A SHOCK- AND VIBRATION-RESISTANT OSCILLOGRAPH GALVANOMETER

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A SHOCK- AND VIBRATION-RESISTANT

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PREFACE

The purpose of this thesis is to provide a limited discussion of the broad field of oscillograph galvanometers. Emphasis will be placed in the field of flight instrumentation. A detailed discussion of the development of an oscillograph galvanometer of the shock- and vibration-resistant type will be given.

The faster speeds and higher altitudes now associated with the air arm of our national defense have continuously caused component parts of missiles and aircraft to be subjected to increasingly rugged environments. Nowhere is this better recognized than in flight instrumentation.

During the flight of a missile, one of the easiest means of simultaneously collecting data from several points of interest on the missile is to record the information obtained from each point on a recording multichannel oscillograph. This is done by connecting the output voltages produced by the transducers (such as strain-gauges, accelerometers, etc.) to the current sensing elements of the oscillograph. These current sensing elements are nothing more than very special adaptations of the large laboratory galvanometers used for indicating either slowly varying or stationary current conditions.

In order for a galvanometer to be acceptable for use in an airborne oscillograph, it must satisfy stringent requirements with regards to reliability, static balance, frequency response, sensitivity, and shock and vibration resistance. A unit which meets these requirements has been developed.

This was accomplished by placing at strategic points three oil-filled capillary tubes around the moving-coil assembly. Then the viscosity of oil in the capillary tubes was adjusted so that maximum damping to external shock and vibration was obtained, along with a satisfactory frequency-response characteristic.

The author wishes to thank James L. Fisher and William R. Johnston for their significant contributions in developing this galvanometer and Century Electronics and Instruments, Tulsa, Oklahoma, where this research project was conducted, for the release of this material.

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CHAPTER I

INTRODUCTION

The basic arrangement of the modern galvanometer was devised by J. A. d'Arsonval in 1882. This arrangement consists of a coil of rectangular cross section and many turns of fine wire suspended on bearings or a gold ribbon so that it is free to rotate in a magnetic field.

The principle of operation depends upon Ampere's Law which states that a conductor carrying current placed in a magnetic field will have a force exerted on it. The direction of this force will be orthogonal to the plane defined by the intersection of the conductor and a particular line of the magnetic field. In galvanometers of the oscillograph type, current is led into the coil by gold ribbons or small springs. These elements also serve as the control springs to return the coil to its initial position when the current is removed.

In general, very sensitive galvanometers which use gold ribbon as the bearings or pivots require a substantially vibrationless support and careful leveling to secure best results. However, the oscillograph galvanometer, which is the basic element of modern recording light-beam oscillographs, is an interesting modification of the permanent-magnet, moving-coil galvanometer. In the oscillograph galvanometer, the main requirement is that the moving coil assembly shall faithfully follow rapidly changing electrical phenomena.

To obtain this result, a moving coil of many turns is suspended on fine gold ribbon between the shaped poles of a powerful permanent magnet. A very small mirror is cemented directly to the ribbon conductor to obtain the lowest possible moment of inertia. In order to record with this galvanometer, an intense beam of light is focused on the mirror and reflected to a rapidly moving photosensitive medium. Galvanometers of this type may be built to respond to frequencies as high as 10,000 cycles per second and, in conjunction with oscillographs, may be used for power system studies, flight instrumentation, geophysical prospecting, and medical research.

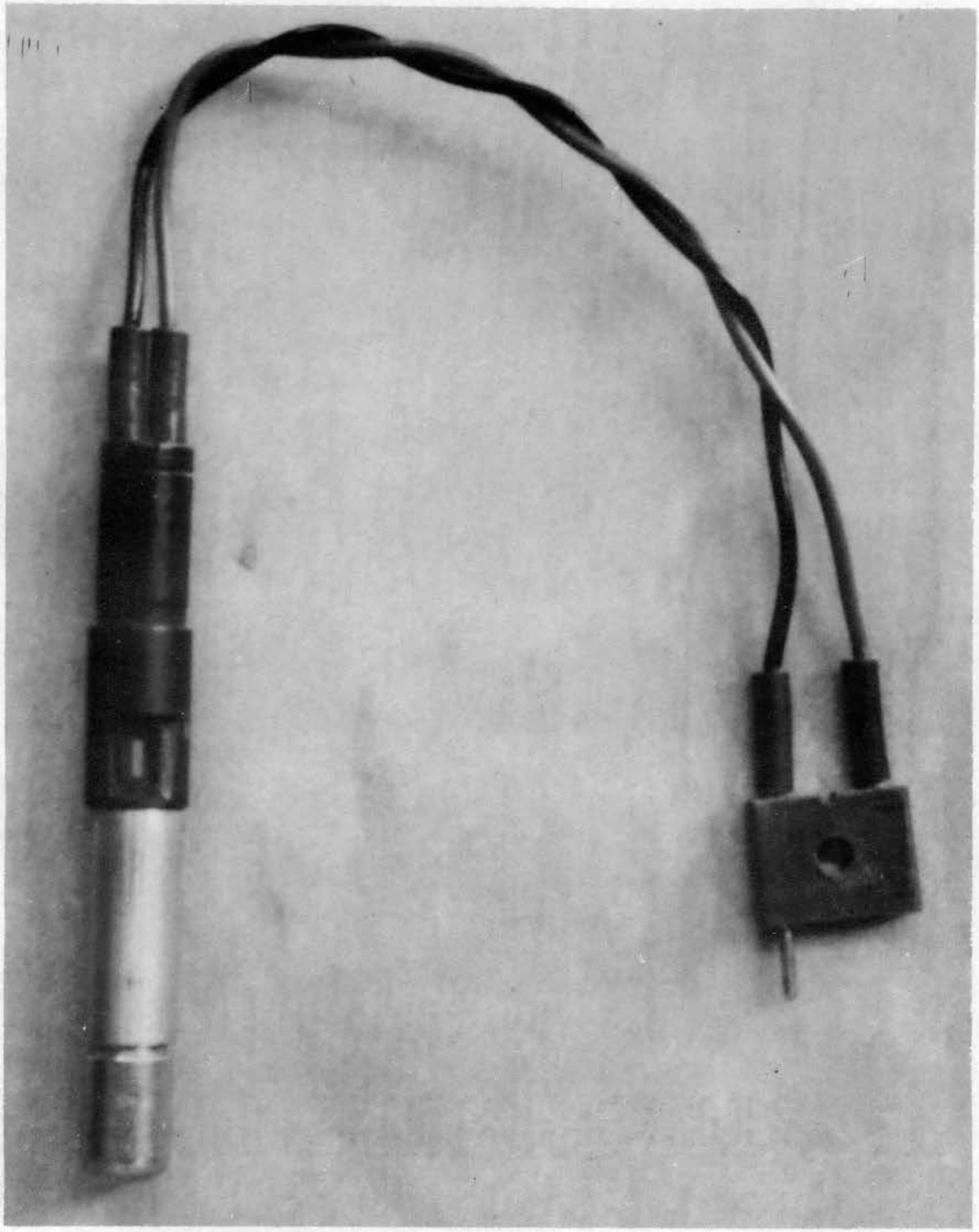
With the advent of more complex and high-speed aircraft and missiles, greater and greater demands have been placed on the instrumentation field to supply recording oscillographs that can withstand large accelerations over a wide frequency range of vibrations. Frequently these oscillographs are launched with a missile and parachuted to earth after a predetermined time; or they may be made part of a missile check-out system, where the missile is carried inside a plane and inserted into the slip stream when it is readied for a simulated firing. The insertion of the missile containing the oscillograph and galvanometers into the slip stream at speeds approaching Mach 2 causes vibrations of 2 to 2,000 cycles per second of approximately ±3 g magnitude, shock loads of approximately 30 g's, and constant accelerations of 10 g's.

The exact specifications the galvanometers must meet are sensitivity, coil resistance, balance, and frequency response specified under static conditions, and they must show no evidence of an intermittent open circuit, short circuit, or permanent physical damage after the following environments: (1) a temperature of 130°F for a period of 4 hours and a temperature of -50°F for a period of 4 hours, (2) a 15 g shock of 11-milliseconds duration in an operate condition, (3) a 30 g shock of 11-milliseconds duration in a nonoperating condition, (4) a 3 g operate and a 10 g nonoperate constant acceleration of 1 minute, (5) a ¼-inch double-amplitude sinusoidal vibration from 2 to 17½ cycles per second and a ±4 g sinusoidal vibration from 17½ to 300 cycles per second in a nonoperate condition, (6) a ±3 g sinusoidal vibration from 30 to 2,000 cycles per second in an operate condition. In addition, the galvanometers must (1) meet the sensitivity, frequency-response, and static-balance specifications during the two temperature environments, (2) recover in ½ second during the shock-operate test, (3) have the mirror reflection displaced from its original zero current position no more than ±0.020 inch at a 6.25-inches optical arm during the 3 g constant acceleration test, and (4) have buzzing or trace movement, except for two bands in the vibration test frequency range, of less than ±0.035 inch at a 6.25-inches optical arm during the operate part of the vibration test. Also during the vibration test, the product of the bandwidth and the excursion from zero to peak in the two bands where the buzz exceeds ± 0.035-inch amplitude shall be no greater than 0.012 inch, and the bandwidth shall be no greater than 0.20. In this instance, bandwidth shall be defined as $2(f_2 - f_1)/(f_2 + f_1)$ where f_2 and f_1 are the frequencies at which the excursion just exceeds ± 0.035 inch.

These requirements pose the major problem with which this thesis is to deal. However, along with this problem there are certain basic requirements the galvanometer must meet, even in static conditions, in order to indicate the electrical phenomena in which the missile user is interested. The more important static specifications briefly stated are: (1) a current sensitivity of 15.9 millimeter per microampere per meter optical arm in a magnetic field of 2,500 gauss; (2) a direct current resistance of less than 150 ohms; (3) a frequency response such that the galvanometer sensitivity at 5.0 cycles per second shall not decrease by more than 8 decibels (60%) of its 0.5 cycle per second value; and (4) a static balance such that for a 180° rotation around its longitudinal axis it shall drift no more than 2 millimeters at a 1-meter optical arm.

It might seem almost impossible to build a galvanometer of the specified sensitivity that could withstand these environmental conditions, but this problem has been solved.

In the suceeding chapters of this thesis, the author will describe a galvanometer that will withstand the required environments and the methods of approach used to reach this goal. It can be stated that approximately 100 galvanometers of this type have been in use in missile check-out systems for more than 6 months and are known to be performing satisfactorily. Figure 1 shows a photograph of this shock- and vibration-resistant galvanometer.



Note: Galvanometer length approximately 2 inches.

Figure 1. A Shock- and Vibration-Resistant Galvanometer.

CHAPTER II

MAJOR DESIGN CONSIDERATIONS

Since a very sensitive galvanometer is required, it is apparent that this galvanometer will have to be one of low frequency, because high sensitivity and high natural frequency are definately incompatible. This may be seen by examining the following formulas for natural frequency and current sensitivity, respectively:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{\Upsilon}{K}}$$

$$S_I = \frac{0.2\,MBlr_mN}{\Upsilon}$$

These formulas may be readily derived from the second order linear differential equation describing galvanometer motion. $K\,d^2\theta/dt + C\,d\theta/dt + \Upsilon\theta = 2Blr_mNi$ where

K = moment of inertia

θ = deflection angle

Υ = total torsional coefficient of the galvanometer ribbon

C = velocity damping coefficient

B = flux density

l = average length of the coil

r = mean radius arm of the middle winding

i = current in abamperes

N = number of turns

M = 2 times the optical lever in millimeters divided by 1,000

S_I = current sensitivity in millimeters deflection per millimeter

f_n = natural angular frequency in cycles per second

$2rln$ = coil area

For the natural frequency derivation, the damping and driving terms are zero. The equation then becomes

$K\, d^2\theta/dt^2 + \tau\theta = 0$ or $d^2\theta/dt^2 + \tau\theta/K = 0$ (3)

Letting D denote d/dt (3) may be written as $(D^2 + C^2)\,\theta = 0$ which has the general solution $\theta = A\cos\sqrt{\frac{\tau}{K}}\,t + B\sin\sqrt{\frac{\tau}{K}}\,t$ (4) where A and B are arbitrary constants. The displacement θ from the center of attraction at time t is given by (4) and the velocity at that instant will be

$$\frac{d\theta}{dt} = -\sqrt{\frac{\tau}{K}}\,A\sin\sqrt{\frac{\tau}{K}}\,t + \sqrt{\frac{\tau}{K}}\,B\cos\sqrt{\frac{\tau}{K}}\,t \qquad (5)$$

If θ and v_0 are, respectively, the displacement and velocity at $t = 0$, then $\theta = \theta_0$ and $v = d\theta/dt$ at $t = 0$. We can then solve for A and B by substituting in equations (4) and (5). Solving (3) and (4) we get $\theta_0 = A$ and $v_0 = \sqrt{\frac{\tau}{K}}\,B$

hence $\theta = \theta_0\cos\sqrt{\frac{\tau}{K}}\,t + \frac{v_0}{\sqrt{\tau/K}}\sin\sqrt{\frac{\tau}{K}}\,t$ or

$$\theta = a\sin\left(\sqrt{\frac{\tau}{K}}\,t + \alpha\right)$$

This is the equation of simple harmonic motion that oscillates between $\theta = \pm a$. The distance "a" from the center to either extreme position is the amplitude of the motion. The amplitude of the motion evidently depends upon the initial conditions.

Now let θ_1 and $(d\theta/dt)_1$ denote the displacement and velocity at any time t_1, then $\theta_1 = a\sin\left(\sqrt{\frac{\tau}{K}}\, t_1 + \alpha\right)$ (6)

$$\frac{d\theta}{dt_1} = \sqrt{\frac{\tau}{K}}\; a\cos\left(\sqrt{\frac{\tau}{K}}\, t_1 + \alpha\right) \qquad (7)$$

The smallest time interval T that must elapse before θ and $d\theta/dt$ again take on the values θ_1 and $(d\theta/dt)_1$, respectively, will be such that $\sin\left[\sqrt{\frac{\tau}{K}}\,(t_1 + T) + \alpha\right] = \sin\left(\sqrt{\frac{\tau}{K}}\, t_1 + \alpha\right)$,

and $\cos\left[\sqrt{\frac{\tau}{K}}\,(t_1 + T) + \alpha\right] = \cos\left(\sqrt{\frac{\tau}{K}}\, t_1 + \alpha\right)$.

However, these relations will hold true only if

$$\sqrt{\frac{\tau}{K}}\,(t_1 + T) + \alpha = \sqrt{\frac{\tau}{K}}\, t_1 + \alpha + 2\pi \quad \text{or}$$

$$T = \frac{2\pi}{\sqrt{\tau/K}}$$

and for no smaller value of T[1]. Therefore

$$f_n = \frac{1}{T} = \frac{\sqrt{\frac{\tau}{K}}}{2\pi} \qquad (8)$$

For the current sensitivity, the acceleration and velocity terms of the differential equation describing galvanometer motion are zero for the static condition. The equation then becomes $\tau\theta = 2Blr_mNi$ or

$$S_I = \theta/i = (2Blr_mN)/\tau \qquad (9)$$

Multiplying both sides of the equation by M, the optical multiplication factor, the sensitivity will be in millimeters deflection per one milliampere[2] or

$$S_I = (M\theta)/i = (2MBlr_mN)/(10K) = (0.2MBlr_mN)/\tau \qquad (10)$$

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[1]H. W. Reddick and F. H. Miller, Advanced Mathematics for Engineers (New York 1955), pp. 73-75

[2]C. A. Heiland and K. C. Rock, "Principles of Multichannel Oscillography," Proceedings of the Instrument Society of America, Volume 9, Part 5, 1954, Paper Number 54-46-1.

The corresponding paradox in using a low-frequency galvanometer is that the suspension ribbon will be of such low torque and low tension that it will cause the coil assembly to have considerable compliance towards vibration and static unbalance. Also, a very sensitive galvanometer requires a considerable coil area, even if the smallest torque ribbon that is practical is chosen for the galvanometer suspension. This large-area coil necessarily will have a large mass which will cause the coil assembly to have compliance towards vibration and static unbalance. Some decrease in coil mass can be attained by using extremely small wire to wind the coil. The smallest practical wire used in the industry at the present time is 1/1000-inch diameter anodized aluminum wire. Aluminum is chosen for its small specific gravity, and the anodized insulation is chosen in preference to enamel because the anodized wire has greater tensile strength.

Since high sensitivity and good resistance to vibration are incompatible, the design becomes a compromise. A galvanometer must be designed that will just meet the current-sensitivity and static-balance requirements. Then the moment of inertia of the coil assembly must be decreased enough to obtain a natural frequency of at least ten times the usable frequency. If a galvanometer of this high frequency can be attained, the galvanometer can be damped several times critical damping, and the noise near its natural frequency and higher frequencies will be greatly attenuated.

CHAPTER III

THE GALVANOMETER COIL ASSEMBLY DESIGN

The design of the galvanometer coil assembly is straightforward once the mechanical design is completed and the designer is concerned with only the natural frequency and the current sensitivity.

Knowing the sensitivity requirement is going to be difficult to meet, it is apparent that the lowest torque ribbon that is practical should be used. At the present state of the art, 0.11-dyne centimeter per centimeter per radian 14 karat gold is that ribbon. The total torsional coefficient "τ" required for the solution of equations (1) and (2) can then be calculated by knowing the total length of free ribbon.

At this point, one should be careful to make the free ribbon at the top and the bottom of the coil equal in length. If this is not done, the rotating mass and ribbon at one end will have one natural frequency as will the rotating mass and ribbon at the opposite end. The two frequencies beating together can cause four major spurious response peaks which will be susceptible to external vibrations of these frequencies. This will make it impossible to damp the galvanometer to ride through these external vibrations and still meet the frequency-response specifications.

Knowing the total torsional coefficient in addition to the flux density and required sensitivity, the designer can use equation (2) to ascertain the required coil area.

The moment of inertia of the entire coil assembly can then be computed and substituted into equation (1). From this the natural frequency can be calculated. If the natural frequency is not as high as desired, it may be increased some by using half beads rather than whole beads for coil supports. Also, the galvanometer mirror may be made thinner if it is not of such large area that it has a tendency to warp and cause an ill-focused reflection. Following the previously outlined procedure, the natural frequency of this shock-resistant galvanometer was found to be 45 cycles per second. This was verified by experimental results.

CHAPTER IV

GALVANOMETER DAMPING

Since oscillograph galvanometers are used to indicate rapidly changing electrical phenomena, it is necessary that the galvanometer mirror deflection be consistently proportional to the instantaneous current over a wide frequency band. This flat frequency response may be obtained either by resistance damping (electromagnetic) or by fluid damping (viscous) the galvanometer coil.

The value of resistance required to damp a galvanometer to its maximum flat frequency response (usually 64% critical) may be computed from the following equation,

$$R_d = (2B^2 l^2 r^2{}_m N^2)/(2\pi f_o K n) \times 10^{-6} - R_g \qquad (11)$$

where n is the damping ratio of actual to critical damping, R_g is the galvanometer resistance, and R_d is the required damping resistance.[3]

Resistance damping is generally used for low-frequency galvanometers; and in this case of a very sensitive low-frequency galvanometer, it could be used to give the frequency-response characteristic specified under the static specifications. However, resistance damping did very little towards

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[3]Ibid., p.8

damping mirror displacements caused by external shocks and vibration. It was for this reason that equation (11) was ignored when current sensitivity and natural frequency were being considered in the design.

The remaining way to make this galvanometer resistant to shock and to get proper frequency response was to fluid damp it. There are several ways in which the fluid damping can be accomplished. The most obvious way is to surround the coil assembly completely with fluid. If the galvanometer is damped by this method, one gets resistance to mechanical shock as well as some gain in the galvanometer current sensitivity due to the refraction of the light by the damping fluid. The new damped sensitivity would be equal to the product of the refractive index of the damping fluid and the undamped sensitivity.

In surrounding the coil and suspension with fluid, the mechanics of damping occurs by the outermost fluid from the motion remaining stationary. Next to this stationary layer of fluid, there is a slightly rotating layer of fluid. Between these two layers there is a shear plane. There is also a shear plane separating each of the layers of fluid between the first moving layer and the layer that actually rotates with the coil. In each of these shear planes, there is a frictional loss of energy which changes the excess kinetic energy into heat. The loss of the excess kinetic energy is the desired damping effect.[4]

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[4]W. Hartel, "Fluid Damping of Oscillograph Galvanometers," Frequenz, May, 1951, pp. 233-245.

In the development of this galvanometer, damping by completely immersing the coil in fluid was tried. This method of damping was abandoned, however, when attempts were made to balance the coil assembly. It was found that a coil assembly can be perfectly balanced in air, but when it is immersed in oil, the up-thruse caused by the oil appears as an unbalance. In a totally immersed coil, the amount of fluid clinging to a particular place on the coil is not constant and gives an indication of coil unbalance. Thus the galvanometer would fail to meet the balance specifications.

Since oil immersion would not work, the next attempted method of fluid damping the galvanometer was by using two oil-filled capillary tubes around the ribbon. Figure 2 shows a sketch of this coil and frame assembly. One tube was placed just above the mirror and the other tube was placed just below the bottom of the coil. In order to obtain the maximum resistance to mechanical vibration, the viscosity of the Dow Corning Number 200 silicone fluid in the tubes was increased to 24,000 centistoke or until the frequency response of the galvanometer barely met the specifications. The galvanometers were then given a cursory test approaching the exact vibration specifications. They failed to meet the vibration specifications during most of these tests.

From these tests it was obvious that more effective fluid damping had to act on the coil assembly, but the fluid damping must not be increased to such as extent that the frequency response failed to meet the specifications.

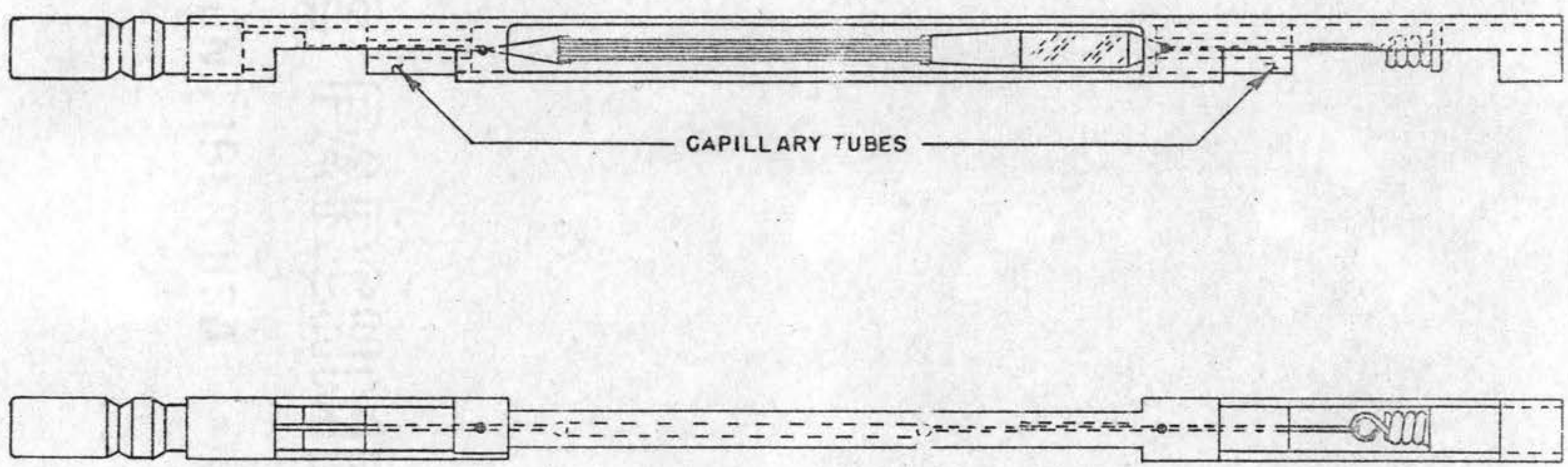

Figure 2. Two-Capillary Tube Coil and Frame Assembly of The Open-Coil Type.

On the basis of these first tests, there seemed to be two possible reasons why the galvanometers were buzzing in excess of the specifications. Either the damping was not acting at the center of mass of the coil assembly, or the coil assembly was not acting as a rigid bar but was acting as two separate masses joined by a flexible member.

Since the first possibility was the easiest to investigate, the viscosity of the fluid in the capillary tubes was changed. Two viscosities of fluid were used this time. The viscosities were changed to equalize the products of the viscosities times their capillary-tube moment arms. At the same time the damping was maximized so the frequency-response characteristic was barely met.

This change in damping fluid ratios decreased the amplitude of buzz, but the decrease was not sufficient to allow the galvanometers to meet the specifications.

The possibility of the coil assembly acting as two separate masses was then thoroughly investigated. Since the coil is approximately 70 per cent of the coil assembly mass, it was felt that the coil could be squeezed and a capillary tube could be placed around the center of the coil.

New coil assemblies of this description were built and tested. A sketch of the frame assembly using the squeezed-coil design and three capillary tubes is shown in Figure 3. These new coil assemblies did a good job of solving the problem of excess buzz during vibration, but this step towards the solution of the buzz problem caused another problem. The coil

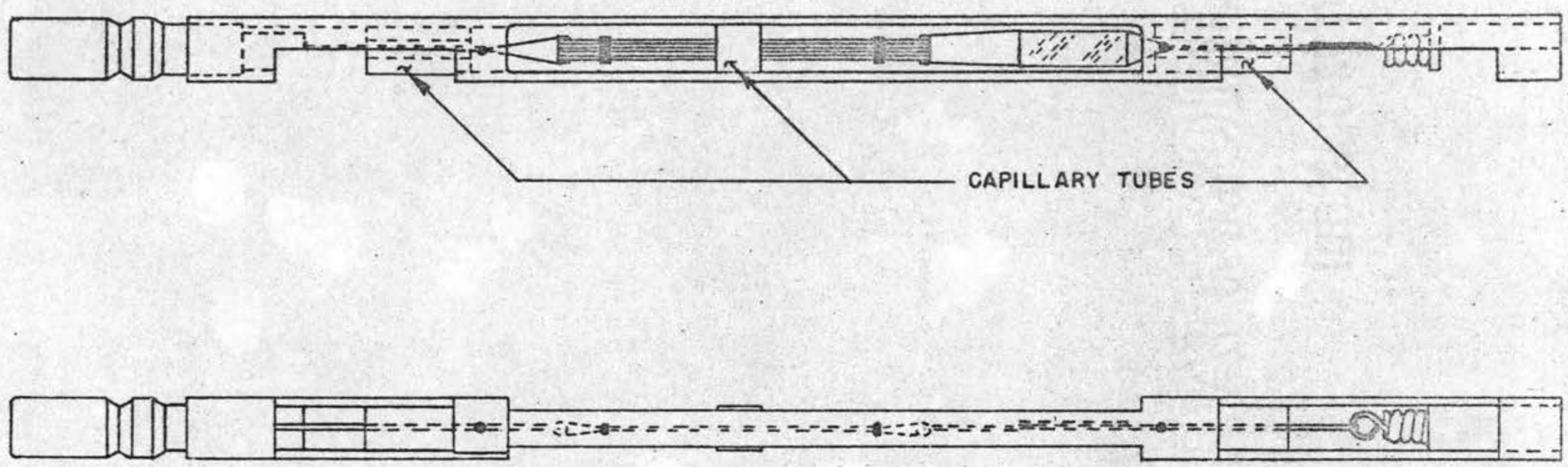

Figure 3. Three-Capillary Tube Coil and Frame Assembly of The Squeezed-Coil Type.

had been squeezed so much in getting the capillary tube around it that the galvanometer sensitivity had decreased below specification. The sensitivity of the galvanometer at this point of the development was approximately 25 microamperes per inch for an optical arm of 6.25 inches.

Various means of increasing the sensitivity and still retaining the coil capillary tube were considered. It seemed a formidable task to increase the sensitivity of the galvanometer by a factor of three and still maintain the previous resistance to vibration by using a coil capillary tube. Some of the more obvious things that could be done to increase the sensitivity were (1) the use of a ribbon with a smaller spring constant, (2) the reduction of the tension on the present ribbon, or (3) the addition of more turns to the coil. A fourth way, which seemed most practical, was to spread the galvanometer coil by using a third bead near one end of the coil and then to squeeze the coil in the small portion between the middle bead and the end bead. The capillary tube would then be placed around this small squeezed portion.

This was done and at the same time enough turns were added to the coil to bring its resistance near the specified 150 ohms maximum. The idea of simply adding turns to the original squeezed coil was not considered because the addition of enough turns to make the galvanometer meet the sensitivity specifications would certainly have caused it to exceed the resistance specification.

Neither were the possibilities of using lighter ribbon or reducing the tension on the present ribbon seriously considered. The reason for this was that a smaller ribbon was not practical, and less tension on the present ribbon would cause the massive coil to be very susceptible to vibration even with a capillary tube placed around the coil.

Samples of the three-bead, three-capillary tube coil and frame assemblies were built and tested. A sketch illustrating this design is shown in Figure 4. Again this galvanometer had good resistance to shock and vibration, but it now had a sensitivity of 13 microamperes per inch. Apparently the only way to gain the desired sensitivity was to remove the damping ring from around the coil and spread the coil accordingly. This made the ribbon section between the mirror and the top bead of the coil the only place the coil assembly could be damped near its center of gravity, where it would do the most good in reducing buzz caused by vibration.

To accommodate the two major changes, new coil assemblies again had to be built. The squeezing of the ribbon between the bottom of the mirror and the top bead of the coil had caused a linearity problem which certainly was not anticipated. What this problem actually amounted to was that the plane of the mirror was not always exactly at a right angle to the plane of the coil. This caused the coil to be in the fringe flux for a zero current condition with the mirror pointed straight ahead. Thus when one polarity of current was applied, the coil would move through a lower flux density and be less sensitive.

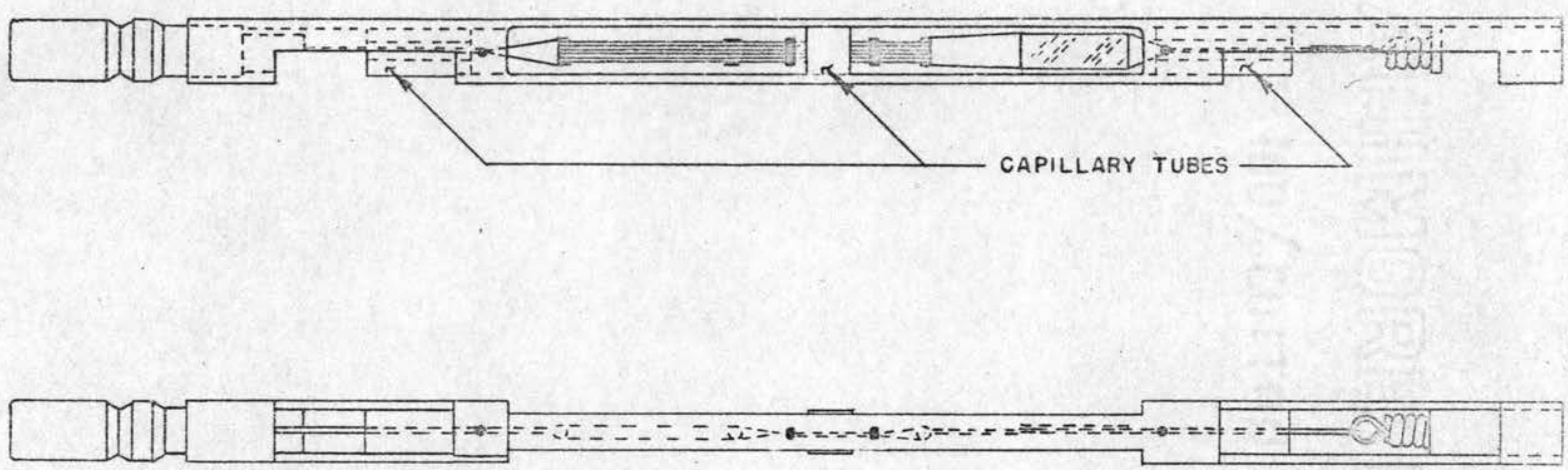

Figure 4. Three-Capillary Tube Coil and Frame Assembly of The Three-Bead Coil Type.

This rotation of the mirror with respect to the coil had not been a problem earlier, since the ribbon previously had formed a rigid yoke in which the mirror could fit. With the squeezed ribbon design, the mirror was joined to the coil by soldering two sides of the mirror yoke together. The lack of torsional rigidity of the connecting rod caused the linearity problem. This problem was finally solved by proper tooling which forced the plane of the mirror to be at right angles to the plane of the coil.

The spreading of the coils was accomplished by placing in the center of the coil a bead of slightly larger diameter than the end beads. With the linearity problem already solved, the test galvanometers were again damped as before and vibration tests were run. This time during the vibration tests, the galvanometers met the vibration specifications, but in many places the amplitude of the buzz almost exceeded the specifications. Again the galvanometers met the sensitivity specifications.

Because the resistance to vibration appeared to be marginal, it was decided to improve the design of this galvanometer to the extent that it could be mass produced with little fear of rejection due to lack of vibration resistance. Increasing the area the damping fluid acted upon appeared to be one of the easiest ways to increase the vibration resistance. It was also a very logical approach since lack of damping area was the main difference between the squeezed coil design, which had good vibration resistance, and the squeezed ribbon design, which did not.

Since the spacing between the mirror and top bead of the coil could not be lengthened, the only way the damping area could be increased was by changing the cross section of the ribbon. This was accomplished by soldering to both sides of the squeezed portion of the ribbon another piece of 0.11-dyne ribbon exactly the same length as the capillary tube.

At the same time the ribbon cross section was increased, the effects of various viscosities of fluids in the capillary tubes were examined. Frequency response curves were taken for the viscosity arrangements shown in Figure 5. It can be noted from these curves that for a very high viscosity fluid in the center tube and a very low viscosity fluid in the ribbon tubes, the galvanometer seems to act simultaneously like a high-frequency galvanometer and a low-frequency galvanometer. This is caused by the fretting action of the fluid on the squeezed ribbon. The effect of the high-frequency galvanometer can be seen from approximately 50 to 80 cycles per second, where a flat response appears on Curve A. Since the damping for Curve A allows the galvanometer to have a flat frequency response between 50 and 80 cycles per second, it appears the galvanometer would be sensitive to external vibrations of this frequency. For this reason many arrangements of fluid viscosities were tried, but the values associated with Curve B did the most to smooth the inflection points that always occurred at 50 and at 80 cycles per second. Therefore, the viscosities of the fluids in the sample models were in the same arrangement and of the same values as the arrangement and values used to get Curve B.

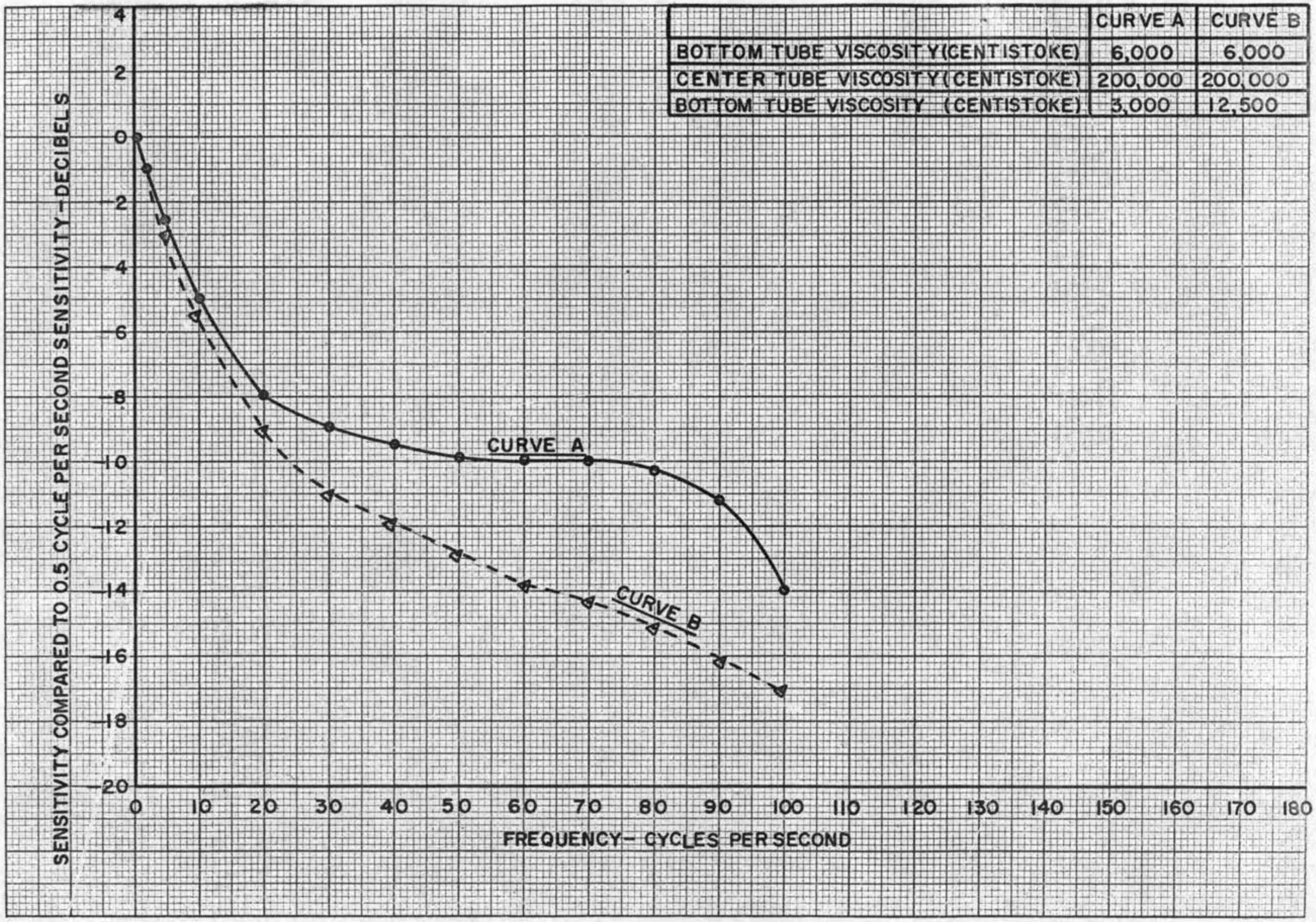

Figure 5. Frequency Response of Two Damping Fluid Arrangements.

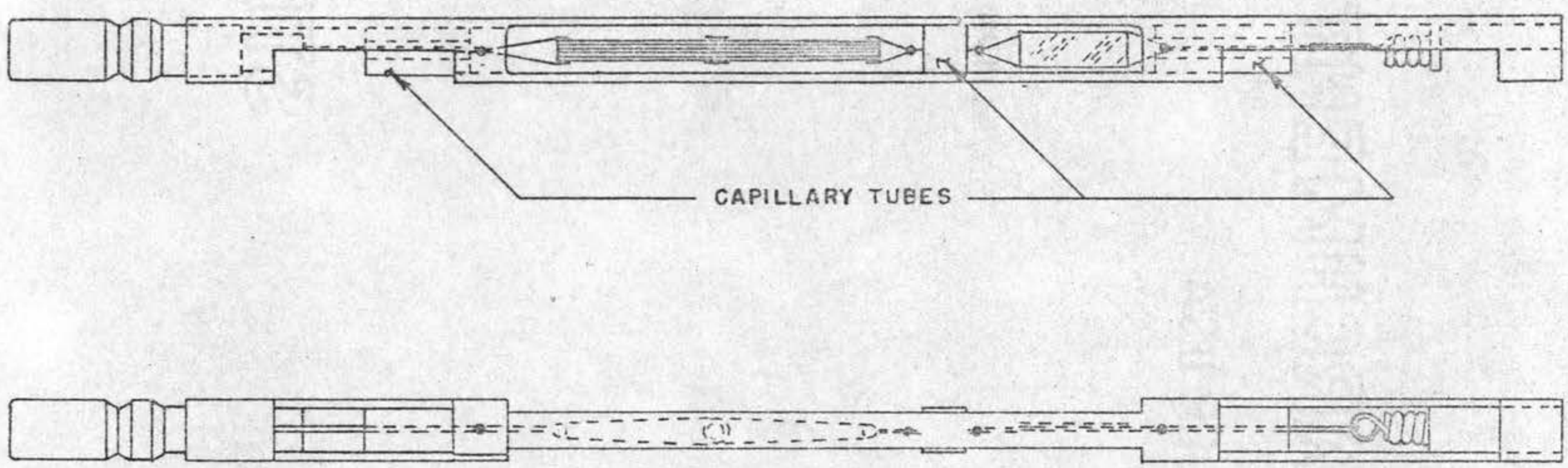

Figure 6. Final Design - The Coil and Frame Assembly.

With the vibration, sensitivity, and frequency-response problems solved, nine samples of this particular galvanometer design had to be built and tested, as is specified in the qualification tests.

CHAPTER V

QUALIFICATION TESTS

Associated with any Government-procurement program is a definate set of specifications the product must meet. In the case of the shock- and vibration-resistant galvanometer procurement program, it is well to reiterate that the galvanometer had to meet certain static specifications before it could qualify for the rugged environmental conditions that were so hard to meet in the development of this galvanometer. For this reason the qualification tests concerning the galvanometer were divided into static tests and environmental tests.

Static Tests

For the static tests, nine specimen were used as was required in the specifications. All nine samples met the dimensional, focal length, dielectric strength, leakage resistance, polarity, direct current resistance, linearity, and hysteresis specifications without any deviations. These tests are quite straightforward and will not be described in detail. However, this is not true of the remaining three items covered in the static tests.

The current-sensitivity requirement was that the galvanometer shall deflect 15.95 millimeters per microampere per meter optical arm in a 2,500-gauss magnetic field. It also stated that the flux density and optical arm length could be extrapolated as required to suit the galvanometer test fixture used.

The current-sensitivity tests were conducted for the nine samples by using a test jig that had a 15.5-inches optical arm. The magnetic assembly used had a flux density of 2,780 gauss. For all the static tests, the same side of the light spot was used to eliminate any error due to variation in spot thickness from galvanometer to galvanometer.

The test was conducted by placing exactly 10 microamperes of current through the galvanometer and then denoting the deflection for the 15.5-inches optical arm.

As seen in Table I and the sample calculations, galvanometer X4 was the only one that met the current-sensitivity specification.

Sample Calculations

$$\frac{15.95 \text{ mm}}{\text{ua}} \times \frac{0.0394 \text{ in}}{\text{mm}} \times 10 \text{ ua} \times \frac{15.5 \text{ in}}{1\text{m}} \times \frac{1\text{m}}{39.4 \text{ in}} \times \frac{2780 \text{ gauss}}{2500 \text{ gauss}} = 2.7 \text{ (in}$$

A plus or minus 5 per cent tolerance was allowed, so the deflection could vary from 2.61 inches to 2.89 inches for the test setup used.

Following the current-sensitivity tests, the frequency response curves were taken. The frequency-response specification

TABLE I

STATIC TEST OF CURRENT SENSITIVITY

Galvanometer (Number)	Deflection (Inches)	Deviation from Specification (Inches)
X1	2.39	0.22
X2	2.41	0.20
X3	2.45	0.16
X4	2.75	0
X5	2.51	0.10
X6	2.41	0.20
X7	2.44	0.17
X8	2.47	0.14
X9	2.48	0.13

TABLE II

STATIC TEST OF FREQUENCY RESPONSE

Galvanometer (Number)	Peak-to-Peak Deflection at 0.5 C.P.S. (Inches)	Peak-to-Peak Deflection at 5.0 C.P.S. (Inches)	Least Allowed Peak-to-Peak Deflection at 5.0 C.P.S.
X1	4.85	4.15	1.94
X2	5.47	4.63	2.19
X3	4.90	4.03	1.96
X4	5.57	4.60	2.23
X5	5.05	3.90	2.02
X6	4.92	4.04	1.97
X7	5.00	4.47	2.00
X8	5.05	4.00	2.02
X9	5.04	4.50	2.02

was that the galvanometer sensitivity at 5.0 cycles per second shall not decrease by more than 8 decibels (60%) of its 0.5 cycle-per-second value.

The same test jig was used for this test as was used for the current-sensitivity test except that an oscillator, instead of a direct-current source, was connected to the galvanometers. For this test the magnetic assembly was heated to its normal operating temperature of 100°F, because the viscosity of the silicone-oil damping fluid at 100°F is only 80 per cent the viscosity of the fluid at room temperature.[5]

To obtain the data from this test, the output voltage of the oscillator at 0.5 cycle per second was increased until the galvanometer had a peak-to-peak deflection of approximately 5.0 inches on the test jig. Then the frequency was changed to 5.0 cycles per second, the voltage was held constant, and the peak-to-peak deflection was recorded. The output voltage of the oscillator was measured with a Sensitive Research thermocouple voltmeter which has an accuracy of plus or minus 0.5 per cent. All nine galvanometers met the frequency-response specifications, as shown in Table II.

The final specification in the static-test requirements is that of static balance. The specifications stated that the galvanometer must have a static balance such that for a 180° rotation around its longitudinal axis it will drift no more than 2 millimeters at a 1-millimeter optical arm.

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[5] _______. Dow Corning Silicone Notebook, Fluid Series Number 3, (Midland, Michigan, 1945), pp. 14-15

The data for the static-balance test was obtained by placing a galvanometer in a jig which contained a light source and a graduated screen. The jig could be rotated through 360^{o} in any direction. The screen was optically 31.1 inches from the galvanometer and was so graduated that each division on the screen was 0.020 inch. The jig contained no magnetic field and the galvanometer was not energized. After the galvanometer was placed in the jig and the spot of light was reflected from the galvanometer mirror to a particular line on the screen, the jig was rotated about the longitudinal axis of the galvanometer to a position 180^{o} clockwise from the last noted position of the galvanometer. The location of the spot on the screen was again noted so one could tell how far the reflected spot had drifted. This drift is caused by the unbalanced condition of the coil and the 2 g acceleration acting upon it. All the galvanometers met the static-balance specification, as shown in Table III.

Sample Calculation

Specification for 180^{o} rotation $= \frac{2mm}{1m} = 0.002$ in/in of optical arm $= 0.062$ in for an optical arm of 31.1 in.

Having completed the static tests, the crucial and lengthy environmental tests were begun.

TABLE III

STATIC TEST OF BALANCE

Galvanometer (Number)	Drift for 180° Rotation (Inches)	Deviation in Excess of Specification (Inches)
X1	0	0
X2	0.030	0
X3	0.030	0
X4	0.050	0
X5	0.040	0
X6	0.040	0
X7	0.020	0
X8	0	0
X9	0.010	0

TABLE IV

ENVIRONMENTAL TEST OF CURRENT SENSITIVITY
(Cold Test)

Galvanometer (Number)	Deflection (Inches)	Deviation from Specification (Inches)
X1	1.152	0.132
X2	1.246	0.034
X3	1.056	0.149
X4	1.306	0
X5	1.158	0.130
X6	1.122	0.127
X7	1.178	0.106
X8	1.212	0.068
X9	1.074	0.091

Environmental Tests

The first environmental test to which the galvanometers were subjected was that of low-temperature operation. For this test, as in all of the environmental tests, the galvanometers were installed in their normal positions in the airborne oscillograph, and the oscillograph heaters were continuously operated. The oscillograph was placed in a low-temperature chamber and allowed to stabilize at $-50^{\circ}F$ for a period of 4 hours. During this period, sensitivity and frequency-response oscillograms were taken; and immediately following the cold environment, a static-balance record was taken. The tabulated results of this test are shown in Tables IV, V, and VI, respectively. The galvanometers passed the frequency-response and static-balance tests without any deviations. However, for the current-sensitivity test, only one galvanometer met the specification; all other galvanometers were low in sensitivity. Naturally one might expect this result, since eight of the nine galvanometers were low in current sensitivity during the static tests. It is well to note here that for all the data taken in the recorder, the information has to be extrapolated for the 6.25-inches optical arm that is used in the recorder.

Sample Calculations

<u>Sensitivity</u> $15.95 \times 0.0394 \times 10 \times \frac{6.25}{39.4} \times \frac{2780}{2500} = 1.108$ in

$1.05\ (1.108) = 1.153$ in; $0.95\ (1.108) = 1.064$ in

TABLE V

ENVIRONMENTAL TEST OF FREQUENCY RESPONSE
(Cold Test)

Galvanometer (Number)	Peak-to-Peak Deflection at 0.5 C.P.S. (Inches)	Peak-to-Peak Deflection at 5.0 C.P.S. (Inches)	Least Allowed Peak-to-Peak Deflection at 5.0 C.P.S. (Inches)
X1	1.96	1.68	0.785
X2	2.21	1.87	0.885
X3	1.98	1.63	0.792
X4	2.25	1.86	0.902
X5	2.04	1.58	0.817
X6	1.99	1.63	0.797
X7	2.02	1.81	0.808
X8	2.04	1.62	0.817
X9	2.04	1.82	0.817

TABLE VI

ENVIRONMENTAL TEST OF BALANCE
(Cold Test)

Galvanometer (Number)	Drift for 180° Rotation (Inches)	Deviation in Excess of Specification (Inches)
X1	0.005	0
X2	0.003	0
X3	0.003	0
X4	0.002	0
X5	0.002	0
X6	0.004	0
X7	0.004	0
X8	0.005	0
X9	0.004	0

Static Balance 2 millimeters per meter = 0.002 inch per inch of optical arm = 0.0125 inch for a 6.25-inches optical arm.

Some difficulty was encountered in reducing the current-sensitivity records. This was caused by the variation in flux density from hole to hole in the magnetic assembly of the oscillograph. The data for correcting this variation is tabulated in Table VII. It was obtained by using galvanometer X6 and comparing its deflection in the bench test magnet with its deflection in each hole of the oscillograph's magnetic assembly. The deflection of X6 in the static tests was 2.41 inches for 10 microamperes of current. It was the ratio of the deflection in each hole of the oscillograph's magnetic assembly divided by 2.41 that was used to modify the sensitivity limits required for each of the nine galvanometer positions.

The next environment to which the galvanometers were subjected was a high-temperature operation test. This test was conducted in a manner similar to that of low-temperature operation. For this test the oscillograph was placed in a high-temperature chamber and allowed to stabilize at a temperature of 130°F for a period of 4 hours. Again the galvanometers met the frequency-response and static-balance specifications with no deviations; the results also showed that X4 was the only galvanometer to pass the current-sensitivity specification. For this test no tabulated data will be given, since it is so similar to the data given for the low-temperature operation test.

TABLE VII

MAGNETIC ASSEMBLY FLUX DEVIATION

Galvanometer (Number)	10 ua Deflection (Inches)	Deflection Divided by X6 Deflection	Required Deflection on Record (Inches) Minimum	Maximum
X1	2.91	1.207	1.284	1.391
X2	2.90	1.203	1.280	1.387
X3	2.73	1.133	1.205	1.306
X4	2.94	1.220	1.298	1.406
X5	2.92	1.211	1.288	1.396
X6	2.83	1.174	1.249	1.353
X7	2.91	1.207	1.284	1.391
X8	2.90	1.203	1.280	1.387
X9	2.64	1.095	1.165	1.262

Following the cold and hot tests, the 15 g operate shock test was run. The requirement for this test was that after a 15 g shock of 11-millisecond duration, the galvanometers must recover in 0.5 second and must meet the current sensitivity required in the static tests. The 15 g shock was to be applied three times in each direction of the vertical, major horizontal, and minor horizontal axes of the galvanometer.

This test was conducted by placing the oscillograph in either a vertical or a horizontal jig mounted to the table of a Barry Impact Shock Machine. The total 18 drops at the 15 g acceleration specified for the three orthogonal axes were then given in the particular jig required. During each drop, 10 microamperes of direct current were applied to all the galvanometers connected in series and an oscillogram was made.

The results of this test showed the galvanometers always recovered from the shock in less than 0.5 second. Too, they always met the current-sensitivity specification after recovering from the shock, except for the deviation noted in the static tests. A sample record is shown in Figure 7. Never in the records or visually was there evidence of an intermittent open circuit, short circuit, or permanent physical damage.

The 30 g shock nonoperate test was made immediately after the 15 g shock test. The procedure for this test was identical to that of the 15 g shock test except the oscillograph was dropped farther and the galvanometers were not operated during these drops.

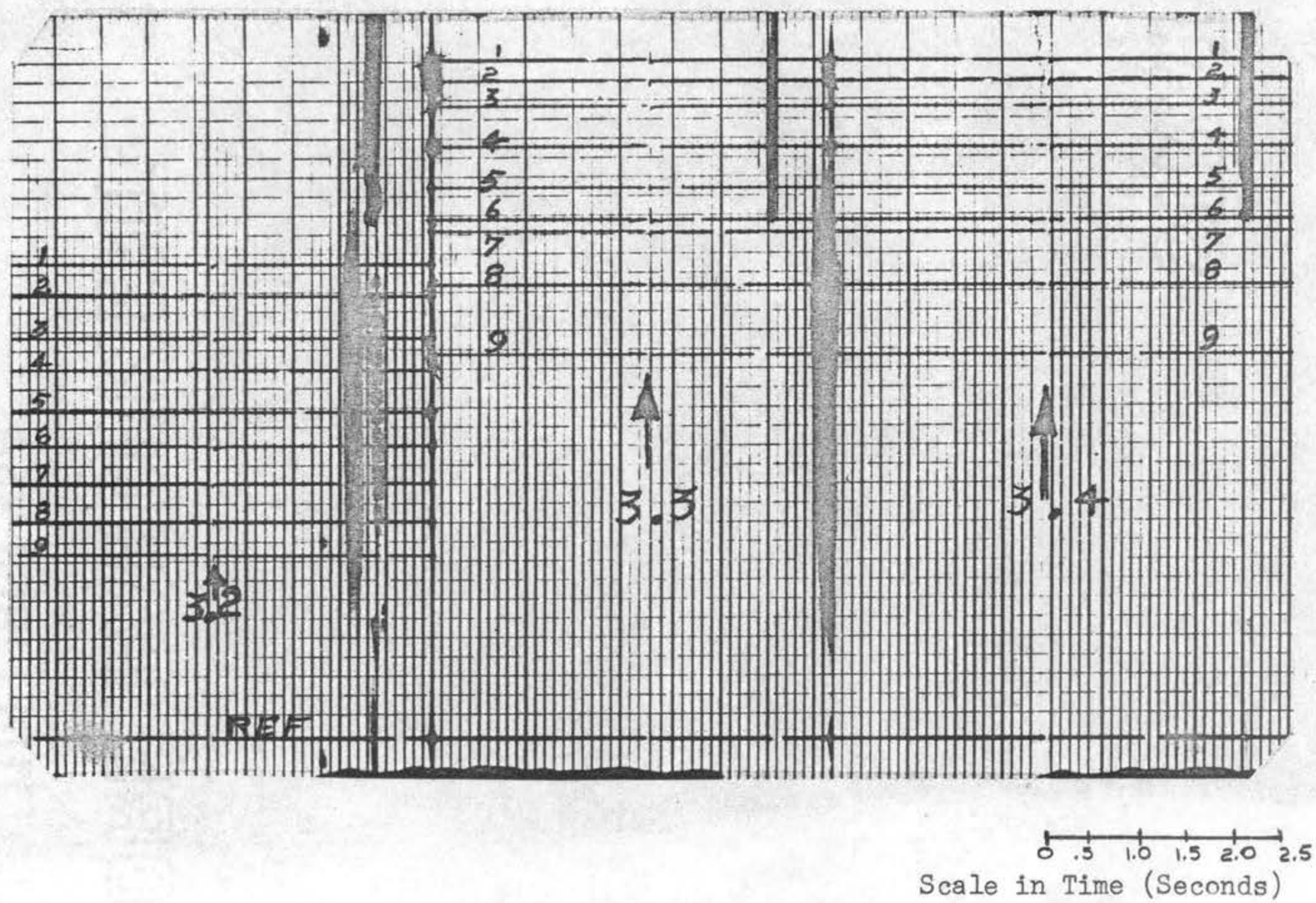

Figure 7. A Portion of An Actual Shock Record.

In this test, just as in the 15 g shock test, all the galvanometers recovered in less than 0.5 second, and never was there an indication of permanent physical damage or an intermittent open circuit or short circuit.

The next mechanical environment to which the galvanometers were subjected was that of constant acceleration. The acceleration requirements were that the galvanometer traces shall be displaced less than 0.020 inch from their original positions under a constant 3 g acceleration for a minimum of one minute. During this test, the galvanometers shall be in an operate condition and meet the current-sensitivity specification. The test shall be performed in all three axes of the galvanometers.

In addition to the 3 g operate test, the galvanometers must withstand a 10 g constant acceleration in a nonoperate condition and show no evidence of an intermittent open circuit, short circuit, or permanent physical damage.

The galvanometers were accelerated for this test in a Genisco Centrifuge. This was accomplished by mounting the oscillograph in a horizontal jig and fastening the jig to the table of the centrifuge. The recorder was then rotated on the table and in the jig so the galvanometers were accelerated in all three axes. For the 3 g test the galvanometers were in an operate condition, and for the 10 g acceleration they were in a nonoperate condition.

The 3 g acceleration test results showed all galvanometer traces displaced less than 0.020 inch except galvanometer X1.

Its trace was displaced 0.028 inch when it was accelerated parallel to the plane of its mirror. Again all galvanometers failed to meet the current sensitivity requirements except X4.

For the 10 g acceleration test, none of the galvanometers showed signs of intermittent short circuits, open circuits, or permanent physical damage.

After the galvanometers were given the acceleration tests, they were subjected to the required vibration environments. The first vibration requirement was that the galvanometers in a nonoperate condition shall be subjected to sinusoidal vibrations in logarithmic sweeps lasting six to ten minutes. The magnitude of the vibrations shall be 0.25-inch double amplitude from 2 to 17.5 cycles per second, and they shall be plus and minus a 4 g amplitude from 17.5 to 300 cycles per second. The galvanometers shall be vibrated in this manner for three hours in each of three orthogonal axes. Following these environments, the galvanometers must pass the static requirements for sensitivity, frequency response, and static balance.

The vibration tests were accomplished by mounting the oscillograph to the table of an MB Vibrator. The mounting fixture was a horizontal jig for the major and minor horizontal vibration axes and was a vertical jig for the vertical vibration axis. The vibrator that was used had a linear rather than a logarithmic sweep control, so it was necessary to divide the frequency range into octaves. Then the total sweep time had to be divided among these octaves so a logarithmic sweep could be approximated. For the six-minute total sweep required, the oscillograph was vibrated from 2 to 17.5 cycles per second in 2.5 minutes at a plus or minus 0.25-inch double amplitude. Then at the plus or minus 4 g amplitude, it was swept from 17.5 to 60 cycles per second in 1.5 minutes, from 60 to 125 cycles per second in one minute, and from 125 to 300 cycles per second in one minute. These sweeps were repeated 30 times in each axis to accomplish the three hours required length of vibration. To monitor the acceleration, a crystal accelerometer was mounted over one of the support blocks of the oscillograph, which was located near the galvanometers and magnetic assembly. The acceleration was also monitored by the vibrator instrumentation.

Following the nine hours total vibration, the galvanometers were tested for static balance, frequency response, and current sensitivity. All the galvanometers met the frequency-response and static-balance specifications required under static conditions. But galvanometer X4 was the only one that met the current-sensitivity specification.

The next and final vibration requirements were that the galvanometers in an operate condition must be vibrated just as they were in the nonoperate condition except that a plus and minus 3 g amplitude must be maintained over a frequency range of 30 to 2,000 cycles per second. The galvanometers must be vibrated in this manner for 6.75 hours in each of three orthogonal axes, and the galvanometer trace movement or buzzing shall be recorded (1) during the first and last frequency sweep cycle with 10 microamperes of current applied and (2) during the second and next to last sweep cycle with zero current applied. The buzzing in these oscillograms must not exceed plus and minus 0.035 inch except for the following limitations: The buzzing may exceed plus and minus 0.035 inch in two bands in the vibration test frequency range if the product of zero-to-peak excursion in inches and the bandwidth during which the excursion exceeds plus and minus 0.035 inch is less than 0.012 inch. Also, the bandwidth shall be no greater than 20 (nondimensional). In this instance, bandwidth shall be defined as $2\ (f_2 - f_1)/(f_2 + f_1)$ where f_2 and f_1 are the frequencies at which the buzzing just exceeds plus and minus 0.035 inch.

The vibration tests for the operate condition were conducted just as the tests for the nonoperate condition, except the sweep ranges for the various octaves were different as may be noted in Table VIII. The length of time required for each sweep was different too, but the four records for each frequency sweep cycle were taken as required.

The results of this test are shown in Tables VIII and IX, where the reduced data is tabulated. In the interest of brevity, data is shown for the most severe plane of vibration only. This plane is the one that is perpendicular to the plane of the mirror. It is the most severe because the narrow side of the galvanometer ribbon is trying to slice through the capillary fluid when the galvanometer is vibrated in this position. A portion of an actual vibration record is shown in Figure 8.

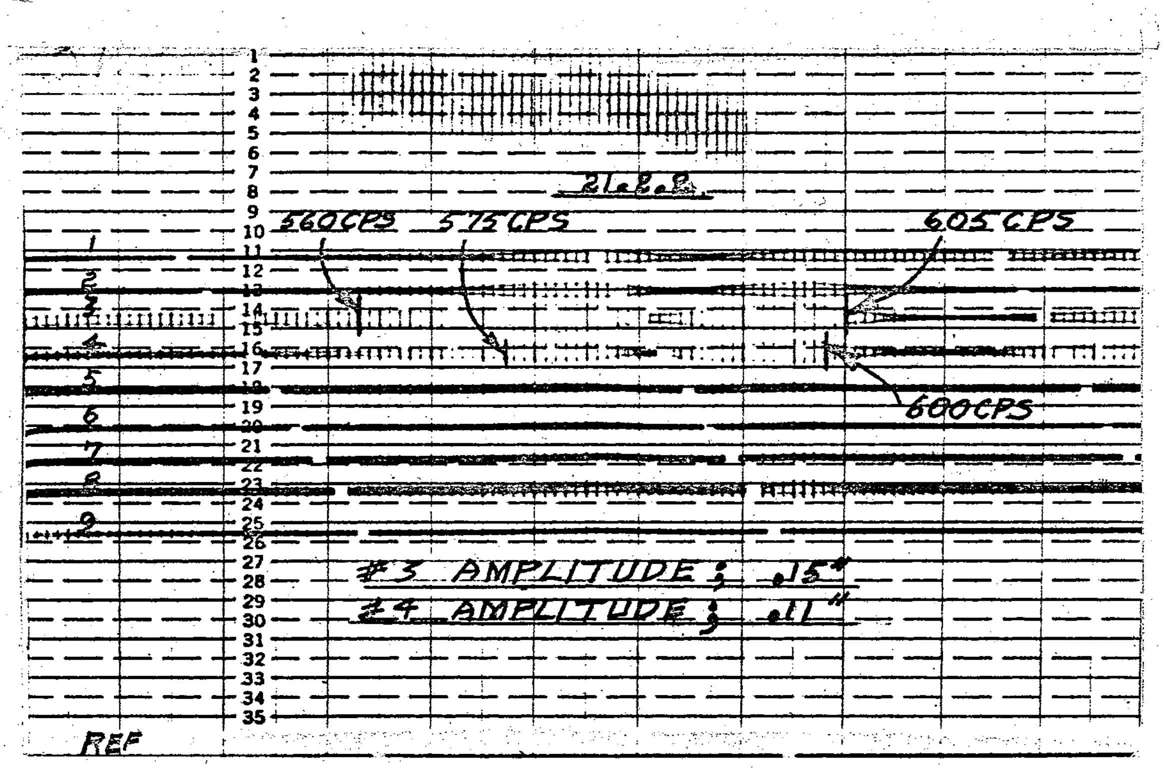

Figure 8. A Portion of An Actual Vibration Record.

TABLE VIII

ENVIRONMENTAL TEST OF BUZZ AMPLITUDE

	Frequency Band where the Buzz Exceeds 0.070 Inch Maximum Peak-to-Peak Amplitude (Inches)								
Galvanometer (Number)	X1	X2	X3	X4	X5	X6	X7	X8	X9
Sweep Range 30-62 C.P.S.	The peak-to-peak buzz on all specimen was less than 0.070 inch in every instance.								
Sweep Range 62-125 C.P.S.	The peak-to-peak buzz on all specimen was less than 0.070 inch in every instance.								
Sweep Range 125-250 C.P.S.	The peak-to-peak buzz on all specimen was less than 0.070 inch in every instance.								
Sweep Range 250-500 C.P.S.	325-365 .09	335-375 .10		365-395 .10					
Sweep Range 500-1000 C.P.S.	525-640 .16	590-660 .12				575-650 .13		320-375 .12	
Sweep Range 1000-2000 C.P.S.			1450-1625 .18						

TABLE IX

ENVIRONMENTAL TEST OF BUZZ AMPLITUDE AND BANDWIDTH PRODUCT

Galvanometer (Number)	F_2 (CPS)	F_1 (CPS)	Maximum Double Amplitude	Band-width	Product of 0.5 Maximum Double Amplitude x Bandwidth
X1	365 640	325 525	0.09 0.16	0.116 0.198	0.00522 0.0158
X2	375 660	335 590	0.10 0.12	0.113 0.112	0.00564 0.00672
X3	1625	1450	0.18	0.114	0.0102
X4	395	365	0.10	0.079	0.00395
X6	650	575	0.13	0.122	0.00795
X8	375	320	0.12	0.158	0.00948

(Vibration normal to the major axis of the galvanometer and normal to the galvanometer mirror)

Sample Calculations

Galvanometer X1

$$\text{Bandwidth} = \frac{2(f_2 - f_1)}{(f_2 + f_1)} = \frac{2(365 - 325)}{365 + 325} = 0.116$$

$$0.5 \text{ maximum double amplitude x bandwidth} = 0.5\ (0.090)\ 0.116) = 0.00522 \text{ inch}$$

It was found in reviewing all the reduced data that only two deviations from the specifications were made in the nine specimen galvanometers. The major deviation was that of current sensitivity Eight of the nine galvanometers tested had low current sensitivity by as much as 10 per cent. The other deviation was where galvanometer X1 failed to meet the 3 g acceleration test. Galvanometer X4 had passed the specifications without reservations.

To make certain that a production run of this type galvanometer would pass the qualification specifications, nine additional galvanometers of the same sensitivity as X4 were built. These galvanometers were then sampled to make certain they would pass all the specifications. The samples were found to pass all the specifications, so the research and development on this project was considered complete.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The author has discussed in the previous chapters a number of the basic problems encountered in developing a sensitive oscillograph galvanometer that would operate properly under severe shock and vibration environments. The use of this galvanometer and its associated oscillograph is in the field of flight instrumentation where component resistance to rugged environments and increased reliability are constant objectives.

The practice of checking out a missile by flying it attached to an aircraft poses some difficult problems, particularly when the oscillograph that is to record the test data is to be flown inside the missile rather than telemetering the flight test data to ground and recording the information on an oscillograph there.

The heart of the oscillograph and the most sensitive part of the instrument is the galvanometer. Since the galvanometer is exposed to a rugged environment, a means had to be found to combat its sensitivity to environment but retain its sensitivity to electricity. It was found that by placing oil-filled capillary tubes around the coil assembly at strategic points and by adjusting the oil to the proper viscosity, a shock- and vibration-resistant galvanometer could be obtained. Of course, this is within limits.

On the basis of actual operating experience, it can be concluded that a shock- and vibration-resistant oscillograph galvanometer is feasible. Its use in flight instrumentation has the one great advantage of not requiring complicated and expensive telemetering equipment to get the flight data back to the ground. In addition, it makes the instrumentation system far less complicated and much more reliable.

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