A PRELIMINARY REPORT ON SOME ASPECTS OF A NON-GRAVIMETRIC METHOD FOR MASS DETERMINATION

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INTRODUCTION

Some months ago the possibility of a device for the measurement of mass under weightlessness, particularly that of a man, was very much in doubt. Many of the proposed schemes, such as a large rotational pendulum or centrifuge seemed unlikely to prove practical and the only experiments that had been performed fell short of the required accuracy. Because of this, the requirement for an accurate mass measurement of the MOL crew, and the fundamental nature of mass measurement in space, an informal program was initiated by AMD in the summer of 1965. The initial phase consisted of a somewhat cursory investigation of possible schemes and the selection of the most promising method.

A memo, in which this method (linear oscillating spring/mass) was analyzed in specific terms of the application, was prepared in September 1965. This memo is included on the following pages. In addition, a three-phase experimental program was started, and some preliminary results of the first phase are reported here, as well as an abbreviated description of the experiment and plans for further work in the area.

DESCRIPTION OF A PLANNED DEMONSTRATION OF MASS DETERMINATION BY LINEAR MASS/SPRING PENDULUM

SPRING/MASS

1.0 After theoretical study of the proposed and possible weightless mass measurement techniques, it appears that an oscillating mechanical system in which period varies as a function of mass is the most promising. The accuracy desired, limits imposed by the characteristics of the human body and other masses to be measured and the constraints imposed by the conditions of measurement have all been considered, together with the practicality and theoretical accuracy of other possible methods in reaching this conclusion. ~~This position has been agreed with by a~~ number of people contacted who have theoretical and/or practical have agreed with this position experience in the field. A second unanimous opinion is that little further is to be gained from theoretical studies without an accompanying practical experiment.

The problems in demonstrating the accuracy of such a system may be arbitrarily divided into three areas:

(1) Theoretical

(2) Instrumental details for earth demonstration

(3) Flight system

1.1 Theoretical:

The solutions of the general differential equations of an oscillating system have been solved in detail since the same equations describe a number of physical systems including mechanical, electrical, and acoustic.

The idealized system (Figure 1.1) consists of a mass M, attached to a restoring force $F_1 = KX$, provided by a massless spring, K, attached to a rigid support. Motion of the particle is assumed to create a linear resisting force of $R \frac{dx}{dt}$.

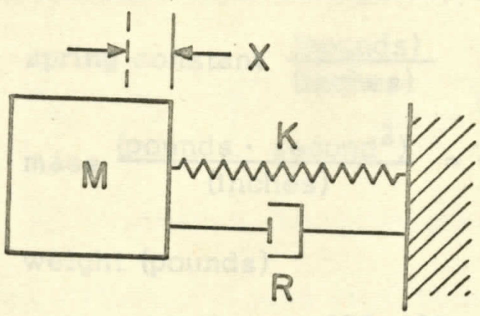


Figure 1.1 Mechanical System Moving in X axis with Mass-M, Spring-K, and Resistance-R.

The general equation of motion of such a system undergoing "natural" oscillation in a single plane, i.e., displaced from its position of rest and allowed to return with outside influence is:

$$M\frac{d^2x}{dt^2} + R\frac{dx}{dt} + KX = 0 \qquad \text{Eq. 1.1}$$

A

There are two possible forms to the solution of the equation depending upon the relative amount of resistance present. If the resistance, R, is equal or greater than $2\sqrt{KM}$, then the mass will return to the position of equilibrium in an exponentional fashion. If, as the case will be here, $\frac{R}{2\sqrt{KM}} < 1$, an oscillation about the equilibrium point will result. If the resistance is zero, an undamped or continuous oscillation will occur whose frequency is given by:

$$F_n = \frac{1}{2\pi}\sqrt{\frac{K}{M}} = \frac{1}{2\pi}\sqrt{\frac{KG}{W}} \qquad \text{Eq. 1.2}$$

Where: F_n = undamped natural frequency (cycles per second) with R = 0

K = spring constant $\frac{\text{(pounds)}}{\text{(inches)}}$

M = mass $\frac{(\text{pounds} \cdot \text{second}^2)}{\text{(inches)}} = \frac{\text{W (pounds)}}{\text{G (inches/second}^2\text{)}}$

W = weight (pounds)

G = (Austin, Texas) $979.283 \ \frac{\text{cm}}{\text{Sec}^2}$

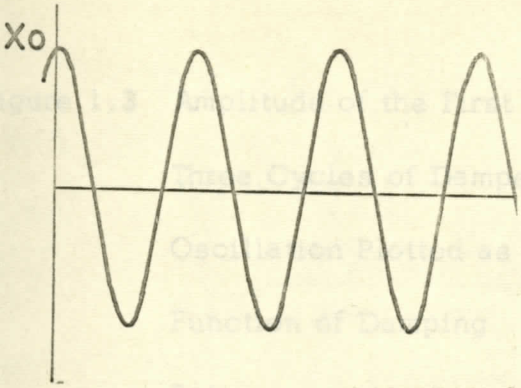
= $385.5437 \ \frac{\text{inches}}{\text{Second}^2}$

1 inch = 2.540005 cm.

The undamped natural period T_n (seconds) = $\frac{1}{F_n}$

$$\tau_n = \frac{1}{F_n} = \pi\sqrt{\frac{W}{KG}} \qquad \text{Eq. 1.3}$$

Amplitude will be equal to the amplitude of the original displacement as in Figure 1.2A.



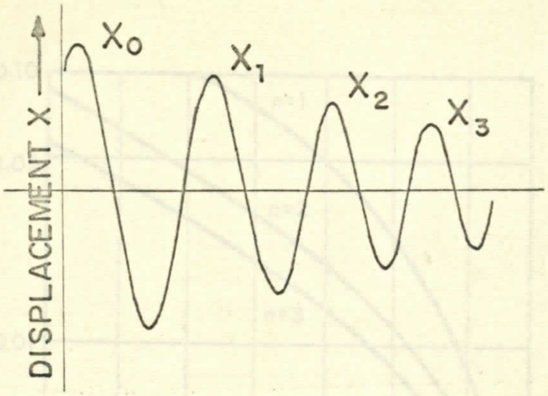


Figure 1.2A. Undamped Natural Oscillation R=O

B. Damped Natural Oscillation $O > R < 2\sqrt{KM}$

If the resistance is not zero, i.e., energy is dissipated as in any practical system, both the frequency and amplitude will be modified from the undamped case as illustrated in Figure 1.2B.

The new frequency will be given by:

$$F_d = F_n \sqrt{1 - \left(\frac{R}{2\sqrt{KM}}\right)^2} \qquad \text{Eq. 1.4}$$

F_d = damped natural frequency where R=0 (cycles per second). In addition, the peak amplitude will decrease by

$$\frac{X_n}{X_o} = e^{-\frac{2nK_d}{1-K_d^2}} \qquad K_d = \frac{R}{2\sqrt{KM}}$$

X_o = Amplitude of original displacement

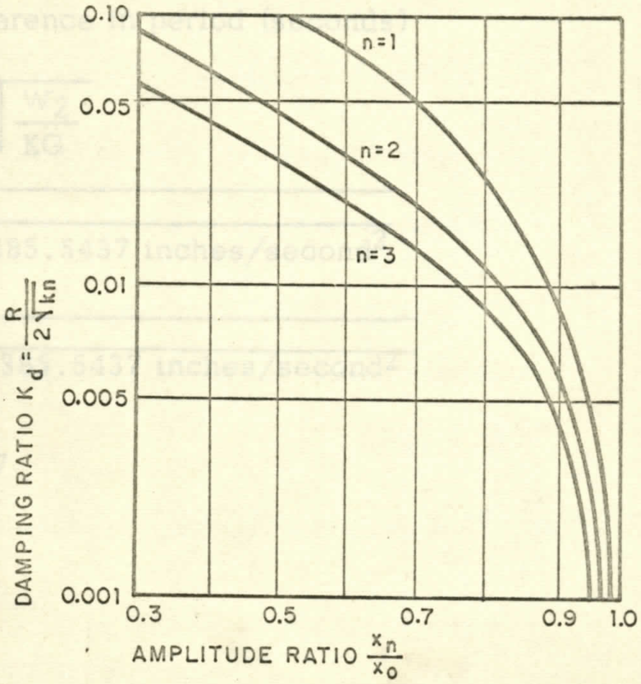
X_n = Peak amplitude of successive damped oscillations

n = Number of cycles

= 1, 2, 3 - - - - -

e = Natural logarithm

Figure 1.3 Amplitude of the First Three Cycles of Damped Oscillation Plotted as a Function of Damping Ratio



The two fundamental questions that arise from purely theoretical considerations then are concerned with period (frequency) determinations and knowledge of R, K&M to determine deviations from the natural frequency. The minimum time resolution $\Delta\tau$ required for idealized measurement of a mass change of .1 pound is calculated here for a typical case of a 150 pound object at a period of approximately 12 seconds.

$$\Delta\tau = \tau_2 - \tau_1 = \text{difference in period (seconds)}$$

$$\Delta\tau = 2\pi\sqrt{\frac{W_1}{KG}} - 2\pi\sqrt{\frac{W_2}{KG}}$$

$$= 2\pi\sqrt{\frac{150 \text{ pounds}}{10 \text{ pounds/inch} \cdot 385.5437 \text{ inches/second}^2}}$$

$$- 2\pi\sqrt{\frac{150 \text{ pounds}}{10 \text{ pounds/inch} \cdot 385.5437 \text{ inches/second}^2}}$$

$$= 1.2397444 - 1.2393297$$

$$= .447 \times 10^{-3} \text{ seconds}$$

$$\sim .5 \text{ milliseconds}$$

This order of time resolution may be readily obtained by a counter of 10^{-4} seconds resolution (10^{-6} seconds resolution is routine) so measurement of time per se is not difficult, but it is obvious that a stop watch will not suffice. As will be shown later, the difficulty will arise from the distance resolution required to obtain this time.

The next consideration, effects of resistance, cannot be determined with such accuracy. The resistance in the real case will not be lumped but will consist of several components which do not readily lend themselves to precise calculation. The two chief sources of resistance arise from: (1) the motion of the mass (man) through a viscous medium (air), (2) the dissipation of the spring. While the spring resistance (hysteresis) will remain a small system constant, the viscous resistance (air drag) will vary with subject configuration and surrounding atmosphere and cause variable deviations from the undamped natural frequency. Since the body will be irregular and variable and the atmosphere is presently unknown, only an estimation may be made of this effect.

Air "drag" at appreciable velocities may be calculated from:

$D = C_d S P$ Eq. 1.~~7~~5

P = dynamic pressure = $\frac{V^2 \rho}{2}$ (slugs second^{2}/feet)

D = drag (pounds)

C_d = coefficient of drag

= 1.28 for flat plate

S = area (feet^2)

ρ = density = 2.38×10^{-3} slugs/feet^3 for normal atmosphere

V = velocity $\frac{\text{(feet)}}{\text{(second)}}$

Resistance $R = \frac{\text{Force}}{\text{Velocity}}$ and combining this with the drag equation:

$R = \frac{C_d S V \rho}{2}$ Eq. 1.~~8~~

Assuming a flat plate area of 3 feet^2 for a seated man in a normal atmosphere with a velocity of 1 foot/second (this is greater than our maximum velocity will be), the resistance is calculated to be

$R = \frac{1.28 \times 3 \times 2.38 \times 10^{-3} \times 1}{2} = 4.57 \times 10^{-3}$ pounds · second/feet.

The Aeromed Laboratory, Wright-Patterson AFB, Ohio, uses values of CdS of 5 feet^2 minimum to 10 feet^2 maximum for the clothed human body. Hoerner also gives values in this range. Taking the 10 foot^2 value will result in an R of $\sim 1.5 \times 10^{-2}$ $\frac{\text{pounds} \cdot \text{second}}{\text{feet}}$.

We may next note the maximum allowable effects of resistance for the accuracies desired (auxillary calibration would be possible but undesirable).

We have seen that an accuracy of $\sim .5 \times 10^{-3}$ seconds in time is required for a change of .1 pound of 150 pounds and for convenience these time figures will be used here. Eq. 1.3 allows calculation of the effect of R and rearranging this in terms of period Eq. 1.4 will allow one to calculate the maximum tolerable R for the given $\Delta\tau$ assuming these are no spring losses or other system errors.

τ_n = Undamped period (seconds)

= 1.2393297

τ_d = Damped period (seconds) = 1.2397444

The preceding formula obviously forms a non linear differential equation -

$$m\ddot{x} + R\dot{x} + R\dot{x}^2 + Kx = 0$$

Laminar Flow drag is given by Dommasch, Airplane Dynamics P-59

$$D_{(force)} = \frac{2\,q\,A\,(1.328)}{\sqrt{R_N\,(Reyn's.\ \#)}}$$

q = dynamic Press or $\frac{1}{2}\rho V^2$

A = area

Again a $\dot{x}^2$ term -

$$K_d = \sqrt{1 - \left(\frac{1.2393297}{1.2397444}\right)^2} = \sqrt{1 - .99933} = 2.58 \times 10^{-2}$$

Also:

$$K_d = \frac{R}{2\sqrt{KM}}$$

$$R = 2K_d \sqrt{KM}$$

$$= 2 \times 2.585 \times 10^{-2} \times 10 \times .389$$

$$= 10.18 \times 10^{-2} \ \frac{\text{pounds} \cdot \text{second}}{\text{inch}}$$

This figure is almost on order of magnitude greater than our worst case total drag. Variations in this drag figure should have negligible effect on the mass determination.

Another consideration is the limited mass of the space ship. This limited mass results in a small amplitude of oscillation of the ship ~~which will shift the frequency of oscillation as follows:~~

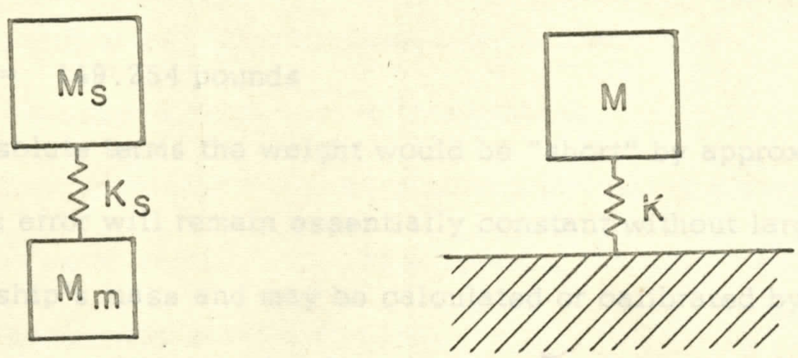


Figure 1.4A Spring/Mass System Attached to Finite Mass B. Spring/Mass System Attached to Infinite Mass

M_m = Mass to be measured

M_s = Mass of ship

K_s = Spring Constant

$$F = \frac{1}{2\pi}\sqrt{\frac{K_s(M_m+M_s)}{M_m M_s}}$$ Eq 1.6

$$\tau = 2\pi\sqrt{\frac{M_m M_s}{M_m+M_s}\cdot\frac{1}{K_s}}$$

The equation for infinite M_s is $\tau = 2\pi\sqrt{\frac{M_m}{K_s}}$ thus the value $\frac{M_m M_s}{M_m+M_s}$

may be considered equivalent to a reduced mass M_e.

Using values of:

$$M_m = \frac{150}{g} \text{ pounds}$$

$$M_s = \frac{30,000}{g} \text{ pounds}$$

$$M_e = \frac{3 \times 10^4 \times 1.5 \times 10^2}{(3.+.0150) \times 10^4} = \frac{4.5 \times 10^6}{3.015 \times 10^4}$$

$$= 149.254 \text{ pounds}$$

In absolute terms the weight would be "short" by approximately .75 pounds. This error will remain essentially constant without large variations in the ship's mass and may be calculated or calibrated by a single on-station measurement with a known mass.*

Mass relativity does not apply to the situation here; and even if it were applicable, the velocities involved are so low as to be entirely negligible.

*It is assumed that the center of mass of the ship is in the same plane of oscillation as the center of the measured mass.

2.0 Experimental Considerations

There seem to be no fundamental theoretical difficulties; therefore, a realistic demonstration of the technique under earth conditions should be made.

It must be pointed out that the Lockheed demonstration of * this method was crude, apparently for lack of materiel support. Unfortunately, the idea is extant that the results represented what might be reasonably expected from such a system.

The essential components of an experiment on earth to demonstrate the validity of the foregoing theoretical conclusions would consist of:

2.1 structure to hold the mass to be weighed

2.2 a spring assembly

2.3 a device to determine precisely when the oscillating mass crosses the point of zero displacement (equilibrium point)

2.4 a counter for determining time periods

2.5 some means of providing displacement along a single axis

2.6 on earth, some method of supporting the weight being measured without adding appreciable friction.

This latter item makes the device more difficult to demonstrate under gravity than under weightlessness.

* LMSC.

The experiment will be described by these sections. The basic arrangement is shown in Figure 2.1.

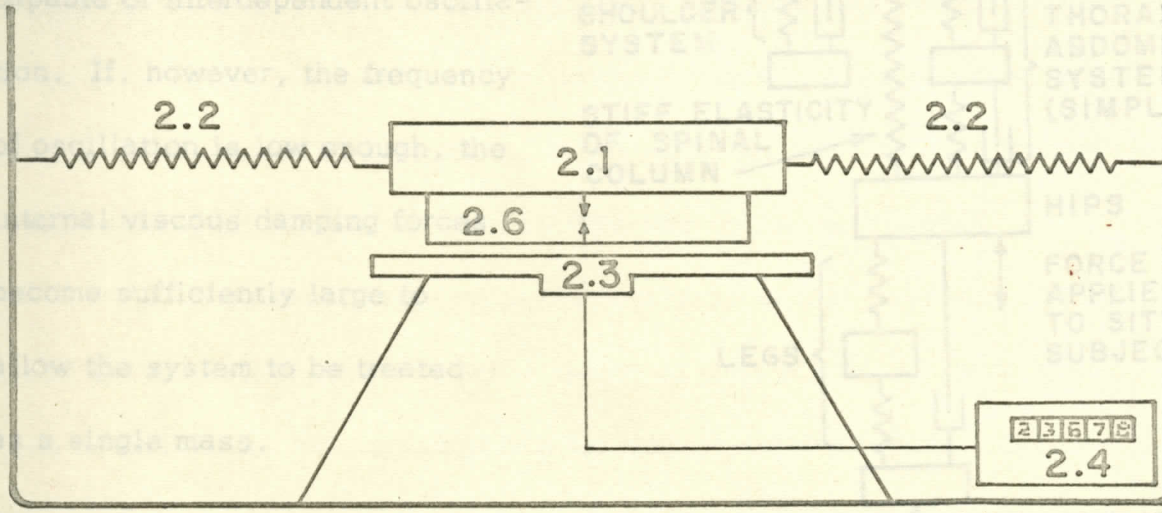


Figure 2.1. Arrangement of System for Measurement of Mass. Parts Legend is on Page 12. Not shown is displacement release 2.5.

2.1 The structure to hold the mass is complicated by the nature of the human body. Indeed, the whole experiment will be more or less influenced by the following considerations.

The human body may be considered to consist of a complex series of subunits. A 2° order approximation is shown in Figure 2.2 using mechanical analogs.

These segments constitute a series of mechanical systems capable of interdependent oscillation. If, however, the frequency of oscillation is low enough, the internal viscous damping forces become sufficiently large to allow the system to be treated as a single mass.

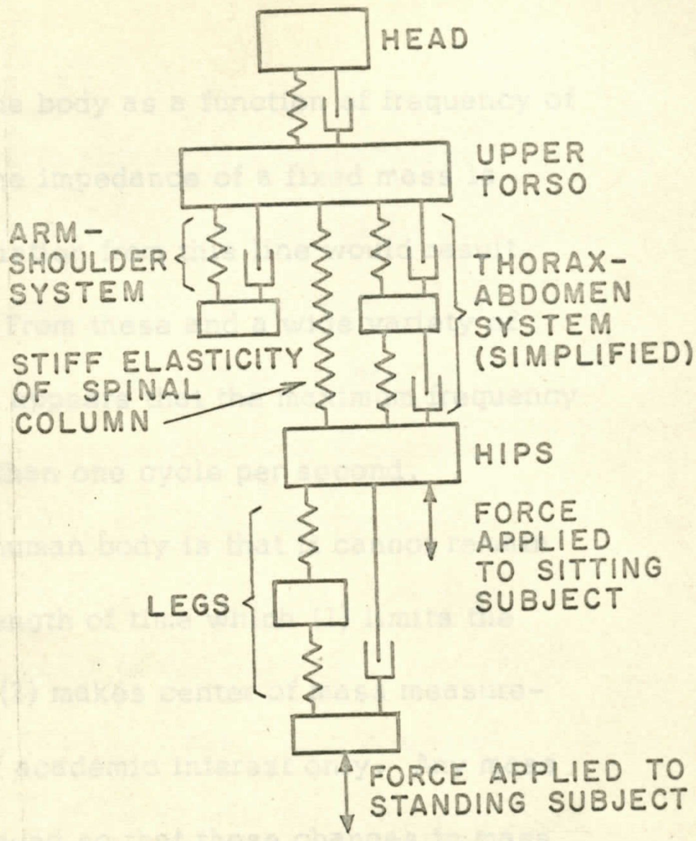


Figure 2.2 Second Order Mechanical Analog of Human Body After Coermann

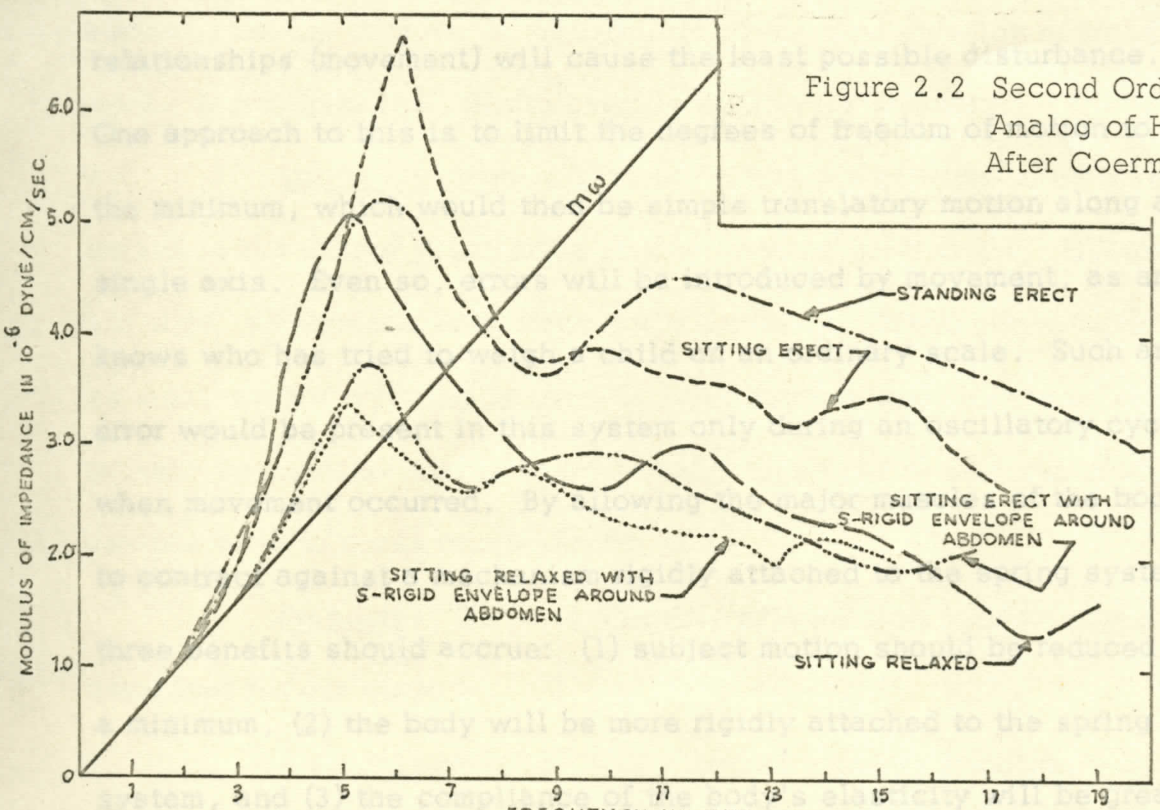


Figure 2.3 Mechanical Impedance of the Human Body Under Several Conditions - Coermann, et al.

A plot of impedance of the body as a function of frequency of vibration is shown in Figure 2.3. The impedance of a fixed mass is shown by the straight line. Any deviation from this line would result in an error in the proposed system. From these and a wide variety of similar experiments by Coermann, it appears that the maximum frequency which should be considered is less than one cycle per second.

A second aspect of the human body is that it cannot remain fixed in one position for any great length of time which (1) limits the time available for measurement and (2) makes center of mass measurements of such variability as to be of academic interest only. Any mass measurement scheme should be arranged so that these changes in mass relationships (movement) will cause the least possible disturbance. One approach to this is to limit the degrees of freedom of motion to the minimum, which would then be simple translatory motion along a single axis. Even so, errors will be introduced by movement, as anyone knows who has tried to weigh a child on an ordinary scale. Such an error would be present in this system only during an oscillatory cycle when movement occurred. By allowing the major muscles of the body to contract against a mechanism rigidly attached to the spring system, three benefits should accrue: (1) subject motion should be reduced to a minimum, (2) the body will be more rigidly attached to the spring system, and (3) the compliance of the body's elasticity will be greatly reduced, i.e., the body will more nearly approximate a fixed mass. Movement may be further reduced by breath holding. The ballistic effects of the cardiovascular system will remain. This latter effect will be small and will be essentially zero over a complete cardiac cycle. For a human mass measurement system then, the "weighing pan" should have a foot board and handholds or other arrangement to allow contraction of the major musculature. The amount of time that a fixed position may be held is a limitation of the maximum period of time during which such a measurement may be made. This measurement period should be as long as possible for as will be shown later, accuracy should vary as the square root of the time duration of measurement. A practical limit would seem to be 10 - 15 seconds.

2.2 Spring Assembly. Several factors are of importance here including the energy dissipative characteristics (hysteresis), linearity, and time, dimensional and temperature stability. When one speaks of springs, we are referring to the precision devices such as those used in many commercial scales in the country today rather than the crude devices used to close doors and the like.

Stability. The long term time stability of precision springs may be neglected for our purpose.

A spring under load will elongate slowly, principally during the initial 24 hours, an effect called "creep." This effect is shown in 2.4.

A spring is subjected to a fixed force F_1 and depending upon its constant K, it will be stretched to a position X_1 from the spring equation F = KX. Depending upon the time and temperature, the spring will gradually elongate to a new position $X_1 + \Delta X$.

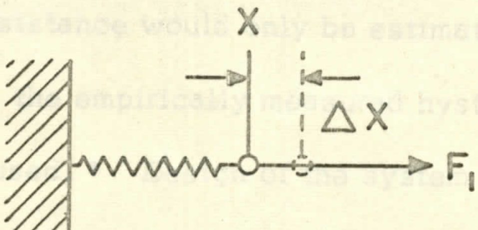


Figure 2.4. Creep or Elongation of Spring Under Load, F_1 - X is Original Position

Since the force is unchanged, this is equivalent to a new spring constant $K_2 = \frac{F}{X + \Delta X}$. The creep of a good spring is typically .01% /24 hours under maximum load which results in a change of .01% in spring constant. P~~ush~~ull-pull springs will be used here which will double the error. However, by simply unloading the spring assembly except when in actual use, this effect is abolished. Normally, spring scales are not loaded except in use.

The rate (spring constant) temperature coefficient of the selected spring material * may be chosen from a range of 0 to 15×10^{-6}.

* Isoelastic ®

The temperature variations of the laboratory vehicle should be small in any case, which eliminates this consideration as a source of significant error.

After communication with individuals who possess extensive experience with springs, there appears to be no exact expression available for the hysteresis of a spring so that calculations of that component of resistance would only be estimates. This factor should be negligible as the empirically measured hysteresis will be .01% on the units to be used. * Design of the system will carefully avoid exceeding elastic limits of the springs. A minor resistive effect could result from twisting of the spring with displacement, but this will be avoided by compound winding.

To summarize, the springs should not present a problem if the best material and techniques available are used.

2.3 The accuracy with which the point of zero crossing is determined is fundamental to the accuracy of the entire system. Although the basic measurement is time, it is dependent upon the distance resolution of the zero crossing detector and the velocity of the mass at zero crossing as follows:

$$\text{Time Resolution} = \frac{\text{Distance Resolution}}{\text{Velocity at Zero Displacement}}$$

* Some measurements recently made here on the resistance losses (hysteresis) of typical units show that these losses are very negligible.

OK

Taking a nominal frequency of 1 cycle per second with a peak displacement of 1 inch will give a peak velocity of

$$\frac{dXo}{dt} = 2\pi \; FXo \sim 6.28 \; \frac{\text{inches}}{\text{seconds}}$$

For a time resolution of 5 milliseconds the distance resolution must then be:

$$\text{Distance} = \text{Velocity} \times \text{Time}$$

$$= 6 \; \frac{\text{inches}}{\text{second}} \times .5 \times 10^{-3} \; \text{seconds}$$

$$= 3 \times 10^{-3} \; \text{inches}$$

A narrow beam of light interrupted by a knife edge has been chosen for the zero crossing detection method. This is shown diagrammatically in Figure 2.5.

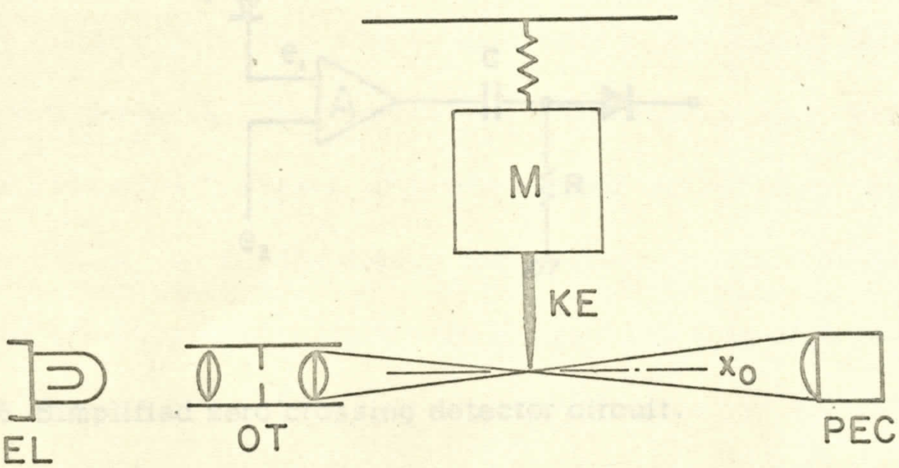


Figure 2.5. Schematic of Physical Arrangement of Zero Crossing Detector

An incandescent bulb E.L. illuminates a slit in the optic tube(OT) assembly which is then focussed as a vertical ribbon of light .001 inch wide x ~ .1 inch deep at Xo. A knife edge K.E. is attached to the oscillating mass M and moves across the axis X. At all points above Xo the photo electric cell PEC is illuminated fully and provides a maximum light output. At Xo the light is cut off in .001 inch and remains off when the mass is below this point. The system thus has an inherent accuracy of .001 inch.

This is further enhanced by the electronic circuitry shown in Figure 2.6 as follows: The voltage e_1 is the output of the photocell while e_2 is fixed at 1/2 maximum voltage of e_1.

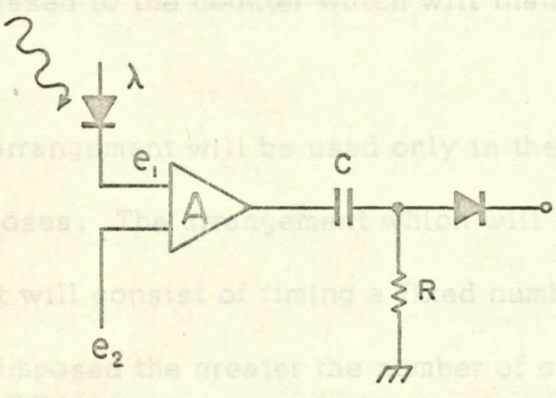


Figure 2.6 Simplified zero crossing detector circuit.

A is a stable high gain differential amplifier that will provide an output of approximately 20 volts for a 1mV. difference between e_1 and e_2.

OK

The slope of the PEC output is several volts/10^{-3} inch as the knife crosses the light beam. This results in a theoretical resoltuion of microinches. Practically there is some noise or motion pulses in other planes with defocussing and other effects. A series of measurements with controlled errors introduced have been made and show that a resolution of 10^{-4} inches may be reasonably expected. This is ~~more~~ ~~than an order of magnitude~~ much greater than the required resolution.

2.4 The output of the zero crossing detector must then be converted to signals controlling the timer. A simple R.C. differentiator will generate a pulse each time zero is crossed. Zero is crossed twice each cycle from alternately opposite directions. Only pulses of a single polarity will be passed to the counter which will then count each complete cycle.

This arrangement will be used only in the testing phases for investigative purposes. The arrangement which will be used during mass measurement will consist of timing a fixed number of cycles. Within the limits imposed the greater the number of cycles counted, the greater the accuracy, assuming random errors. The time accumulated will be a direct function of the number of counts (true cycles) while the random errors (noise of motion pulses) will accumulate as the square root of the number of counts. The signal to error ratio will then increase as the square root of the number of cycles taken. The timer used in the experiment will be an ordinary Hewlett Packard 523D with a maximum time resolution of 10^{-6} seconds. Overall system time resolution should be $< 5 \times 10^{-5}$ seconds.

2.5 A system for initial displacement should present no great problem. The magnitude of initial displacement will be a compromise among several factors including distance resolution available, working distance of springs, space available and bearing size. A nominal distance of 1 inch total peak to peak displacement has been chosen here. Since the bearing used will allow only rectilinear motion, some form of simple stop at .5 inch maximum deflection with a positive manual release is needed.

2.6 Essentially frictionless support is limited to a few choices here of which the most obvious is an air bearing. A quick and dirty approximation of such a bearing is a block of dry ice supporting a smooth surface. Such makeshift is not justified here, and a simple linear air bearing with lateral and bottom surfaces will be used. Such a bearing may for our purposes be considered frictionless. An air supply of a few P.S.I., and low volume will be required for operation.

The first phase of the demonstration will consist of assembling the components and testing the validity of the derived calculations including the resolution, accuracy and stability of the proposed instrument using fixed masses. A second phase will consist of construction of a man carrying version and development and test of the features peculiar to this application. If successful, a third phase should be considered which consists of flying or otherwise simulating MOL conditions with the two devices using cylindrical bearings to determine their behavior under weightlessness and to gain operational experience with this principal. Information and guidance should be provided to the contractor during all phases as soon as valid results are obtained.

3.0 Conceptual Designs

Assuming that the principles described will hold, one must then determine the possibility of achieving a practical system under conditions imposed by space flight. These conditions include severe limitations on size, weight, power, complexity (particularly of operation) as well as a variety of environmental conditions including vibration and G loading during powered flight, sub-normal atmospheric pressure and possible unusual atmospheric composition.

The oscillating mass scheme lends itself well to such conditions. The condition of weightlessness will be an asset. The only bearings required under zero G are to restrain small forces from deviating the mass out of the desired axis of oscillation. ~~A small pair of cylindrical air bearings operating with 1-2 PSI are all that should be required. The air flow rate will also be low such that a small bleed from a bottle~~

Fig 3.2 A

Fig 3.2 B

Figure 3.2

Very schematic drawing of device to determine mass of small fixed objects. Fig A is partial cutaway showing the spring arrangement and a counter/scale, B. The optical zero crossing detector, E, F, G, and dual air bearings, D, are shown in 3.2 B. H is the weighing pan containing a partially filled tube whose mass is being measured. Air for the bearing will enter via tubes, C.

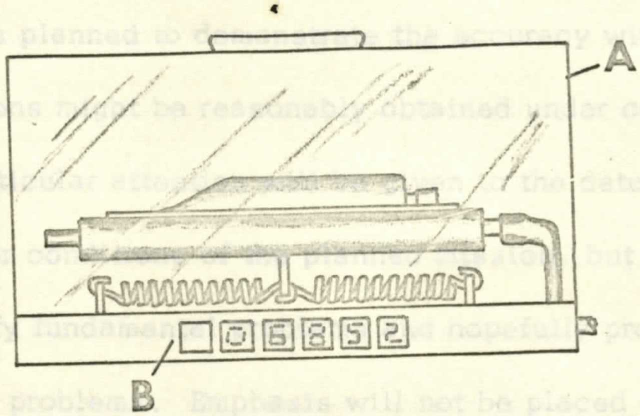


Fig 3.2 A

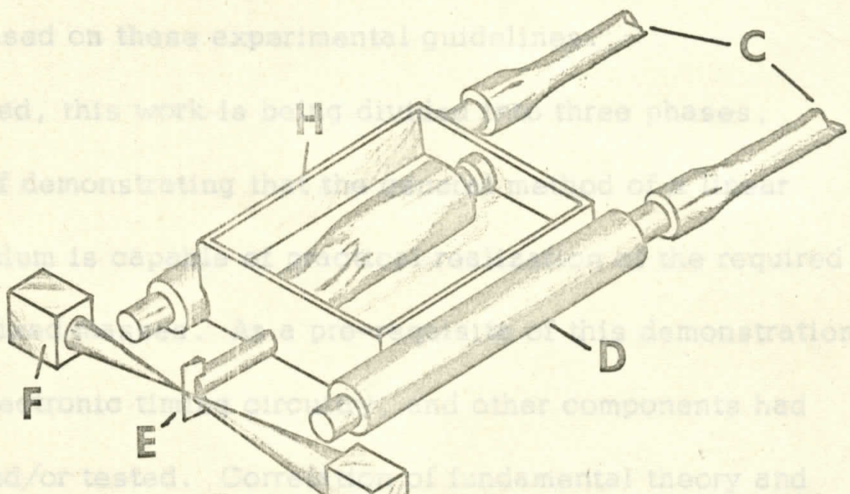


Fig 3.2 B

Figure 3.2

Very schematic drawing of device to determine mass of small fixed objects. Fig A is partial cutaway showing the spring arrangement and a counter/scale, B. The optical zero crossing detector, E, F, G, and dual air bearings, D, are shown in 3.2 B. H is the weighing pan containing a partially filled tube whose mass is being measured. Air for the bearing will enter via tubes, C.

4.0.0 Experimental Work

This work is planned to demonstrate the accuracy with which mass determinations might be reasonably obtained under conditions of weightlessness. Particular attention will be given to the determination of the mass of man under conditions of the planned mission, but this work should also identify fundamental problems and hopefully provide some solutions to these problems. Emphasis will not be placed on design of flight hardware, except as required to prove concepts ~~it is obviously beyond our facilities and mission to provide flight-ready equipment~~, rather efforts are being made to establish guidelines for the design of such equipment and will include proposed general designs based on these experimental guidelines.

As noted, this work is being divided into three phases. Phase I consists of demonstrating that the general method of a linear spring/mass pendulum is capable of practical realization of the required accuracies using fixed masses. As a pre-requisite of this demonstration, the air bearing, electronic timing circuitry, and other components had to be developed and/or tested. Correlation of fundamental theory and experimental results are a large part of this phase.

Phase II will consist of construction and testing of a man-carrying version of this system. It will be based on work done in Phase I, and much of the hardware developed there will be used. The chief problems to be resolved are the effects of the non-rigid mass of man and optimum arrangement of the pendulum for such non-rigid mass determinations. Theoretical verification of experimental conclusions about the magnitude of wind resistance and similar effects not investigated in Phase I will be done at this time.

During both phases I and II, careful note will be made of any phenomena which will affect the results of this system under weightlessness in practical installations in the proposed laboratory or other vehicles.

Phase III will concern itself chiefly with the theoretical and experimental aspects of a practical installation.

4.1.0 Work Accomplished

Phase I. Two oscillating spring/mass systems have been completed. The first was simple a "bread board" version shown in Figure 4.1.1, done as an expedient to verify the performance of various items of hardware including the air bearing and timing system. This "bread board" was completed and briefly tested during September.

A second version of the pendulum was constructed in October using many of the original components but differing little from the original arrangement except for considerably more mechanical rigidity. This second version has had and will continue to have a series of small modifications for the improvement of its performance. The device will be described in its present configuration.

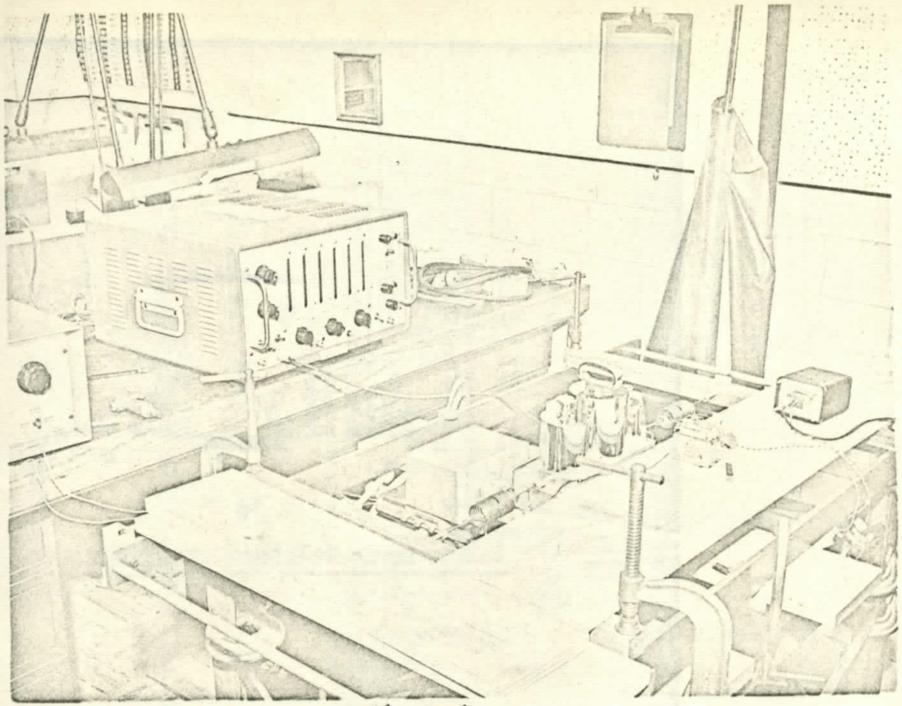
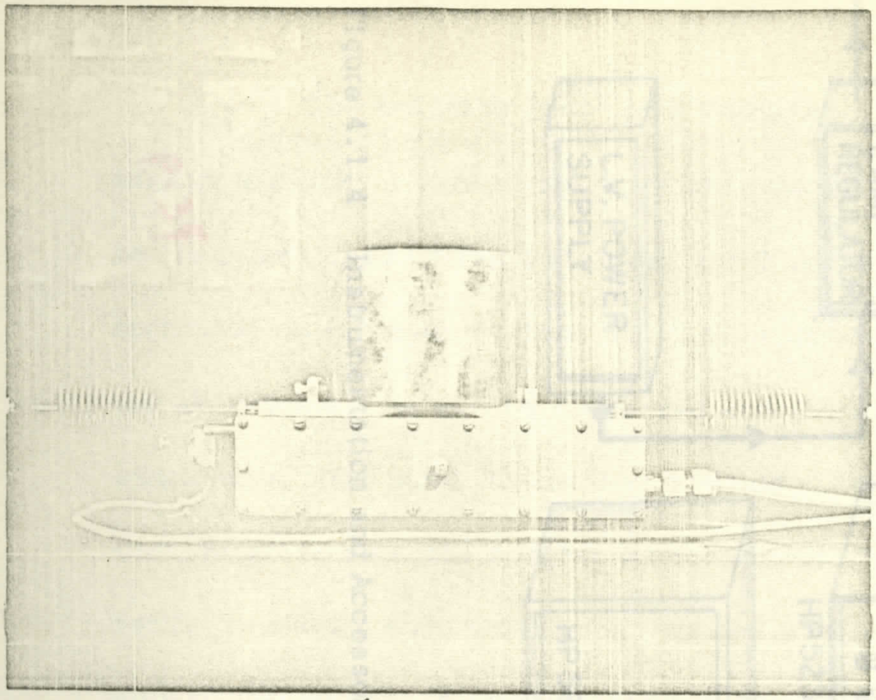


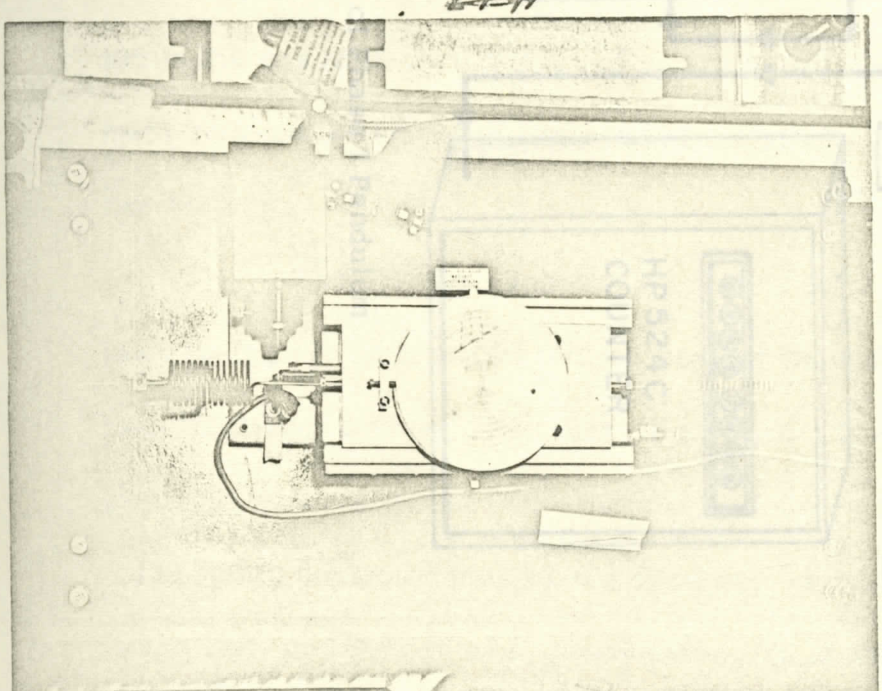
Figure 4.1.1. First version (bread board) of spring/mass pendulum.

Figures 4.1.2, 4.1.3, and 4.1.4 show the layout of the complete arrangement including auxillary instrumentation. This is essentially the same as described in the section 2.0 and the components will be described in the same order.



4.1.2

Figure 4.1.2. Side view of air bearing with 9 KG weight. Zero crossing detector at left. Mechanical release not installed.



4.1.3

Figure 4.1.3. Top view of second version of pendulum mounted on stationary shake table. Exciter lamp housing of crossing detector in upper left.

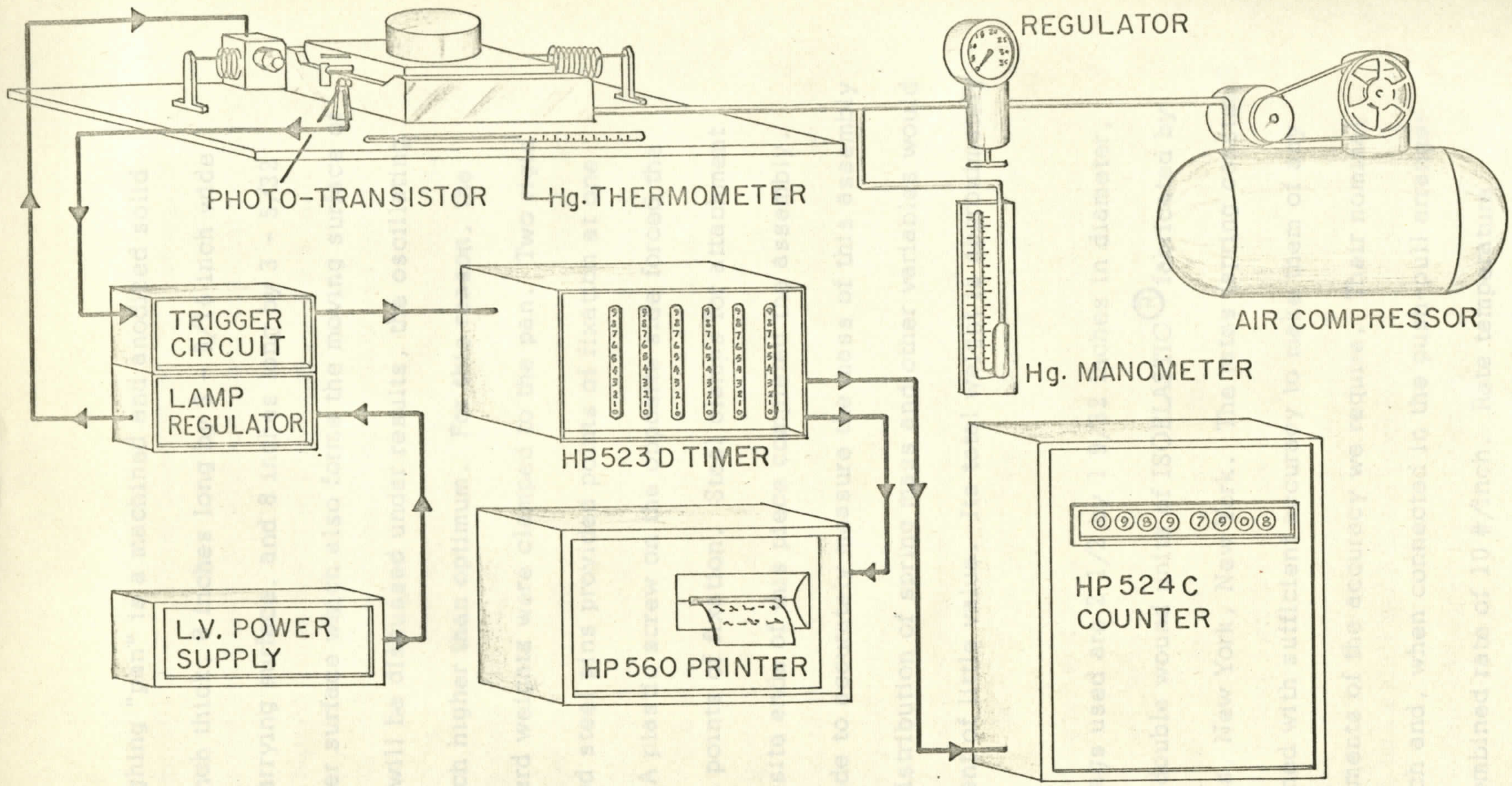


Figure 4.1.4 Instrumentation and Accessory Arrangement of Phase I Pendulum

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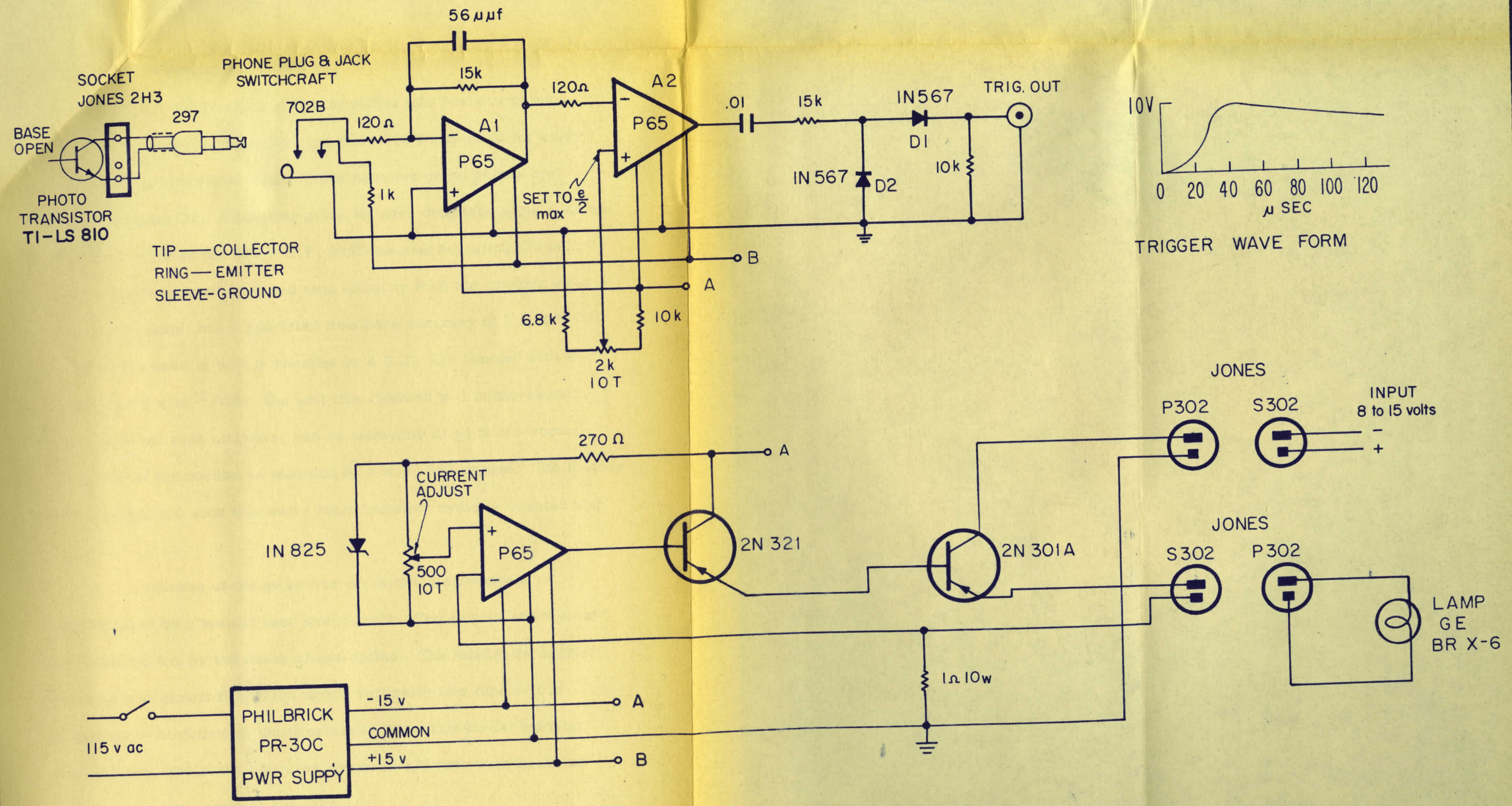
The weighing "pan" is a machined and anodized solid aluminum block, 1 inch thick, 8 inches long by 3 - 9/16 inch wide on its upper, load carrying surface, and 8 inches long by 3 - 5/32 inch wide on its lower surface which also forms the moving surface of the air bearing. As will be discussed under results, the oscillating frequencies were much higher than optimum. For this reason, the circular brass standard weights were clamped to the pan. Two rigid vertical, plastic shod steel pins provided points of fixation at one side of the weight. A plastic screw on the opposite side forced the weight against these points of fixation. Steel clamps for attachment of the spring to opposite ends of this piece completed the assembly. No attempts were made to accurately measure the mass of this assembly since the assumed distribution of spring mass and other variables would make this measurement of little value. Its total weight is approximately two pounds.

The springs used are 2 1/2 by 1 9/32 inches in diameter, open helical 14 turn double wound units of ISOELASTIC® fabricated by John Chatillon & Sons, New York, New York. The rates (spring constant) could not be determined with sufficient accuracy to make them of any great use in measurements of the accuracy we require. Their nominal single rate is 5 #/inch and, when connected in the push-pull arrangement here, have a combined rate of 10 #/inch. Rate temperature coefficient is less than $10^{-5}/^{\circ}C$. Other features of their design followed the guidelines of section 2.2. Although they are claimed by their manufacturer to have a linearity of 0.1 percent over a 3 inch working distance, their maximum working displacement has been 3/4 inch. Each spring is stretched approximately 1/2 inch to allow a linear working force over this range.

The heart of this system is the zero crossing detector for its performance limitations will set the maximum performance limits of the entire system. The basic scheme described in section 2.3 is used. The circuit is given in Figure 4.1.5, and Figure 4.1.6 is a photo of the mechanical arrangement. A GE BRX-6 exciter bulb operated at a regulated (~1 percent) .8A, 3 1/2V., illuminates the slit of a salvaged 35 mm motion picture sound reproducer optic tube assembly. This slit is focussed to .001 inches wide by ~ .1 inch high at the plane of the light interrupter and falls on a TI LS 810 silicon photo transistor operated with an open base. A razor blade is used as light interrupter and is clamped to the pan by a rod. The emitter-collector current is a reasonably linear function of incident light and is converted to voltage by the operational amplifier, A-1, and its associated circuitry. Although it has a full on-full off accuracy of approximately .001 inches, this is further enhanced by the differential amplifier A2



OPTICAL PERIOD DETECTOR & LAMP CURRENT REGULATOR

Figure 4.1.5

as described in section 2.3. An R.C. circuit differentiates the resulting square wave output of this amplifier into positive going spikes of 20 micro-seconds rise time and ~ 10 V amplitude for every crossing of the other direction. These negative going pulses are clipped by diode D2. A positive pulse for each complete cycle remains. The pulses are then fed into a H.P. 523D counter actuating the period timing through internal start and stop circuitry from the common input line. This counter has a specified time base accuracy of 2×10^{-6}/WK and this time base in turn is checked by a H.P. 524 counter with an accuracy of 5×10^{-8}/WK. The unit time counted is 1 micro-second, and as with all such counters, has an ambiguity of ± 1 micro-second. The output of the counter is recorded by a H.P. 560 printer. The display delay is adjusted such that every other complete cycle is counted and printed.

Release of the mass from an initial displacement is accomplished by a manual sear arrangement. The sear is attached to the weighing pan by the shank of one spring. The release is another hardened and ground flat which moves vertically in a tube and is connected to a horizontal thumb release. *Maximum initial working* displacement (Xo) of the pendulum has been 3/8 inch with maximum peak to peak oscillation of 3/4 inch.

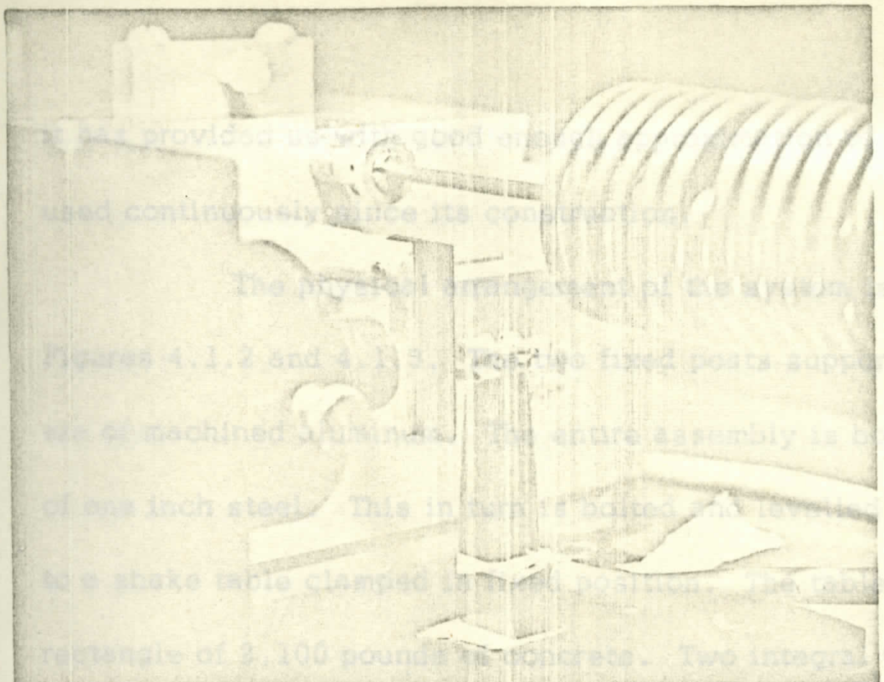


Fig 4.1.6

Figure 4.1.6. Physical arrangement of zero crossing detector. Lamp-housing and optic tube assembly on left. Photo transistor is adjacent to razor blade which is used as light interrupter.

Another critical element of the system is the air bearing, for it must not only constrain the motion of the mass to a single axis and support the weight being measured but must do this with negligible friction and without adding acceleration to or otherwise disturbing the oscillation. Although a coaxial linear air bearing has a theoretical advantage in holding motion to the nearest approximation of a straight line (two are required to prevent rotary motion) their weight carrying ability is much less than a flat bearing. The unit shown was empirically built by two master machinists and although improvements can be made, it has provided us with good enough approximation of the ideal to be used continuously since its construction.

The physical arrangement of the system is shown in Figures 4.1.2 and 4.1.3. The two fixed posts supporting the springs are of machined aluminum. The entire assembly is bolted to a sheet of one inch steel. This in turn is bolted and levelled at four corners to a shake table clamped in fixed position. The table is bolted to a rectangle of 2,100 pounds of concrete. Two integral transverse 'I' beams support this on four 10 inch diameter concrete piers through vibration dampers. The piers are placed in the earth but are very shallow.

Air supply for the bearing has been a portable 80 - 120 PSI compressor/tank through a diaphragm regulator to a nominal pressure of 190 mm Hg ($\sim$ 5 PSI). Bearing supply pressure is measured by means of a mercury manometer which can probably be read to $\pm$1 mm. A mercury thermometer calibrated to 0.1°C. is used to read base plate temperature and thermo couples are used to indicate any differential temperature between spring, air, and base plate. This arrangement has been housed in a World War II building with extremely poor short and long term temperature control.

4.1.2 Phase II

A man-carrying version of the bearing has been completed and is shown in Figures 4.2.11 and 4.2.12. Only cursory investigation has been made of the behavior of this bearing.

A prototype "pan" with hand holds, foot board, and head rest and the zero crossing detector are complete. Construction of the electronics are in progress and preliminary operation should be under way by completion of this report.

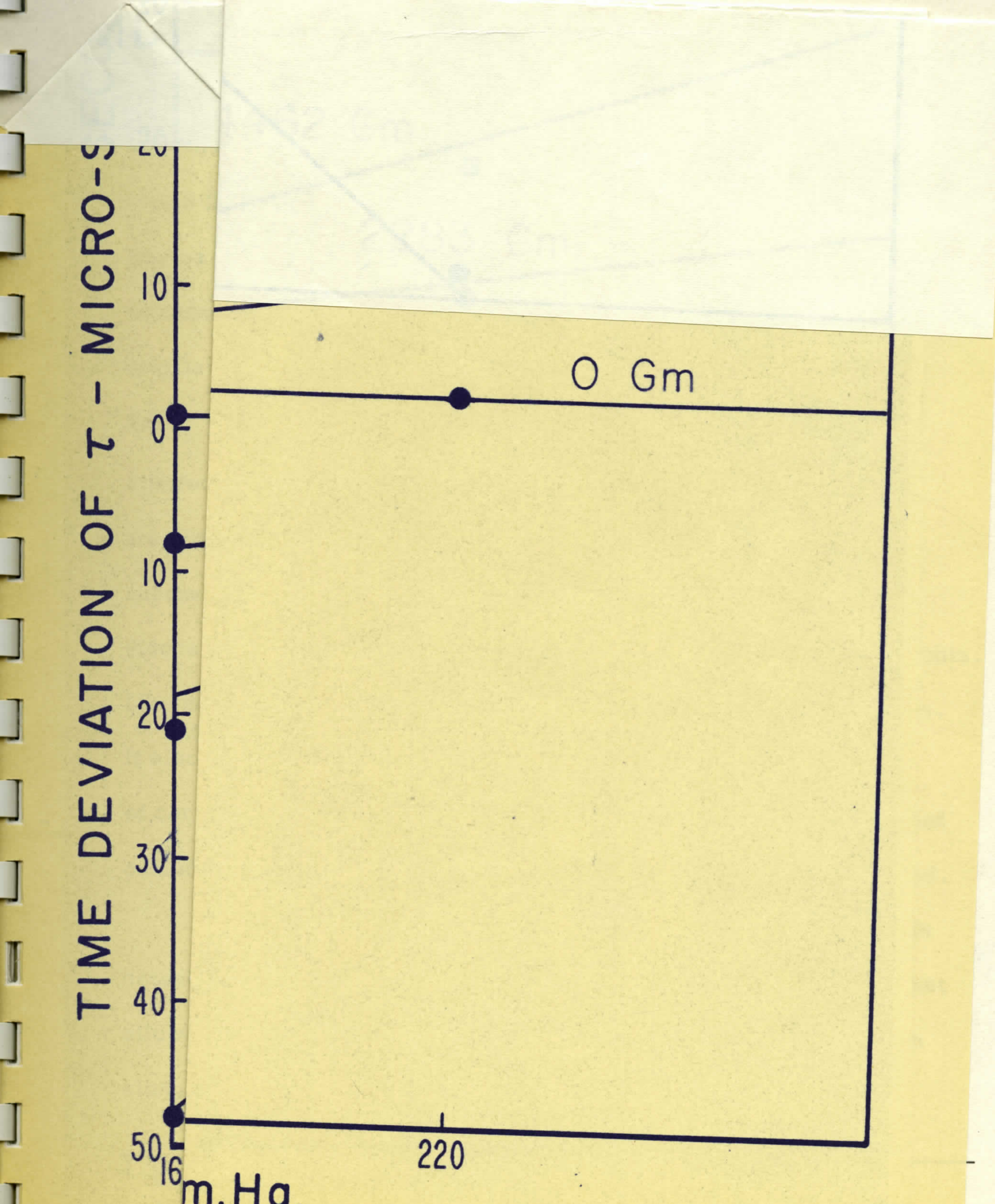
4.1.3 Phase III

Some very preliminary studies have been started in this area and will be collaborated ?on in by a consultant, Dr. Palmatier, an experimental physicist at the University of North Carolina. Some time prior to the completion of these studies an experimental program will be started.

4.2.0 Results

Phase I. Prior to the present arrangement, as alternatives to the air bearing, several low friction schemes were tried including plastic and precision ball bearings running on hardened and polished steel rods. Although exceedingly low by conventional standards, the coefficients of frictions were hopelessly large to obtain our planned damping coefficients and these attempts were quickly abandoned.

The performance of the air bearing has not been quantitatively studied. Since the behavior of this bearing may not be comparable to that of coaxial or other arrangements, which may finally be used, it was elected not to study these units in detail except as they notice-



p-4

Figure 4.2.1 Variation of

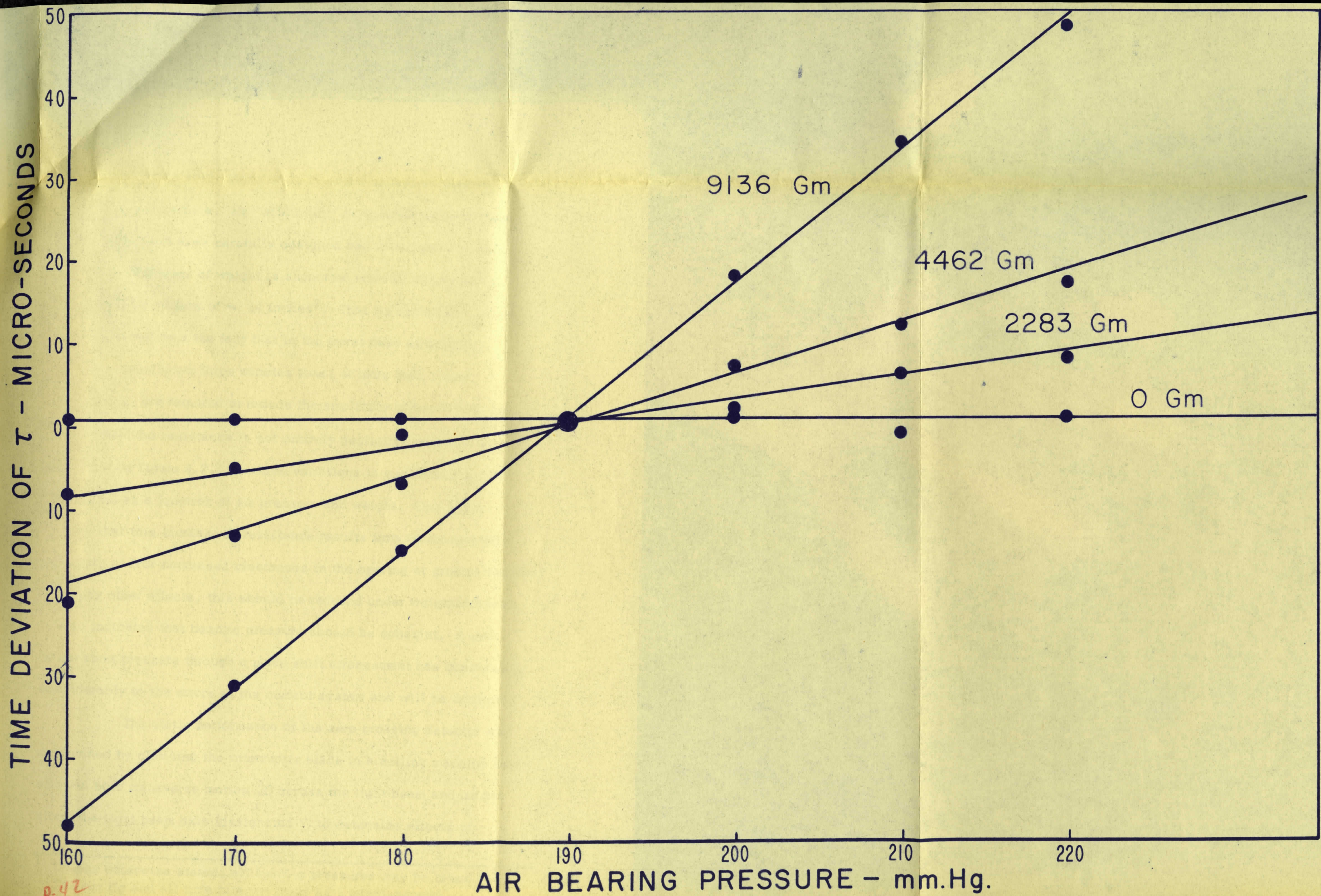


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Figure 4.2.1 Variation of period as a function of air bearing pressure and load was elected not to study these units in detail except as they noticeably affect performance. Its "efficiency" is reasonably good when compared to much more carefully designed and constructed units. More than 60 pounds of weight is supported with 30 PSI pressure with a bearing surface of $\sim$ 24 inches^2. That its resistance is low may be inferred from the fact that in the worst case of damping (minimum mass) some three minutes time, or more than 1,000 oscillations, are required to reduce the amplitude of oscillation by 1/2.[1] That the resistance is not entirely negligible may also be inferred from Figure 4.2.1 in which variations in oscillation period are plotted as a function of air pressure and weight. One might assume that this increase in resistance results from increasing air viscosity and/or decreased clearances in the bearing at greater weights. Like may other effects, this should be reduced under weightlessness. It also indicates that bearing pressure should be constant. A lack of constant pressure through a make shift arrangement has contributed considerably to the errors in the current system and will be corrected.

The static performance of the zero crossing detector was determined by clamping the interrupter blade in a milling machine that allowed both transverse motion (X) across the light beam and motion along the light beam axis (designated Y) to determine effects of

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[1] Unless otherwise stated, all bearing pressures may be taken as 190 mm Hg and all time interval units as 1 micro-second.

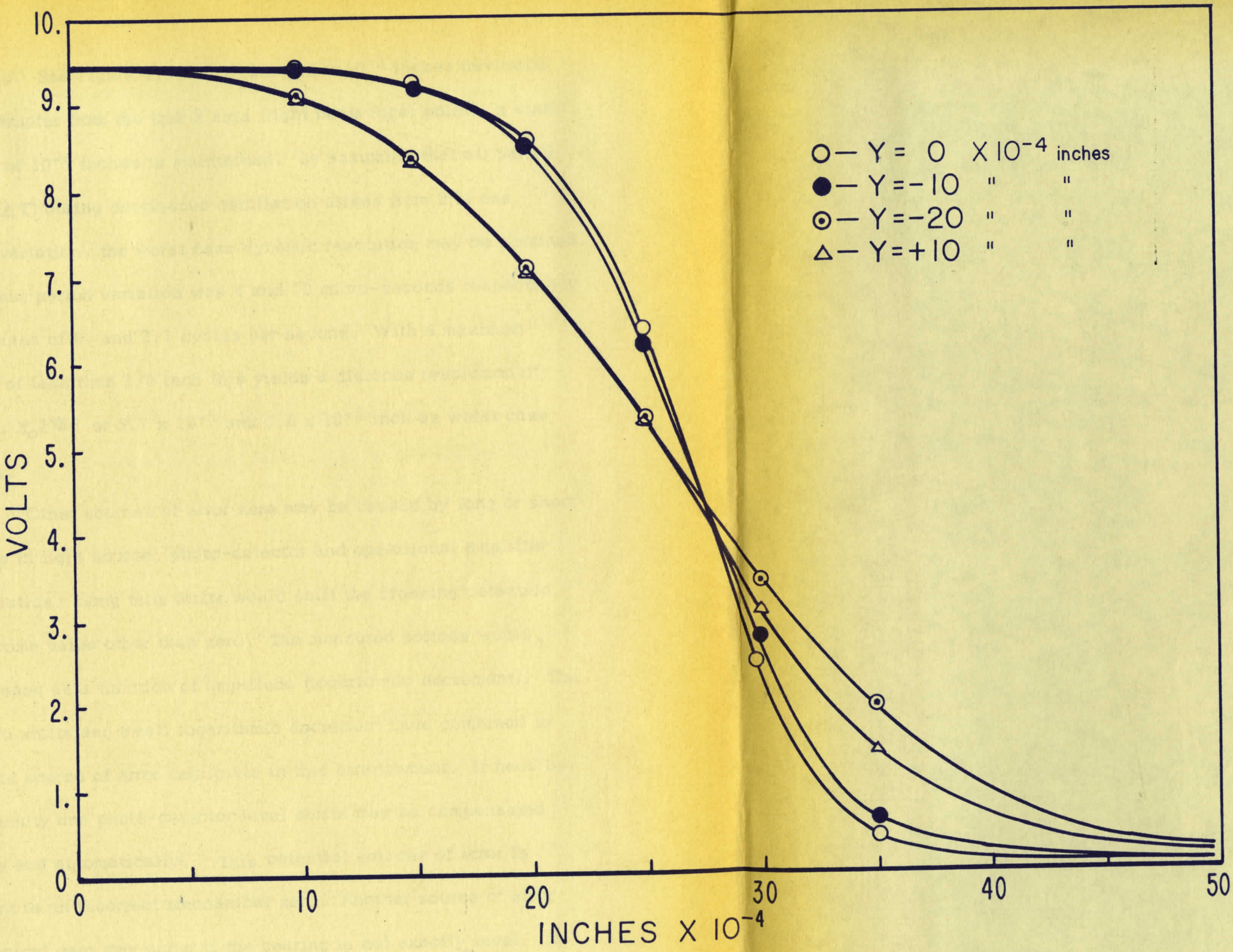


Figure 4.2.2 Output of photo cell amplifier as a function of static transverse (X) and longitudinal (Y) displacements through the light beam.

defocussing. See Figure 4.2.2. Within $\pm$ 2 x 10^{-3} inches deviation of the interrupter from the true X axis (light beam focal point), a static resolution of 10^{-4} inches is maintained. By assuming that all period variation ($\Delta \tau$) during continuous oscillation arises from this one source of variation, the worst case dynamic resolution may be obtained. The maximum period variation was 4 and 10 micro-seconds respectively at frequencies of 6. and 2.1 cycles per second. With a maximum amplitude of less than 3/8 inch this yields a distance resolution of $\Delta X = \Delta T \cdot X_o 2\pi f$ or 5.7 x 10^{-5} and 5.0 x 10^{-5} inch as worst case resolution.

Other sources of error here may be caused by long or short term drifts in light source, photo-detector and operational amplifier characteristics. Long term drifts would shift the crossing detection level to some value other than zero. The measured periods would then decrease as a function of amplitude (logarithmic decrement). The small zero shifts and small logarithmic decrement have combined to render this source of error negligible in this arrangement. If need be, lamp intensity and photo-detector level shifts may be compensated for easily and automatically. This potential ~~sources~~ source of error is equivalent to an incorrect mechanical zero. Another source of error in mechanical zero may occur if the bearing is not exactly level. In this situation, differing weights will each have different static and dynamic zero displacements. The optical arrangement is also subject to electrical and light interference. The former is avoided by routine shielding. Fluorescent lights or other varying high intensity sources will produce a jitter on the photo-detector waveform with zero crossing errors. The detector is also light shielded as a routine precaution.

It is obvious that the light slit must be brought to the exact point of focus in the light interrupter plane to ensure maximum resolution. The edge of the interrupter blade must be exactly parallel to the edge of the light slit image for the same reason. After the initial set-up, the only adjustment made during weeks of operation was setting of the electrical zero crossing level and this was precautionary rather than necessary.

The operational amplifier currently used in the zero crossing detector is a utility unit with a modest slew rate of approximately 1/2 volt/micro-second which results in the rise time of 20 microseconds. The H.P. period timer uses separate start and stop level detectors which in our case have suffered slow drifts. The relatively low rise time of the trigger has resulted in long term timing error. This will be corrected by a faster differential amplifier and/or further shaping prior to actuating the counter as well as closer attention to correct counter function.

Fundamental performance of the oscillating mass/spring system has been arbitrarily divided into three overlapping areas, largely on the basis of somewhat different physical mechanisms which cause a degradation in performance.

Resolution has been defined as the ability to detect small differences in weight over a short period of time, say several minutes, and may be measured by the variation in cycle to cycle periods ($\Delta\tau$) during a single measurement and variation in period during repeated measurement trials. In the latter case it is more meaningful to compare the values of some statistical distribution of several cycles.

Stability is defined as the variation in repeated trials over longer periods of time, say hours to weeks or more.

Linearity - the last attribute, which has had less attention, is the variation of the practical device from its theoretical behavior. If the period is squared and plotted as a function of mass, a line should result: $T^2 = C_1 + C_2M$. Constant C_1 will be present in all real systems and will be a function of the minimum mass of the system while C_2 will be a function of the spring constant. In the application here, where a limited number of devices will be used, the exact shape of this curve is of no great concern for any continuous curve of single direction may be calibrated and used if the criteria of resolution and stability are met. As will be shown, however, the device does behave very much as predicted by theory.

Only cursory investigation was made of the first pendulum. For a short time period prior to delivery of the precision springs, ordinary steel springs were used and their unsuitability for such an application was obvious. Temperature and rate instability were the chief problems. The precision springs had been purchased for use with much greater masses and the resulting oscillation period was too short when used with the weights which could be carried by the bearing. Rather than wait for procurement of suitable springs or for fabrication of a larger bearing, it was elected to obtain data with fixed weights until the larger bearing and/or other springs become available.

With the arrangement shown in Figure 4.1.1, a variation in period of 30 micro-seconds or more was present at all weights. This allowed a weight resolution of better than 1 part per 10^4 at higher weights with signal to noise ratio of 1:1 or better. The stability of the device was on the order of 100 micro-seconds over most of the range of weights. The chief source of these errors was in the lack of mechanical stability and in extraneous oscillations transmitted to the pendulum. A factor graphically illustrated by this "bread board" is the effect of viscous damping, not just in the immediate area of the bearing but in any structure which might be involved in the smallest amount of transmitted vibration. A mechanical resistance at any point of the structure would remove energy. This could be expected but was frequently and strikingly illustrated in unexpected fashion. Any movement of the object being measured was, of course, intolerable as regard to introducing error and if any degree of viscous damping accompanied this motion, the pendulum motion would be rapidly arrested.

The second version of the pendulum (Figures 4.1.2 and 4.1.3) has been in more or less continuous use since October 1965. The data given here must be considered no more than what it is--raw data which is representative of the performance of the device presented in descriptive rather than analytical form.

Thus far, only large quantities of data are ~~only~~ available for resolution studies which still ha~~s~~ve to be statistically analyzed. Some data has been gathered for stability studies but it is far from complete and will not be considered except for one or two general comments. Data ~~is~~ are available for linearity studies, but these have not been completed.

Figure 4.2.3 is a histogram of the variation in period ($\Delta\tau$) during sustained oscillation. The data shown is are representative of many hundreds of runs made over the past two months. The same reasonable care that is taken with any precise scale must be used here. ~~The~~ Weight clamps are necessary to obtain this resolution at the lowest added weight and the weighing area must be free of traffic or vibrations from heavy machinery and the like. One sustained oscillation was recorded at each of five different masses. A mechanical release set for an initial displacement of 3/8 inches was used. Air pressure was 190 mm Hg, set before each oscillation, but this air was obtained from a relatively small tank with large pressure variations, especially over the total time required for recording at the greatest mass. These pressure variations were reflected at the output of the regulator and account for some of the spread at the larger masses.

The counter time base was one micro-second. ~~Weights used were simple spread of the period values at the lower masses.~~ Weights used were simple polished sections of round brass stock calibrated to a stated accuracy of better than .01%. Working at these time resolutions, it is necessary to avoid transmitting external vibration to the pendulum. Even walking in the vicinity of the device in its present installation will cause an appreciable spread in the values. This has implications which will be studied in detail in Phase III.

WEIGHT NUMBER	WEIGHT POUNDS	WEIGHT GRAMS
I	2.0001	907.245
II	2.0043	909.127
III	5.0352	2283.946
IV	9.8373	4462.012
V	20.1428	9136.584

Table 4.1.1 - Calibration of Weights against two standards. Metric calibration was used in all calculations.

A second consideration is how well the period of oscillation will be repeated with the same weight. Without removing the weight or in any way changing the experimental conditions, six successive series of oscillations were recorded for more than 20 cycles. The pendulum was stopped, reset, and released between each run. The deviation and mode of 20 periods were tabulated and are plotted in Figure 4.2.4.

At this point, it may be well to question the use of the mode rather than the mean which was discussed in section 2.4. In the absence of external pertubations and with a perfect zero crossing detector, it may be assumed that the period repeats itself to a much higher degree of accuracy than is being recorded, i.e., there is a single natural mode of oscillation. The effects which have been previously discussed prevent this from occurring, but if these effects are random and not too frequent, i.e., the frequency of the disturbing effects are considerably lower than the frequency of oscillation, then the natural mode of oscillation should appear more frequently than any other. Since errors are randomly distributed, in a small number of samples there may be a considerable sampling assymmetry with significant shifts of the mean. After handling many hundreds of trials, this indeed seems to be the case and the mode rather than mean has been used recently in our work.

The previous use of exactly the same situation for repeated trials demonstrates the ~~present~~ performance of which the present pendulum/ instrumentation system is capable ~~of~~. In practical work, some changes, such as changing of weights, are bound to occur. The effects of simply removing and replacing weights between repeated trials was were next examined in the same fashion and the results plotted in Figure 4.2.5.

The very much greater spread in values may be noted particularly with weights III and V. The larger part of these variations probably arises from shifting of the center of force of the weight on the bearing. The weights were rotated approximately 60° between each trial. Weight III was notably assymmetrical while any variation in the heaviest weight would produce a more pronounced effect. This may be assumed to be a function of the air bearing and will be further investigated.

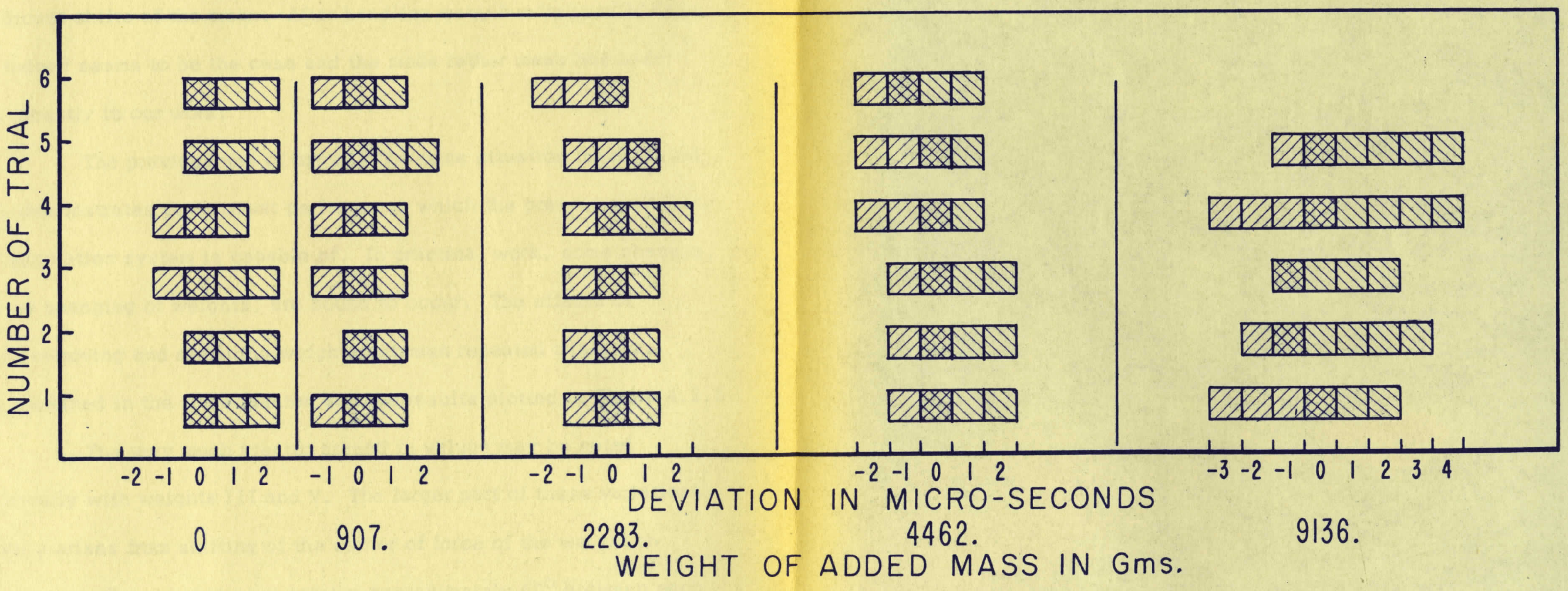


Figure 4.2.4 Variation of period ($\Delta\tau$) during repeated trials without disturbing weights or other conditions between trials. All trials were recorded but one trial was inadverdantly omitted at the maximum weight. The mode of the cycles is identified by cross hatching.

It could be argued that the shorter periods used here render the results questionable since the periods to be used will undoubtably be much longer. A longer period of the same amplitude will decrease the resolution of the zero crossing detector in an inverse ratio. There will be an increase in allowable error as a direct function of the period of oscillation. These effects should then offset each other over a reasonable range of period. The effects of viscous resistance and weight shifts from acceleration will be reduced at lower frequencies. The results here will probably be poorer than those achieved at lower frequencies.

Stability: As noted, the results of this have not been analyzed. In fact, this data will be repeated in its entirety after the pendulum has been housed in a more suitable environment and controlled temperature with a more constant air supply. I will hazard a guess that the long term variation of the mode, exclusive of temperature and other predictable effects has been in the region of 5 micro-seconds for a period of .16 seconds to 20 micro-seconds for a period of .48 seconds. As expected, since no attempts were made to compensate for it, a marked temperature effect is present. Figure 4.2.9 shows this at one period using a small scale thermocouple which could not be read more closely than $1^{O}F$. The source of this temperature effect will be identified and measured more precisely, but is probably the spring, since no temperature tolerance was established for this 'item and 'stock' units were used.

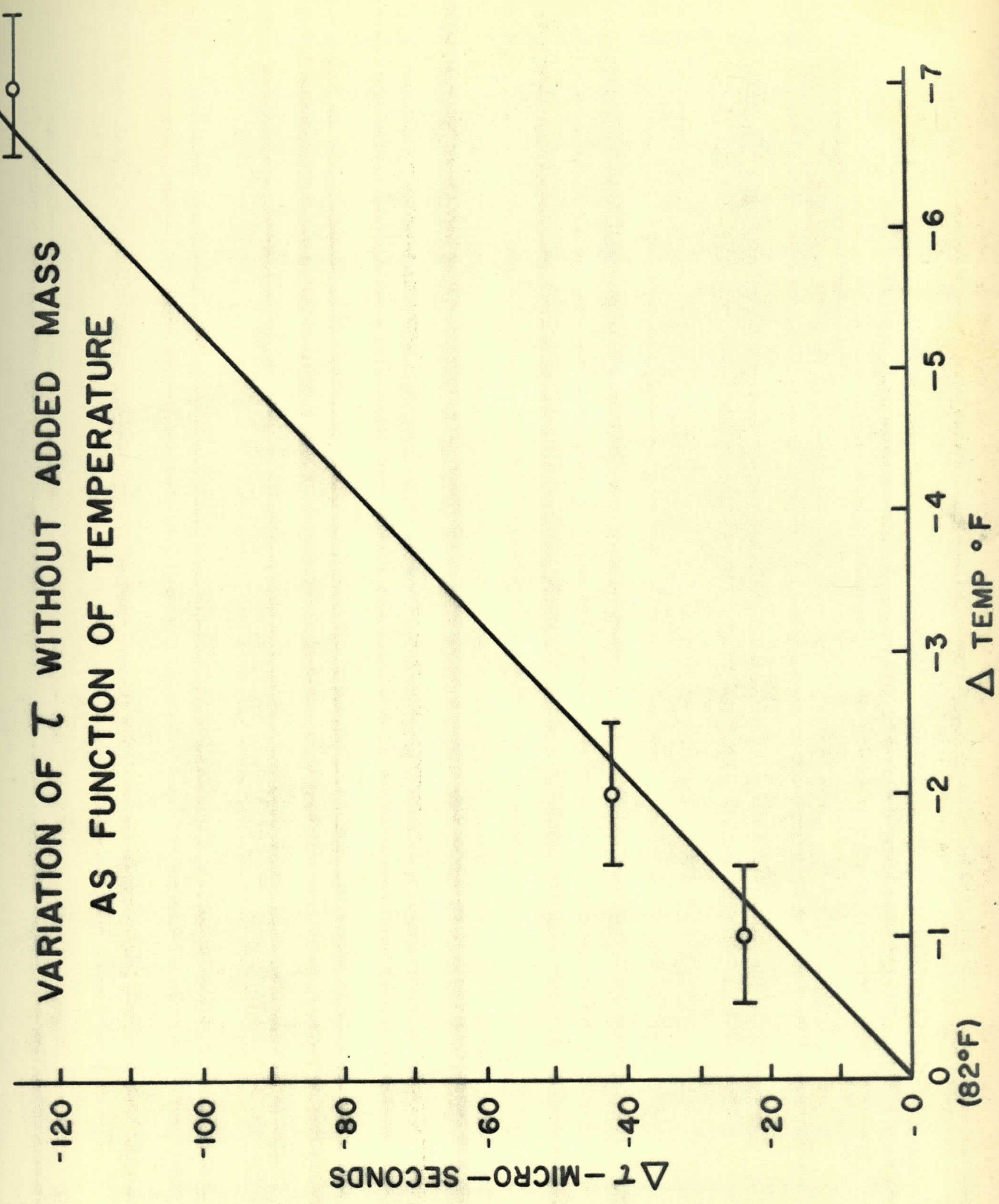


Figure 4.2.9 Variation of period as function of temperature at minimum mass.

It is useless to attempt to graphically demonstrate the "linearity" of the device because of the small deviations. However, Figure 4.2.10, plotted on a 3 x 4 foot graph before reduction, was included to show the good approximation of a straight line. The slope of the mid-portion of the line is constant to four significant figures while there is a decrease of less than 1/2% in the lowest portion. Error limits and measured variation in resolution are shown in Figures 4.2.13, 4.2.14, and 4.2.15.

4.2.1 Phase II

Only cursory examination has been made of the air bearing completed for this portion of the experiment and shown in Figures 4.2.11 and 4.2.12. Its efficiency is reasonably good, for at 10 PSI pressure it will support at least 400 pounds. This weight may be shifted over the bearing, from one extreme edge to another without apparent effect. Its resistance is low for many minutes are required for the amplitude to decrease by one half. Some interesting effects have already been noted when man is placed in oscillation on this device, very low amplitude and at $\sim$ 1 cycle per second, sub-liminal compensatory effects will rapidly damp the oscillation unless the man contracts the major musculature and this is only partially effective. Closing the eyes reduces this effect. It may be that frequency and amplitude will not be dictated primarily by the impedance characteristics of the human body.

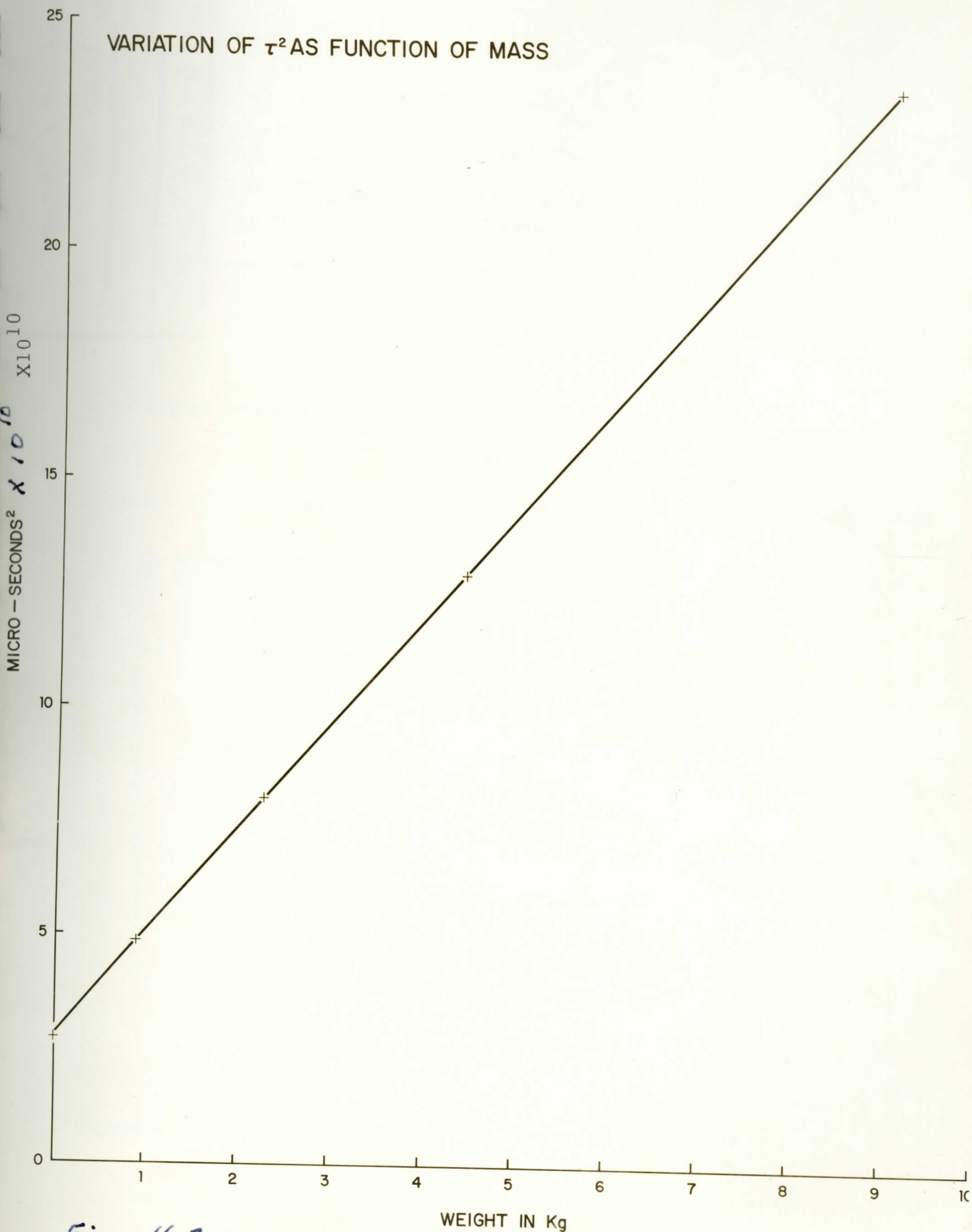
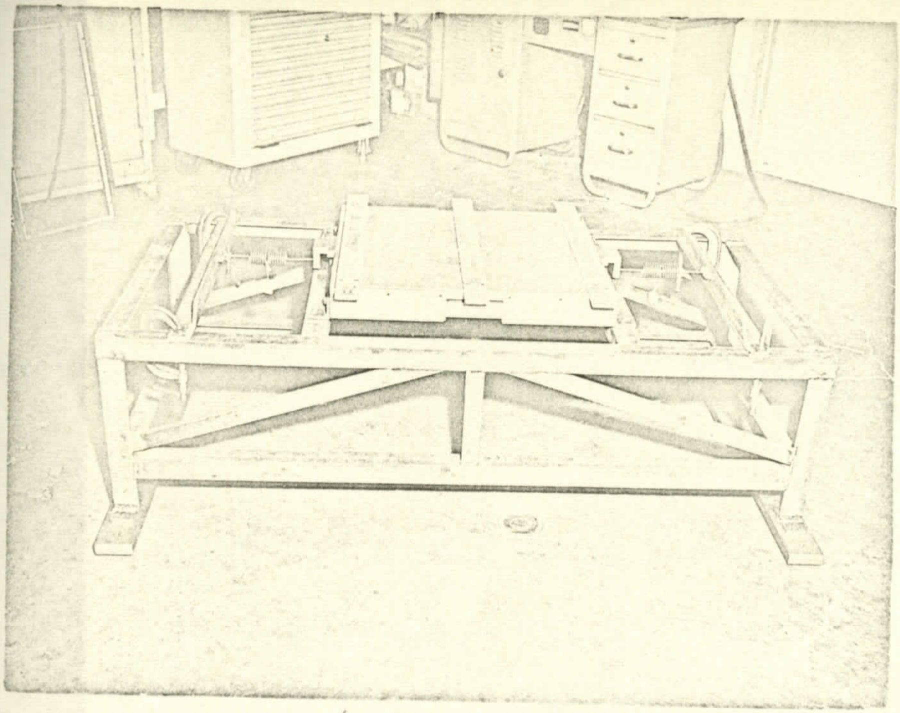


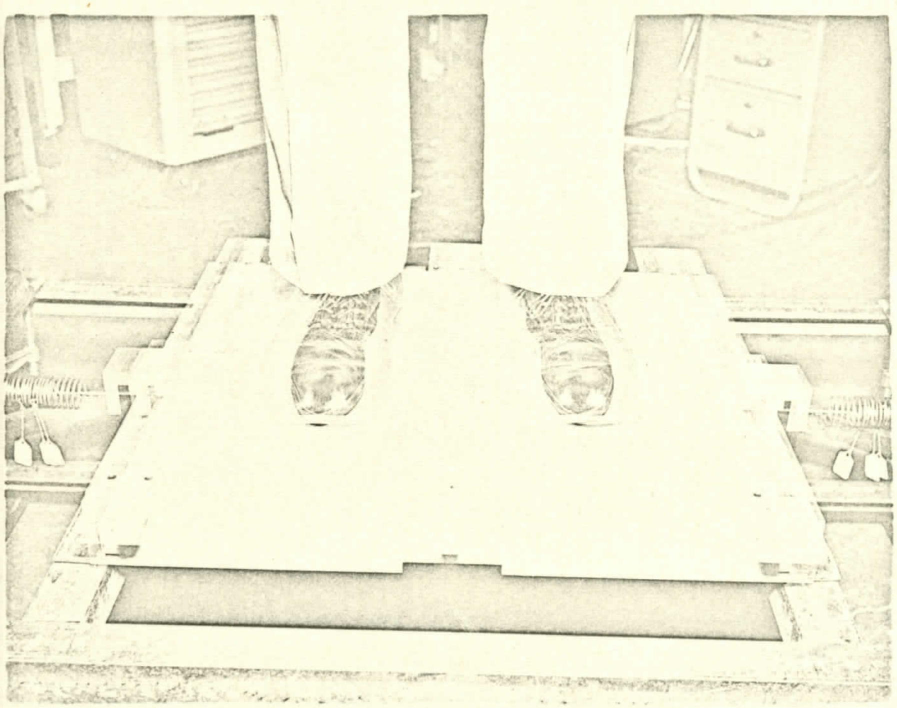
Fig. 4.2.10

Figure 4.2.10



4.3.1 4.2.1

Figure 4.2.11 Partially completed man-carrying version of the pendulum



4.3.2 4.2.2

Figure 4.2.12 Man standing on air bearing in oscillation

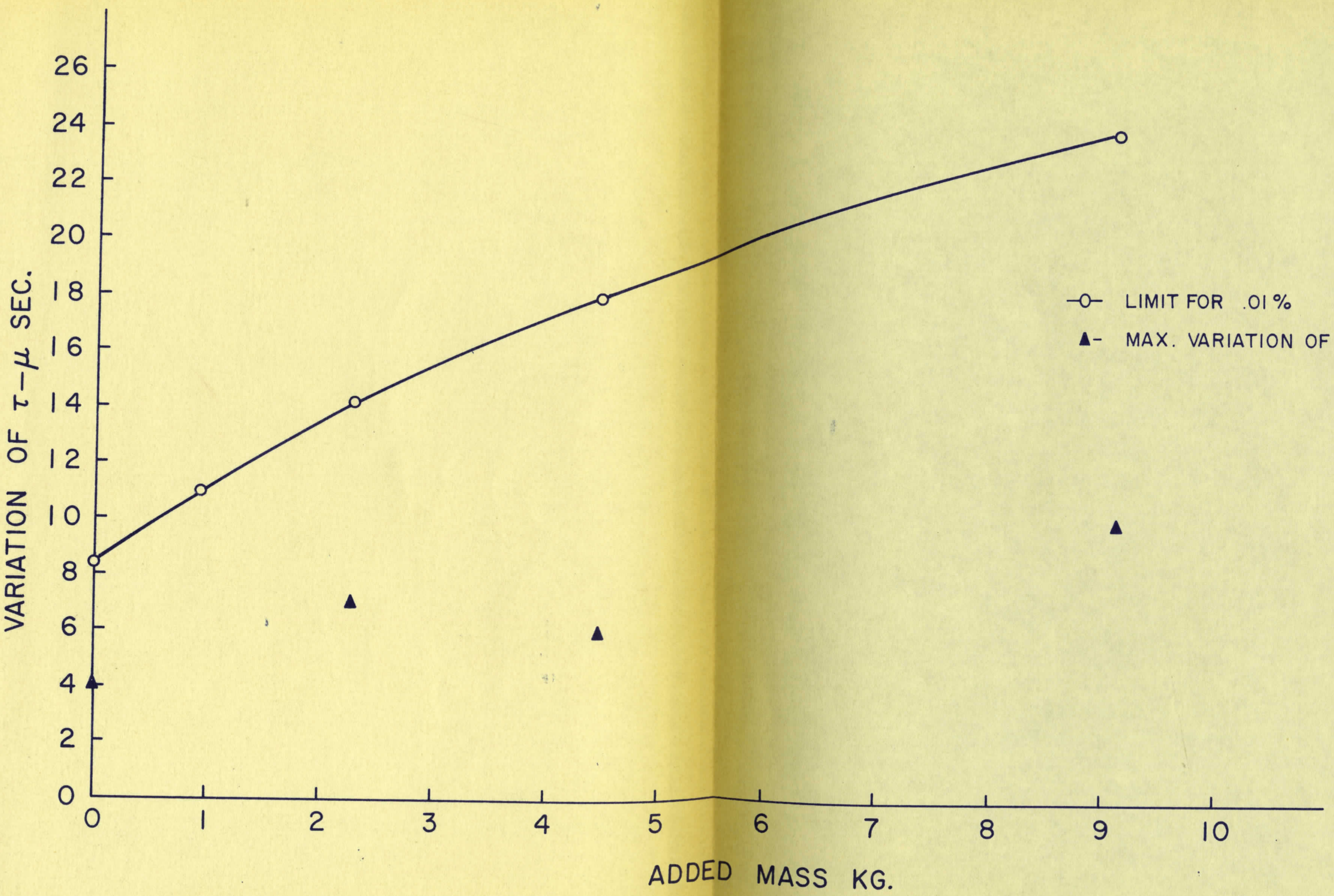


Figure 4.2.13 Variation of period of all cycles of a continued oscillation of greater than 100 cycles at various masses.

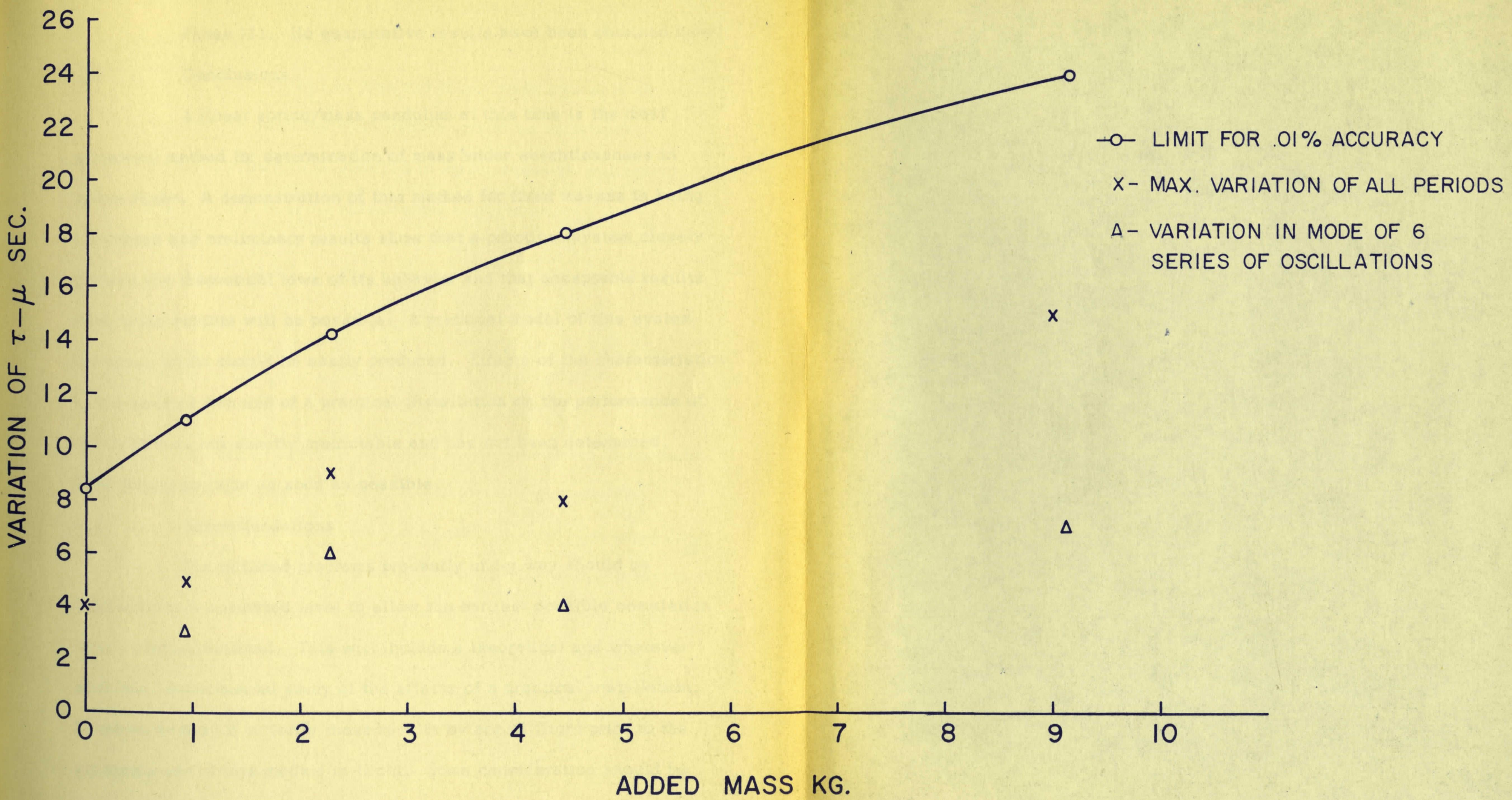


Figure 4.2.15 Variation of all periods and of the mode of 20 measured cycles during 6 trials at various weights with removal and rotation of weights between trials.

4.2.2 Results

Phase III. No quantitative results have been obtained here.

5.0 Conclusions

A linear spring/mass pendulum at this time is the most promising method for determination of mass under weightlessness in space flight. A demonstration of this method for fixed masses is being conducted and preliminary results show that a practical system closely follows the theoretical laws of its behavior and that acceptable results with fixed weights will be possible. A practical model of this system for space flight should be easily produced. Effects of the characteristics of the body of man and of a practical installation on the performance of the system is not exactly predictable and has not been determined. This should be done as soon as possible.

6.0 Recommendations

The outlined programs presently under way should be continued at a supported level to allow the earliest possible completion of the studies outlined. This will include a theoretical and wherever possible, experimental study of the effects of a practical installation. It seems desirable to verify these results by actual flight prior to the projected use of this method in flight. Some consideration should be given to the use of this method in quantitative studies involving masses other than man. As much information as possible about the characteristics of the proposed vehicle which will effect this system's performance (mass, size weight and power limitations, rigidity, vibration levels, viscous damping, etc.) should be determined and made available as soon as possible. All possible coordination should be made with contractors and other personnel involved to insure maximum utilization of results obtained and to avoid unnecessary duplication.

During the oft delayed assembly of this collection of comment and data, a great deal more work, both theoretical and experimental, has been done and as time allows will be reported in some form, hopefully, more polished than the present. All of this work continues to support the contention that masses other than brass weights, including man, may be measured with a high degree of accuracy with this system. We will continue to explore and define this degree of accuracy.

Dwgs. of scales –
Photos " "
Run bearing for effect of pan