© ISA 1985 - Paper #85-0154
0096-7238/85/467-476/$0 + .50PP

INSTRUMENT TO MEASURE WEIGHT IN SPACE

Ruell F. Solberg, Jr.
Senior Research Engineer
Electromagnetics Division
Southwest Research Institute
P. O. Drawer 28510
San Antonio, Texas 78284

ABSTRACT

Methods and techniques to measure the weight or the mass of objects were developed thousands of years ago. There has not been significant technological advancement for many centuries. However, the normal methods of weight measurement are inadequate for microgravity conditions or the near zero gravity environment associated with space exploration and travel. An instrument was developed which uses the inertial properties of mass to measure that mass. The instrument can measure specimens from less than one gram (0.002 pound) to over 10,000 grams (22 pounds) with an accuracy on the order of ±0.05 percent.

INTRODUCTION

Techniques and methods to measure the weight or mass of objects date back to early man. Measurement of weight was extremely important in the development of commerce. The balance or scales allowed the weight or mass of unknown items to be determined by comparison with known weights or standards. However, technological advancement of the balance has been very low through most of history. Developments during the last century have been directed to the ability to measure very small quantities with extreme resolution (for example, to micrograms and tenths of micrograms for microbalances) and to increase the speed of measurements.(1,2)

The balance is an instrument which compares the net vertical forces on objects, including those from gravitational attraction, air buoyancy, and rotation of the earth. However, on the surface of the earth the forces from air buoyancy and earth rotation are comparatively small. The weight of an object is, then, primarily the force with which a body is attracted toward the earth.

However, with the advent of space travel, gravimetric-types of measurements of objects were no longer satisfactory, i.e., gravitational forces (weights) vary to the extent that gravity varies and effectively may not exist. For example, for orbit around the earth, gravitational acceleration is counteracted by the radial acceleration of the spacecraft and its contents; the result is weightlessness. However, since mass is constant under these conditions, characteristics of the masses of objects have been utilized to determine their weight equivalents.

Some laboratory and experimental models of nongravimetric mass measurement equipment were constructed by the Aerospace Medical Division at Brooks Air Force Base, Texas starting in 1965. William E. Thornton and John Ord were involved with the Manned Orbiting Laboratory (MOL) for the U. S. Air Force and had determined that the ability to measure weight during space flight was extremely important in determining, monitoring, and analyzing the health of astronauts. Southwest Research Institute began providing engineering support in 1966. The MOL program was canceled, but the National Aeronautics and Space Administration (NASA) then had applications for the developments.

Many tests, changes, and improvements culminated in two types of mass measurement devices, which were called specimen mass measurement device (SMMD) and body mass measurement device (BMMD), for use on NASA's Skylab.(3-5) The SMMD was designed to measure the mass of food residue, vomitus, and feces from 50 to 1,000 grams (0.11 to 2.20 pounds); and the BMMD was designed to measure the mass of astronauts and had a capacity of 57 to 100 kilograms (125 to 220 pounds).

The purposes of the mass measurement devices for Skylab included demonstration that accurate nongravimetric measurements could be performed in space flight, validation of the theoretical behavior of the devices, and to support biomedical experiments requiring mass measurement. The SMMD and BMMD were used and operated successfully on Skylab and provided data for biomedical analyses.(6-10) The concern about physiological changes to the human body under weightlessness have proven to be valid also.(11,12) A new generation instrument, the small mass measurement instrument (SMMI), is ready for use with Space Shuttle.(13,14)

There have been other interests in measuring mass independent of gravity and in using similar concepts to that presented here. However, the accuracies have been quite poor, the sample size has been limited to very small values, the measurement process has been laborious, or only limited information has been available.(15-20)

THEORY OF OPERATION

The small mass measurement instrument can be compared operationally to a single degree of freedom, undamped spring-mass system in which the mass oscillates sinusoidally at the natural frequency of the system if it is offset from its neutral position and released. The inertial properties of the mass and the stiffness of the spring provide the elements of an oscillator. From classical physics it is known that the period of oscillation (inverse of the natural frequency) is proportional to the square root of the mass and inversely proportional to the stiffness of the spring, i.e.,

$$T = \frac{1}{f} = 2\pi \sqrt{m/k} \quad , \qquad (1)$$

where:

T = period of oscillation,
f = natural frequency,
m = equivalent mass of the oscillating system, and
k = stiffness of the spring.

The equivalent mass of the system, m, includes a portion of the mass of the spring. If the period of oscillation can be measured precisely, then the system can be calibrated by measuring the periods of items whose mass, or weight, are known. Then the masses of specimens have a relationship to the periods of oscillation.

Figure 1 is a typical curve depicting that relationship for a configuration similar to the SMMI. Note that the curve is plotted semilogarithmically; and while the curve appears linear for the small specimen weight values, the shape of the curve is obviously nonlinear if the scale is expanded on linear graph paper. If a curve, a table, or an equation is developed for such an instrument, then the mass of a specimen can be determined from measurements of its period of oscillation. Alternatively, a computer could store the calibration data and use an algorithm to calculate the mass of the specimen.

INSTRUMENT DESCRIPTION

Figure 2 is a picture of the SMMI with a set of calibration masses. The SMMI is designed to be rack-mountable. Envelope dimensions of the SMMI are approximately 310 millimeters (12.22 inches) high by 483 millimeters (19 inches) wide x 483 millimeters (19 inches) deep. The weight of the SMMI is about 18 kilograms (40 pounds). The accuracy requirements for measurement of rigid specimens are given in Table 1.

The electrical interface of the SMMI is a single electrical connector and a ground connection. Power requirements are 15 watts average at +28 ±4 volts direct current and 0.6 amps. The SMMI is designed for the power and environmental conditions of Spacelab. The SMMI is modular in construction and is designed so that certain modules can be easily replaced or repaired.

MECHANICAL

Most of the SMMI is enclosed to minimize the effects of disturbances from air currents and floating articles in space. A clear removable plastic cover allows visibility by the operator. Specimens to be measured are placed on a tray inside the plastic cover. The tray has a removable, perforated rubber cover so that odd-shaped items can be attached under weightless conditions. Figure 3 shows an item being placed on the tray.

Plate fulcra springs attach the tray to a frame assembly. The plate fulcra springs suspend, locate, and provide restoring forces to the tray for simple harmonic motion. The springs are essentially friction-free and are fabricated from special materials with a very low thermoelastic coefficient, corrected for thermal expansion effects. The tray oscillates in the directions of its longest dimension. The oscillation amplitude is approximately five millimeters (three-sixteenths inch) from the neutral position.

While plate fulcra springs are somewhat common, especially for weighing instruments, they are complex to analyze precisely. They are also called such things as flexures, flexure pivots, flexure plates, elastic joints, flexure strips, metallic flexures, crossed flexure pivots, elastic fulcrum, and flexure bearings.(21-25) In its simplest form, a plate fulcrum is a strip of elastic material rigidly attached to two parts, which move with respect to each other. Figure 4(a) illustrates this schematically. The tray of an SMMI would be represented by the movable element and the frame by the fixed element. In normal practice, only small deflections are involved with plate fulcra. Single strip and multiple-strip assemblies may be designed to provide various combinations of motion and constraint along or about specific axes. Deflection or rotation occurs as the result of elastic deformation of the strip. By selecting the dimensions of the strip and the means of attachment to the structure, relative motion of the parts can be free in one direction and extremely constrained or rigid in all other directions. Additional advantages of plate fulcra include extremely low friction or damping, freedom from wear, high durability, and no requirement for lubrication.

Analysis of the spring characteristics of a parallel-motion plate fulcra [(Figure 4(a)] system can be performed where each strip is essentially a flat spring under lateral loading. One end of the strip is made integral with the fixed element; and the other end, attached to the movable element, is free to move in one direction, but restrained from motion in all other directions. In this arrangement, with the strips parallel to each other, the movable element remains parallel to the fixed element as it translates along the path of an arc. The center of rotation of the movable element, as a whole, is at infinity, because it does not rotate. If a force, F, is applied to the movable element perpendicular to the strip, the movable element is displaced in a direction parallel to the force. The relationship between the force F and the deflection of the movable element depends on the length, thickness, and width of the strips. Figure 4(b) shows one of the flat springs in a deflected position. The deflection is given by

$$y = \frac{Fl^3}{12EI}, \qquad (2)$$

where:

l = length of the strip,
F = lateral force,
E = modulus of elasticity, and
I = moment of inertia.

In order to prevent buckling and to overcome the lack of torsional stiffness where long strips must be used, the strips may be designed with a stiffened center section, as illustrated by Figure 4(c). This forces bending to take place only in the relatively thin sections at each end of each strip. In effect, four such strips were used for the SMMI. Note that Figure 4(c) is the same as 4(b) except for the stiffened center portion. The relationship between the lateral force and the deflection in the stiffened strip shown in Figure 4(c) is given by

$$y = \frac{Fl\left(L^2 + Ll + \frac{l^2}{3}\right)}{EI} \qquad (3)$$

where:

l = length of the plate fulcrum and
L = length of the stiffened portion.

Figure 4(d) shows a more practical configuration of a plate fulcra spring. The spring rate of the plate fulcra is a function of the modulus of elasticity and dimensions of the spring and is expressed as force per unit of deflection. The combined spring rate of four strips like those shown in Figure 4(d) is

$$k = \frac{4Ebh^3}{D^3(1-r^3)}, \qquad (4)$$

where:

D = combined length of stiff portion and plate fulcra,
r = L/D,
b = width of the reduced section, and
h = thickness of the reduced section.

Equation (4) can be substituted into equation (1), and dimensions of potential plate fulcra springs can be determined through a trial and error process. Lower frequency oscillations, for periods of about one-half second for an empty tray, were chosen to minimize the errors caused by accelerations/decelerations on the specimens during tray oscillations.

ELECTRICAL

An electrical actuator provides forces and motions through a series of mechanisms to offset the tray from its neutral position, set a sear, lock the tray, unlock the tray, and release the sear. The sear is a trigger-like device which allows the tray to start oscillating. The actuator automatically stops the tray from oscillating and makes mechanical preparations for the next measurement. The actuator is controlled completely by the MMI controller.

A zero crossover detection assembly includes an infrared light-emitting diode and an optical detector, or photodiode, for transmitting and receiving a light beam which is interrupted when the tray oscillates. The first two periods of oscillation are gated out to allow extraneous vibrations to be somewhat damped. The following three periods are measured, averaged, and used by the MMI controller.

The MMI controller is configured around a R6502 microprocessor with electrically programmable read only memory and random access memory. The controller has a liquid crystal display (LCD) with two rows each of 32 characters. Figure 5 shows the MMI controller providing a message of the weight of a specimen which has been measured and a prompt to the operator.

A keyboard allows the operator to more intimately interface with the SMMI. The operator can also obtain information stored in memory and perform diagnostic operations. Calibration masses can be deleted and added, and various other instructions can be given to the SMMI.

MASS ALGORITHM

A number of types of equations were checked empirically for goodness of fit to the data of period versus mass, shown typically by Figure 1. The shape of the curve suggests that a power function equation should provide a good match. A power function curve, or modified geometric curve, is of the form

$$M = AT^B + C \qquad (5)$$

where:

M = mass of specimen,
T = period of oscillation, and
A, B, and C = constants.

A sliding power function was found to provide the best results in which only three nearby calibration masses are used to determine the constants. The SMMI chooses the three calibration mass values which have periods closest to the period measured for a specimen or unknown mass. The exponent of the equation is solved using a binary search technique while the other constants are solved automatically using the least squares technique. Therefore, the mass equation (5) is allowed to vary and does not remain constant over the range of the SMMI.

RESULTS

Significant testing of the SMMIs has been performed on earth; however, the true tests will occur when the SMMIs are used on Spacelab in earth orbit. Results so far have been quite good.

The environment for space travel is different than many other situations, and the SMMI was designed to withstand space conditions. Requirements have included limitations on materials, shock, vibration, off-gassing, temperature, and susceptibility and emissions of electromagnetic radiation.

A slow drift was experienced with the SMMIs which limited the repeatability and accuracy for small mass specimens. It was not possible to completely eliminate the drift, so the SMMI was programmed to automatically require a self-check periodically. If an empty tray measurement has not been performed recently, the SMMI requests that it be allowed to do this when a measurement of a specimen is to be performed. The SMMI then automatically corrects for any drift that has occurred.

SUMMARY

Requirements existed for NASA to measure mass under microgravity or near zero gravity conditions. Standard weighing or mass measurement equipment was not suitable. Flight-qualified mass measurement instruments were developed and used on Skylab, and a significantly improved small mass measurement instrument with semiautomatic features was developed for the Space Shuttle program. Many details were described and discussed in regard to the development and design of these mass measurement instruments.

The SMMI uses the inertial characteristics of mass to measure that mass. The characteristics of a simple oscillating spring-mass system for which the period of oscillation is a function of the mass of the system is utilized. The instrument has a range of less than one gram (0.002 pound) to over 10,000 grams (22 pounds) with an accuracy on the order of ±0.05 percent for rigid specimens. The SMMI has a microprocessor, keyboard, and liquid crystal display so that the operator can enter and delete data and receive messages or prompts and specimen mass values. The SMMI also has a memory and self-calibration and diagnostic features.

ACKNOWLEDGMENTS

Many people contributed to the success of the work reported herein. Particular acknowledgment is given to those who served as project engineers for the SMMI at NASA Johnson Space Center: Elena Huffstetler, Stanley Luczkowski, William Young, and Brock Westover. Key personnel for the SMMI program at SwRI included Bill Oakey, John Cater, Jim Nixon, Gene Rimmer, Jim Cook, Tom Campbell, and George Hunt. William E. Thornton of the U. S. Air Force and NASA was a strong advocate of mass measurement devices for Skylab.

REI
1.
2.
3.
4.
5.
6.
7.
8.
9.
10.
11.
12.
13.

REFERENCES

1. Gast, Theodor, "Vacuum Microbalances, Their Construction and Characteristics," Journal of Physics E: Scientific Instruments, Vol. 7, 1974, pp. 865-875.

2. Leonard, Ralph O., "The Electromagnetic Microbalance: The History and the Present State of the Art," American Laboratory, Vol. 6, No. 6, June 1974, pp. 58-60, 62, 64, and 65.

3. Walters, Samuel, "Weightless Weighing," Mechanical Engineering, Vol. 94, No. 5, May 1972, p. 41.

4. "Vibrating 'Scales' Will Weigh You In Space," Design News, Vol. 27, No. 6, March 20, 1972, p. 10.

5. "'Scales' to Monitor Astros," San Antonio Express, Final Edition, February 22, 1972, p. 2.

6. "The Good Life in Space," Time, Vol. 101, No. 17, April 23, 1973, p. 60.

7. "Skylab Astronaut Activities Depicted," Aviation Week & Space Technology, Vol. 99, No. 16, October 15, 1973, p. 37.

8. "Inside the Crew of the Skylab 2," Medical World News, Vol. 14, No. 46, December 14, 1973, pp. 26-27.

9. Ross, Charles E., "Skylab 1/2 Preliminary Biomedical Report," JSC-08439, National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Houston, Texas, September 1973, pp. 191-198.

10. Thornton, William E. and Ord, John, "Physiological Mass Measurements in Skylab," Richard S. Johnston and Lawrence F. Dietlin, editors, Biomedical Results from Skylab, NASA SP-377, National Aeronautics and Space Administration, Washington, D.C., 1977, pp. 175-182.

11. Bodde, Tineke, "The Body's Answer to Zero Gravity," Bioscience, Vol. 32, No. 4, April 1982, pp. 249-251.

12. Perry, Tom W. and Reid, Donald H., "Spacelab Mission 4--The First Dedicated Life Sciences Mission," Aviation, Space, and Environmental Medicine, Vol. 54, No. 12, December 1983, pp. 1123-1128.

13. "Device 'Weighs' Objects in Zero Gravity," Industrial Research & Development, Vol. 25, No. 9, September 1983, pp. 69-70.

14. "Tipping the Scales in Space," Mechanical Engineering, Vol. 105, No. 6, August 1983, p. 87.

15. "Weighing a Man in Space, Where He Is Weightless," Product Engineering, Vol. 38, No. 25, December 4, 1967, pp. 30-32.

16. Sarychev, V.A., et. al., "Measurement of Mass Under Weightless Conditions," Cosmic Research, Vol. 18, No. 4, Jan. 1981, pp. 386-397 (Translated from Kosmicheskie Issledovaniya, July-August 1980, pp. 536-549).

17. Bruzzi, Luciana, "A Direct-Reading Inertial Balance," Physics Education, Vol. 13, No. 4, May 1978, pp. 239-240.

18. Andrews, D.R., "A Gravity-Insensitive Technique for Measuring Mass Changes in Hostile Environments, Including Erosion," Journal of Physics E: Scientific Instruments, Vol. 16, No. 8, August 1983, pp. 803-806.

19. Erdem, U., "Force and Weight Measurement," Journal of Physics E: Scientific Instruments, Vol. 15, September 1982, pp. 857-872.

20. Senda, Osamu, et. al., "Density Measurement of LPG by Vibrating Method," Transactions of the Society of Instruments and Control Engineers, Vol. 16, pp. 387-390.

21. Doeblin, Ernest O., Measurement Systems: Application and Design, McGraw-Hill, New York, 1966, pp. 338-352.

22. Gurrich, I.T. and Perel'man, E.I., "Computing Bars with Elastic Joints for Weighing and Dynamometric Devices," Measurement Techniques, Vol. 17, No. 7, December. 1974, pp. 1130-1132 (Translated from Izmeritel'naya Tekhnika, July 1974, pp. 91-92).

23. Lowe, J.F., "Elastic Deformations Move Micromanipulator Without Backlash," Design News, Vol. 28, No. 11, June 4, 1973, p. 61.

24. "Novel Suspension System Keeps Its Perfect Balance," Product Engineering, Vol. 44, No. 9, September, 1973, p. 13.

25. Masuo, Ryuichi and Chikayoshi, Maeda, "Performance of Elastic Fulcrum in a Beam Balance," 19th Annual ISA Conference Proceedings, Vol. 19, Part I, 1964, Preprint No. 21.2-1-64.

TABLE 1

Accuracy Requirements

Specimen Weight	On Earth	In Earth Orbit
1 to 25 g. (0.002 to 0.055 lb.)	±0.05 g. (±0.0001 lb.)	±0.025 g. (±0.000055 lb.)
25 to 1,000 g. (0.055 to 2.20 lb.)	±0.5 g. (±0.001 lb.)	±0.5 g. (±0.001 lb.)
1,000 to 2,000 g. (2.20 to 4.41 lb.)	-	±0.5 g. (±0.001 lb.)
2,000 to 10,000 g. (4.41 to 22.05 lb.)	-	±5 g. (±0.01 lb.)

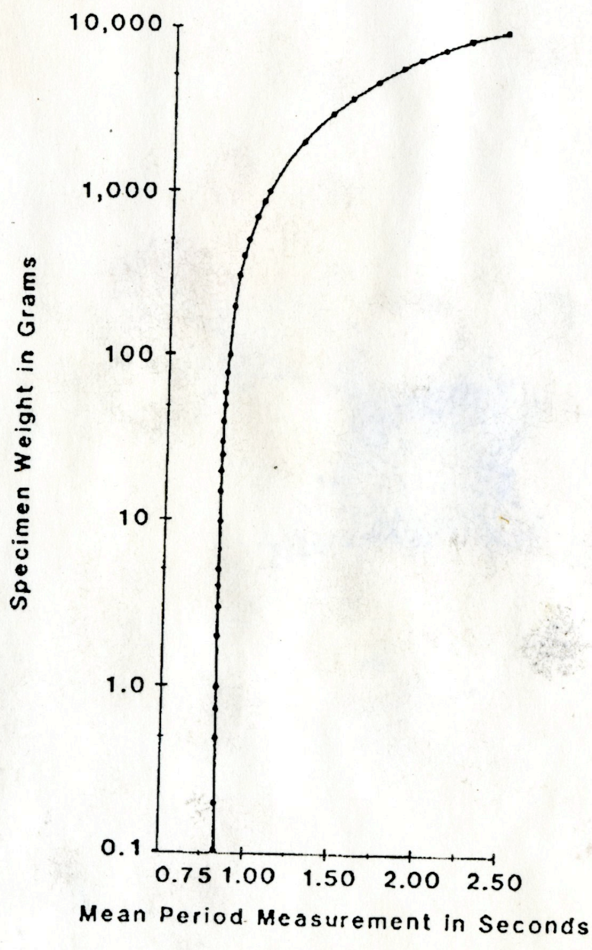

Figure 1. Typical Period-Mass Relationship

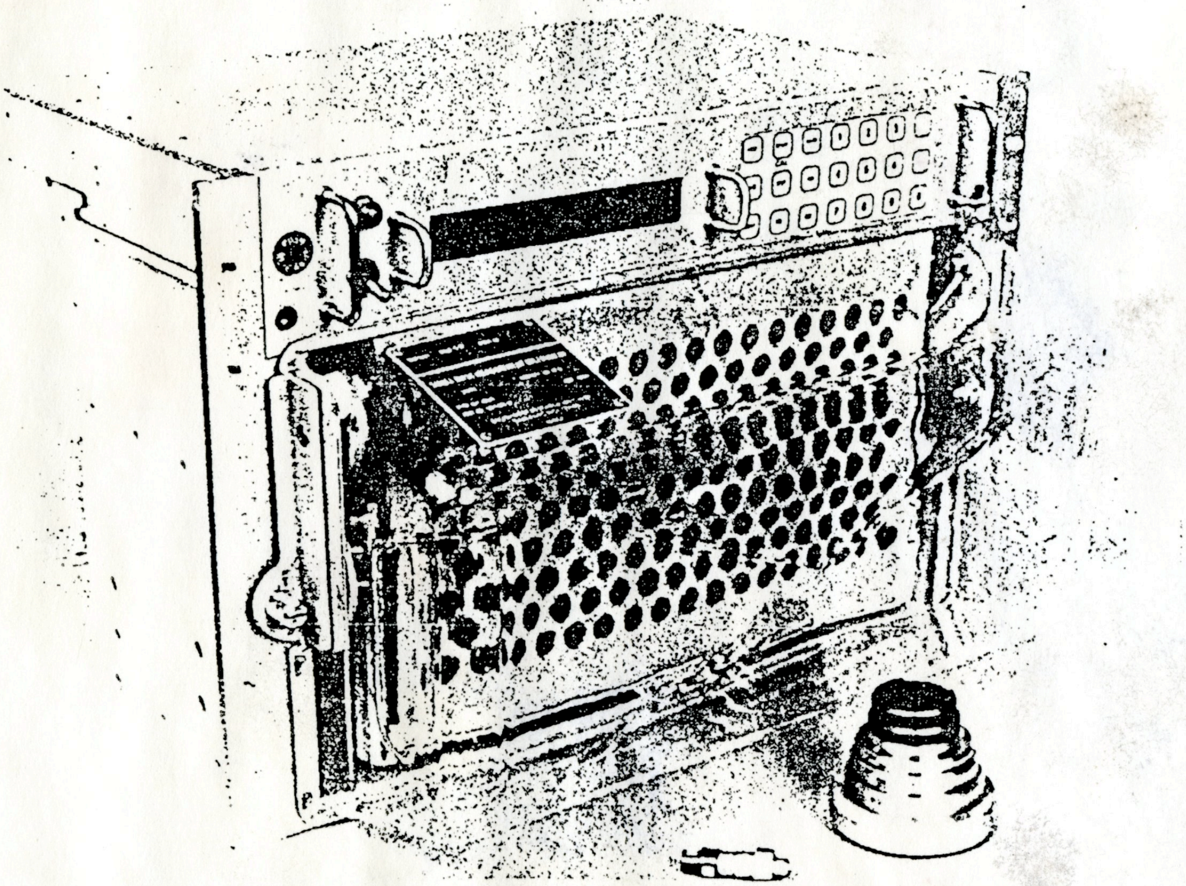

Figure 2. SMMI With Calibration Mass Set

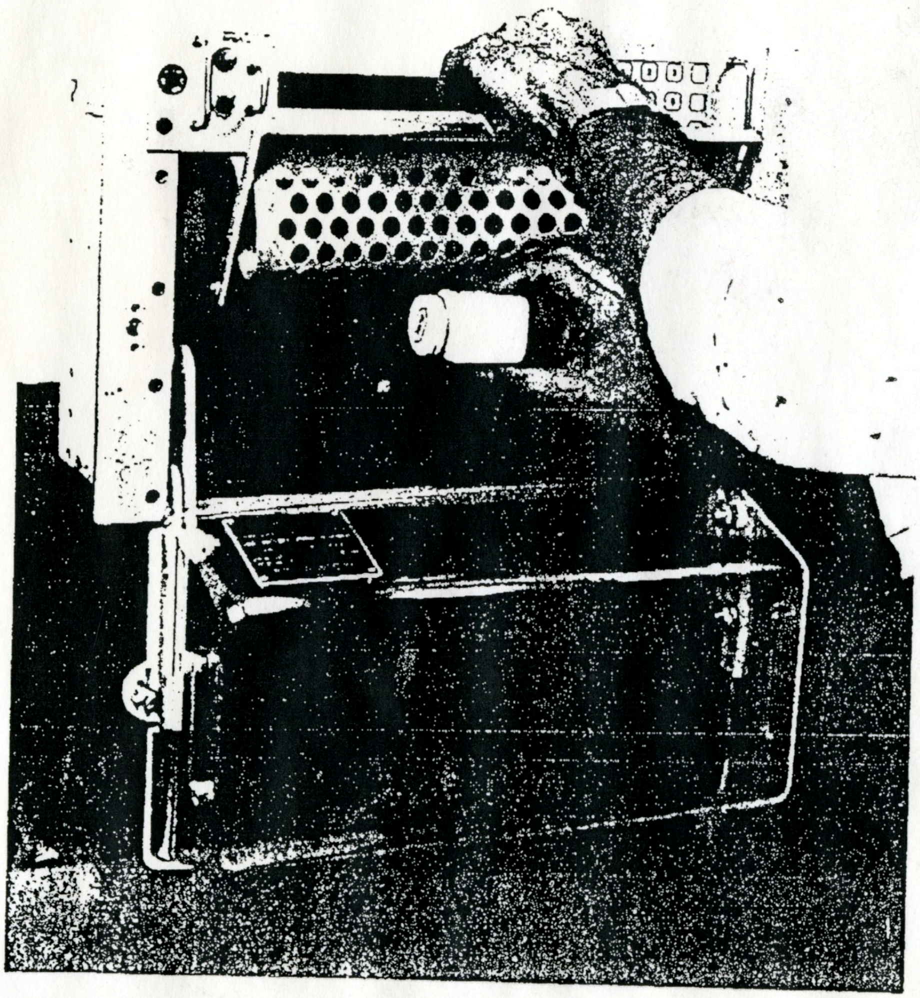

Figure 3. Specimen Being Positioned On Tray Of SMMI

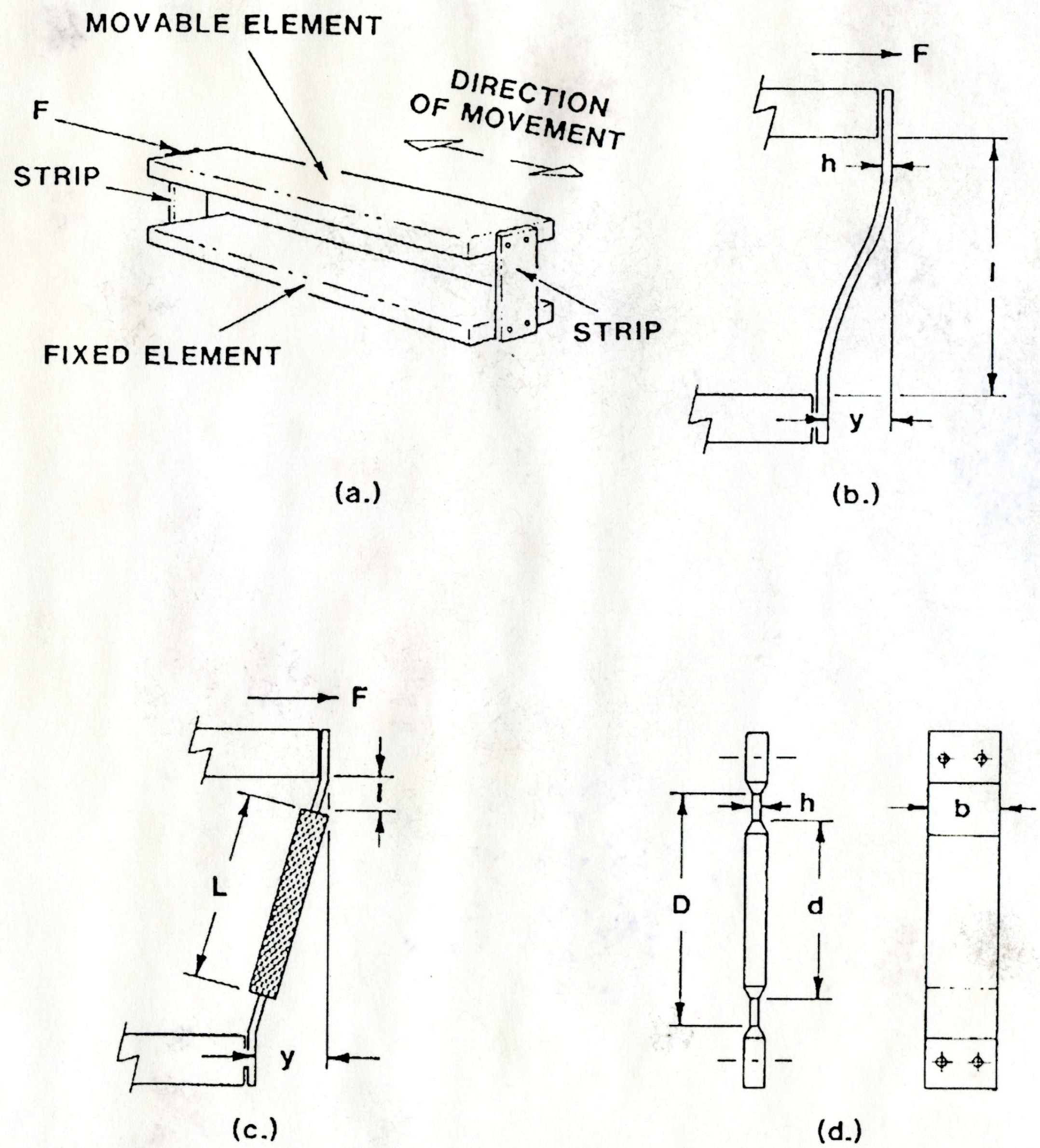

Figure 4. Plate Fulcra Spring Configurations