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Technical Report 32-1342

*Analysis of Problems Related to Slingshot Shock
Machine High-Velocity Shock Testing*

J. W. Shipley



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**JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA**

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Preface

The work described in this report was performed by the Environmental Sciences Division of the Jet Propulsion Laboratory.

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Abstract

This report describes some engineering analysis done in connection with a program to upgrade a slingshot shock machine. The purpose of this upgrading was to make the machine suitable for conducting qualification tests on spacecraft hardware. Primarily, what was needed was to:

- (1) Provide information which will more clearly specify the setup for a given test, particularly in the area of acceleration level and pulse duration.
- (2) Indicate possible modifications which will improve the operation of this machine as a test instrument.
- (3) Improve the techniques of making motion measurements so that more validity could be attached to the tests conducted.

Analysis of Problems Related to Slingshot Shock Machine

High-Velocity Shock Testing

I. Introduction

The technique of using a slingshot device to produce high-velocity shocks is a concept that has been developed over the last few years. A machine of this type exists in the Environmental and Dynamic Testing Laboratory of the Jet Propulsion Laboratory at this time, which is capable of imparting a square-pulse acceleration greater than 20,000 g with a pulse duration of up to 1.5 ms. The objective of this study is to examine the present machine as a high-velocity shock testing machine with the following goals in mind:

- (1) Provide information which will more clearly specify the setup for a given test, particularly in the area of prediction of acceleration level and pulse duration.
- (2) Indicate modifications which will improve the operation of this machine as a test instrument.
- (3) Discuss the control instrumentation requirements for the slingshot machine and give an account of various procedures for making the motion measurements required to verify its performance.

The conceptual operation of the present machine can be described rather simply. The setup of the machine is given in Fig. 1. The bungee cord is loaded to a small pre-tension and the sled is drawn back to a desired length between two rails. It is released from a distance which will give it a desired velocity at impact. The impact tool on the front of the sled impacts into the copper target block to create the desired pulse. In the actual operation, several problems exist:

- (1) The bungee cord is not consistent. Its spring rate changes with each shot, making it difficult to predict impact velocity accurately.
- (2) The cord during the sled travel is excited in such a manner that it causes, in some cases, second or third shocks to occur. This also fatigues the cord, adding to the first problem; and this phenomenon contributes to the failure of instrumentation cabling.
- (3) The agreement between the various methods of determining the acceleration is not good.
- (4) There are limitations on the pulse shape which are not clearly defined.

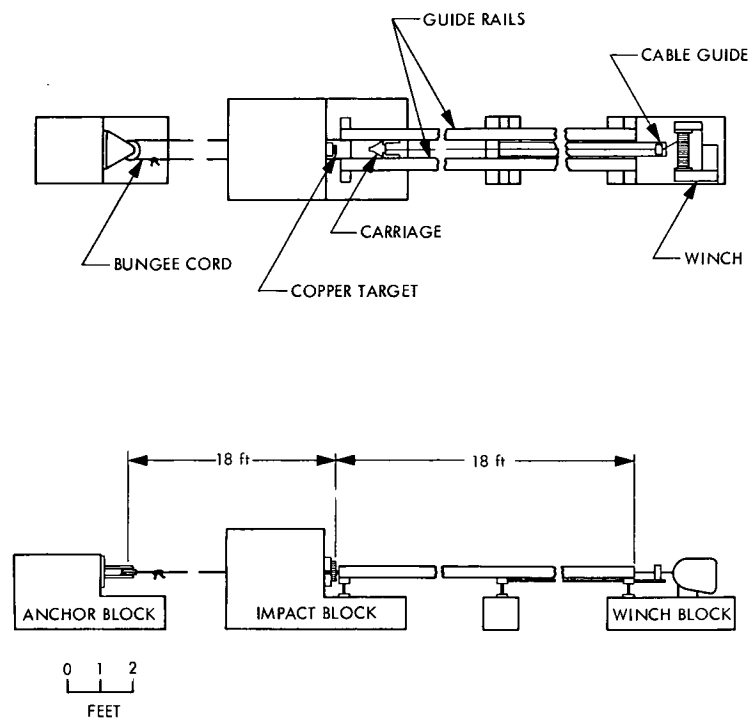


Fig. 1. General configuration of shock machine

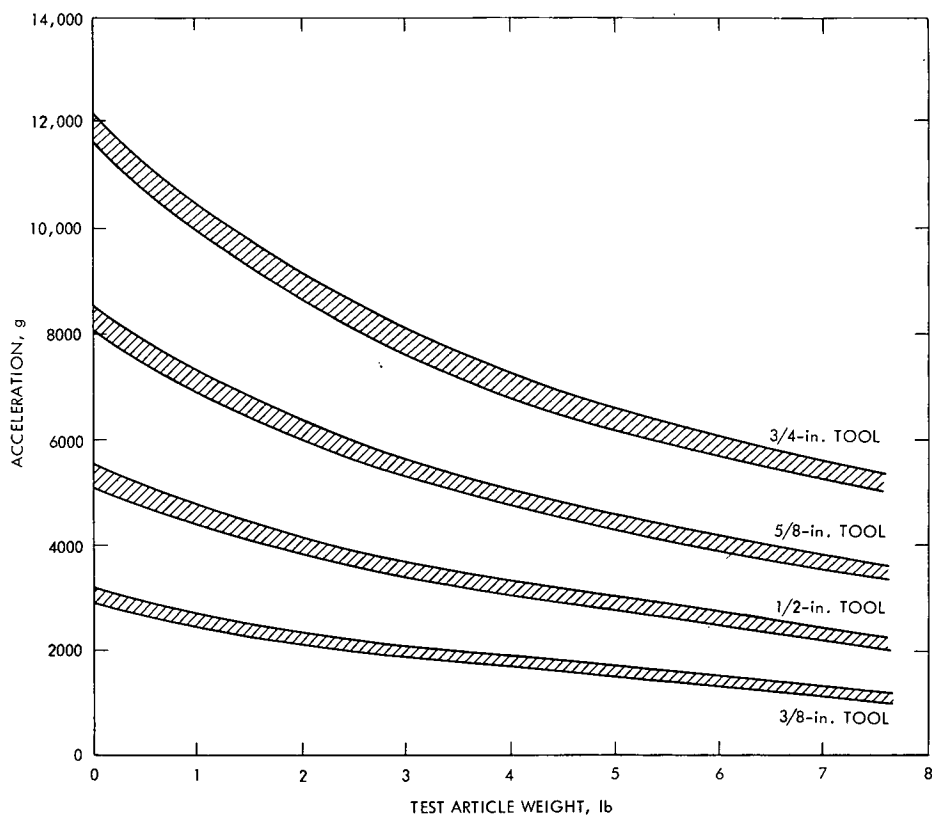


Fig. 2. Acceleration vs sled loading for 3/8- to 3/4-in. impact tools

It is convenient to cover these problem areas by dividing this study into two parts: (1) a study of the actual shock pulse which the slingshot produces, and (2) a study of the mechanism used to create the energy (velocity) required to produce the pulse. Also, separate sections are included to discuss the control instrumentation.

II. Shape and Other Limitations of the Shock Pulse

The ideal pulse shape for the slingshot machine is a rectangular acceleration pulse. The zero rise time and zero decay time for such a pulse are not physically obtainable. Therefore, in discussing this pulse several quantities should be considered.

- (1) Rise time: the time required to go from 10 to 90% of the maximum acceleration.
- (2) Decay time: the time required to go from 90 to 10% of the maximum acceleration.
- (3) Pulse duration: the time the acceleration stays within 10% of its maximum value.
- (4) g -level: the maximum acceleration in g is relatively close to calculations, made with Newton's second

law using this pressure figure, the impact tool area, and the sled mass, Figs. 2 and 3. Also, within practical limits, as discussed below, the acceleration levels are independent of velocity and pulse duration.

The physical mechanism used to produce the pulse on the slingshot is to impact a copper target with a steel impact tool, Fig. 4. This impact produces a plastic flow in ductile copper which occurs in two regimes. At impact (contact) the block is deformed with no clear penetration. This flow occurs during the rise time of the pulse which is generally of less than 0.2 ms in duration. The second flow regime accounts for the actual pulse duration. This regime occurs during the development of the hole in the block and it is characterized by constant force. The pressure is about 152,000 psi, which is relatively independent of the diameter of the tool used. This can be seen by the fact that the acceleration levels obtained by the slingshot can be calculated directly using Newton's second law. The factors involved are this pressure figure, the impact tool frontal area, and the sled mass. The graphs in Figs. 2 and 3 were derived using this method, and they agree with test values. The decay

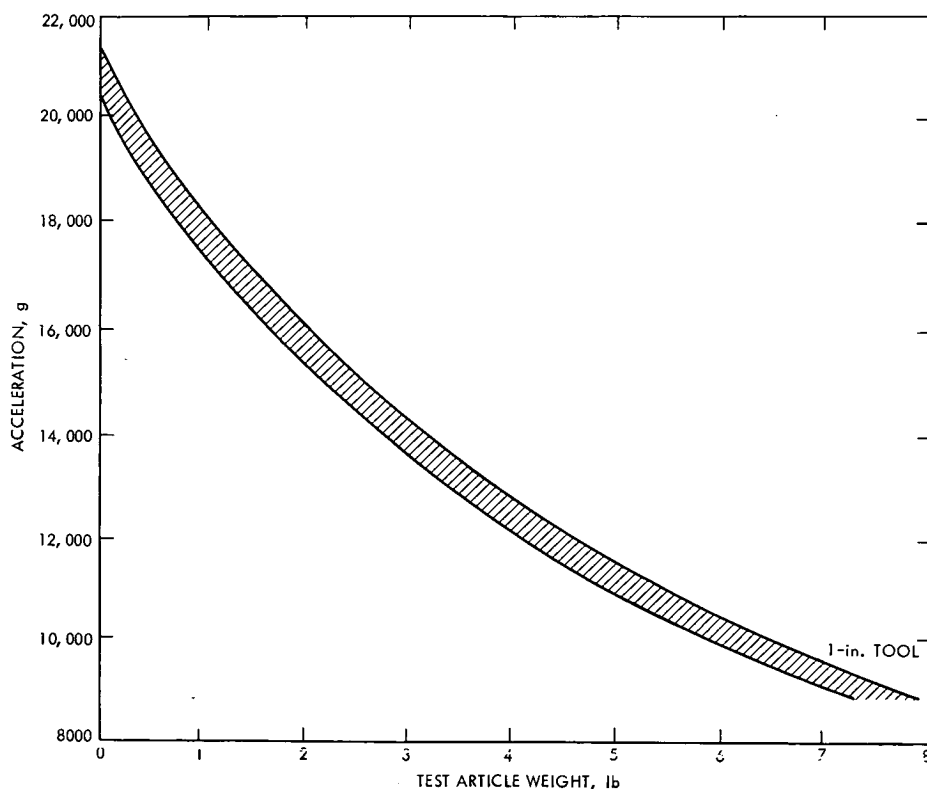


Fig. 3. Acceleration vs sled loading for 1-in. impact tool

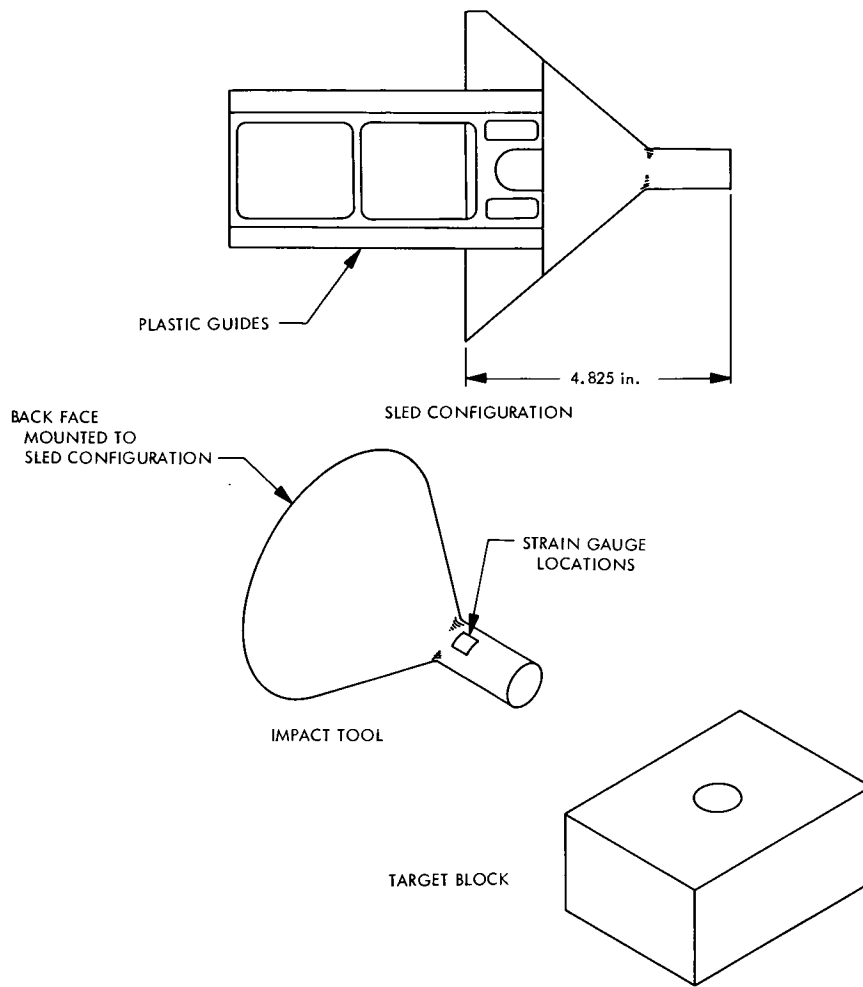


Fig. 4. Impact tool, target block, and sled configuration

time is generally on the order of 0.1 ms, slightly dependent upon the package weight and the g -level. The impact velocity has little to do with the g -level and only affects the pulse duration, as long as the plastic flow is predominantly in regime two.

There are two phenomena resulting from the basic design concept which have an effect on the pulse shape. These are mentioned here as limitations on the machine rather than as areas of possible improvement.

The first is a limitation on the pulse width. The duration of the pulse becomes smaller as the impact velocity is decreased, while the rise time remains constant. This results in a trapezoidal rather than rectangular pulse. Therefore, as a practical limit, pulses of duration of less than 0.3 ms are below the capability of the slingshot machine.

The second limitation is a somewhat undesirable property of the sled configuration in that the sled does not act as a rigid body, but rather as an elastic system. This can be seen in the 6 and 12 kHz ringing in the accelerometer records in Fig. 5. The frequencies of this ringing are about the same as the frequencies of the first two compressional modes of a simple bar of about the same length, 9 and 18 kHz.

III. Impact Velocity

The major difference between the slingshot machine and the classical drop tester is the method of obtaining the velocity necessary to produce the shock pulse. The advantage that the slingshot has over the drop tester is apparent when one considers that it would require about a 620-ft drop height to achieve the 200 ft/s impact ve-

locity which the 36-ft horizontal slingshot approaches. The slingshot technique has several disadvantages, however; these are mentioned in the introduction.

The motion of the sled was studied theoretically, and mapped with the aid of high-speed motion pictures, to obtain a clearer understanding of these problems so that some improvements could be suggested.

The motion of the sled, during the time between the release of the sled and the impact, is considered to follow the motion of an elastic string in which one-dimensional longitudinal wave motion exists. The differential equation of this motion is

$$a^2 \frac{\partial^2 u}{\partial x^2} = \frac{\partial^2 u}{\partial t^2}$$

where

a is the speed of sound (a longitudinal wave) in bungee, and

$$a^2 = \frac{Klg}{\gamma}$$

where

u is the displacement of the cord from its unstretched length.

x is the position along the cord.

t is time.

K is the linear spring constant of the cord, both parts of Fig. 1.

g is the acceleration due to gravity.

γ is the weight of bungee per unit length.

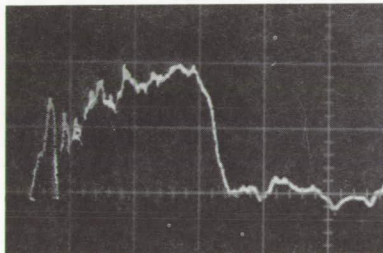
l is the unstretched cord length.

The initial conditions are

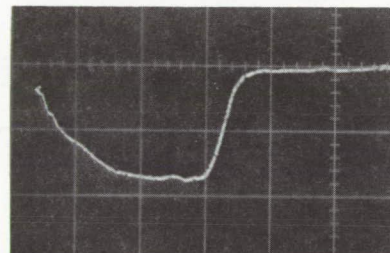
$$\frac{\partial u}{\partial t}(x,0) = 0$$

$$u(x,0) = Cx$$

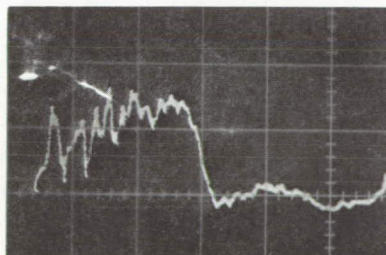
C is the ratio of the extended length to the unstretched length.



IMPACT VELOCITY: 98 ft/s
HORIZONTAL SENSITIVITY: 0.2 s/div
VERTICAL SENSITIVITY: 5 k g/div



IMPACT VELOCITY: 98 ft/s
HORIZONTAL SENSITIVITY: 0.2 s/div
VERTICAL SENSITIVITY: 2.5 k lb/div
(FORCE; NOT ACCELERATION)



IMPACT VELOCITY: 69 ft/s
HORIZONTAL SENSITIVITY: 0.2 s/div
VERTICAL SENSITIVITY: 5 k g/div

Fig. 5. Acceleration vs time records for an unloaded sled with a 5/8-in.-diam impact tool for various impact velocities

The boundary conditions are

$$u(0,t) = 0$$

$$AE \frac{\partial u}{\partial x} \bigg|_{x=l} = \frac{-W}{g} \frac{\partial^2 u}{\partial t^2} \bigg|_{x=l}$$

The second condition relates the force required to accelerate the sled to the tension in the cord.

The solution of the displacement of the string is

$$u(x,t) = 4Cl \sum_{i=1}^{\infty} \frac{\sin \frac{\beta_i x}{l} \cos \frac{\beta_i at}{l}}{\beta_i (2\beta_i + \sin 2\beta_i)}$$

The sled velocity is

$$\frac{\partial u}{\partial t} \bigg|_{x=l} = -4Ca \sum_{i=1}^{\infty} \frac{\sin \beta_i \sin \beta_i \frac{at}{l}}{2\beta_i + \sin 2\beta_i}$$

The β_i are eigenvalues for this problem, determined by the equation

$$\frac{W_1}{W_2} = \beta \tan \beta$$

where

W_1 is the weight of the cord

W_2 is the weight of the sled configuration

A computer program was written to solve the expressions for displacement and velocity. To obtain a solution, only four quantities need be supplied: a , l , C , and

W_1/W_2 . Considering the curves in Figs. 6 and 7 for extension vs force in the 1/2- and 3/4-in. bungee cord, the choice of spring length and spring constant for an equivalent linear spring are not obvious. Using the actual unstretched length of 16.75 ft and a speed of sound of 225 ft/s, determined from these curves, solutions were obtained which agree well with the velocity maps made using high speed photography, Figs. 8-13.

Several things can be concluded from this study:

- (1) The present method of pre-tensioning is inadequate to take full advantage of the elasticity in the bungee cord, particularly for the 1-in. cord.
- (2) The motion of the cord appears to be somewhat that of a longitudinal wave until the wave reaches the pulley, Fig. 1. Then, part of its kinetic energy is reflected back in a longitudinal wave and part in a transverse wave, discussed in the next paragraph.

From the theoretical study of the cord motion, it was noted that the longitudinal wave reaches the pulley generally after the sled has travelled two-thirds its total displacement and is reflected back to the sled about the time it reaches impact. However, most of the kinetic energy in the cord is coupled into a transverse wave that is reflected back at a slower velocity, about 100 ft/s. The transverse wave reaches the sled in under 1/5 s. This wave has a rather large transverse displacement which tends to fatigue the bungee. Also, it causes the sled to move away from the copper block after impact, hit the rails and other obstructions in the impact area, and rebound back into the target block. All the impacts which occur during this process are additional shocks which a specimen will experience in a test. A suggestion for avoiding this problem is given in the recommendations.

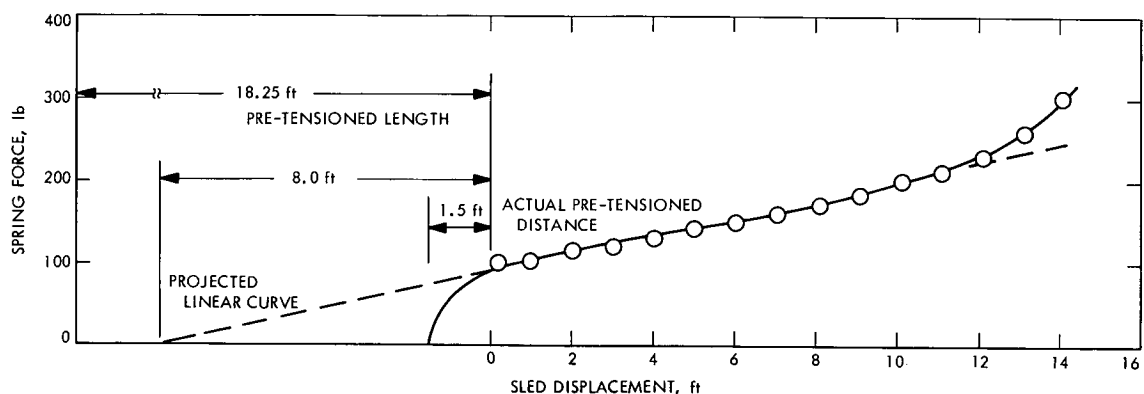


Fig. 6. Tension vs sled displacement for 1/2-in. bungee cord

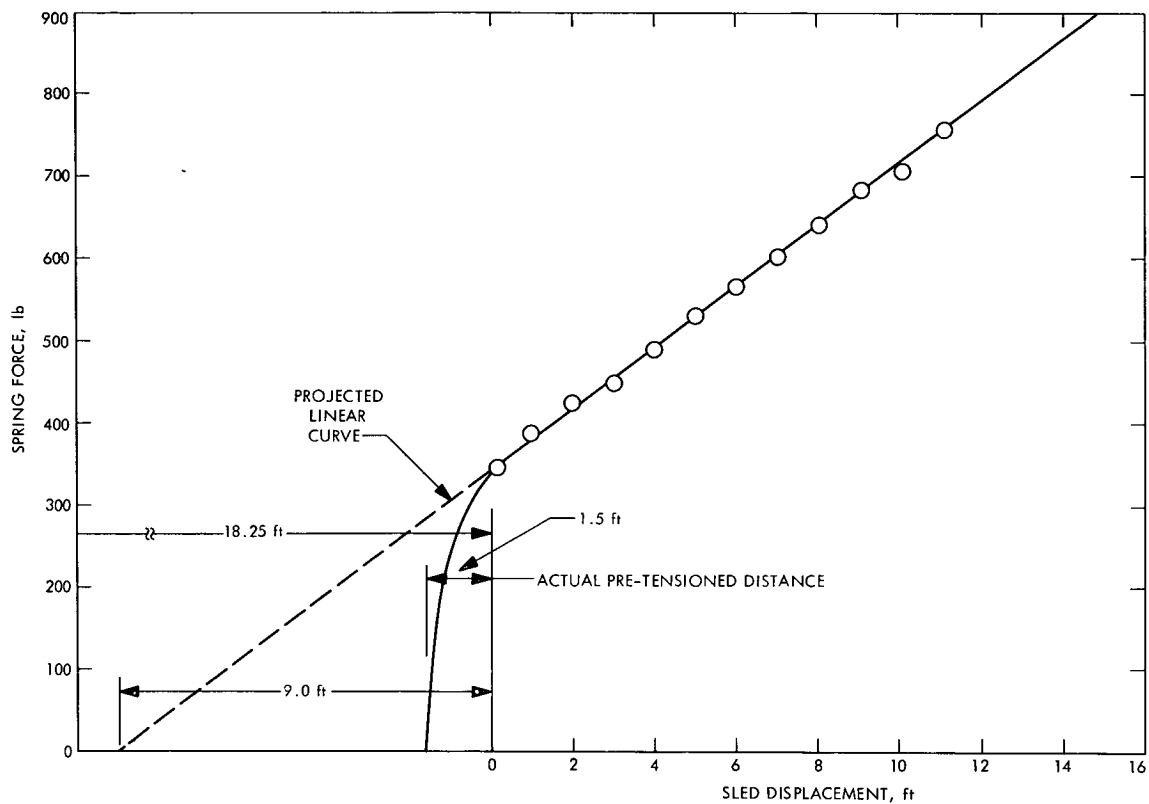


Fig. 7. Tension vs sled displacement for 3/4-in. bungee cord

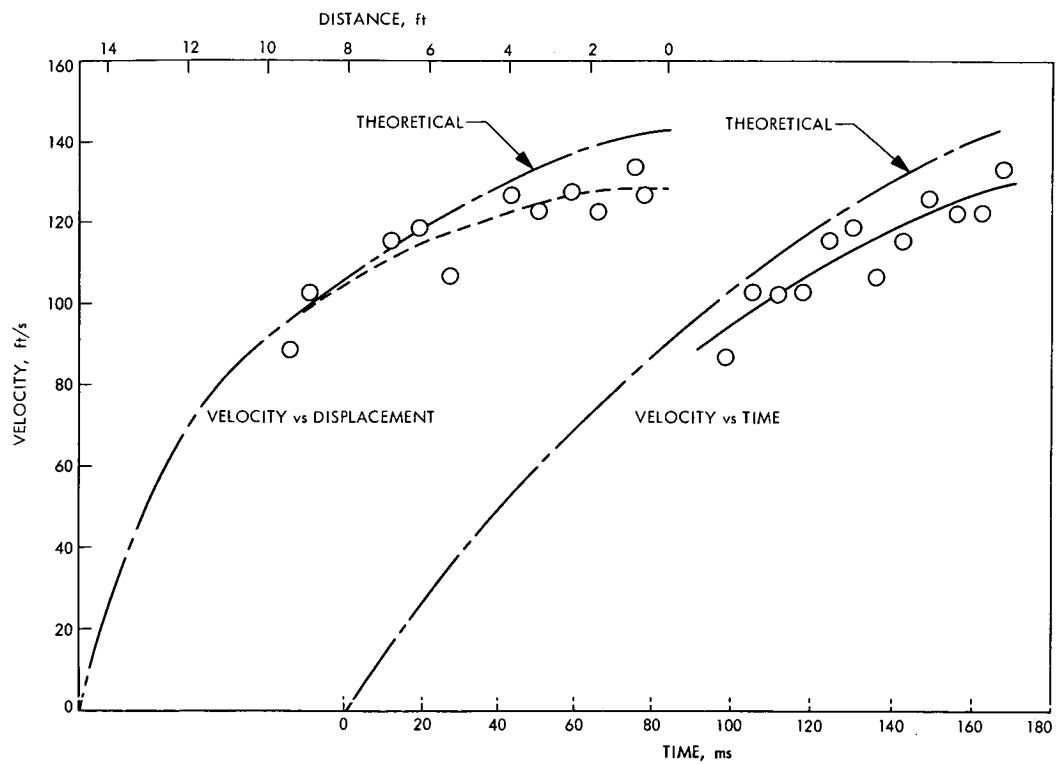


Fig. 8. Velocity map for 1/2-in. bungee cord: sled weight, 6.5 lb; sled displacement, 14.7 ft

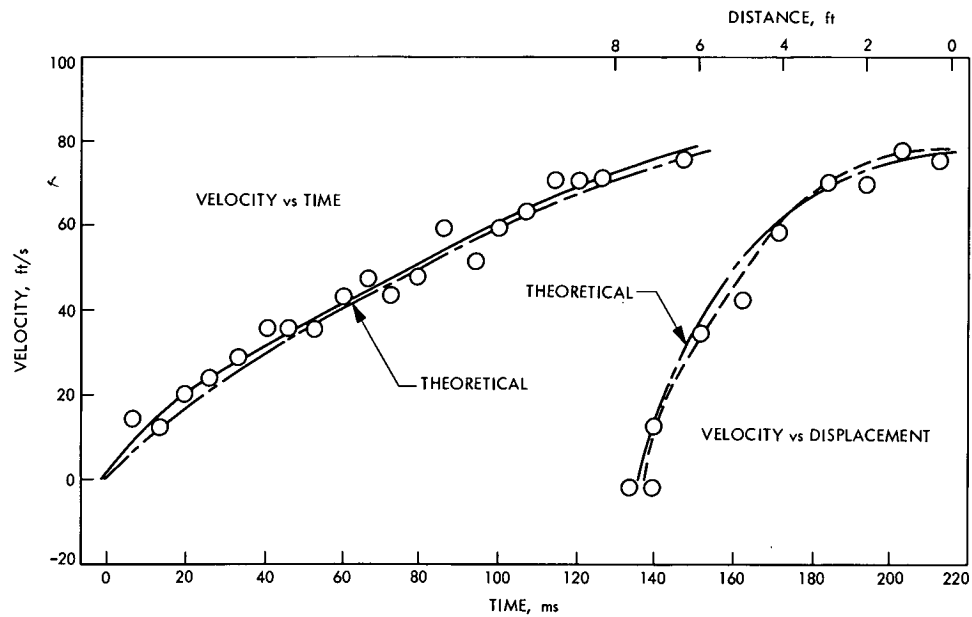


Fig. 9. Velocity map for 1/2-in. bungee cord: sled weight, 6.5 lb; sled displacement, 7.3 ft

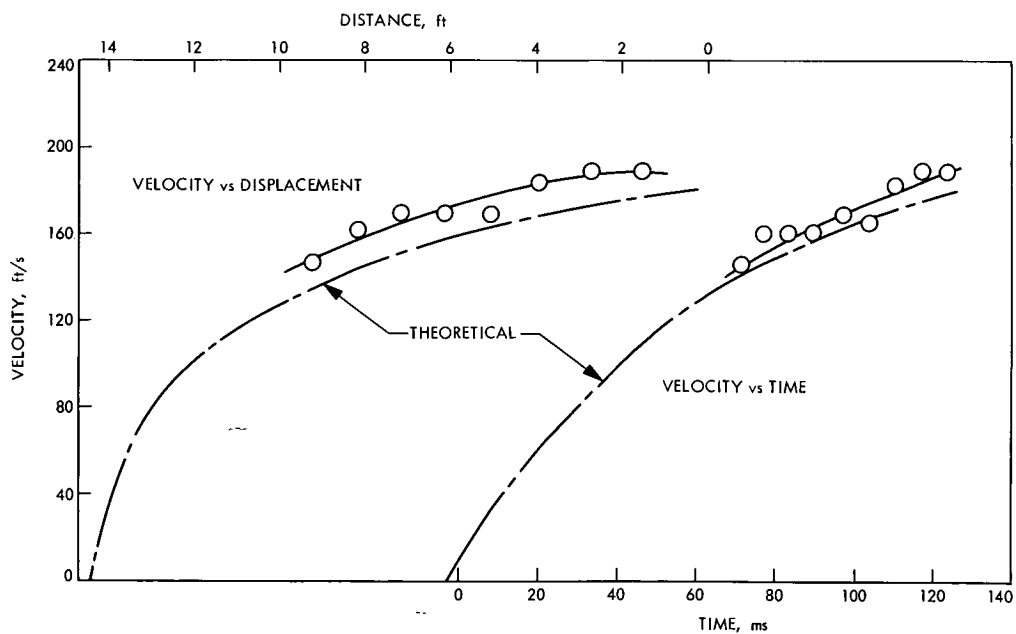


Fig. 10. Velocity map for 3/4-in. bungee cord: sled weight, 6.5 lb; sled displacement, 14.7 ft

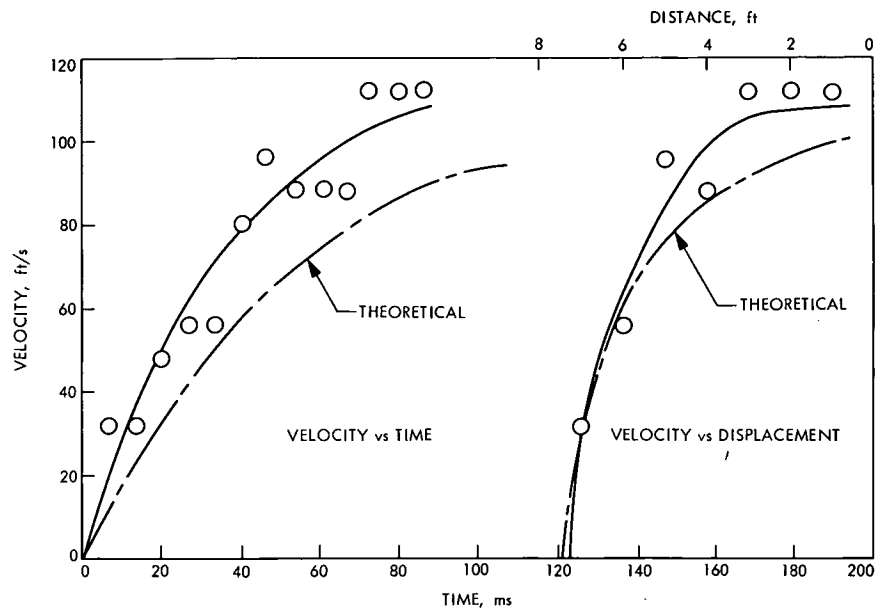


Fig. 11. Velocity map for 3/4-in. bungee cord: sled weight, 6.5 lb; sled displacement, 7.3 ft

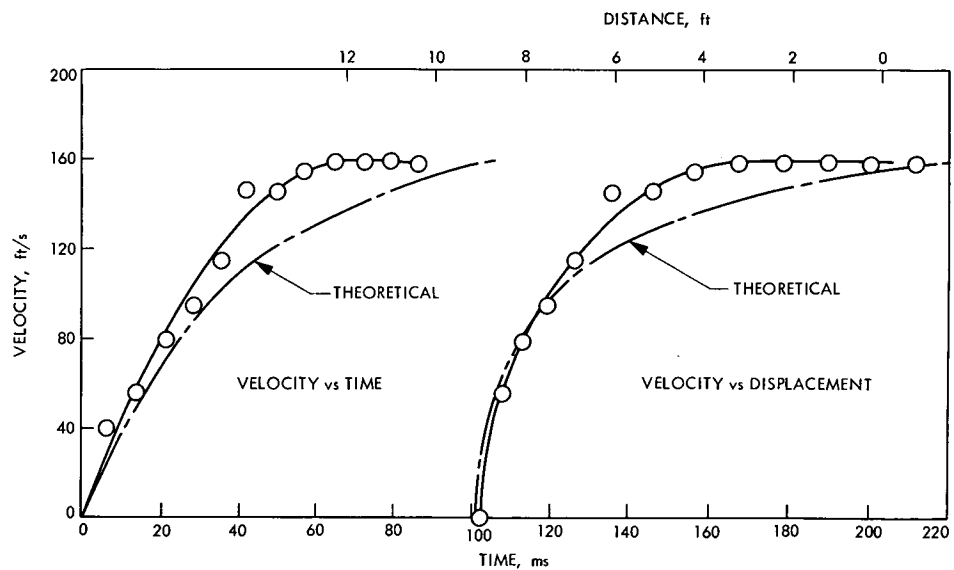


Fig. 12. Velocity map for 1-in. bungee cord: sled weight, 6.5 lb; sled displacement, 11 ft

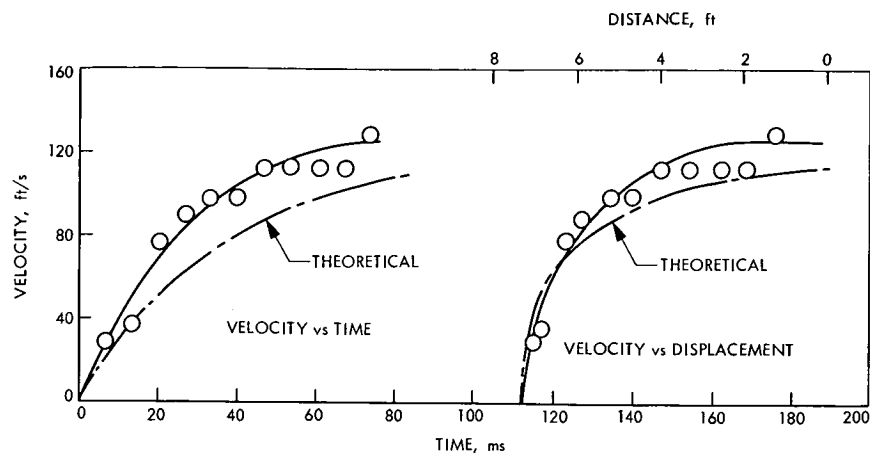


Fig. 13. Velocity map for 1-in. bungee cord: sled weight, 6.5 lb; sled displacement, 7.3 ft

IV. Control Instrumentation

There are at present three methods available for determining the g -level of a shock produced by the slingshot machine.

First, under the assumption that the pulse is rectangular, an estimate of the g -level can be made by measuring the depth of penetration d of the impact tool into the copper target block and recording impact velocity V with a photo cell system. The g -level is

$$g\text{-level} = \frac{1}{2} \frac{V^2}{d}$$

Since a rectangular acceleration pulse has the smallest peak value of any pulse for a given depth of penetration, this will always be a conservative estimate of the g -level. This method can give an estimate as much as 50% below the actual value.

Second, a system exists for determining the g -level with a piezoelectric shock accelerometer. The transducer used is an Endevco 2225 Accelerometer, which has its crystal mounted in shear. The accelerometer output is picked up with a charge amplifier and is FM-recorded on magnetic tape. The pulse can then be placed on a memoscope. The system has sufficient linear dynamic range to avoid saturation problems and a dc- to 30-kHz frequency response. This system is not formalized enough yet to make an intelligent estimate of its error, but it should be possible to get the error below 3% except for the reading-error associated with the scope which will be about 5%. The accelerometer sensitivity calibration at

present is done with sine excitation which could result in as much as 2.5% error in a shock measurement.

It is also possible to measure the g -level by measuring the decelerating force with a strain gage, Fig. 2. A full bridge is mounted on the tool to employ the tool as a force link. The bridge is dc-excited, and its output is amplified and FM-recorded, as is the accelerometer output, and read from the same memoscope. This system also has a large enough linear dynamic range to avoid saturation and a frequency response of from dc to 100 kHz. Calibration is achieved in this case by static loading. Again, this system has not been analyzed enough yet to make an intelligent estimate of its error, but it should be possible to obtain an error of less than 3%, including calibration, except for the scope reading error which will be about 5%. Since this system determines the force level by monitoring strain and not acceleration, the record is relatively ring-free, as can be seen in Fig. 5. This makes the force a more easily read quantity, and the g -level can be obtained, using Newton's Second Law, by dividing the sled weight. A small error is involved in this procedure since some of the weight of the bungee should be included in the sled weight, but from preliminary tests this error is not significant. Another error of the same type can occur in low g -level shots where the plastic guides do not break. In this event the 0.93-lb weight of the guides should be added to the sled weight.

V. Recommendations

Improvement in the operation of the slingshot should be made in two areas.

A number of the difficulties with the bungee cord could be avoided by employing a more sophisticated pre-tensioning device, such as the screw mechanism in Fig. 14, in which the bungee cord is terminated into an adjustable shock absorber and no knots are used in the active portion of the cord. Also, motion of the sled after impact could be reduced by making a transverse-wave suppressor. Such a device would be mounted on the rear of the target support. The device would consist of a block about $4 \times 15 \times 20$ in., with two 1.375-in.-diam holes for

the bungee cord to go through. The block would split in two pieces to allow for changing bungee cables, Fig. 15.

From a comparison of the strain gage work with the accelerometer work, it might be more desirable to use force readings for verifying *g*-levels and the quality of the pulse shape. In any event, more work should be done on the agreement of the force link and accelerometer readings.

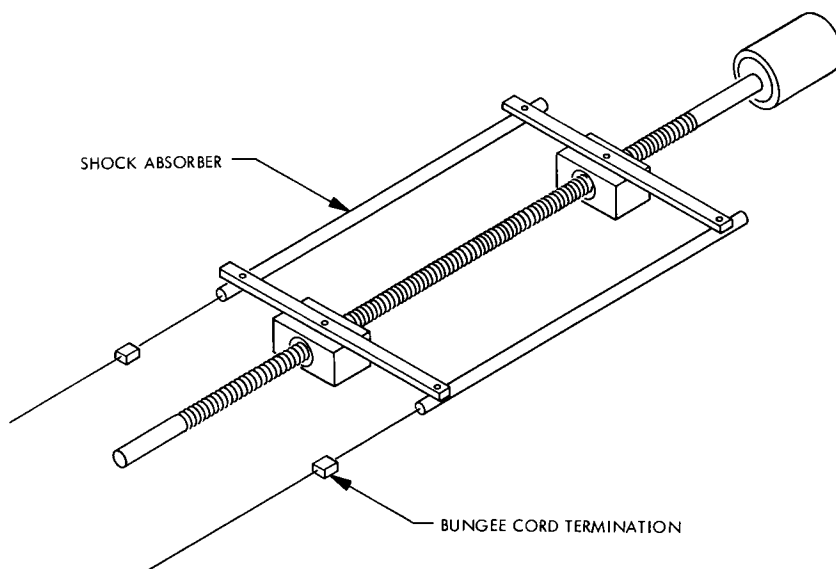


Fig. 14. Pre-tensioning device

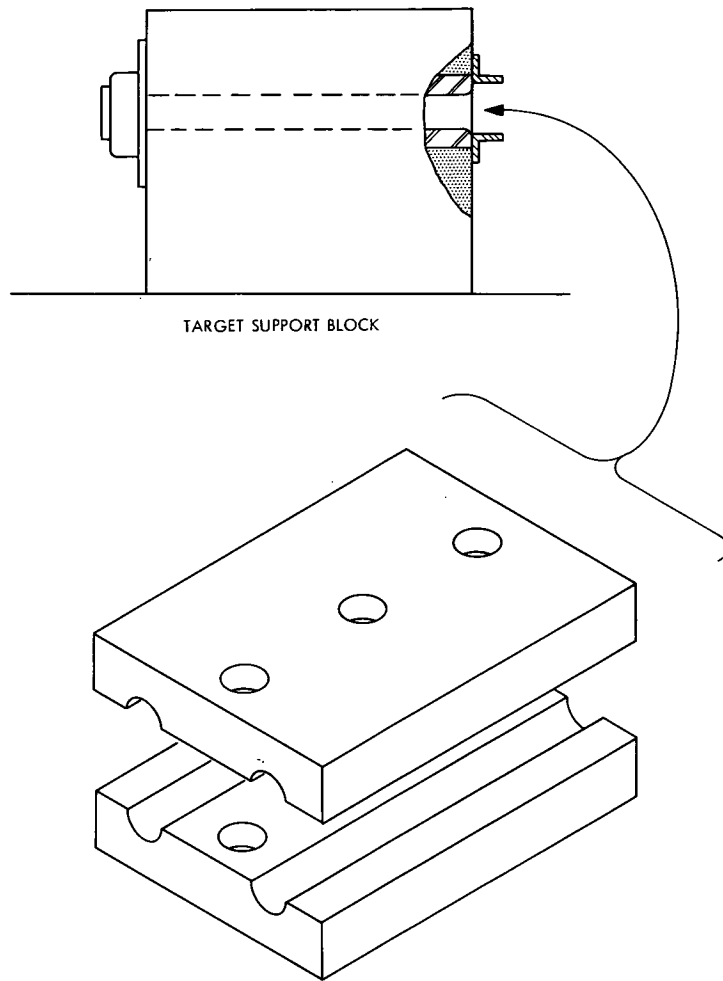


Fig. 15. Transverse wave suppressor