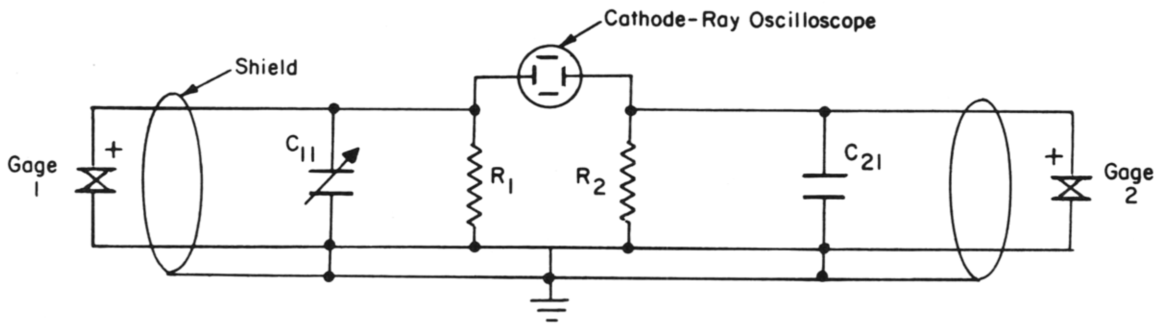

Figure 3 – Circuit for Measuring Relative Sensitivities of Two Piezoelectric Gages

$$\frac{(KA)_1}{(KA)_2} = \frac{C_1}{C_2} \qquad [3]$$

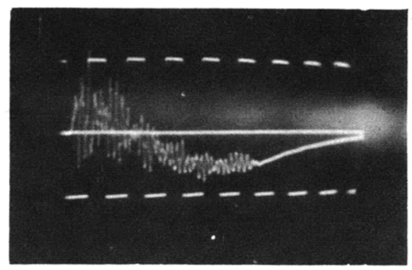

Figure 4 – Oscillogram of Difference Voltage Signal from Two Gages in Test Chamber

$(KA)_1$ is the polarization charge generated by piezoelectric gage 1 per unit applied pressure. C_1 is the *total* input capacitance of the Circuit of gage 1 and includes the terminal capacitance C_{11}, the parallel gage capacitance, and any shunt capacitance in the leads. The subscript 2 refers to the other gage and its circuit.

The precision with which the relative sensitivities of the two piezoelectric gages can be measured with this circuit depends in part on the precision with which a null voltage can be reached. An absolutely null voltage is never reached because the higher modes are not the same at the two gage locations. Figure 4 is an oscillogram of the residual difference voltage between the two gages whose outputs were shown separately in Figure 2. The cathode-ray gain has been increased in Figure 4, so that the amplitude of the calibration voltage is now 1/10th as much as in Figure 2. It appears that the residual voltage (averaging out the harmonics) is about 1 percent of the peak voltage in Figure 2.

If there is appreciable difference in the sensitivities of the two piezoelectric gages, there would have to be a like difference in the capacitances for the two circuits at balance, and the time constants (RC) of the two circuits would be different. This might cause some error in the null balance. In that event, the time constants of the two circuits can be made about the same by shunting one of the inputs of the amplifier until R_1C_1 is approximately equal to R_2C_2.

Another circuit for comparing two piezoelectric gages is shown in Figure 5. The two gages are connected in series across the single input R_1 of the amplifier for the cathode-ray oscilloscope. There is no need to match the gains of two sides of the amplifier. In fact, the method is completely independent of the characteristics of the amplifier. Furthermore, the

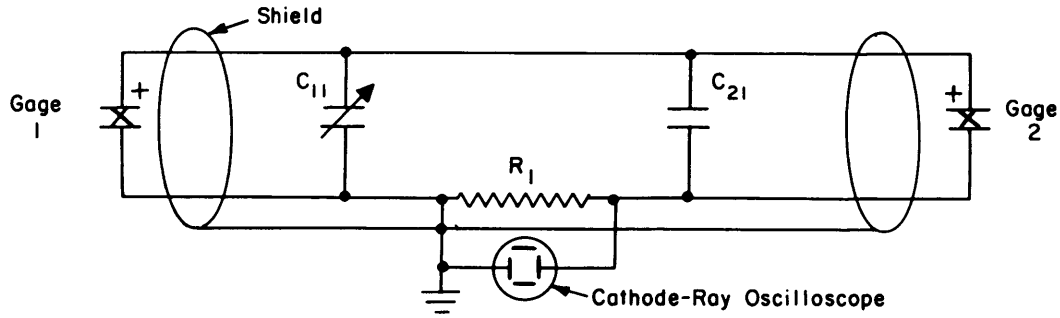

Figure 5 – Alternate Circuit for Measuring Relative Sensitivities of Two Piezoelectric Gages

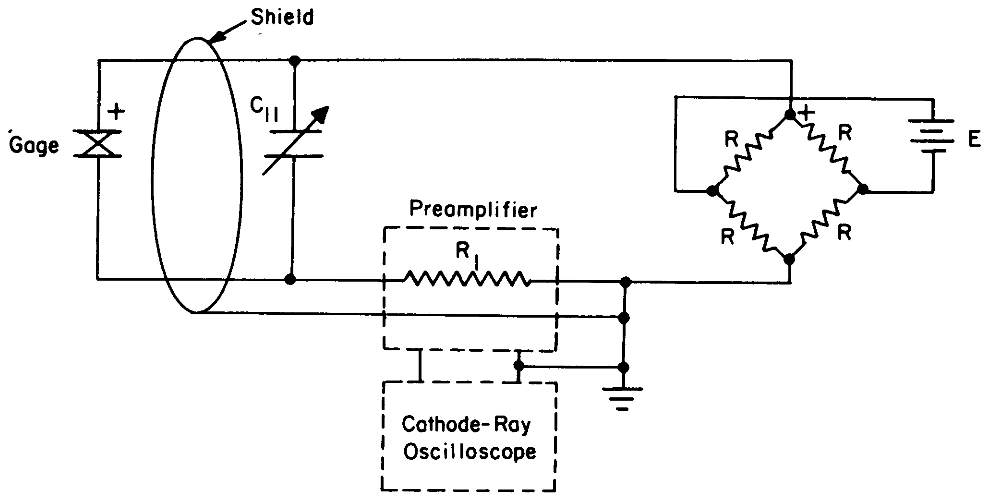

Figure 6 – Circuit for Measuring Relative Sensitivities of Piezoelectric Gage and Resistance-Bridge Gage

signals from the two gages have the same time constant. When C_{11} is adjusted to give a null voltage signal across the cathode-ray oscilloscope, the relative sensitivities are given by

$$\frac{(KA)_1}{(KA)_2} = \frac{C_1}{C_2} \qquad [4]$$

where C_1 and C_2 are, as before, the total circuit capacitance on each side, including gage capacitance and cable capacitance. This condition is derived in Appendix B. Since this circuit requires both sides of one of the two piezoelectric gages to have a high resistance to ground, the gage must be constructed to permit this with adequate shielding. If both gages are already mounted on coaxial cable, a second shield should be placed over one cable and connected to ground.

Figure 6 shows a circuit to be used in comparing a piezoelectric gage with a low-impedance, resistance-bridge, diaphragm pressure gage as a reference, or vice versa. The voltage signal from the low-impedance gage opposes that from the piezoelectric gage, and the difference voltage is detected with the cathode-ray oscilloscope. R_1 is the input resistance of the preamplifier to the cathode-ray oscilloscope. A preamplifier may be necessary because the output voltage of the low-impedance gage is ordinarily of the order of 10 mv to 20 mv, and the difference voltage between this and the output of the piezoelectric gage should be reduced to 0.1 mv if any precision is expected in the calibration. The procedure in using this circuit is the same as before. The capacitor C_{11} is varied until a null balance is achieved at the time of the peak pressure in the pulse. Then the relative sensitivity of the two gages is given by

$$\frac{KA}{F} = C_1 E \qquad [5]$$

where C_1 again is the total input capacitance of the circuit to the preamplifier, E is the d-c voltage applied to the bridge of the low-impedance gage, and F is the bridge factor of the low-impedance gage and is defined as the open-circuit output voltage per unit bridge voltage and per unit applied pressure. F must be known independently, or the equation can be reversed to give F in terms of known values of KA. Equation [5] can be derived by the same type of circuit analysis as was given in Appendix B for Equation [4].

An alternate circuit for comparing a piezoelectric gage with a resistance-bridge gage is shown in Figure 7. In this latter circuit, the bridge is in series with the terminal capacitor C_{11}, and the condition for a null balance is

$$\frac{KA}{F} = C_{11} E \qquad [6]$$

where C_{11} is only the terminal capacitance and does not include the gage capacitance or cable capacitance.

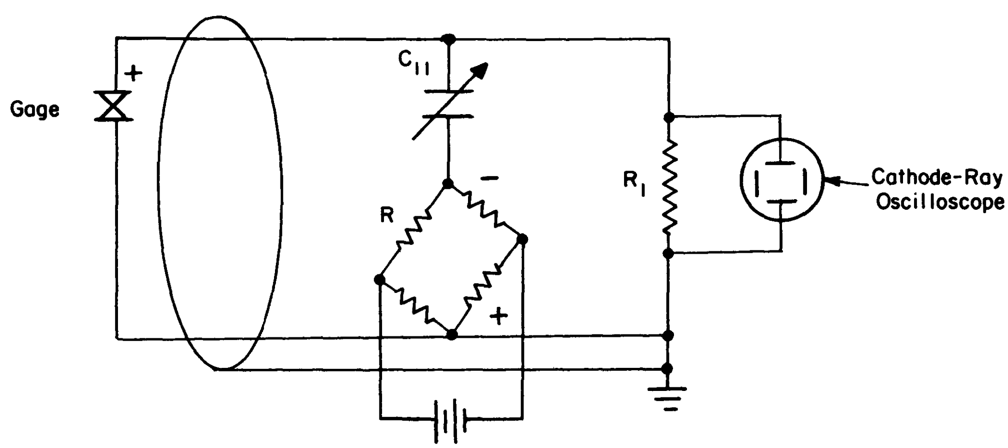

Figure 7 – Alternate Circuit for Measuring Relative Sensitivities of Piezoelectric Gage and Resistance-Bridge Gage

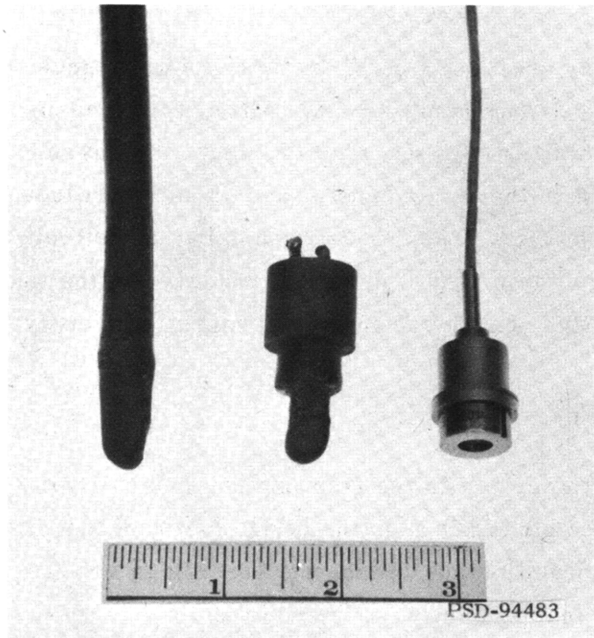

Figure 8 – Pressure Gages Tested by Null-Method Calibration

TEST RESULTS

These techniques have been used to obtain dynamic calibrations of seven gages of which six are ¼-in., 4-ply, tourmaline-crystal gages from Crystal Research, Inc., and one is a diaphragm pressure gage, Consolidated Engineering Corp. Type 4-311. Three of the piezoelectric gages were mounted on Simplex coaxial antimicrophonic cable and were insulated with coats of Bostick and Gaco Neoprene. Three of the piezoelectric gages were mounted on lead wires in a solid micarta bushing and were insulated with very thin coats of Gaco Neoprene and some Bostick at the base. The diaphragm gage is about 5/8 in. in diameter, with a flush diaphragm and with a sensing element made of a bridge of unbonded strain-gage wires. The gage types are shown in Figure 8.. All gages are listed in Table 1 together with their sensitivities as measured by various techniques.

TABLE 1 – Pressure Gages and Their Sensitivities

Most sensitivities are average values; the number of tests is indicated in parentheses.

1	2	3	4	5	6	7*	8
Gage	Mounting	Mfg. Calibration	TMB Bursting Diaphragm	NOL Microcoulometer	TMB Underwater Explosion	Null Method Calibration	TMB Static Test
Sensitivity in micromicrocoulombs per psi							
562	Cable	2.25	--	--	2.31(7)	2.15	
563	Cable	2.15	--	--	2.18(5)	2.06	
566	Cable	1.65	--	--	1.98(5)	1.59	
119	Bushing	1.93	2.06 ±0.02(6)	1.93 ±0.004(3)	--	[2.06]	
120	Bushing	1.91	--	1.96 ±0.007(3)	--	2.05	
121	Bushing	1.93	--	--	--	2.01	
Sensitivity in microvolts per volt per psi							
CEC 4-311	Flush Diaphragm	1.04	1.09 ±0.02(7)		--	1.03	1.04(2)

*Deduced from the third column of Table 2 as described in Appendix D.

An interesting feature of the measurements is a signal which appears to be associated with cavitation in the liquid. The phenomenon is described in Appendix C.

DISCUSSION OF RESULTS

All the manufacturers' calibrations listed in Column 3 were made on unmounted gages; all other calibrations were made with mounted gages. The calibrations in Column 4 were made by the bursting diaphragm method in the chamber of Figure 1 with the piston hole sealed off and with a cathode-ray oscilloscope to record the signal. The calibrations listed in Column 5 were kindly made by the Underwater Explosions Division of the Naval Ordnance Laboratory with their apparatus which uses a quick-opening valve to release the pressure and a micro-coulometer with about a 1-sec response time to measure the signal. This is presumably the same technique used by Crystal Research, Inc. The calibrations of Column 6 were obtained by exposing the gages to an underwater explosion of 1.05 lb of pentolite at a standoff of 8.0 ft and assuming that the peak pressure was 2130 psi as given in Reference 1. This last method is probably the least reliable. For the low-impedance diaphragm gage, the static calibrations were made by applying known static pressures with a dead-weight controlled hand pump and measuring the bridge unbalance with a Baldwin SR4 strain indicator. Column 7 lists the sensitivities as determined by the dynamic method of this report. They will be explained subsequently.

The immediate results of the dynamic calibrations by the null method are listed in Table 2. Those with the piezoelectric gages were made with the circuits of Figures 3 and 5; those with the CEC gage were made with the circuit of Figure 6. Table 2 lists only the *relative* sensitivity of the two gages in each test because only relative values are directly determined. The relative sensitivity can also be computed for the piezoelectric gages from the manufacturers' calibration data listed in Table 1. These computed data are also listed in Table 2 for comparison with the null-method data. It appears that the data are in good agreement. The maximum difference in the two columns of relative sensitivity data is 3 percent.

In order to translate the relative sensitivity measurements into absolute calibrations for each gage, it is necessary to accept a calibration of at least one gage (from Table 1) as an accurate reference standard. It had originally been intended to use the CEC diaphragm gage for this purpose because it had been anticipated that this gage would have a unique, linear, and reliable calibration over the pressure range and the frequencies of interest. The static calibration of the gage was reproducible and linear within 1 percent of its nominal value. There were no apparent insulation or mounting problems to affect the gage, and the dynamic tests showed no resonance frequencies below about 13,000 cps in water. However, the calibration tests using a sudden pressure release showed the gage to have about a 5 percent greater response than to statically applied pressures. The reasons are unknown, but, until the differences can be resolved, the CEC diaphragm gage cannot be used as a reliable,

TABLE 2

Relative Sensitivities Measured by Null Method and Computed from Other Methods

Gage 1	Gage 2	Sensitivity Gage 1 / Sensitivity Gage 2: Null Method	Sensitivity Gage 1 / Sensitivity Gage 2: From Table 1, Column 3
562	563	1.05 ±0.01(3)	1.05
563	566	1.29 ±0.02(3)	1.30
566	562	0.73 ±0.01(3)	0.73
120	119	0.99 ±0.01(2)	0.99
121	120	0.98 ±0.00(2)	1.01
562	CEC	2.06 ±0.09(11) microcoulombs	
563	CEC	2.03 ±0.03(6) microcoulombs	
566	CEC	1.83 ±0.04(12) microcoulombs	
119	CEC	1.99 ±0.02(2) microcoulombs	
120	CEC	1.98 ±0.02(3) microcoulombs	
121	CEC	1.96(1) microcoulombs	

unequivocal reference standard for these calibrations. Furthermore, it is not apparent that any of the piezoelectric gages can be used as unequivocal standards because these also appear to show higher sensitivities when measured by a method which releases the pressure quickly and measures the signal quickly (before it can be modified by any signal due to the pyroelectric effect). Thus the TMB calibration of Gage 119 by a "fast" method is about 6 percent higher than the value determined by the Naval Ordnance Laboratory. The errors due to the pyroelectric effect had previously been amply confirmed in the experiments described in Reference 4.

Hence an unequivocal choice of the reference standard is not possible, and the choice is largely a subjective matter with the presently available evidence. The "bursting diaphragm—cathode-ray oscilloscope" calibration of Gage 119 has been chosen as the reference standard. This gage was chosen because some reasons can be given for suspecting errors in all the other calibrations, but, except for the greater difficulty in making the test, there is no apparent cause for error in a method which releases the pressure and measures the signal in times which are short compared with the decay time of the circuit and with the time for temperature effects to modify the signal.

With this choice that $(KA)_{119} = 2.06 \times 10^{-12}$ coulombs per psi, the data of Table 2 relating to Gages 120, 121, and the CEC gage were worked up to give the sensitivities of these gages, and thence the data relating to Gages 562, 563, and 566 were used to calculate the sensitivities of the latter gages. The method employed is explained in Appendix D and gives equal weight to each of the measurements of Table 2. The results are shown in Column 7 of Table 1.

The null-method results show no consistent pattern when compared with the manuufacturers' calibrations. For Gages 562, 563, and 566, the new calibrations are about 5 percent lower than those of the manufacturers. For Gages 119, 120, and 121, the new calibrations are about 5 percent higher than those of the manufacturer. The apparent decrease in sensitivity of the first set of gages may be due to the presence of the coating and insulation, but this explanation is largely speculative.

In general, then, the "pressure-pulse-null-method" calibration technique has a precision approaching 1 percent, which compares with other standard methods of calibration. However, the various methods may yield mean values which differ by 5 to 10 percent, and it is not yet known which method is most accurate. Such differences may be partly responsible for the reported differences in the pressures from TNT charges as measured by British and American sources. The situation might be clarified if a "round-robin" of calibration measurements of selected piezoelectric gages is made by several laboratories in the United States and Great Britain.

CONCLUSIONS

The null method has the advantages that no recording is required and that a dynamic response is measured. The method, like other standard methods, yields results that are self-consistent. However, the various methods of calibrating gages for the measurement of explosion pressures yield values which differ by 5 to 10 percent. No certain explanation is known for the differences, and there is no way, at present, of determining which methods are most accurate. A start may be made by a program of round-robin calibration tests of piezoelectric gages.

APPENDIX A

PRESSURE DISTRIBUTION IN CHAMBER

A simplified problem will be considered: To find the pressure variation in a uniform, rigid tube filled with water, closed at one end, with a free piston (with same diameter as tube) at the other end which is suddenly given an initial velocity into the tube.

Let $u(x, t)$ be the particle displacement of the liquid layer at distance x from the closed end at time t after impact,

v be the initial velocity of the piston,

m be the mass per unit area of the piston,

y be its displacement at time t,

ρ be the density of water,

c be the velocity of sound in water, and

a be the length of the tube.

Then the differential equation which describes the action in the water is the wave equation

$$\frac{\partial^2 u}{\partial x^2} - \frac{1}{c^2}\frac{\partial^2 u}{\partial t^2} = 0 \qquad [7]$$

The initial conditions are

$$u = \frac{\partial u}{\partial t} = 0 \text{ for } t = 0, \text{ all } x \qquad [8]$$

$$\frac{dy}{dt} = -v \text{ for } t = 0 \qquad [9]$$

and the boundary conditions are

$$\rho c^2 \left(\frac{\partial u}{\partial x}\right)_{x = a} = -m\frac{\partial^2 y}{\partial t^2} \qquad [10]$$

$$u = 0 \text{ for } x = 0, \text{ all } t \qquad [11]$$

This system of equations can be solved by using Laplace transforms to give $u(x, t)$ and then to give the pressure in the chamber $P = -\rho c^2 \frac{\partial u}{\partial x}$

$$P = 2\rho c v \sum_n \frac{\cos \alpha_n \sin(ct\ \alpha_n/a)\cos(x\ \alpha_n/a)}{\alpha_n + \sin \alpha_n \cos \alpha_n} \qquad [12]$$

where the summation is taken over all the positive roots of

$$\alpha_n \tan \alpha_n = \frac{\rho a}{m} \qquad [13]$$

Hence the pressure in the tube can be considered as a superposition of contributions from a series of normal modes whose characteristics depend on the values of α_n and thus on $\rho\, a/m$. Each mode contributes a pressure which varies harmonically in space and in time with a wavelength $\frac{2\pi a}{\alpha_n}$, a period $\frac{2\pi a}{c\alpha_n}$, and an amplitude $\frac{2\rho c v \cos \alpha_n}{\alpha + \sin \alpha_n \cos \alpha_n}$.

If the mass of the piston plus hammer is much larger than that of the water in the tube, i.e., if $m \gg \rho a$, then the roots of Equation [13] are easily estimated to be

$$\alpha_1 \doteq \sqrt{\frac{\rho a}{m}} = \sqrt{\frac{L}{M}} \qquad [14]$$

$$\alpha_n \doteq 2(n-1)\pi \left[1 + \frac{L}{M}\,\frac{1}{(4n-2)^2}\right] \doteq (n-1)\,2\pi \quad n \geq 2 \qquad [15]$$

where L and M are defined on page 4.

$$\begin{aligned} P \doteq{} & \rho c v \sqrt{\frac{M}{L}} \sin\left(\sqrt{\frac{L}{M}}\frac{ct}{a}\right) \cos\left(\sqrt{\frac{L}{M}}\frac{x}{a}\right) \\ & + \sum_{n \geq 2} \frac{\rho c v}{(n-1)2\pi} \sin\left[(n-1)\frac{2\pi ct}{a}\right] \cos\left[(n-1)\frac{2\pi x}{a}\right] \end{aligned} \qquad [16]$$

The contribution of the lowest mode can also be written

$$P_1 = \rho c v \sqrt{\frac{M}{L}} \sin\left(\frac{\rho\, cAt}{\sqrt{ML}}\right) \cos\left(\sqrt{\frac{L}{M}}\ \frac{x}{a}\right) \qquad [17]$$

This agrees with Equation [2] previously derived for the chamber except that the Equation [2] was not restricted to uniform cylinders and does not show the variation of pressure with position that is given by the cosine factor of [17]. The maximum pressure difference in the tube, in the fundamental mode, due to this cosine factor is $\left(1 - \cos\sqrt{\frac{L}{M}}\right) = 6.5$ percent. Hence we might expect the same approximate pressure gradient in the actual chamber, i.e., about 6.5-percent pressure difference over the length of the chamber, or maybe 2-percent difference at the two piezoelectric gage locations.

With this same assumption that $M \gg L$, the higher modes in the chamber are seen to be harmonics of each other, and the wave lengths are integral fractions of the chamber length. The amplitude of the second mode is about 6 percent of the fundamental. The amplitude of the next higher mode should be one-half of that. or about 3 percent of the fundamental, etc.

APPENDIX B

NULL-BALANCE CIRCUIT

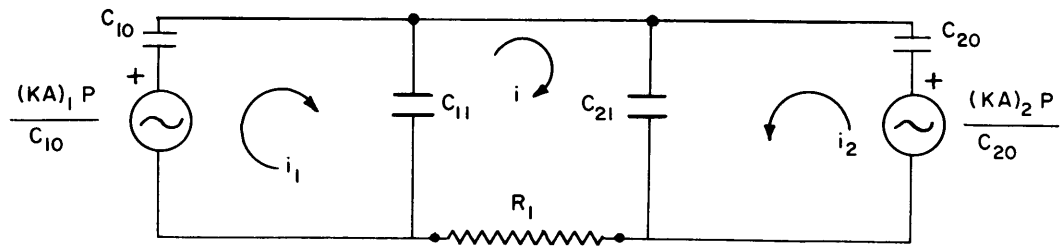

Figure 9 – Equivalent Circuit for Figure 5

The equivalent circuit for the comparison of two piezoelectric gages is shown in Figure 9. Each gage is equivalent to a generator of $emf = \frac{KAP}{C_0}$ and output impedance C_0 equal to the capacitance of the gage itself. C_{11} and C_{21} are the terminal capacitances in each circuit. R_1 is the input impedance of the detector. $P(t)$ varies in some arbitrary way with time. Take the partial currents i_1, i_2, and i as indicated and consider the Laplace transform of each circulating current:

$$\bar{i}(p) = \int_0^\infty e^{-pt}\, i(t)\, dt$$

then

$$\bar{i}\left(R_1 + \frac{1}{pc_{11}} + \frac{1}{pc_{21}}\right) - \bar{i}_1 \frac{1}{pc_{11}} + \bar{i}_2 \frac{1}{pc_{21}} = 0$$

$$-\bar{i}\frac{1}{pc_{11}} + \bar{i}_1\left(\frac{1}{pc_{11}} + \frac{1}{pc_{10}}\right) = \frac{(KA)_1 P}{C_{10}}$$

$$+\bar{i}\frac{1}{pc_{21}} + \bar{i}_2\left(\frac{1}{pc_{21}} + \frac{1}{pc_{20}}\right) = \frac{(KA)_2 P}{C_{20}}$$

The equations can be solved for $\overline{V} = \bar{\imath} R$, which is the transform of the voltage across the detector.

$$\overline{V} = \left[\frac{(KA)_1}{C_{10} + C_{11}} - \frac{(KA)_2}{C_{20} + C_{21}} \right] \frac{p\overline{P}}{p + \dfrac{1}{R_1(C_{10} + C_{11})} + \dfrac{1}{R_1(C_{20} + C_{21})}}$$

$V(t)$ depends upon $P(t)$ which has not been specified. But even without specifying $P(t)$, it is obvious that the amplitude of V is proportional to the factor in brackets and that $V(t)$ has a decay time (to a step pressure pulse) of $R_1 C$ where $\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$ and C_1 and C_2 are the total capacitances of circuits 1 and 2, respectively. Hence the conditions for a null balance $V(t) \equiv 0$ or $V(p) \equiv 0$ is that

$$\frac{(KA)_1}{(KA)_2} = \frac{C_{10} + C_{11}}{C_{20} + C_{21}} = \frac{C_1}{C_2} \qquad [18]$$

The circuits of Figure 6 and 7 for the comparison of a piezoelectric gage and a resistance-bridge gage can be analyzed in a similar way. It should be remembered that the equivalent circuit of the resistance-bridge gage is simply a generator with an *emf* of $FEP(t)$ and a output impedance R equal to the bridge resistance.

APPENDIX C

CAVITATION PRESSURES

If there were no energy losses and no cavitation, the piston in the chamber would oscillate about the equilibrium position and the liquid would alternately compress and expand with equal amplitude. However, the records show that cavitation occurs when the tension becomes excessive. Note in Figure 2, where the timing marks are 1 msec apart, that the pressure signals are sharply cut off about a millisecond after the chamber pressure drops below the zero axis which corresponds to atmospheric pressure. The same cut-off occurs when the pressures are measured with the diaphragm gage. At this time, the measured pressures, on this and other oscillograms, range from 160 to 195 psi below atmospheric, or from −145 to −180 psia. It has sometimes been assumed in underwater explosion research that cavitation occurs whenever any absolute tension occurs in the water. These data, however, indicate that even tap water can withstand tensions of the order of 150 psi for a millisecond or so. Cavitation effects were not investigated in detail, and it is not known just where in the chamber the cavitation occurred.

The fact that there may be appreciable tensions in the water may be of some consequence to the use of the apparatus to calibrate gages. For this means that the piezoelectric gages themselves may be subject to appreciable tensions, and the construction of the gage must be such as to permit this without harm to the gage. It was conceivable that the conductive coating on the crystal, or the insulation coating, might separate under sufficient tension but there was no indication of any damage to the piezoelectric gages because of repeated tension pulses.

APPENDIX D

CALCULATION OF SENSITIVITIES

The problem is to compute a series of "best" values for the sensitivities of the seven gages from the relative sensitivity measurements relating to $(KA)_{120}$ in Table 2. Assuming they are equally reliable

$$3(KA)_{120} = 1.02(KA)_{121} + 1.98F + 0.99(KA)_{119}$$

Similar equations can be written for $(KA)_{121}$ and $(KA)_{119}$ giving the set of simultaneous equations

$$1.01(KA)_{120} + 1.99F = 4.12$$

$$3.00(KA)_{120} - 1.20(KA)_{121} - 1.98F = 2.04$$

$$0.98(KA)_{120} - 2(KA)_{121} + 1.96F = 0$$

which were solved to give

$$KA_{120} = 2.05; \qquad (KA)_{121} = 2.01; \qquad \text{and } F = 1.035$$

In like manner, there are three independent measurements of $(KA)_{562}$ and $(KA)_{563}$ and two of $(KA)_{566}$ in terms of F and of each other. (The relative sensitivities of Gage 566 and the CEC gage have been discarded because they are markedly inconsistent with the others.) These yield a new set of equations.

$$3.00(KA)_{562} - 1.05(KA)_{563} - 1.37(KA)_{566} = 2.12$$

$$-0.95(KA)_{562} + 3.00(KA)_{563} - 1.29(KA)_{566} = 2.09$$

$$-0.73(KA)_{562} - 0.78(KA)_{563} + 2.00(KA)_{566} = 0$$

which were solved to give

$$(KA)_{562} = 2.15; \qquad (KA)_{563} = 2.06; \qquad (KA)_{566} = 1.59$$

All values for KA are in micromicrocoulombs per psi. The values for F are in microvolts per volt per psi.

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1. Pressure gages – Calibration.
2. Underwater explosions – Pressure – Measurement.
I. Gesswein, Joseph
II. Chertock, George
III. NS 724-018.

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