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A BALLISTIC TECHNIQUE FOR ACCURATE MEASUREMENT OF TOTAL IMPULSE--ETC(U)
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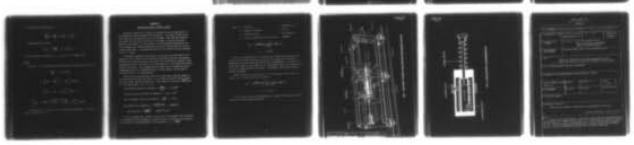

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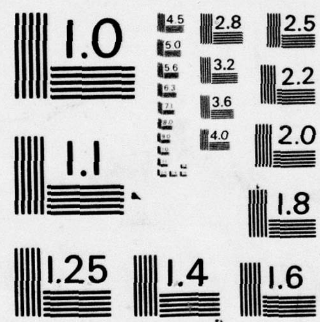


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# Memorandum

## No. 675

# A Ballistic Technique for Accurate Measurement of Total Impulse and Thrust of Rocket Motors with Short Burning Times

D. S. Dean

March 1976





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## A BALLISTIC TECHNIQUE FOR ACCURATE MEASUREMENT OF TOTAL IMPULSE AND THRUST OF ROCKET MOTORS WITH SHORT BURNING TIMES,

by

(10) D.S./Dean

(18) DRIC

(19) BR-53533

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SUMMARY

A method is described whereby a rocket motor impulse lasting a few milliseconds may be spread over a longer period to allow it to be recorded by conventional methods with an accuracy of ±0.2%. Instantaneous thrust is also recorded with an accuracy of ±2%. Most of the problems encountered with a ballistic pendulum are avoided and only the static calibration of a load cell is required before use.

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# CONTENTS

## 1 INTRODUCTION

To obtain a faithful reproduction of transients in any measuring system the natural frequency of the system is usually arranged to be higher than the highest Fourier component of the transients. A reasonably flat amplitude response can be obtained by damping but this results in phase errors, which increase as the resonant frequency is reached. The resonant frequency must thus be high enough to reduce errors to an acceptable level at the highest frequency to be recorded.

When the thrust of a rocket motor is measured, the highest component is usually present during the initial rise of thrust, and the natural frequency, determined by the mass of the motor and the compliance of the measuring system, should be well above this. For motors with burning times of only tens of milliseconds it may be impracticable to increase the stiffness of the measuring system sufficiently to record the thrust/time curve accurately.

Systems in which all the terms of the equation of motion of the mass are measured and combined to give the external forces acting on the mass (i.e. the thrust of the motor), are feasible but difficult to construct and adjust. An alternative approach is to reduce the stiffness of the system to zero and measure the acceleration of the mass as in the impulse and thrust measuring device described herein.

## 2 BALLISTIC MEASURING SYSTEMS

Various ballistic measuring systems have been used to measure short duration forces, the most common being the ballistic pendulum. This was initially considered as a solution to the problems of thrust measurement in motors with high thrust and short burning times. It depends upon the fact that in the absence of other forces:

$$\int_0^t F dt = MV$$

where F is the instantaneous thrust
t is the time for which the thrust acts
M is the moving mass
V is the final velocity assuming the mass to be initially at rest.

This is true if the mass and pendulum length are sufficient for the mass to move negligibly during the impulse. The impulse is deduced by measuring the final position of the mass at the peak of its swing. Usually its increase in height is measured directly or indirectly to give its gain in potential energy, which is equal to the initial kinetic energy and hence the impulse is known. A thrust/time curve may be obtained from an accelerometer mounted on the pendulum, but the accuracy is limited and calibration is difficult. An analysis of this simple case is given in the first part of Appendix 1.

The appendix then considers the case in which displacement of the mass during the impulse is significant, so that allowance must be made. Its displacement must be measured at the end of thrust as well as at maximum swing. This assumes that the thrust can be considered to rise and fall instantaneously and remain at a constant value when applied. A real rocket motor is likely to generate a thrust which varies with time, so that $F$ must be known as a function of displacement and measured with an accelerometer. Acceleration and velocity may also be derived by direct measurement or appropriate differentiation of displacement along the arc of swing, but accuracy is not likely to be great.

The practical problems involved in the realisation of an accurate device are considerable. The mass of the pendulum, including anything attached to it must be known, and this changes with consumption of the motor charge. With a reasonable pendulum length the mass must be large (about 1000 kg with current motors) to minimise travel during the burning time. This involves a suspension having a substantial mass and this, with the finite size of the main mass, means that the moment of inertia of the combination about the pivot must be calculated or measured. A parallel motion suspension avoids the problem of the distributed mass of the pendulum, but the inertia of the suspension must be known.

Measurement of the position of the centre of gravity of the mass at its maximum swing is difficult and allowance may be necessary for any motion in directions other than the intended direction of swing. This is particularly important if the measuring point on the mass is not at the centre of gravity and there is rotation about the centre of gravity. It is convenient to measure angular swing near the pivot, but there must be no bending or vibration in this region if errors are to be avoided. Frictional losses in the bearings needed to support the large mass may have to be evaluated, probably by measuring successive swings, and some means of arresting the pendulum must be provided.

Most of these problems can be overcome by allowing the mass to move horizontally after the impulse, and measuring the integral of the force required to bring it to rest.

## 3 DESCRIPTION OF SYSTEM USED

The system finally selected is shown in Fig. 1. It consists of a mass $M$, the value of which need be known only approximately, supported on three low friction linear bearings sliding on horizontal rods. The motor to be tested is mounted on the rear face of the block so that it accelerates the mass along the rods for a short distance without resistance during the motor firing time. An accelerometer mounted in the block on the motor axis near the front face produces a thrust/time curve since $F = Ma$, where $a$ is the acceleration. It is situated in this position to keep it as remote as possible from shock excitation from the rocket motor. The mass of the block is approximately 1000 kg to ensure reasonable lengths of travel during the firing time and reasonable final velocities with motors in the impulse range of 400 to 1500 N sec for which the equipment was designed. Since the block is an approximate 500 mm cube its lowest resonant frequency is such that $\lambda = 1$ m, i.e. 5 kHz. If this frequency is excited a low pass filter must be incorporated in the recording system to cut at a suitable frequency below this value. The accelerometer used in the initial experiments is an Endevco Model 2262-1000 piezo resistive type to match into existing instrumentation. It has an output of 0.5 mV per $g$ and a natural frequency of 10 kHz, response being flat to within ±5% from 0 to 2000 Hz. This latter characteristic governs the cut-off frequency of the thrust measuring system in most cases.

After the end of motor burning the mass travels a short distance and is then brought to rest by a device which applies a constant decelerating force. The time for which this is applied is inversely proportional to the magnitude of the force and is chosen to be such that normal recording and integrating systems can be used. A typical combination is 4000 N for 250 ms resulting from a motor impulse of 1000 Ns.

The initial decelerating device was designed as an oil filled piston and cylinder pressurised to a pre-selected value from a nitrogen gas reservoir sufficiently large to prevent the pressure from altering significantly during the arresting period. This design is described in Appendix 2 as it may be required if difficulty is experienced with the device now employed. Subsequently it was found that a commercial device exists in which the cylinder is perforated with a series of adjustable orifices which are closed in turn by the piston to achieve a similar effect. This is shown in Fig. 2.

The retarding device is mounted on the end of the frame carrying the rods which support the mass, the frame being supported by flexures. The frame is coupled by a rod flexure to a load cell and damper unit which measures the force applied to the retarder. The time integral of this force is equal to the motor total impulse if there are no losses in the system.

## 4 SYSTEM ACCURACY

Friction of the linear bearings could cause inaccuracy although their coefficient of friction is probably less than 0.005 when they are in good condition. To avoid such errors, whatever the condition of the bearings, the support rods are mounted on flexures so that the load cell measures the frictional forces generated in the bearings. Frictional forces in the retarding device are also measured by the cell so that losses from these effects are negligible.

The accuracy of measurement of total impulse depends on the load cell and recording devices. Since the retarding device gives rise to a sensibly constant decelerating force, the load cell may be operated close to its working maximum and should hence be capable of an accuracy of 0.1%. Digital recording and analysis devices used are capable of an accuracy of better than 0.1%. The cell is calibrated with a standard cell of 0.05% accuracy to achieve an overall accuracy of 0.2% in total impulse measurement.

Any stored elastic energy in the measuring system or retarding device may result in the mass acquiring a small velocity in the reverse direction after its arrest. If this is significant it will be necessary to latch the mass to the arrester and subtract any negative thrust thus produced from the integral.

The error in accelerometer measurement of thrust may be evaluated as follows. Let the permissible error be 1% and assume a coefficient of friction of 0.01. Since the mass is 1000 kg the frictional force is approximately 100 N, so that the minimum thrust is 10000 N to achieve 1% accuracy. If the total impulse is known to within 0.2% a greater error than 1% in thrust is probably acceptable. Accuracy is probably limited by the accelerometer to ±5% for the higher Fourier components of the thrust transient, but can be shown to be within this limit[1] provided that the rise time of the rocket motor thrust is not less than 2 ms. Except during the thrust transient an accuracy of ±2% is achieved.

Air drag is negligible since the force on the block at maximum velocity with the greatest total impulse envisaged is about 3 N and since this acts for 20 ms at most the error in impulse is 0.06 Ns.

## 5 USE OF THE EQUIPMENT

Assume that a motor of total impulse I Nsec and maximum thrust F Newtons is to be tested. The thrust at the load cell must be spread over about 0.25 sec or longer to permit a sufficiently accurate integration of the thrust. The range of the load cell must thus be such that it can measure accurately a force, F, where

$$F = \frac{I}{0.25} \text{ N} .$$

The linear decelerator must be adjusted to provide this decelerating force.

The maximum acceleration of the mass is given by

$$a = \frac{F}{10^3} \text{ m sec}^{-2}$$

so that the gain of the accelerometer amplifier must be set to accommodate the accelerometer output at this value.

The load cell must be calibrated in the usual manner with reference to the site standard.

The mass must be in its starting position and the motor attached to it firmly. To obtain an accurate thrust representation all mating surfaces must be machined flat to the best engineering tolerances and a film of grease may be applied to take up any remaining clearance between surfaces.

Recording of load cell output must be by a digital system with a resolution of better than 1 part in 1000, and a sampling rate not less than 1 kHz and preferably above 5 kHz.

The accelerometer measurement must be recorded by a digital system with a sampling rate of at least 10 kHz or by an analogue system with a flat response to 2 kHz.

The thrust integral is obtained directly from the digital recording of the load cell output. The accelerometer recording can be integrated in terms of trace displacement (d) against time (t). Thus, for the accelerometer calibration constant, K :

$$K\int d\,dt = \int F dt = I$$

$$\therefore K = \frac{I}{\int d\,dt}$$

No direct calibration of the accelerometer is therefore required.

## 6 CONCLUSION

This equipment permits measurement of the total impulse of motors with short burning times, with the same accuracy and using the same auxiliary equipment as for motors with long burning times. The thrust/time curve can be recorded using an accelerometer which does not need to be directly calibrated. It is easier to use and avoids most of the errors inherent in a ballistic pendulum. The mass needs to be known with only sufficient accuracy to permit adjustment of the range of the measuring systems, and only a static calibration of the load cell is required. It is capable of measuring total impulse with an accuracy of ±0.2% and instantaneous thrust, within frequency limitations, to ±2%.

## APPENDIX 1

### Analysis of ballistic pendulum

Assume a pendulum of mass $M$ and effective length $l$. Let it move from rest under the action of a force $F$ through an angle $\alpha$ so that its centre of mass moves along an arc by a distance $s$. Let its velocity at any instant be $v$.

**CASE 1**

Let the force $F$ be impulsive, so that any movement of the mass during the application of the force is negligible and the initial velocity after the impulse is $v_i$.

We have

$$M \frac{d^2s}{dt^2} = - Mg \sin \alpha$$

or

$$Mv \frac{dv}{ds} = - Mg \sin \frac{s}{l}$$

$$\therefore \quad M\int_{v_i}^{o} v\,dv = - Mg\int_{o}^{s_2} \sin \frac{s}{l}\, ds$$ where $s_2$ is the maximum displacement

$$M \left[ \frac{v^2}{2} \right]_{v_i}^{o} = - Mg \left[ - l \cos \frac{s}{l} \right]_{o}^{s_2}$$

$$\frac{- Mv_i^2}{2} = Mgl \frac{\cos s_2}{l} - mgl = (\cos \frac{s_2}{l} - 1)$$

$$\therefore \quad \int F\, dt = Mv_i = M\sqrt{2gl\ (1 - \frac{\cos s_2}{l})} \quad .$$

It is necessary to know $M$, $g$ and $l$ and to measure $s_2$

CASE 2

Let the force F be applied instantaneously and remain at a constant value until removed instantaneously after an interval t during which the mass moves a distance s , and acquires a velocity v .

$$M \frac{d^2s}{dt^2} = F - Mg \sin \alpha$$

or
$$Mv \frac{dv}{ds} = F - Mg \sin \frac{s}{l}$$

$$\therefore \quad M\int_o^{v_i} v\, dv = F\int_o^{s_1} ds - Mg\int_o^{s_1} \sin \frac{s}{l}\, ds$$

$$M\left[\frac{v^2}{2}\right]_o^{v_i} = F\left[s\right]_o^{s_1} - Mg\left[-l \cos \frac{s}{l}\right]_o^{s_1}$$

$$F = \frac{Mv_i^2}{2s_1} + \frac{Mgl}{s_1}\left(1 - \cos \frac{s_1}{l}\right)$$

$$\therefore \quad \int Fdt = \int \left[\frac{Mv_i^2}{2s_1} + \frac{Mgl}{s_1}\left(1 - \cos \frac{s_1}{l}\right)\right] dt \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Measurement of $v_i$ , $s_1$ and t would enable $\int F\, dt$ to be evaluated but accurate velocity measurement is not easy and it is usual to measure the maximum swing of the mass.

After the force ceases we have, as in case 1,

$$M\int_{v_i}^{o} v\, dv = - Mg \int_{s_1}^{s_2} \sin \frac{s}{l}\, ds$$ where $s_2$ is the displacement of the mass at full swing.

Integrating, $$M\left[\frac{v^2}{2}\right]_{v_i}^{o} = Mg\left[l \cos \frac{s}{l}\right]_{s_1}^{s_2} .$$

Evaluating and dividing by $s_1$

$$-\frac{Mv_i^2}{2s_1} = \frac{Mgl}{s} \left( \cos\frac{s_2}{l} - \cos\frac{s_1}{l} \right) .$$

Substituting in (1) gives

$$\int F\,dt = \int \frac{Mgl}{s} \left( 1 - \cos\frac{s_2}{l} \right) dt$$

*It is now necessary to measure* $s_1$ , $s_2$ and $t$ to evaluate $\int Fdt$ .

CASE 3

The force $F$ varies with time but conditions are otherwise as for case 2.

$$M\frac{dv}{dt} = F - Mg\sin\frac{s}{l}$$

$$\therefore \int_0^t Fdt = M\int_0^{v_i} dv + Mg\int_0^{s_1} \sin\frac{s}{l}\,dt$$

$$\int_0^t Fdt = Mv_i + Mg\int_0^{s_1} \sin\frac{s}{l}\,dt$$

$$\int_0^t Fdt = M\sqrt{2gl\left( \cos\frac{s_1}{l} - \cos\frac{s_2}{l}\right)} + Mg\int_0^{s_1} \sin\frac{s}{l}\,dt .$$

In addition to $s_1$ and $s_2$ it is now necessary to know how $s$ varies with $t$ from rest to $s_1$ .

## APPENDIX 2

### Decelerating device (initial design)

The device consists of a piston and cylinder filled with hydraulic oil and pressurised from a nitrogen filled reservoir. The piston is held at the outer limit of its travel by a lip on the cylinder. When the mass contacts the piston after the motor has fired, it is brought to rest by the force applied by the piston. If the reservoir is large enough the pressure on the piston changes only slightly during the stroke and the measured force does not increase excessively. The measuring system can thus work in the most accurate part of its range.

To prevent acceleration of the mass in the reverse direction after it is brought to rest a restrictor valve comes into operation when the flow between cylinder and reservoir reverses. The size of the restriction is chosen so that the measured force at the load cell is less than 0.1% of that during the forward stroke of the piston. This ensures that any small error in timing the thrust integration results in a negligible error in total impulse, and the mass is returned gently to its starting point.

Typical sizes and operating values can be calculated using the example in the main body of the text of a force, R , of 4000 N acting for 250 ms, resulting from a motor impulse of 1000 N sec. This requires a pressure of $\frac{4000}{a}$ where a is the piston area. Let d = 0.1 m.

Then pressure required in cylinder is $\frac{4000.4}{\pi.10^{-2}} = 0.51\ \text{MNm}^{-2}$.

Velocity of the block after the impulse is $v = \frac{I}{M} = 1\ \text{ms}^{-1}$.

This is brought to rest in a distance $s = \frac{v^2M}{2R} = 0.125$ m .

The volume of oil displaced $= \frac{\pi.10^{-2}\ 0.125}{4} = 0.00098\ \text{m}^3$ ,

$\therefore$ the flow rate is $\frac{0.00098}{0.25} = 0.00392\ \text{m}^3\ \text{sec}^{-1}$ .

If it is assumed that a pressure drop of 1% of the pressure in the reservoir is acceptable for flow through the connector from the cylinder to the reservoir, i.e. 5100 $\text{Nm}^{-2}$, the minimum radius of the connector, $r_i = \frac{Q.81\eta}{\pi P}$

where $Q$ = flow rate = $0.00392 \text{ m}^3 \text{ sec}^{-1}$

$l$ = length of connector = $10^{-3}$ m

$\eta$ = viscosity of oil = 0.05 Pascal sec

$P$ = pressure difference across connector = $5100 \text{ Nm}^{-2}$

$$r_i^4 = \frac{0.00392 \cdot 8 \cdot 10^{-3} \cdot 0.05}{\pi \cdot 5100} \text{ m}^4$$

$$r_i = 3.145 \text{ mm} .$$

This is easily achieved, but allowance must be made for the pressure rise in the reservoir, which progressively reduces the stroke and the flow rate, depending on the size of reservoir which can be accommodated. In practice an initial gas volume of three times the oil displacement results in a pressure rise of up to 1.5 times the initial pressure. This permits sufficiently accurate impulse measurement.

Return flow must be restricted to $10^{-3}$ of the forward flow, so that the radius, $r_2$, of the restrictor is given by

$$r_2^4 = \frac{0.00392 \cdot 10^{-3} \cdot 8 \cdot 10^{-3} \cdot 0.05}{\pi \cdot 510 , 10^3} \text{ m}^4$$

$$r_2 = 0.177 \text{ mm} .$$

A hole of this size can be incorporated in a simple light flap valve which closes as the mass reverses direction.

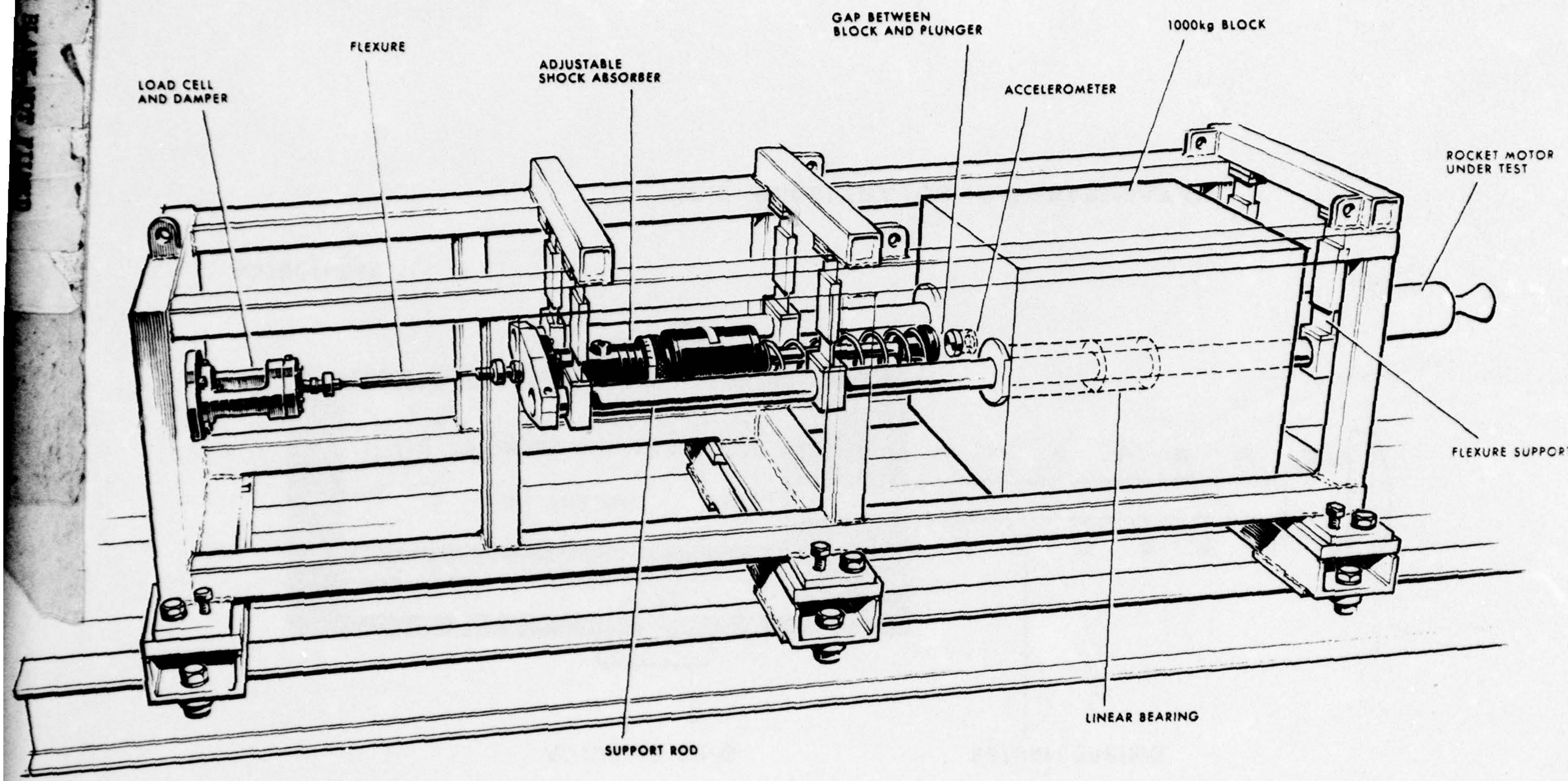


FIG.1 BALLISTIC THRUST AND IMPULSE MEASURING DEVICE

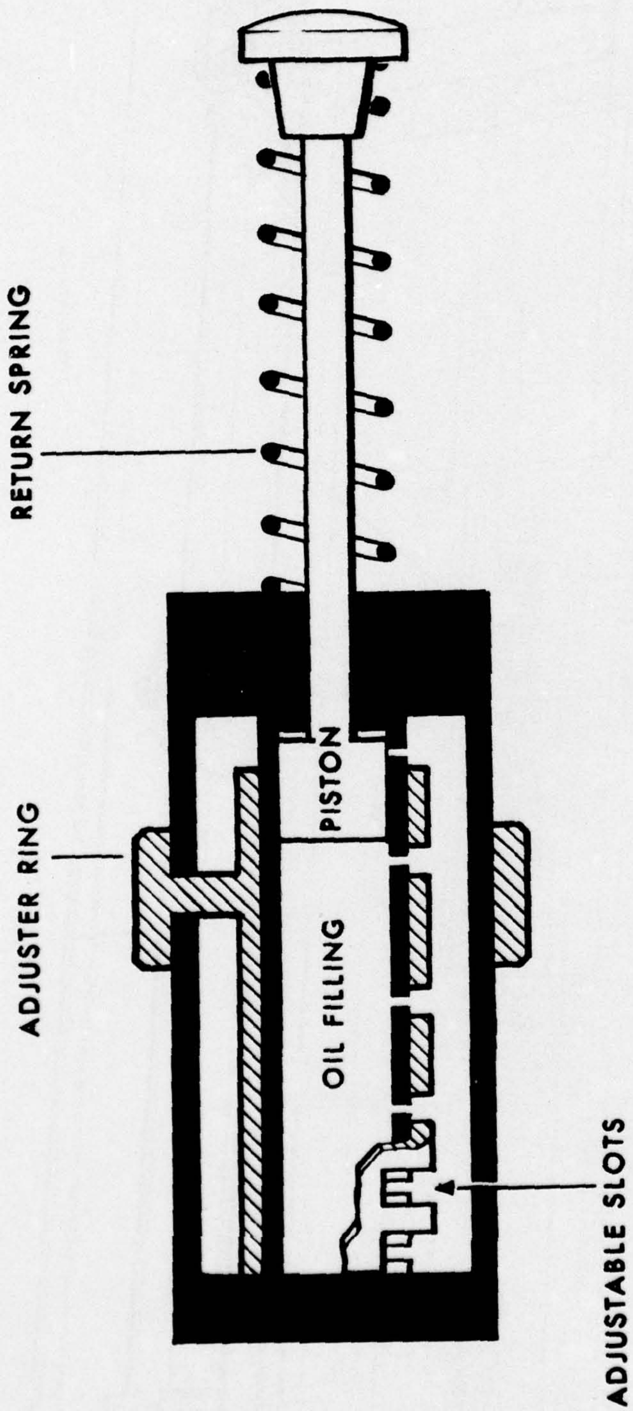


FIG.2 DECELERATOR (DIAGRAMMATIC)

DOCUMENT CONTROL SHEET

(Notes on completion overleaf)

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| 5. Originator's Code (if known) | 6. Originator (Corporate Author) Name and Location |
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7a. Title in Foreign Language (in the case of translations)

7b. Presented at (for conference papers). Title, place and date of conference

| 8. Author 1, Surname, initials | 9a Author 2 | 9b Authors 3, 4... | 10. Date | pp | ref |
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15. Distribution statement

15. Descriptors (or keywords)

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continue on separate piece of paper if necessary


Abstract

A method is described whereby a rocket motor impulse lasting a few milliseconds may be spread over a longer period to allow it to be recorded by conventional methods with an accuracy of ±0.2%. Instantaneous thrust is also recorded with an accuracy of ±2%. Most of the problems encountered with a ballistic pendulum are avoided and only the static calibration of a load cell is required before use.