Meas. Sci. Technol. **11** (2000) 1819–1823. Printed in the UK PII: S0957-0233(00)15854-0

Penetrator launch diagnostics from breech pressure measurements during operation of an air cannon

R D Lorenz and S E Shandera

Lunar and Planetary Laboratory, 1629 E University Boulevard, University of Arizona,
Tucson, AZ 85721-0092, USA

E-mail: `rlorenz@lpl.arizona.edu`

Received 27 July 2000, accepted for publication 11 September 2000

Abstract. We report breech pressure measurements during the firing of an air cannon. We find that the pressure record is a useful and convenient diagnostic of the penetrator projectile motion during launch—supplementing or replacing beam- or wire-breaking speedometers and on-board accelerometers. With little effort, launch speed can be measured with a 2σ error of 1.75 m s^{-1} or better than 5%.

Keywords: air pressure, projectile velocity, air gun, cannon, penetrators, ballistics

1. Introduction

Penetrators are dense, usually slender, vehicles designed to emplace instrumentation at some shallow depth by impact into a planetary surface. Interest in these vehicles remains high [1], although to date no penetrator mission has been successful: the two Russian Mars-96 penetrators were lost in a launch failure [2], and no data were received from the two 'Deep Space 2' (DS-2) penetrators [3] in NASA's New Millennium flight validation programme, although they are believed to have reached the Martian surface on 3 December, 1999. Two penetrators are planned to be launched to the moon in coming years in the Japanese Lunar-A mission [4], and several NASA mission proposals to comets and the moon also involve penetrators [1].

A penetrator mission usually entails a long and expensive programme of tests, to verify penetration performance and component survivability, and to evaluate the value of instrumentation such as impact accelerometers in determining the target surface properties. These tests may involve drop from aircraft, acceleration by rocket sled, conventional (powder) guns or even rubber catapult. One convenient apparatus for modest impact speeds is the air cannon—where the projectile is accelerated by pressurized air released from a reservoir.

Assessment of penetration performance, or investigation of impact-related effects such as heating, charging or comminution of the target material, requires documentation of the velocity at impact. This can be obtained by a variety of methods, some of which are quite cumbersome. Usually velocity is not sensed directly but from the derivative of position measurements. The latter include breakwires (which can be in the target [5] as well as immediately ahead of it), light gates or optical position sensing [6] or microwave interferometry [7]. Accelerometer records can sometimes be integrated to derive velocity (e.g. [8, 9]), although zero offset shift can be a problem. Here we show how a simple pressure sensor can be used to measure speed.

2. Experimental apparatus

The air cannon in this investigation (figure 1) is a 3 inch (7.6 cm) bore gun, powered by compressed air held in a 15 gallon (0.057 m^3) tank, typically at 3 bar above ambient pressure. The projectile (figure 2) is a 40 mm diameter hemisphere-nosed slug 100 mm long (roughly equivalent in size, shape and mass to the forebody of the DS-2 penetrators), held in a biconic spool sabot, which fills the bore of the gun. The sabot is held in place in the gun by a 2 mm graphite shear pin (a pencil lead); the forebody is held in the sabot by a similar pin, which fails at impact.

The accelerometer used in these tests is a piezoelectric device, Endevco 2225, generating 0.76 pC g^{-1}. The charge signal is conducted along a 10 ft Kevlar-reinforced coaxial cable, which passes through the breech plate to a charge amplifier. The cable uncoils during firing from the inside of the sabot. The accelerometer signals and performance of the airgun are described in an earlier paper [10].

Note that coiling the cable inside the projectile avoids applying significant tension to the cable, reducing the likelihood of cable break. Since the cable has a mass of about 50 g, the accelerated mass of the projectile drops by about 5% during the launch event. To prevent the cable from uncoiling during loading, it is held in place with two short

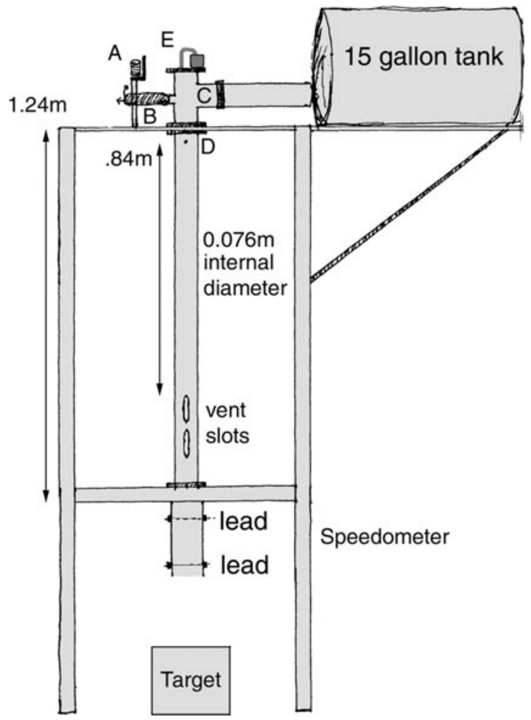

Figure 1. Schematic drawing (to scale) of the airgun. Operation of the solenoid (A) raises retaining arm (B) allowing the plunger valve in (C) to be pushed to the left and permitting air from the tank to flow into the breech. Pressure behind the projectile builds, recorded by the sensor (E) and causes the pin at (D) to fail. The projectile is accelerated down the barrel into the target.

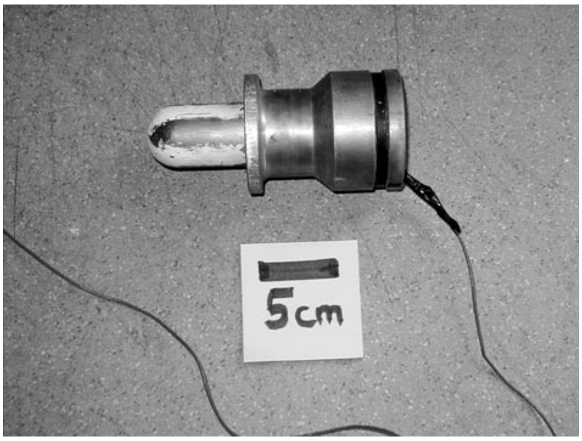

Figure 2. Photograph of the projectile with Kevlar-reinforced coaxial cable. The black band at the rear is a notch for retaining the projectile in the gun barrel with a shear pin. The round-nosed forebody has white paint stripes to record abrasion during penetration.

lengths of electrical tape. It is easily demonstrated by holding the cable and dropping the assembled projectile that the tape sustains a drag load of only a few N—at most a few per cent of the accelerating force during gun firing.

The pressure sensor is a micromachined silicon pressure transducer (Omega model PX139-100A4V), with built-in amplification and temperature compensation. Provided with a regulated 5V supply, the device provides an output signal linearly related to applied absolute pressure: 0.25 V at 0 bar, 4.25 V at 6.8 bar (100 psi). Note, however, that any pressure sensor with an adequately short time constant would be equally suitable. The sensor is coupled to the breech region of the gun by a small length of clear plastic tubing.

A set of four 1 kΩ resistors in series has a 9 V battery applied across it, and the centre voltage is monitored. Two of the resistors are shorted by graphite pencil leads held across the path of the projectile, spaced by 15 cm. When the first lead breaks, the voltage undergoes a step change as the potential division changes. The time between this and a second voltage step caused by the failure of the second lead allows the projectile speed to be determined.

The four voltages (accelerometer, pressure sensor, the lead-break speedometer and a charging sensor not described further here) were recorded with 16 bit precision at 20 kilosamples per second using an IoTech Daq 216B data acquisition card mounted in a laptop PC. Auto-triggering on the accelerometer channel was found to be unreliable, so sampling was initiated by manual command for 1.5 seconds, a fraction of a second before the fire button was pressed to actuate the valve.

3. Results

A suite of 17 shots was performed in summer 2000, to evaluate accelerometer records in a number of different materials, to study triboelectric charging and the effects of different penetrator nose shapes. Most shots recorded data on all four channels. Accelerometer data were corrupted or lost on five of the 17 shots on which data were to be taken: two due to operator error, failing to initiate data acquisition correctly, two due to wire breaks during firing and one due to overranging because of extreme deceleration on a hard target.

Pressure sensor data were successfully acquired on all of these shots, with the exception of the two acquisition failures. A typical pressure sensor record is shown in figure 3, with the speedometer and accelerometer signal superimposed.

An initial transient seen in the pressure record (and indeed in all measurement channels at 348.6 ms) is the electromagnetic coupling of the actuation of the firing valve solenoid. The solenoid motion, and the movement of the plunger valve, take some 20 ms, and the pressure rises to a maximum in 5 ms.

When the pressure exceeds about 0.8 bar, the graphite shear pin holding the projectile in the gun barrel breaks: this is signalled by the strong spike at 361.0 ms and subsequent rapid oscillations in the accelerometer signal.

A pressure maximum is reached at $t = 364$ ms, with a maximum pressure close to the original tank pressure. After this maximum the accelerating projectile increases the gas volume behind it and so the pressure falls. Superimposed on the steady decrease is an oscillation with a period of about 8 ms, giving a trough at 368 ms and a peak at 373 ms. This oscillation is believed to be an acoustic signal excited by the air flow (i.e. a 'whistle')—this has also been seen in accelerometer signals on lighter airgun-launched projectiles (Kargl, personal communication, 2000).

A sharp drop in the deceleration signal is evident at 403.7 ms when the projectile passes the vent slots at 0.85 m. These slots are intended to bleed off pressure near the end

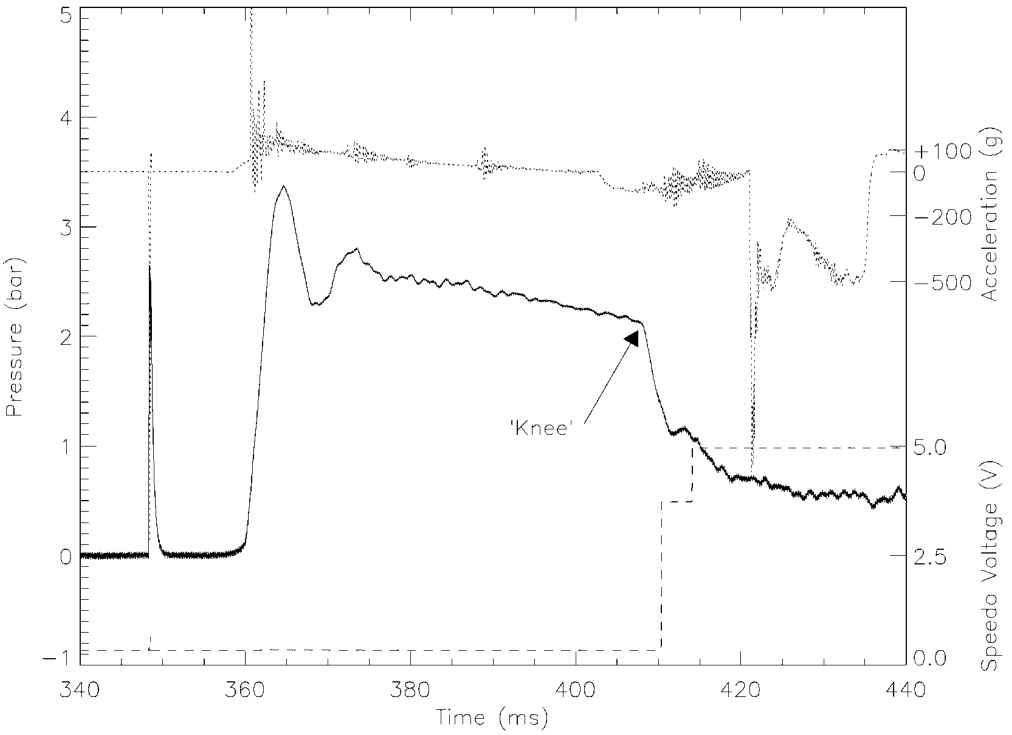

Figure 3. 100 ms segment of an experiment data record. The pressure record (solid line, left scale) shows a solenoid spike, a sharp rise to a slowly declining plateau, then a sharp drop. The deceleration record is the dotted line (right hand scale). The speedometer voltage is shown by the dashed line. Note that the pressures shown here are relative to ambient, not absolute.

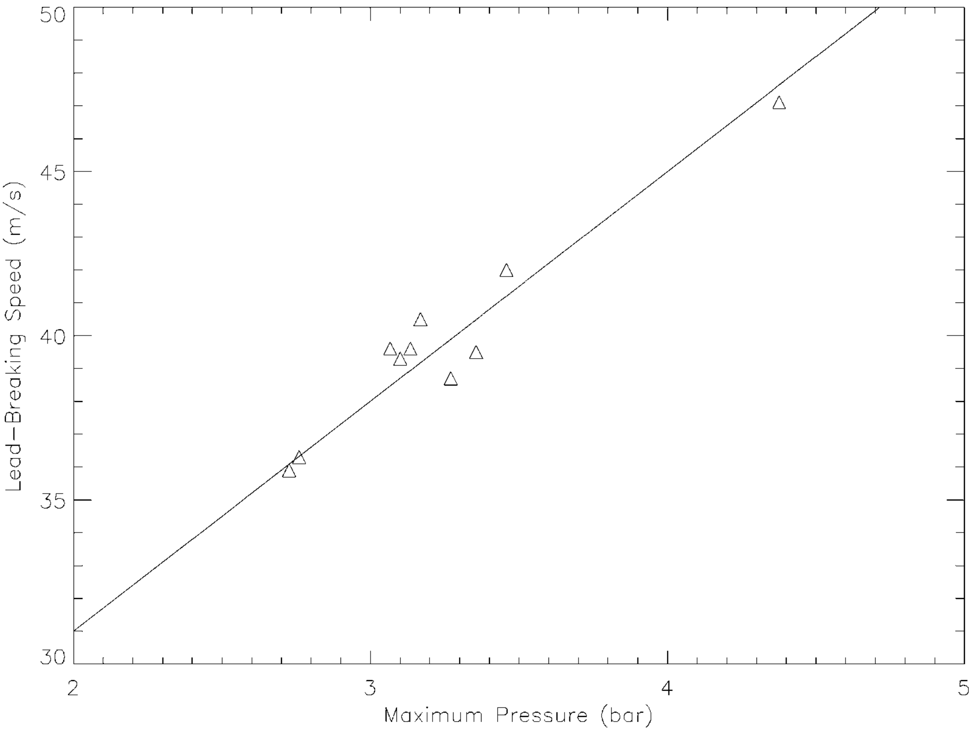

Figure 4. Correlation of peak pressure with velocity recorded by the speedometer. For a given gun and projectile, the correlation is very good: the line of fit is $V = 17 + 7P_{max}$.

of the acceleration phase to minimize the strength of the air jet that impinges on the target immediately after the projectile, since this air jet would erode the target surface and undesirably disperse the material.

The pressure record suffers a similar change in slope at 408.1 ms (marked 'knee' in the figure), 3.4 ms after the knee in the accelerometer curve. The delay is simply the sound speed propagation time from the vent

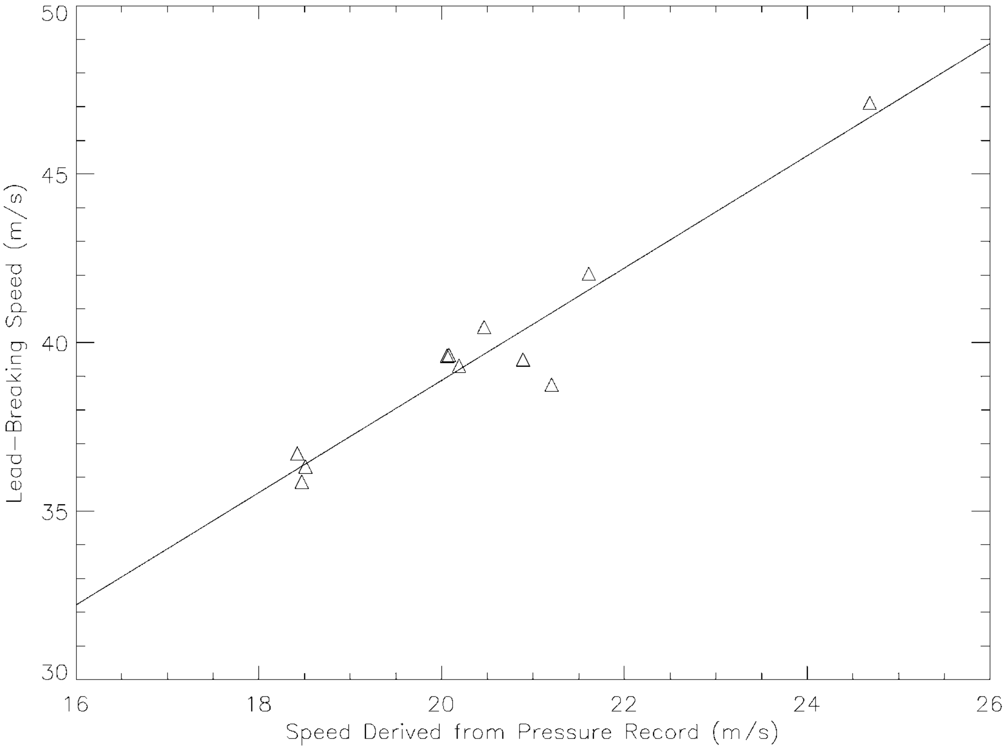

Figure 5. Correlation of average speed during acceleration phase, as determined from the pressure record alone $V_p = 0.85/(t_{knee} - t_{pmax})$ with that recorded by the speedometer. The line of fit is $V = 6.7 + 1.56V_p$.

slots themselves to the pressure sensor (the sensor is about 25 cm—taking the flexible tube into account—behind the projectile launch position, thus is ∼1.1 m from the slot: 1.1 m/340 m s^{-1} = 0.0032 s). After this point, the pressure sensor provides little useful information.

The projectile crosses the two speedometer leads at 410.2 and 414.1 ms respectively, indicating a speed of 36.6 m s^{-1}. Impact occurs at 421.0 ms and lasts about 15 ms.

4. Analysis and discussion

The pressure sensor provides a record of events during the launch process. The initial launch pressure of 3 bar corresponds to a force of about 1 kN on the back of the projectile, which has a mass of 1.1 kg: the initial acceleration should therefore be around 100 g, as observed. The deceleration signal appears to drop faster than expected. It was previously hypothesized [9] that this is an artifact of the imperfect charge amplifier on the accelerometer signal or that the pressure dropped rapidly because the flow from the reservoir was too slow to keep up with the increasing volume behind the projectile. The pressure sensor rules out this latter mechanism, pointing to a charge amplifier problem (in any case integration of the accelerometer signal does not yield the correct velocity).

Empirically, for a given projectile mass, the launch velocity correlates very well with the peak pressure in the record (figure 4): velocity can be determined to 1 m s^{-1} using this quantity alone (formally, the standard deviation is 0.87 m s^{-1}, or about 2.2%). This accuracy is quite adequate for penetration investigations, which by their very nature are rarely exercises in precision.

If projectiles of different masses were used, the correlation would change. However, the time marker afforded by the knee in the pressure record (corrected for propagation time) allows a more general speed determination. This time, combined with the launch time places a constraint on the velocity history of the projectile (the integrated velocity must pass through the vent position at the observed time). The pressure record itself, or to a close approximation a constant assumed acceleration, could be used to construct a model position history (parabolic, for a constant acceleration): tuning the model to match the time reference allows the launch velocity to be estimated. Crudely, if the acceleration is considered constant, then the time difference gives the average velocity of the projectile down the barrel.

The launch time can be determined from the spike in the accelerometer record, when the shear pin fails. It was noted that in 11 out of 12 records, the shear pin failed at a pressure within a remarkably consistent pressure range of 0.82 to 0.86 bar—corresponding to ∼385 N. Thus the pressure record *alone* can be used to determine the launch time—no other instrumentation is needed. The data plotted in figure 5 actually use the time of the peak in the pressure record as a proxy for launch time: these recorded speeds make no assumptions about projectile mass.

The pressure-derived average speed is around half of that recorded by the speedometer, as would be expected from uniform acceleration: since the acceleration is a little higher at the beginning, the ratio between the speeds is less than 2.

Note that the projectile also accelerates a little more in the distance between the vents and the speedometer. Making an empirical line fit to the data yields a speed estimate that has a standard deviation σ of 0.88 m s^{-1}. A 95% confidence level accuracy of the method is therefore 1.76 m s^{-1}.

Note that vent slots are not necessary to apply the pressure-sensing method of speed determination—the air loss when the projectile leaves the gun barrel could act as a time marker similar to the vent 'knee'.

5. Conclusions

A breech pressure sensor is a simple, inexpensive and useful supplement to other instrumentation on an airgun: the pressure record provides several time markers during the launch event.

In principle, the pressure sensor provides little information that could not be obtained from a perfectly operating accelerometer and/or speedometer system. However, a pressure sensor is easier to install than a purpose-built lightgate system, and requires less effort per shot than a wire-break speedometer. Further, accelerometer operation is not required for every shot (for example if only penetration depth is being evaluated), and risks cable break; for the launch phase at least, a pressure sensor makes an acceptable proxy, and can even be used to investigate nonidealities in the accelerometer measurement chain.

The pressure history also allows insight into the gun operation, such as to what extent the pipe flow from the reservoir, or the size of the reservoir itself, are limiting factors on firing speed.

Acknowledgments

This research was supported by the NASA DS-2 project. S E Shandera was supported during the early part of this work by the Arizona Space Grant Consortium. We thank B Verts for mechanical assistance with the gun and G Kargl for useful discussions.

References

[1] Ball A J and Lorenz R D 2000 Penetrometry of extraterrestrial surfaces: a historical overview *Penetrometry in the Solar System* ed N Kömle *et al* (Austrian Academy of Sciences) at press
[2] Surkov Yu A and Kremnev R S 1998 *Planet. Space Sci.* **46** 1689–96
[3] Smrekar S, Catling D, Lorenz R, Magalhães J, Moersch J, Morgan P, Murray B, Presley M, Yen A, Zent A and Blaney D 1999 *J. Geophys. Res.* **104** 27 013–30
[4] Nakajima T, Hinada M, Mizutani H, Saitoh H, Kawaguchi J and Fujimura A 1996 *Acta Astronautica* **39** 111–19
[5] Allen W A, Mayfield E B and Morrison H L 1957 *J. Appl. Phys.* **28** 370–6
[6] Hearst J R and Lynch C S 1994 *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.* **31** 243–51
[7] Hakala W W 1965 Resistance of a granular medium to normal impact of a rigid projectile *PhD Thesis* Virginia Polytechnic Institute, Blacksburg
[8] Kömle N I, Ball A J, Kargl G, Stöcker J, Thiel M, Jolly H S, Dziruni M and Zarnecki J C 1997 *Planet. Space Sci.* **45** 1515–38
[9] Thompson J B III 1975 Low-velocity penetration of low-cohesion soil deposits *PhD Thesis* University of California, Berkeley
[10] Lorenz R D, Moersch J E, Stone J A, Morgan A R Jr and Smrekar S E 2000 *Planet. Space Sci.* **48** 419–36