A Gage for the Measurement of Transient Hydraulic Pressures

By

E. F. RICE

Instructor in General Engineering

Bulletin No. 32

October 1952

Engineering Experiment Station

Oregon State System of Higher Education

Oregon State College

Corvallis

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Foreword and Acknowledgments

The study reported in this bulletin was inspired by the need for a method of recording continuously the transient pressures obtained in hydraulic structures and their models. In particular, the writer was searching for a means of measuring and recording the fluctuating pressures within siphon spillway models that were being tested as part of a study for a doctoral thesis.

The writer gratefully acknowledges the counsel and encouragement of S. H. Graf, director of the Engineering Experiment Station. Professor Graf also made available funds for the completion of the project for publication.

Acknowledgment is also made of the assistance of Roy H. Shoemaker, Jr., of the Department of Civil Engineering, and Raymond M. Lockwood of the Department of General Engineering, for their aid in the experimental work and for their valuable suggestions. As Mr. Shoemaker had previously constructed and tested a pressure cell of similar characteristics, his suggestions were particularly pertinent.

Professor G. W. Holcomb of the Department of Civil Engineering not only made available his laboratory and equipment, but also stimulated the original investigation by his helpful comments.

The writer also extends his appreciation to C. A. Mockmore, head of the Department of Civil Engineering, and to all others whose friendly encouragement aided in the completion of this report.

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A Gage for the Measurement of Transient Hydraulic Pressures

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I. Summary and Introduction

1. **Summary.** A pressure pickup was designed and calibrated for use in testing hydraulic laboratory models and appurtenances. An electric resistance strain gage was mounted on a brass diaphragm to respond to strain caused by pressure. When the diaphragm was placed in a "cell" that could be attached readily to a hydraulic structure, a pressure gage resulted that was rugged enough to withstand water hammer, yet sufficiently sensitive to measure surface waves in a small tank. The variations of resistance of the strain gage were amplified and recorded (as a measure of fluid pressure) by a "universal" strain analyzer and oscillograph. The gage was used for pressure measurement with a siphon spillway model, for measurement of water hammer, pump hammer, and for recording pipe line impact pressures of sonic frequency. It should be applicable also to studies of other phenomena such as cavitation and surge tank operation.

2. **Background.** Pressure measuring devices are of universal use in fluid mechanics laboratories and elsewhere. Of the numerous manometers, hook gages, piezometers, and the like, only two are commonly used to supply a continuous record: float gages and Bourdon tubes are frequently mounted to record comparatively slow fluctuations in liquid surface level or in fluid pressure.

In order to measure rapidly fluctuating pressures encountered in aerodynamic research, or to record the fleeting pressures incident to blast measurement, pressure pickups have been specially designed. Other devices have been placed in earthen dams and under highways to make records of pressure and of pressure changes.

3. **Purpose of study.** None of these special devices was adapted for use in measuring the high-frequency variations obtainable in an ordinary fluid mechanics laboratory. Accordingly, it was decided to design an instrument capable of measuring the transitory

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pressures obtained in hydraulic laboratory structures. Specifically, a device was wanted to record the fluctuations of pressure occurring in a siphon spillway model. Such a gage would have to be fairly sensitive, accurate, and yet reasonably rugged and inexpensive.

Several gages of all-plastic construction were made and found sensitive enough, but they were unreliable because of the non-linear stress-strain relationships and the plastic flow of the diaphragm.

A cell containing a brass diaphragm was found to be satisfactory, and it is the brass cell, equipped with diaphragms of two different thicknesses, that is the subject of this bulletin.

II. Fundamental Concepts

1. **General arrangement.** The pressure cell as installed for calibration appears in Figure 1. Calibration was accomplished by raising and lowering the water surface in a long tube. Tables 1 and 2 are records of the various water levels and the corresponding oscillograph pen deflections for each of the two diaphragms.

After calibration the gage was fitted to various pipes and models. Copper tubing was used for some and flexible plastic tubing for other installations. (It was found that short copper tubes are better suited for pressure cell mounting because of the damping

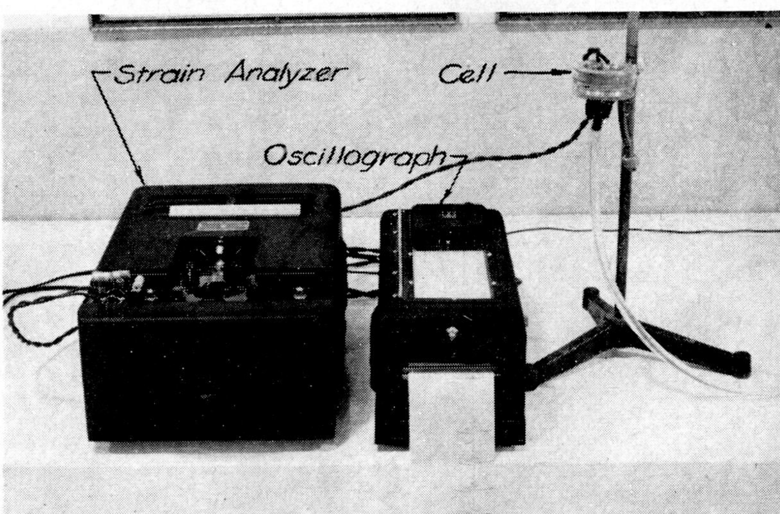

Figure 1. Pressure gage installed for calibration.

effect of the plastic tubing, and because of the distortion of the signal in long tubes of any material.)

The pressure cell was mounted as near as possible to the point of measurement. Electrical leads were run from the cell to the strain analyzer and oscillograph, which were placed on a sturdy table moved nearby.

2. **Diaphragms.** Two types of diaphragms were used. Type "A" was a piece of 0.010 inch brass shim stock soldered to a brass ring, as shown in Figures 2 and 3. Type "B" was a piece of 0.026 inch brass shim stock mounted the same as A, but not sweated to its brass ring.

Table 1. CALIBRATION OF 0.010 INCH BRASS DIAPHRAGM, TENSIONED

Reading	Staff gage	Pressure	Deflection lines
	Cm	*Cm of water*	
167	150.0	0.0	0 0
168	170.3	20.3	1.8
169	190.0	40.0	3.7
170	210.0	60 0	5.3
171	230.1	80.1	7.0
172	250 8	100.8	8.9
173	270.5	120.5	10.2
174	290.7	140 7	11.8
175	280.1	130.1	11.0
176	259.9	109.9	9.2
177	240.7	90.7	7.8
178	221.2	71.2	6 1
179	199.1	49.1	4.2
180	180.6	30 6	2.7
181	160.2	10.2	0.8
182	140 3	− 9.7	− 1.0
183	119.9	− 30.1	− 2.8
184	99.9	− 50.1	− 4.7
185	79.9	− 70 1	− 6.3
186	60.1	− 89.9	− 8.3
187	40.0	−110 0	−10 2
188	20.0	−130.0	−12.1
189	0.2	−149.8	−14.1
190	9.8	−140 2	−13.0
191	29.8	−120 2	−11.1
192	49.8	−100.2	− 9.2
193	69.9	− 80.1	− 7.2
194	90 1	− 59.9	− 5.3
195	110.0	− 40 0	− 3.4
196	130.0	− 20.0	− 1.7
197	150.0	0.0	0.0

Staff gage set initially at elevation 150.

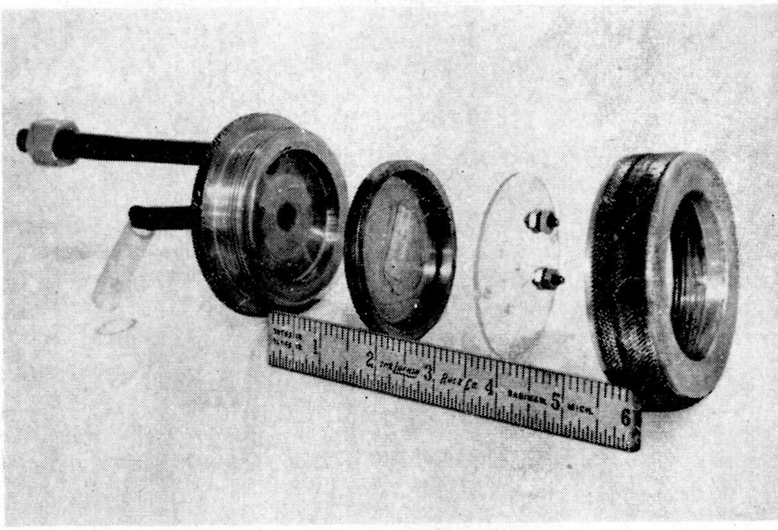

Figure 2. Exploded view of pressure cell.

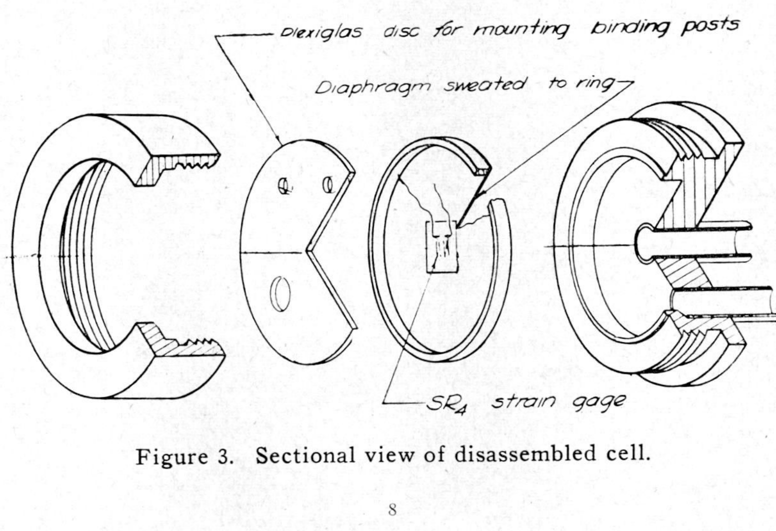

Figure 3. Sectional view of disassembled cell.

Table 2. CALIBRATION OF 0.026 INCH BRASS DIAPHRAGM

Reading	Staff gage	Pressure	Deflection lines
	Cm	*Cm of water*	
A	150.0	0.0	0.0
B	200 2	50 2	1.8
C	250.3	100 3	4.3
D	298 1	148.1	6.4
E	250 3	100.3	4.7
F	199.5	49.5	2.7
G	151.5	1.5	0.7
H	99.8	− 50.2	−1.7
I	50.0	−100.0	−4.0
J	0.2	−149.8	−6 2
K	50.0	−100 0	−4.7
L	99.6	− 50.4	−2 0
M	150 3	0.3	0.0
N	200.3	50.3	2.2
O	251.0	101.0	4.4
P	298.4	148.4	6.6
Q	250.7	100 7	4.7
R	199.0	49 0	2.5
S	150.0	0 0	0 1
T	100.3	− 49.7	−1.3
U	50.1	− 99.9	−3.8
V	0 2	−149.8	−6.1
W	50.3	− 99.7	−4.2
X	99.7	− 50.3	−1.9
Y	150.0	0.0	0.2

Staff gage set initially at elevation 150.

The A-type diaphragm was expected to stretch somewhat as it was clamped to the projecting ridge of its mating part, and thus avoid the "oilcan effect" of popping from one point of equilibrium to another.

Type B was expected to be flat and rigid enough to make pretensioning unnecessary. Apparently both gages worked as anticipated as no trouble occurred within the range tested.

3. **Strain gages.** SR-4 strain gages, type A-7, made by the Baldwin-Hamilton Corporation, Philadelphia 42, Pennsylvania, were used in all tests. These gages, whose active elements covered an area of $\frac{1}{8}$ in. x $\frac{1}{4}$ in. on the diaphragm, had a resistance of 120 ± 0.3 ohms and a gage factor of 1.93 ± 2 per cent.

4. **Strain analyzer and oscillograph.** A universal analyzer, model BL-320, and a model BL-201 direct-inking oscillograph, manufactured by the Brush Development Company of Cleveland, Ohio, were used throughout the tests. These instruments are normally used to analyze strains in structural elements.

The gage on the diaphragm acted as one leg of a Wheatstone bridge. The other three legs of the bridge circuit were precision resistors of the same rating as the strain gages. It was felt unnecessary for the purpose of this study to provide a temperature-compensating dummy gage in one leg of the bridge since the temperature of the air and water touching the diaphragm did not fluctuate appreciably during the tests. It is recommended, however, that under less favorable conditions a dummy gage be attached to pressure cells.

The analyzer and oscillograph combination is capable of handling vibrations up to a frequency of about 120 cycles/sec. The oscillograph could be operated at chart speeds of 1, 5, and 25 lines per second.

III. Design and Construction

1. **Diaphragm design.** Thin circular plates, clamped along their circumference, tend to have two positions of equilibrium when subjected to equal pressure on both faces. This phenomenon, which has been called the "oilcan effect," is due initially to the non-planar condition of the plate, and perhaps to the yielding of the support.

To avoid such an effect, designers of diaphragm-type instruments have (1) distorted the diaphragms intentionally, as in some types of barometers, (2) prestretched the material, or (3) used a thick diaphragm. The last two of these methods were tested during the course of this study.

The thin diaphragm has the advantage of high sensitivity, as it deflects readily under small pressures. It must be pretensioned, however, to avoid the effect mentioned above. It is limited in the amount of pressure it can handle, because at some pressure, positive or negative, it ceases to behave like a beam with tension on one side and compression on the other, and begins to act like a rubber balloon in tension all over. The calibration curve of such a diaphragm would be a straight line only at very low pressures.

Another property of a thin diaphragm is its comparatively large deflection. In deflecting, any diaphragm changes the volume of the pressure chamber of which it forms one wall. This change in volume must, of course, cause a motion of liquid in the tube. If this motion is of appreciable frequency and amplitude, damping of the signal by the pressure cell itself precludes accurate measurement.

For these reasons a thicker diaphragm was chosen for measurement of higher pressures. The main disadvantage of a thick diaphragm is that its deflection is relatively small so that the strain signal must be amplified more than for a thin diaphragm. Consequently, a thick diaphragm results in a gage less sensitive to slight changes in pressure.

A material of low elastic modulus would be welcome as a compromise, as a thick diaphragm of such material would exhibit most of the desirable characteristics mentioned above while retaining some of the sensitivity of the thinner brass. Unfortunately, nearly all available materials of low elastic modulus have a non-linear relation of stress and strain.

Brass was found to be an acceptable material, but in order to achieve satisfactory sensitivity with brass, the diaphragm thickness had to be selected consistent with the accuracy desired and with the intensity of pressure expected.

2. **Shell.** The housing, or shell, of the cell is important only in its function of providing a leakproof, rigid bearing for the diaphragm, and as a means of attaching it to the point of pressure measurement. The design used in these tests is shown in Figures 2 and 3.

Two holes were found to be necessary in order to fill the gage completely with water. It is difficult to get consistent measurements if a cell or its pressure line is only partly filled, so an extra hole was provided for bleeding-off entrapped air. This does not imply that the gage is unsuitable for measuring air pressure; the gage and its pressure line must either be entirely full or entirely empty to obtain reproducible results.

Some consideration was given to cutting a cavity in a brass block and sweating a diaphragm over it. Such a gage could undoubtedly be made simple, economical, and successful. (The plastic gages previously mentioned were of such a design.) The design finally selected for these tests was chosen because it lent itself to pretensioning and to changing diaphragms. The plexiglas disk provided a simple mount for the strain gage binding posts, in addition to forming a cushion to equalize bearing on the inner brass ring. A silicone stop-cock lubricant was used as lubricant and seal.

3. **Suggested modifications.** In addition to the solid block design mentioned above, it might be possible to mount a diaphragm on a housing of transparent material so that troublesome air pockets can be found and eliminated. A plastic base would be satisfactory for this purpose, and it would also provide an insulated mount for the binding posts. Glass, or plastic-impregnated glass fiber might be useful for diaphragms. It might even be desirable to design a gage with a permanently oil-filled cavity in order that strain gages might be mounted on both sides of the diaphragm. Properly placed in a bridge circuit, such an arrangement of gages would double the sen-

sitivity of a pressure cell while sacrificing none of its range. For specialized purposes, it would be possible to design a gage that would screw directly into a commercial pipe fitting at the point of pressure measurement to avoid the attenuation of signals due to fluid motion in a long tube.

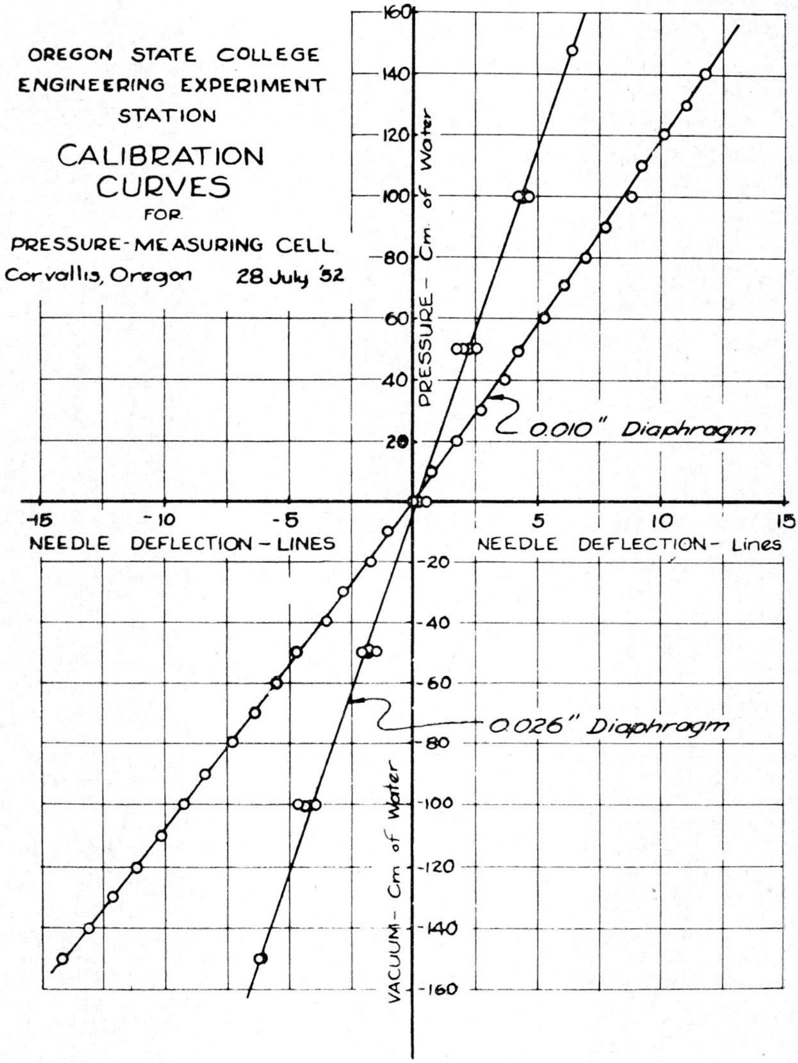

Figure 4. Calibration curves.

IV. Calibration

For calibration of the two diaphragms, the cell was mounted near a vertical glass water-tube that could be filled or emptied through suitable valves. So that the surface elevation of the water could be read to an accuracy of about one-tenth of a centimeter, graduated meter-bars were mounted on each side of the tube. Static pressure in the tube was transferred by a flexible plastic hose to the pressure cell mounted nearby. The instruments were so adjusted that the pen did not deflect from the center line of the chart for zero pressure on the gage. As the water level was raised or lowered with respect to the level of the gage, the pen would swing to the left or right of the chart centerline. The calibration curves of Figure 4 show the deflection in lines plotted against the pressure in centimeters of water. Note that while the data for the thick diaphragm plot has a straight line within the limits of chart readability, the curve for the thinner (stretched) diaphragm has a slight upward concavity.

V. Performance

1. **Water hammer.** Figures 5 and 6 are records of water hammer obtained by closing a valve at the discharge end of a length (about 35 feet) of 5/16 inch copper tubing. Water in the tube flowed by gravity from a tank whose surface elevation was about six feet above the level of the outlet.

2. **Siphon spillway operation.** Siphon spillways remain among the more mysterious of hydraulic structures, because of the scarcity of pressure records. Such structures operate at subatmospheric pressure, and cavitation occurs at the crests when the siphon operates under a head of one atmosphere or more.

Figures 7 and 8 are records of the variation of vacuum in a siphon spillway model.

3. **Pump hammer.** Figures 9 through 19 are records made of the unusual pulsations of a three-inch pump installed in the hydraulics laboratory at Oregon State College.

4. **Sonic pressure waves.** Figure 20 was taken at the highest chart speed. A pipe containing still water under pressure was struck a sharp blow with a hammer. It is interesting to note the rapidity with which the waves died out after about a fifth of a second of relatively constant amplitude.

VI. Discussion

1. **Precision of gage.** The gage tested had a precision limited chiefly by the maximum possible amplification of the signal. As may be seen from the various charts, the entire range of the instrument covers only 40 chart lines, or 20 lines on either side of the centerline, for a given amplification. (The gages used in these tests were operated at the highest obtainable amplification except for some of the more energetic pulses of pump hammer that had to be reduced by a factor of a fifth or a tenth.) For the diaphragms used, the gage moduli were about 12- and 23-cm of water per line of pen deflection, respectively, for the thin and thick diaphragms. Since chart readings are estimated to the tenth of a line, this implies a precision of plus or minus 1.2 and 2.3 cm of water.

In measurements of dynamic pressures, additional errors may be present due to the attenuation of signals in long approach tubes, and to the damping effect of flexible hoses and diaphragms as they yield and recover from pressure fluctuations. The magnitude and type of such errors are small for fluctuations of low frequency and/or low amplitude, and are relatively smaller for thick diaphragms than for thin. To minimize them in future tests, a short stiff tube should be used to connect the gage to the pressure point, or, better still, the gage should be attached directly to the structure with no intervening tube. In such cases larger openings would be desirable for the accurate measurement of wave shapes of high frequency and magnitude.

2. **Applicability to hydraulic laboratories.** Figures 5 to 20 illustrate the type of data that can be accumulated with a gage of this nature. Many other applications are possible. For a device to be practical for research or instruction in a laboratory, however, it must be versatile, rugged, and reasonably cheap. If the first cost can be met, its usefulness, accuracy, and freedom from "bugs" will be factors in its economy.

VII. Conclusions

1. Such gages as the one here described are simple and inexpensive to make and are simple to use; however, the necessary associated equipment is relatively quite costly.

2. Research in some fields can be promoted by the use of such an instrument.

3. Gages of this type are useful in the field of fluid mechanics, and the recording and amplification equipment are well-suited for use in other independent fields, such as structural strain analysis.

4. Modification along the lines suggested, and perhaps along other lines, might result in a device of even greater usefulness.

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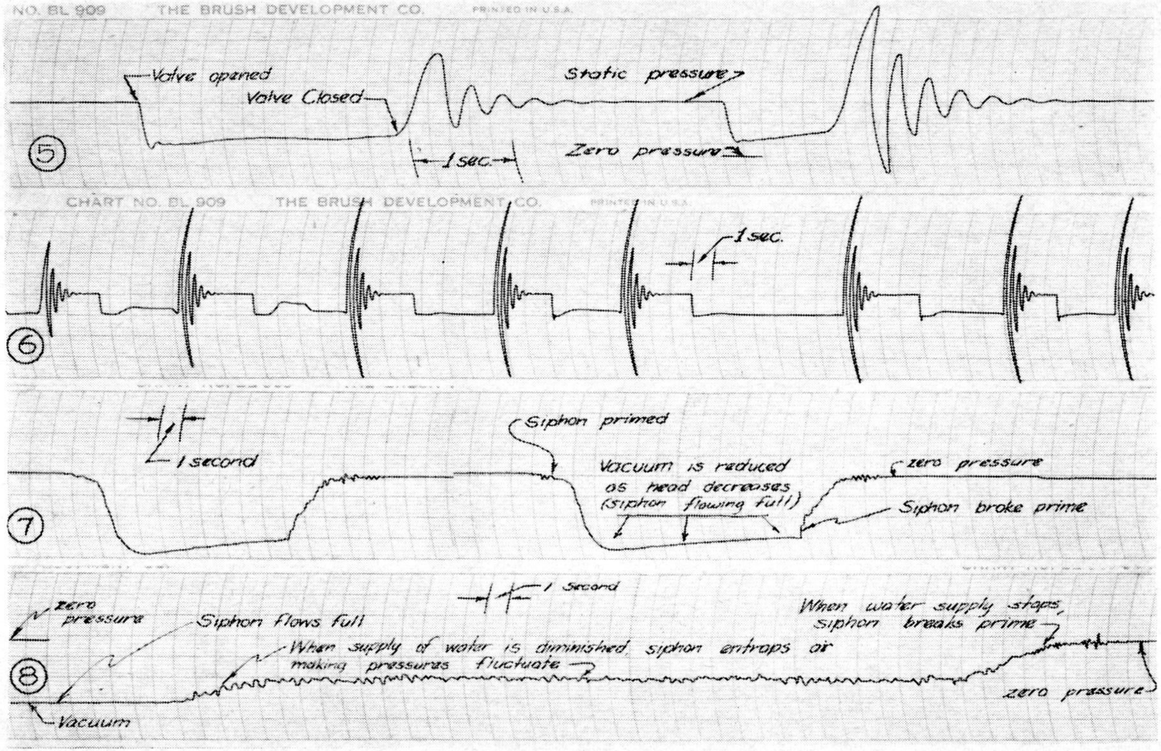
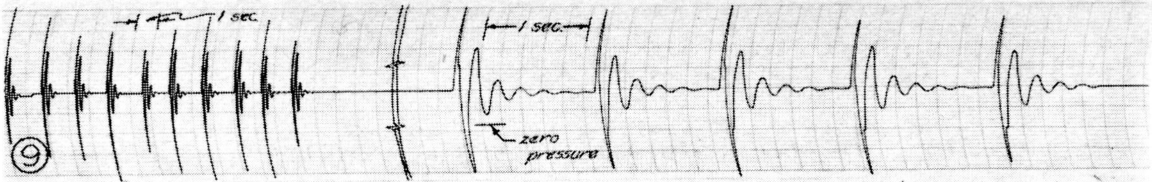


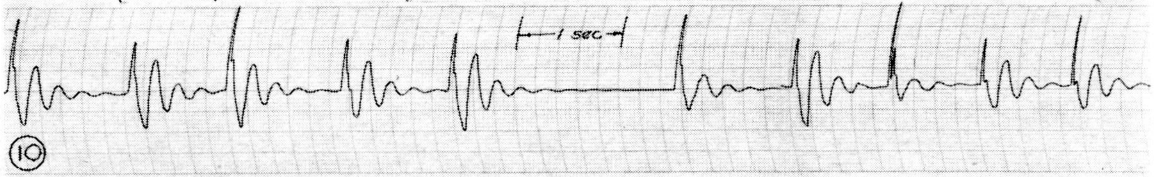
Figure 5. Water hammer is caused by suddenly stopping the flow through a conduit.

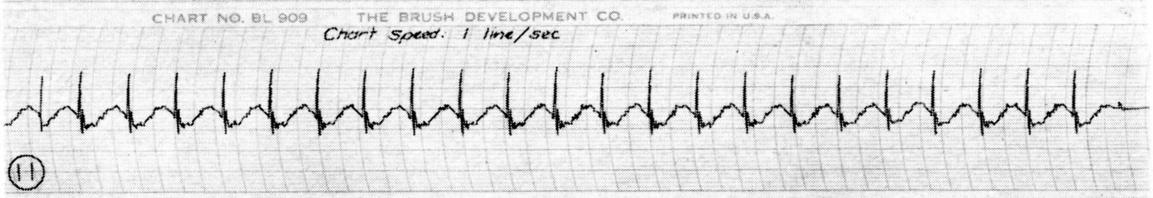
Figure 6. At reduced chart speed, water hammer shows as a more compressed curve. Chart motion is to the left.

Figure 7. Siphon spillway model exhibits strong vacuum as it primes and flows full.

Figure 8. Erratic negative pressures occur in a siphon spillway model flowing at partial capacity.







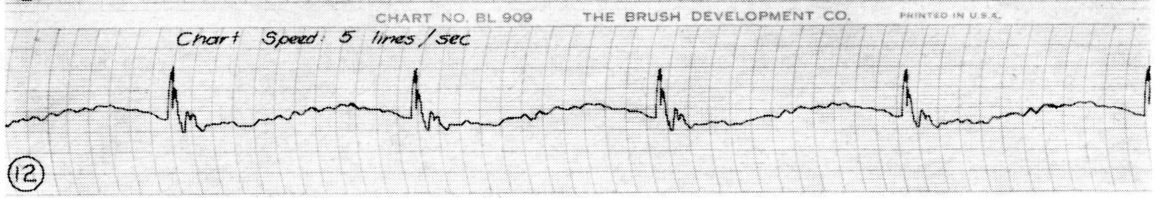


Figure 9. Pressure waves develop when a hose is subjected to impact, as when a vehicle crosses a fire hose. (These waves were caused by finger pressure on a laboratory tube.)

Figure 10. Dying wave groups result from manually squeezing a flexible plastic tube (Tigon).

Figure 11. Beat developed by a three-inch laboratory pump at low flow. Average pressure on gage: 24 psi.

Figure 12. At faster chart speed, beat curve is more legible.

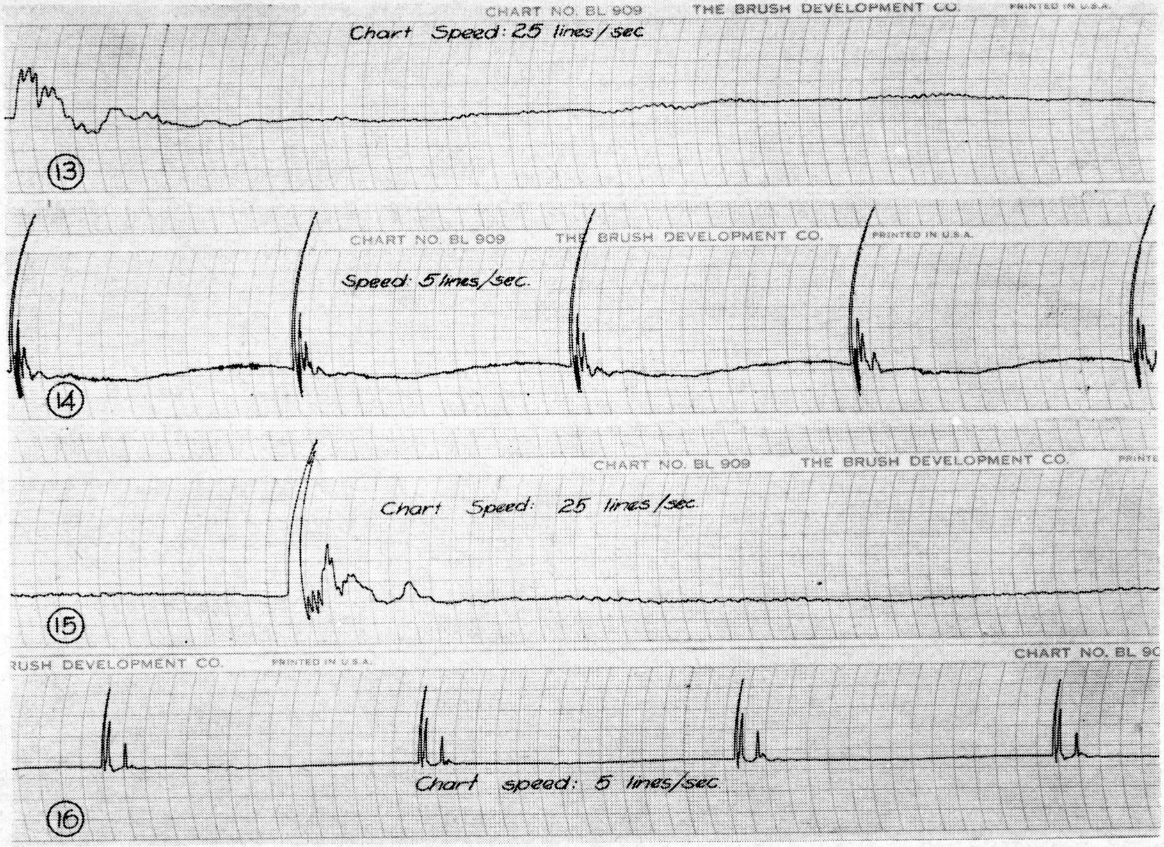
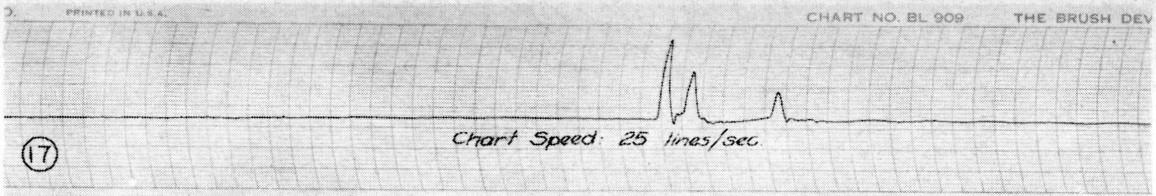


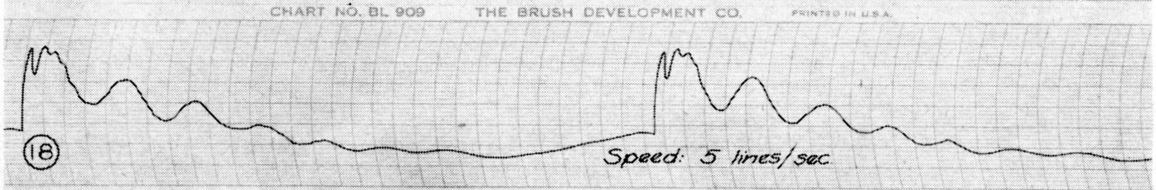
Figure 13. Chart speed is further increased for complete legibility.

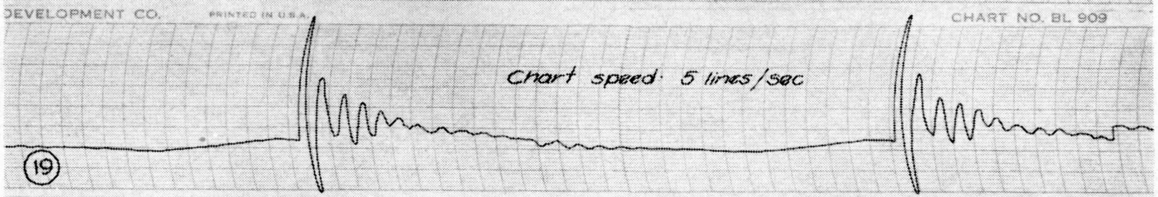
Figure 14. Higher pump speed changes frequency and form of beat.

Figure 15. One cycle of the beat in Figure 10 is shown at highest chart velocity.

Figure 16. Increased flow results in an entirely different form of beat.







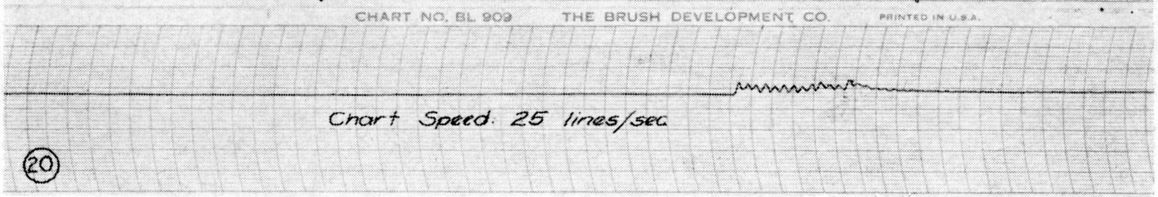


Figure 17. Increased flow results in an entirely different form of beat. (Same as Figure 16, but at increased chart speed.) Figures 16 and 17 have ordinates one-fifth of their true height by reduced amplification.

Figure 18. Unusual beat curve taken on the vacuum side of pump.

Figure 19. Pressure side of pump shows widely fluctuating pressure during beat.

Figure 20. Water pipe, hit with hammer, developed pressure fluctuations of about 62.5 cycles per second.

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