The measurement of mass -

Although Mass is one of the 3 fundamental physical quantities its physical value ~~measurement is made~~ is derived from measurements ~~in terms~~ of other quantities that usually relate to motion. In ~~terms of~~ relation to force the general equation for motion of ~~of~~ a mass is

$$F = \sqrt{(MA)^2 + \frac{M^2V^4}{4}}$$

F = Force
M = Mass
A = Acceleration
V = Velocity

~~The almost universal measurement of mass is dependent upon the first term of the equation where the~~

The first term of the equation relates to linear motion while the second ~~term~~ deals c̄ radial motion. The almost universal measurement of mass ~~is depen to~~ in a relatively constant accelerati~~on~~ve field (gravity) such as on earth ~~is depe~~ is described by the first term of the equation

F = M A - The force developed by the mass (or mors commonly the ratio of forces) in the field of acceleration of M/sec/sec. is measured.

In the negation ~~absence~~ of such a field, acceleration or some other quan. must be applied and the resultant effects measured. The quantities of motion ~~quantities affects~~ that must be applied and those that may be ~~&~~ measured can ~~may~~ be determined from ~~by an~~ arrangements of the general equation.

1.1 1st Term: F = M A

	Applied or Known		Desired		Meas.
1.1.1	A	X	M		Force
1.1.2	Force	÷	M		Acceleration

1.2 2nd Term: $F = \frac{1}{2} M V^2$

1.2.1	Velocity	M		Force
1.2.2	Force	M		Velocity

although not immediately apparent, ~~mass~~ by means of this equation and known restoring forces provided by an elastic medium, the mass may be determined as a function of ~~at~~ time of oscillation. These equations will be described later.

The measurement of mass under weightless conditions will become as routine and accurate as it currently is on the earth's surface. The difference at the moment is several thousands of years of experience ~~in an a free force field~~ in a ubiquitous gravity.

The measurement of the mass of man in current space conditions imposes a number of restrictions including ~~non~~

1. non-rigidity of the human body
2. physical limits tolerated by the human body

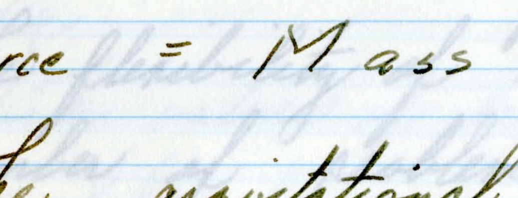
3. Minimum instrumentontion including space, power, time, operational simplicity
4. Relatively high accuracy (approx. .1% or 1 part in 1000)

A considerable amount of theoretical work and a ~~more~~ much smaller amount of experimental work has been done on the problem which will be reviewed as a function of the various possible approaches.

Meas-   Derived   Applied

Force = Mass × Acceleration

The gravitational force (acceleration) developed by nearby ~~objects~~ masses traveling in orbit c̄ man are much too small, irregular and variable to be considered.



$$G = \frac{m_1 m_2}{D^2}$$

* Even if rigorous control of the external body is maintained plus cessation of respiration, the heart ~~to~~ and viscera are in more or less continuous motion although the hearts displacement of mass is cyclic.

$A = \frac{F}{M}$

a wide variety of schemes, some quite practical are possible through application of known or measured forces ~~and~~ in a linear axis c̄ measurement of acceleration or its ~~derivatives~~ integrals, velocity & distance. ~~& time~~

One of the more critical, if not most critical aspects of the measurement will be in the proper application ~~and~~ of forces to the body in a desired reference system and deserves special comment.

The flexibility of the body causes a number of problems. The body seldom maintains a fixed configuration for an appreciable length of time. Even if one makes vigorous attempts to maintain a fixed relationship of the various members of the body, this ~~m~~ can be maintained for only short periods of time. The evidence of this may be seen on the parade ground.*

~~the~~ One practical ~~importance~~ aspect of this is that the measurement should be of short duration. ~~calculation on~~ Other consequences of the flexibility of the body are the requirements that acceleration be kept below a value which causes shifts in their spatial relationship. ~~to each~~ Also any measurement which depends upon establishment or maintenance of a fixed center of mass for more than a short period will be done only c̄ great difficulty.

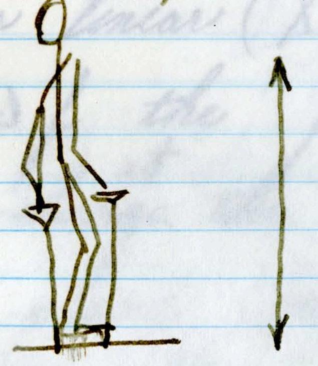
The values of acceleration required to produce shifts of various segments of the body are not readily available. ________

reports on this in terms of frequency of sinusoidal oscillation but unfortunately does not give amplitudes of the test values so that meaningful accelerations cannot be determined.

It would appear then that the

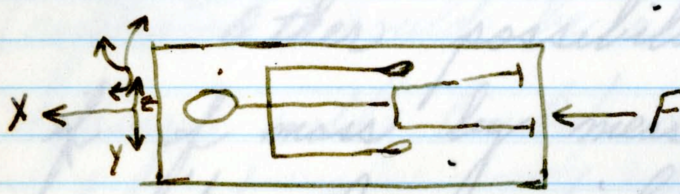
first problem lies in restricting the body motion to the minimum degrees of freedom for the measurement and ~~avoid~~ avoiding rotatory or other measurements that depend upon a known center of mass.

A variety of restraints, couches and the like might be used in an attempt to maintain a fixed center of gravity, however ~~under the restrictions of the measuring condi~~ they would probably have little superiority over use of the large skeletal ~~to~~ muscles working against rigid supports to accomplish the same goal. One such

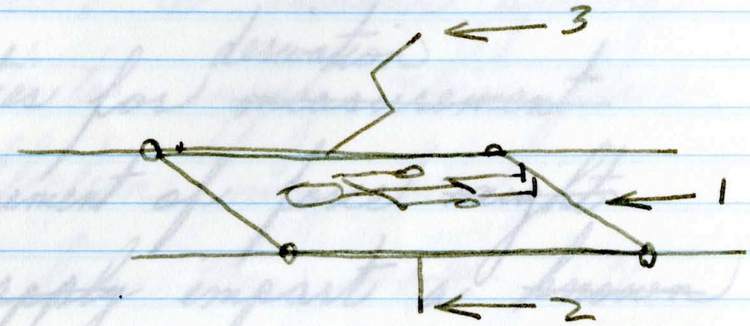


arrangement is shown in which the subject tenses large muscles against ~~hand~~ foot and hand supports. This should provide a high degree of fixation especially in the vertical plane shown here -

A corollary of rigid fixation is application of forces and measurement in such a manner that only the desired directions are achieved - Examples are shown below -



A



B

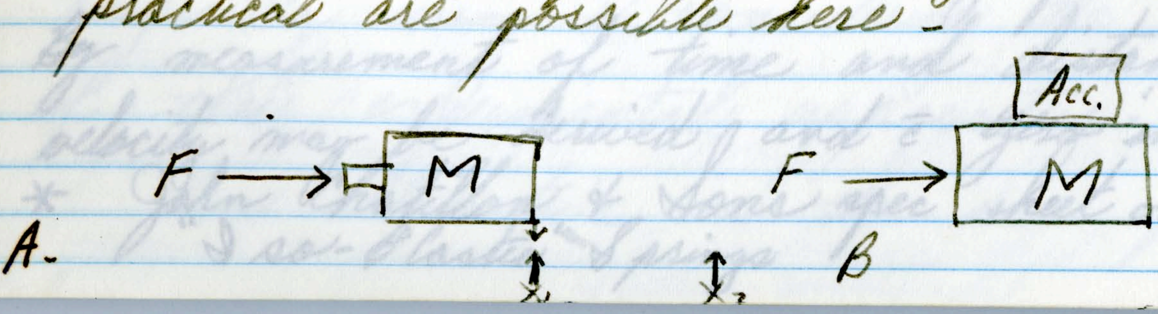
In A the table and subj. are weightless and free to move in 6 axes, three translational or linear (X Y Z) and 3 ~~rotatatory~~ rotational. If the force applied at F is not ~~along~~ at the center of mass in the Y Z plane movement can (and will) occurs in all six of these planes. This situation is obviously intolerable for simple measurement -

In B the table and mass are constrained by four frictionless bearings to move only in the X axis. The force (or X component of force) and measurements may now be applied at any point in the Y, Z plane ~~that~~ is rigidly attached to the ~~table~~ table. The advantages should be obvious.

Other possibilities for derivation ~~measurement~~ of mass by measurement of force ~~might~~ exist. One might ~~apply~~ impart a ~~known~~ ~~or measured~~ velocity to the mass and measure the force~~s~~ to ~~provide~~ required to produce known or measured decelerations.

$$A = \frac{F}{M}$$

A wide variety of ~~practical sch~~ schemes, some ~~many~~ of which might be practical are possible here.



In A the mass is accelerated past two points of known distance X_1 & X_2 by a known or measured force F (~~pf~~ preferably this force would be constant). ~~Prod~~ Production of this standard force would be difficult. Assuming the deflection is small, a linear spring (calibrated) could be used to supply this force. Springs with limited deflection may be designed $\bar{c}$ considerably less than ~~.01%~~ .1% deviation of force as a function of distance with temperature coefficients of $< 10^{-5}$ % / °F and hysteresis error of .05% of deflection*.

The measurement of both distance and time may be may with simple instrumentation (Capacitance or optical pickoffs $\bar{c}$ errors of say ~~[illegible]~~ $1\text{-}2 \times 10^{-4}$ " & counters $\bar{c}$ accuracy of $\pm 1 \times 10^{-6}$ sec) By measurement of time and distance velocity may be derived, and $\bar{c}$ zero initial velocity

* John Chatillon & Sons spec sheet on "Iso-Elastic" Springs

1. Distance $= \frac{1}{2} a t^2$ & $a = \frac{2\,dist}{T^2}$

and from this acceleration & mass. A ~~possibility~~ more accurate arrangement to avoid starting errors (i.e. effects of shift in viscera etc would ~~have~~ measure ~~distance~~ velocity over two ~~spr~~ distances. The first derived velocity would then be used ~~in~~ with the 2° velocity to determine acceleration from $D = V_1 + \frac{1}{2} a t^2$

& $\frac{2(D - V_1)}{t^2} = a$.

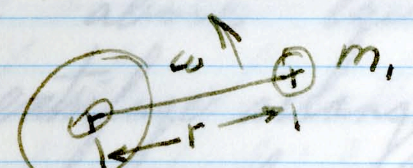
A simpler ~~and~~ variation of this ~~will~~ scheme using an oscillating spring-mass system will be described later. Other ~~or~~ known sources of force include long solenoids & possibly small compressed gas jets. Lockheed A/C investigated this scheme using a spring wound capstan and a wooden trolley. Accuracy was only a few percent which is not surprising ~~using &~~ considering the crudity of ~~this~~ experimental apparatus.

An alternative is the use of

a relatively constant force which is accurately measured by means of a strain gage or other arrangement. Although NBS* states that force meas. of <.1% may be "easily" achieved, a commercial mfg. would not consider a guarantee of <.5%Δ.

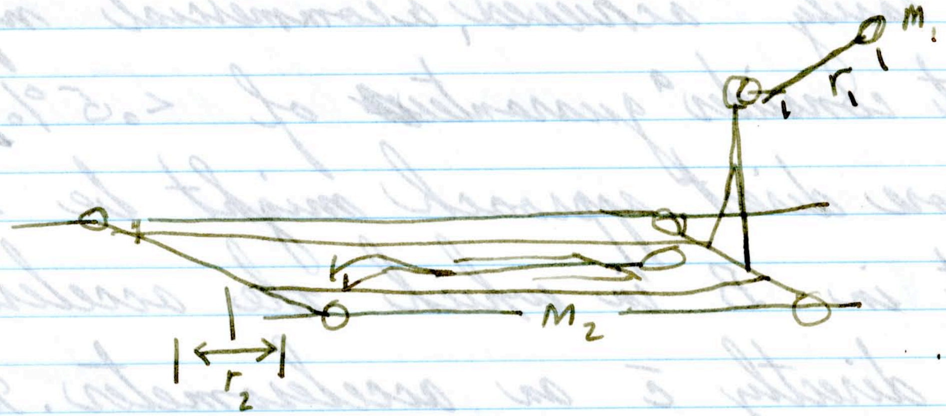
A more direct approach might be the arrangement in B in which the acceleration is meas. directly c̄ an accelerometer. Here again accuracy of the accelerometer is a problem.

One common source of a known sinusoidal force, is the rotating bob wt. If ~~r, ω & m,~~ the radius r & angular rate ω of rotation of the mass m_1 is known



a standard force is provided. Although this could be used diretly an alternative is to ~~provide~~ rigidly attached a ~~a~~ 2° mass free to oscillate along the plane of

* personal communication c̄ metrology dept. NBS
Δ " " c̄ Statham Instruments



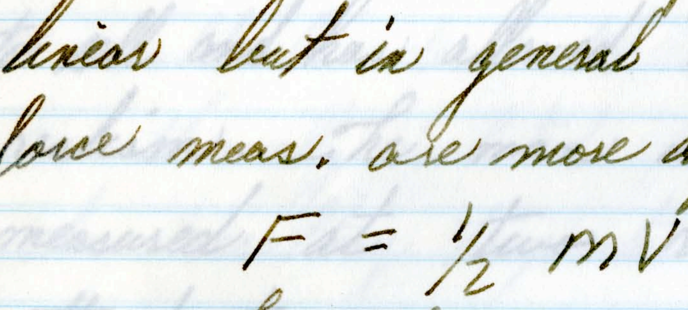
m1
r1
M2
r2

rotation. The amplitude of ~~rotation~~ sinusoidal oscillation of the 2° mass m_2 will then be an inverse ratio of the $m_1 : m_2$ ratio and ~~am~~ radius of rotation r_1 - Accessory equipment and accuracy problems of the amplitude transducer reduce the attractiveness of this scheme.

~~In addition~~ ~~rotational~~ angular motion may ~~us~~ be used in these applications rather than linear but in general angular rate, distance & force meas. are more difficult than linear.

$$F = \tfrac{1}{2} m V^2$$

The above equation leads immediately to a centrifuge arrangement. ~~Although~~ ~~this~~ This seems plausible and may be made work c̄ small fixed weights



Even here the the problems of knowing center of mass and accurately measuring mass ~~ex~~ still apply. The problem of ~~a rotating~~ force measurement is compounded by ~~the~~ by its being in rotation and angular rate must also be known to ~~a high degree of~~ greater than the desired degree of accuracy ~~since~~ since this term is squared.

The use of a centrifuge as a mass measurent of man can be of only academic interest unless one has a centrifuge to sell and has allowed cupidity to overcome realism. The man would have to be measured at two radii of rotation to attempt to overcome the ~~problem of lack~~ lack of knowlege of center of mass. The size and complexity of instrument and intrumentation are enough to veto this application. It is surprising that Douglas achieved the accuracy they did (several %) c̄ this arrangement.

~~At t~~ If one considers other equations for deriving mass in terms of other quantities and gives ~~to~~ free rein to imagination a variety of scheme may be devised that are in the centrifuge class.

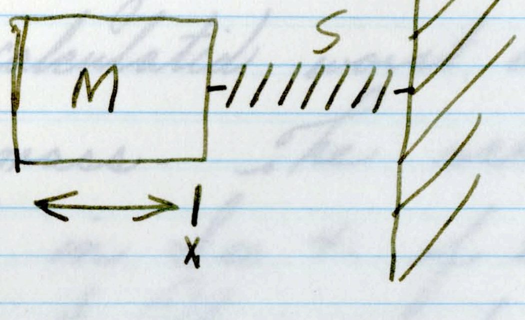
For example ~~to~~ mass has energy associated $\bar{c}$ it: $E = \frac{1}{2} m V^2$

After ~~By~~ giving the mass a known velocity V (or meas. it) ~~the mass m could be~~ it could be decelerated to zero velocity ~~in~~ by a thermally isolated resistive media and the resulting temperature change measured.

A mass ~~con~~ $\bar{c}$ velocity V could be allowed to collide $\bar{c}$ a 2° elastic mass, say through a spring, and the resultant velocity of the 2° mass measured to ~~determine velocity of V~~ derive mass.

One of the more attractive and simple schemes involve determination of frequency or period of the mass in an oscillating spring / mass system.

If the mass m, is attached to a ~~system~~ spring which provides a restoring force as a function of ~~distanc~~ spring length ~~s~~ and the mass is displaced from zero and allowed to move freely it will perform a damped sinusoidal oscillation. ~~Damp~~ The damping, or decrease in oscillation c̄ time is a function of the amount of spring dissipation & air & other resistance. If the resistance is great enough an exponential return to zero will occur. Frequency of the oscillation ~~w~~ is given by



$$F = \frac{1}{2\pi\sqrt{MK - \frac{R^2}{4M^2}}}$$

If as is usually the case R is small the R^2 term may be neglected & ∴

M = Mass
K = spring constant
T = period of time

$$F = \frac{1}{2\pi\sqrt{MK}} \quad \& \quad T = 4\pi^2\sqrt{MK}$$

& $T = K\sqrt{M}$.

One scheme using this arrangement using rotatory motion ~~was~~ has been proposed, c̄ a calculated worst case accuracy of .7% body mass. The scheme is described in detail in Sec 4. of the Equipment Development Plan and elsewhere.

It consists of a vertical torsion bar to provide restoring force to a horiz. rigid beam c̄ contour couch at the end. The device ~~could~~ would be placed in a relatively large oscillation, 2 ft., and the periods measured at two different radii. With knowlege of the period at 2 radii and the spring constant mass may be computed. This device has the disadvantages of size & rather large ~~operating~~ room ion. Resistance & visceral shift effects might be of importance where amplitude is large c̄ ~~large vel~~ relatively large velocities and acceleration.