REPORT A69-2

STRAIN GAGE INSTRUMENTATION FOR A LIGHT GAS GUN

by

P. D. FLYNN

May 1969

This document has been approved for public release and sale; its distribution is unlimited.

DEPARTMENT OF THE ARMY
FRANKFORD ARSENAL
Philadelphia, Pa. 19137
REPORT A69-2

STRAIN GAGE INSTRUMENTATION FOR A LIGHT GAS GUN

by

P. D. FLYNN

AMCMS Code 5011.11.85804
DA Project 1T061102B33A04

This document has been approved for public release and sale; its distribution is unlimited.

Pitman-Dunn Research Laboratories
FRANKFORD ARSENAL
Philadelphia, Pa. 19137

May 1969
This paper was presented at the IEEE (3rd) International Congress on Instrumentation in Aerospace Simulation Facilities held at the Polytechnic Institute of Brooklyn Graduate Center, Farmingdale, N. Y., 5-8 May 1969. It was published by the Institute of Electrical and Electronic Engineers, Inc., New York, N. Y., in the Congress Record, May 1969, pp. 184-189.
ABSTRACT

Variable-resistance strain gages were used to study the operating characteristics of a light-gas gun. Gages were cemented on the outer surface of the gun at several locations in order to determine chamber pressure, piston velocity, and pressures in the central breech. The high-pressure transition section deforms plastically in most rounds, and a method is suggested for estimating maximum pressures from strain-time records. Results are given for various helium pressures and powder charges.

INTRODUCTION

The velocity limitations of conventional guns are well known. Various methods have been used to obtain higher velocities, and light-gas guns are in rather widespread use. The Physics Research Laboratory recently completed installation of a piston-compression light-gas gun in its hypervelocity test facility. In order to optimize the performance of the gun in the range of projectile impacts of interest to Frankford Arsenal, strain gage instrumentation was developed to monitor the dynamic behavior of the gun. The purpose of this paper is to describe the techniques which were used and to present typical results which suggest the potential usefulness of strain gages in this field.

TEST PROCEDURES

Experimental Setup. Figure 1 gives an overall view of the light-gas gun and hypervelocity test facility which can be used to fire projectiles in controlled atmospheres from high vacuum to 100 psig. All firings reported in this paper were made into air at 10 mm of mercury absolute pressure. The first section of the light-gas gun consisted of a 40 mm breech mechanism, chamber and barrel from a surplus naval anti-aircraft gun. The barrel was modified so that it could be coupled to a pump tube (36 in. long, 4.00 in. OD, 1.63 in. ID). Fittings were installed on the pump tube so that the gun could be evacuated and a light gas introduced. Helium was used in these tests. An 18 in. long section was used between the pump tube and the central breech or high-pressure transition section.

The high-pressure section (13 in. long, 7 in. OD) provided the transition from the 1.63 in. ID pump tube to a caliber .60, smooth-bore launch tube (75 in. long). After completing the tests reported in this paper, the central breech was sectioned and photographed, Fig. 2. This figure also shows a projectile (steel cube, 10 grains), carrier (aluminum, 87 grains), shear disk (aluminum, 0.020 in. thick), disassembled lexen piston and steel slug (total weight 820 grams), and a 40 mm shell used in a typical firing.

Strain Gages. Type 364-1000 strain gages were selected because they have a high gage factor ($F = 3.26$) and a high resistance ($R = 1000 \Omega$).
The change in gage resistance depends on the strain, $\epsilon$, and the manufacturer's gage factor, $F$, is defined such that

$$\Delta R_g / R_g = F \epsilon$$

For small values of $AR_g / R_g$, we obtain from Eqs. (2) and (3) and from Eqs. (4) and (1), we obtain

$$c = \frac{AR_g / R_g}{F} \frac{\Delta R_g}{V_g}$$

The outputs of the strain gage circuits were recorded on two Tektronix dual-beam oscilloscopes using various plug-in units.

Tube with Internal Pressure. From Lamé's solution, the circumferential and radial stresses, $\sigma_\theta$ and $\sigma_r$, in an elastic thick-walled cylinder subjected to static internal pressure, $p$, are

$$\sigma_\theta = \frac{p R_e}{2 t^2} (1 + b^2 / a^2)$$

where $V$ is the constant power supply voltage, $R_g$ is the gage resistance, and $R_b$ is the ballast resistance. Differentiating with respect to $R_b$ we obtain

$$\frac{dV_g}{dR_g} = \frac{V R_b}{(R_b + R_g)^3}$$

The change in gage resistance depends on the strain, $\epsilon$, and the manufacturer's gage factor, $F$, is defined such that

$$\Delta R_g / R_g = F \epsilon$$

For small values of $AR_g / R_g$, we obtain from Eqs. (2) and (3)

$$\Delta V_g = \frac{V}{R_b + R_g} \cdot \frac{R_b}{R_g} \cdot R_g F \epsilon$$

and from Eqs. (4) and (1), we obtain

$$c \cdot \frac{AR_g / R_g}{F} \cdot \frac{\Delta R_g}{V_g}$$

Dynamic strains were determined by measuring the voltage change, $\Delta V_g$, as a function of time.

In each circuit, two gages were used in series ($R_g = 2000 \Omega$) to increase the output and to average the surface strains at each location. Four potentiometer circuits were connected in parallel across a laboratory power supply with ballast resistors of about 7500 $\Omega$ each for the strains $(\sigma_\theta p_1$, $(\sigma_\theta p_1$, $(\sigma_\theta p_1$, and $(\sigma_\theta p_2$. Altec constant current sources were used for $(\sigma_\theta p_2$ and $(\sigma_\theta p_2$, and for these strains, Eq. (5) reduces to

$$\epsilon = \frac{1}{F} \frac{\Delta V_g}{V_g}$$

The change in gage resistance depends on the strain, $\epsilon$, and the manufacturer's gage factor, $F$, is defined such that

$$\Delta R_g / R_g = F \epsilon$$

For small values of $AR_g / R_g$, we obtain from Eqs. (2) and (3)

$$\Delta V_g = \frac{V}{R_b + R_g} \cdot \frac{R_b}{R_g} \cdot R_g F \epsilon$$

and from Eqs. (4) and (1), we obtain

$$c \cdot \frac{AR_g / R_g}{F} \cdot \frac{\Delta R_g}{V_g}$$

Dynamic strains were determined by measuring the voltage change, $\Delta V_g$, as a function of time.

In each circuit, two gages were used in series ($R_g = 2000 \Omega$) to increase the output and to average the surface strains at each location. Four potentiometer circuits were connected in parallel across a laboratory power supply with ballast resistors of about 7500 $\Omega$ each for the strains $(\sigma_\theta p_1$, $(\sigma_\theta p_1$, $(\sigma_\theta p_1$, and $(\sigma_\theta p_2$. Altec constant current sources were used for $(\sigma_\theta p_2$ and $(\sigma_\theta p_2$, and for these strains, Eq. (5) reduces to

$$\epsilon = \frac{1}{F} \frac{\Delta V_g}{V_g}$$

The outputs of the strain gage circuits were recorded on two Tektronix dual-beam oscilloscopes using various plug-in units.

Tube with Internal Pressure. From Lamé's solution, the circumferential and radial stresses, $\sigma_\theta$ and $\sigma_r$, in an elastic thick-walled cylinder subjected to static internal pressure, $p$, are

$$\sigma_\theta = \frac{p R_e}{2 t^2} (1 + b^2 / a^2)$$

where $V$ is the constant power supply voltage, $R_g$ is the gage resistance, and $R_b$ is the ballast resistance. Differentiating with respect to $R_b$ we obtain

$$\frac{dV_g}{dR_g} = \frac{V R_b}{(R_b + R_g)^3}$$

The change in gage resistance depends on the strain, $\epsilon$, and the manufacturer's gage factor, $F$, is defined such that

$$\Delta R_g / R_g = F \epsilon$$

For small values of $AR_g / R_g$, we obtain from Eqs. (2) and (3)

$$\Delta V_g = \frac{V}{R_b + R_g} \cdot \frac{R_b}{R_g} \cdot R_g F \epsilon$$

and from Eqs. (4) and (1), we obtain

$$c \cdot \frac{AR_g / R_g}{F} \cdot \frac{\Delta R_g}{V_g}$$

Dynamic strains were determined by measuring the voltage change, $\Delta V_g$, as a function of time.

In each circuit, two gages were used in series ($R_g = 2000 \Omega$) to increase the output and to average the surface strains at each location. Four potentiometer circuits were connected in parallel across a laboratory power supply with ballast resistors of about 7500 $\Omega$ each for the strains $(\sigma_\theta p_1$, $(\sigma_\theta p_1$, $(\sigma_\theta p_1$, and $(\sigma_\theta p_2$. Altec constant current sources were used for $(\sigma_\theta p_2$ and $(\sigma_\theta p_2$, and for these strains, Eq. (5) reduces to

$$\epsilon = \frac{1}{F} \frac{\Delta V_g}{V_g}$$

The outputs of the strain gage circuits were recorded on two Tektronix dual-beam oscilloscopes using various plug-in units.

Tube with Internal Pressure. From Lamé's solution, the circumferential and radial stresses, $\sigma_\theta$ and $\sigma_r$, in an elastic thick-walled cylinder subjected to static internal pressure, $p$, are

$$\sigma_\theta = \frac{p R_e}{2 t^2} (1 + b^2 / a^2)$$
Equation (10) can be used to calculate ballis-
tic pressures so long as the loading is quasi-
static, the material responds elastically, and the
gun approximates a thick-walled cylinder. It will
be shown that these conditions were met reasonably
well at the chamber. However, the high-pressure
section deformed plastically, and a modified form
of Eq. (10) will be suggested later for estimating
the maximum pressure produced during compression
of the helium and impact of the piston.

RESULTS AND DISCUSSION

Seven preliminary rounds were fired in which
the piston configuration changed from an all lexan
design (21 in. long) to short lexan pistons weigh-
ted with cerrobend (a low melting bismuth alloy),
lead, or steel. Several types of projectiles were
used, and the helium pressure and propellant
charge were varied.

For the tests reported in this paper, a new
high-pressure section was installed, and the com-
ponents shown in Fig. 2 were similar throughout
these tests. Table 1 lists the helium pressures
and powder charges used in Rounds 8-14. The high-
pressure section was measured before and after
each test, and the outside and inside diameters at
strain gage station P2 are listed in Table 1.
Measurements were also made on the chamber, pump tube, and 12 in. section, and the light-gas gun was dimensionally stable except at the high-pressure section.

Strain Gage Records. Figure 5A shows typical strain versus time traces for all gages except \((e_{2})_p\) in Round 11. The slight disturbances on the left-hand side of these traces were due to the synchronizing or firing pulse, and fortunately these initial disturbances decayed rapidly and did not affect the strain gage records. The circumferential strain \((e_2)_p\) increased rather smoothly and appeared to be similar to a pressure-time curve. The longitudinal strain \((e_1)_p\) increased too, but high frequency oscillations were recorded on two oscilloscopes, Figs. 5A, B. Impact of the piston produced a more accurate measure of the piston velocity, using a delayed and faster sweep to the right on the oscilloscope, Fig. 5B. The strains in the gun as seen at later times on the traces in Fig. 5A, e.g., \((e_2)_p\) decreased abruptly and went off scale whereas \((e_1)_p\) decreased sharply because of coupling through Poisson's ratio.

Piston Velocity. As previously noted, strain gages were mounted circumferentially at two stations on the pump tube, 12 in. apart, symmetrically placed with respect to the second clasp. Average piston velocities were calculated by dividing this base line by the time interval between the traces in the \((e_1)_p\) and \((e_2)_p\) traces, Table 2. Although these piston velocities were not the maximum values in the pump tube, it is interesting to note that the average values obtained at this location were independent of helium pressure and varied linearly with charge.

Table 2 Piston Velocities and Chamber Pressures

<table>
<thead>
<tr>
<th>Round</th>
<th>Piston Velocity (ft/sec)</th>
<th>Maximum Chamber Pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>((e_1)_p)</td>
<td>((e_2)_p)</td>
</tr>
<tr>
<td>8</td>
<td>1600</td>
<td>201</td>
</tr>
<tr>
<td>9</td>
<td>1700</td>
<td>186</td>
</tr>
<tr>
<td>10</td>
<td>1700</td>
<td>186</td>
</tr>
<tr>
<td>11</td>
<td>1800</td>
<td>201</td>
</tr>
<tr>
<td>12</td>
<td>1700</td>
<td>186</td>
</tr>
<tr>
<td>13</td>
<td>1300</td>
<td>77</td>
</tr>
<tr>
<td>14</td>
<td>2500</td>
<td>562</td>
</tr>
</tbody>
</table>

Chamber Pressure. The strains \((e_1)_p\) and \((e_2)_p\) were used in Eq. (10) to calculate maximum chamber pressures, Table 2. Since the \((e_2)_p\) traces were relatively smooth curves, the maximum values were obtained easily. The corresponding values of \((e_1)_p\) were obtained by estimating its mean values. The error introduced in Eq. (10) by using this procedure was small because \((e_1)_p\) was multiplied by Poisson's ratio \((\nu = 0.3)\) and \((e_2)_p\) was less than \((e_1)_p\). Pressures were transmitted through the shell to the barrel, and the wall ratio was \(\nu = 0.5/0.322/1.933\) at the strain gages. The maximum chamber pressures were independent of helium pressure and increased rapidly with increasing charge. A standard charge of 318 gram of SDN 8709 powder when used with a standard 20 mm projectile weighing 890 grams has a chamber pressure of 47,300 psi. Using the same charge and a piston of 820 gram, a pressure of 40 kpsi was obtained in the light-gas gun, and this value compares favorably with the rated chamber pressure.

High-Pressure Section. The pressures developed in the central breech during Rounds 8-11,14 produced permanent deformations, Table 1. The residual circumferential strain, \((e_2)_{res}\), at the outer surface was calculated from the change in diameter, \(\Delta (\OD)\), i.e.,
(eq)\text{res} = \frac{5(00)}{2} \quad \text{(11)}

for each round, Table 3. The strain-time records of (eq)\text{p2} also gave values of (eq)\text{res} as shown in Fig. 6 and listed in Table 3. It should be noted that a change in outside diameter of 0.001 in. corresponded to $340 \mu e$, so that under these circumstances the values of (eq)\text{res} obtained by these two methods were in fairly good agreement.

Since the high-pressure section deformed plastically, Eq. (10) was not applicable. Measurements of (eq)\text{p2} showed that it was small compared to (eq)\text{p3}. In order to estimate that maximum pressure, (eq)\text{p2} was neglected in Eq. (10) and (eq)\text{p2} was replaced by (eq)\text{el} as defined in Fig. 6, i.e.,

$$P_{\text{max}} = \frac{\nu-1}{2} \cdot \frac{E}{1-\nu^2} \cdot (eq)\text{el} \quad \text{(12)}$$

The p vs. (eq)\text{p2} behavior of the tube is shown in Fig. 7, assuming a linear recovery from $P_{\text{max}}$: The slope of this line, i.e.,

$$S = \frac{\nu-1}{2} \cdot \frac{E}{1-\nu^2} \quad \text{(13)}$$

was calculated using values of $E = 30 \times 10^6$ psi and $\nu=0.3$ for steel and $\nu$ based on the dimensions of the tube.

Table 3 Residual Strains and Maximum Pressures

<table>
<thead>
<tr>
<th>Round</th>
<th>(eq)\text{res}</th>
<th>(eq)\text{p2}</th>
<th>(eq)\text{el}</th>
<th>(eq)\text{p2}</th>
<th>P_{\text{max}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>720</td>
<td>840</td>
<td>1000</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>1150</td>
<td>1210</td>
<td>1400</td>
<td>370</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>2010</td>
<td>1800</td>
<td>2410</td>
<td>610</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>140</td>
<td>240</td>
<td>1250</td>
<td>320</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>0</td>
<td>860</td>
<td>210</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>0</td>
<td>0</td>
<td>510</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>2720</td>
<td>3040</td>
<td>3350</td>
<td>800</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 6 Sketch of ($eq)_p2$ vs. Time

Fig. 7 Sketch of $p$ vs. ($eq)_p2$

Fig. 8 $P_{\text{max}}$ vs. Helium Pressure

After each test, the values of $P_{\text{max}}$ calculated in this way are listed in Table 3 and plotted in Fig. 8. For the same helium pressure and powder charge in Rounds 8 and 11, it is interesting to note that this procedure gave approximately the same values of $P_{\text{max}}$ even though the high-pressure section had been either severely overstrained in Rounds 8-10 and was nearly stable dimensionally in Round 11. Although the data in Fig. 8 are very limited, it appears that this type of graph will be useful in selecting operating conditions for the light-gas gun.

Assuming an elastic-plastic material and the maximum shear theory of yielding, it can be shown that a thick-walled cylinder becomes fully plastic at a pressure, $P_{\text{ult}}$ given by

$$P_{\text{ult}} = \sigma_m \cdot ln \nu \quad \text{(14)}$$
where $y$ is the tensile yield point of the material. The high-pressure section was made of 4340 steel, Rockwell C30, with $y = 120,000$ psi.

Using the initial dimensions, i.e., $w = 6.948/1.628$, we obtain $P_{ult} = 174,000$ psi. Rounds 12 and 13 were the only rounds in this series of tests which did not introduce additional permanent deformations, and the values of $p_{max}$ were comparable to $P_{ult}$. Rounds 8, 9, 11 gave somewhat higher pressures as would be expected. Assuming that the values of $p_{max}$ for Rounds 8, 9, 11, 12, 13 are reliable, extrapolation of these data as in Fig. 8 would indicate that the rather high pressures calculated for Rounds 10 and 14 by using Eq. (12) are reasonable values.

CONCLUDING REMARKS

Strain gages provided valuable information on the operating characteristics of the light-gas gun. They were cemented on the outer surface so that the gun was not weakened by drilling and tapping as is usually done for pressure gages and velocity probes. However, the output of a strain gage is generally only an indirect measure of some ballistic parameter of interest. In the present work, the interpretation was relatively straightforward for piston velocities and chamber pressures, whereas the calculations for maximum pressures in the high-pressure section involved several simplifying assumptions. Equation (12) seems to give reasonable values of $p_{max}$ and Fig. 8 appears to be a useful way of comparing various operating conditions of the gun. Further experimental and theoretical work is needed to determine the range of applicability of the proposed method for calculating $p_{max}$.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the cooperation and technical assistance of J.T. Gilbert in all phases of this work. Sincere thanks are expressed to the following: J.P. Shields and E.A. Webster, Jr. conducted the firings in the hypervelocity test facility, J.R. Revell performed all of the required machining, and J.A. Brittain measured critical sections of the gun. This work was undertaken at the request of the Hyperdynamics Branch, and the helpful discussions and encouragement received from L.F. Baldini, H.E. Fatzinger, and J.R. Kymer are gratefully acknowledged.

REFERENCES


3. Automation Industries, Inc., P.O. Box 245, Phoenixville, Pa. Budd Metalfilm Strain Gages and Accessories, Catalog BG24C0/B.


Variable-resistance strain gages were used to study the operating characteristics of a light-gas gun. Gages were cemented on the outer surface of the gun at several locations in order to determine chamber pressure, piston velocity, and pressures in the central breech. The high-pressure transition section deformed plastically in most rounds, and a method is suggested for estimating maximum pressures from strain-time records. Results are given for various helium pressures and powder charges.
<table>
<thead>
<tr>
<th>KEY WORDS</th>
<th>LINK A</th>
<th>LINK B</th>
<th>LINK C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain Gages</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ballistic Pressures</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light Gas Guns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experimental Mechanics</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>