Mass Measurement in W̄

I. Background

II. Theory
    Inertia
    Radiation

III. Practice
    A. BMMD
    B. F=MA
    C.

IV Future

I. Introduction

Gravimetric mass determination ~~is~~ allows such simple and precise measurement that ~~it is~~ it is the universal method of choice except for a few special situations. ~~One only fully appreciates the~~ The simple elegance of a beam ~~when~~ balance is ~~only~~ appreciated only when one is forced to find an alternative method, as in space flight. This paper is a brief review of the methods, problems, and successful development of methods for mass determination in weightlessness. It is based primarily on experience in the U.S. programs.

Mass measurement is essential to a variety of scientific studies, especially on long missions which may require such measurements for on going work. ~~and~~ Life sciences frequently requires mass measurements from a variety of objects and materials over a range of micrograms to ~~human bodies as large~~ as large as a 100 kg.m. human body, for both investigational and operational purposes.

~~The~~ Spring mass oscillators ~~was~~ were the first successful devices developed in 1965, ~~and fl~~ first flown in 1974 and remain the only devices in current use. ~~in the U.S. program~~. An alternative arrangent of this method was flown by the USSR in ~~Several~~ Development of a replacement ~~is~~ for the U.S. ~~BMMD is~~ (human) body mass measurement is ~~and~~ in work in NASA and possibly ESA.

~~Simple~~ Basic theory - ~~Forces produced by~~ Inertial forces of a mass are indistinguish from gravitational and offer ~~x~~ an alternative measurement method by acceleration or momentum. If densities are known volumetric methods, especially c̄ liquids ~~may~~ might be considered as may radiation absorption ~~absorption~~ methods, however inertial methods are generally simpler.

An almost endless iteration of metodologies are possible and some classification scheme is useful. One first order classification ~~base~~ ~~scheme~~ of inertial methods might be:

I, Linear Acceleration
II, Angular "
III, ~~In~~ Momentum

Various basic arrangements ~~f~~ may be grouped under these headings -

A ~~I~~. Linear Acceleration -

Newtons first law ~~providing~~ is ~~the basis~~ provides ~~for~~ the simplest theoretical method.

$$\text{Force} = \text{Mass} \cdot \text{Acceration and } M = FA^{-1} \quad \text{Eqn. 1}$$

| Fig 1 | ↕ dv 3 sp-

A measurement system then requires;
1. A ~~x~~ constant or known Force
2. Means of measuring acceleration
3. Constraint of the system to translational motion

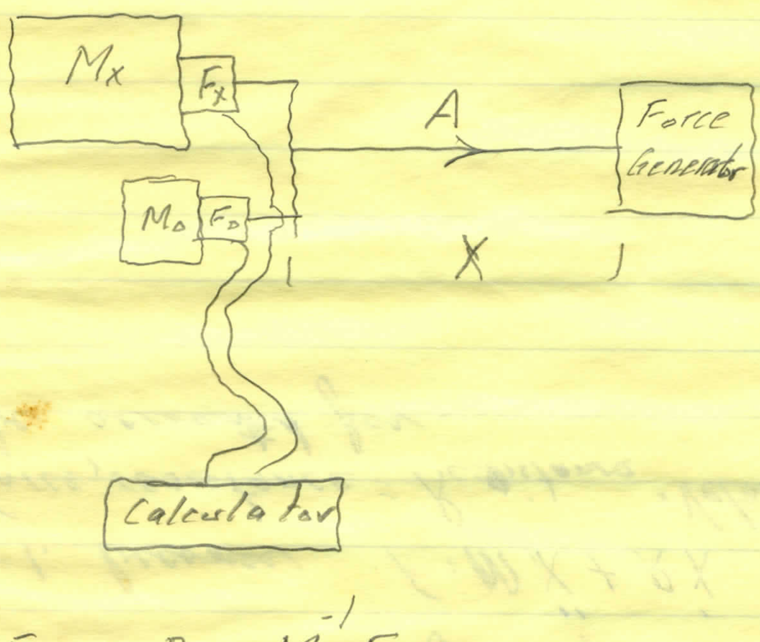
In practice the ~~in~~ need to impart

acceleration and velocity to the object requires both space and a safe means of deceleration.

Advantages are that nonrigid masses including liquids may be measured by allowing the initial acceleration to be an ullage maneuver to seat or settle the mass into a ~~regid stable body~~ single system and ~~using the~~ then making the measurement during continued acceleration. Add 3A from rear of pg.

2. ~~A variant of the above is~~ Comparison of the forces produced by two masses ~~sd~~ subjected to the same acceleration is a variant of the preceding which avoids measurement of acceleration.[1]

Fig 2



F = MA

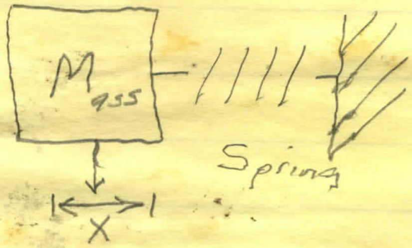
$$\text{Here} \quad M_X^{-1} F_X = A = M_0^{-1} F_0$$

$$\text{and} \quad M_X = F_X F_0 M_0^{-1} \qquad \text{Eqn. 2}$$

1. One can plausibly argue that acceleration is frequently measured from the force produced by acceleration of a known mass i.e. $M_0 F_0$ is an accelerometer. (over)

If friction such as air drag is present
~~the~~ ~~Equation~~ Eqn.-1. becomes $F = M\ddot{X} + R\dot{X}$ Eqn. 1A
wher ~~R~~ Force, resistance = $R_{esistance}$ · Velocity $(\dot{X})$
and must be accounted for.

3. The spring-mass oscillator is another variant of linear acceleration which ~~trans~~ allows measurement of a single variable in ~~the~~ time ~~domain~~, our simplest and most accurate measurement domain.



Mass·Accelration = Force

Displacement (X)·Spring Constant (S) = Force

and $M\ddot{X} = SX$ Eqn. 3

Fig. 2

If the mass is constrained to linear motion (translation), displaced from rest position and allowed to ~~d~~ oscillate it will do so at a ~~fixed~~ characteristic frequency given by solution of Eqn 3:

$$\cancel{f} = \omega = \sqrt{M^{-1}S} \ \& \ f = (2\pi)^{-1}\sqrt{M^{-1}S} \quad \text{Eqn. 4}$$

$\omega = 2\pi$ Frequency & Period (T) = Frequency^{-1} Eqn. 5

such that:

$$f^2 = (2\pi)^{-2} M^{-1} S \quad \text{Eqn. 6}$$

and: $T^2 = (2\pi)^2 M S^{-1}$ Eqn. - 7

with stable springs then mass may be determined from:

K = constant $M = KT^2$ Eqn - 8

and the constant K may be determined by ~~place~~ calibration of the system may be accomplished by measuring the period of the system $\bar{c}$ a known mass M_o as in Fig. 3

In practice there are ~~two~~ other effects which ~~affect~~ modify this response.

If any friction or other damping, such as air drag, is present the Eqn. 3 becomes

$M\ddot{X} + R\dot{X} - SX = 0$, where and the solution for oscillation frequency and period become:

$$f^2 (2\pi)^2 = \left(M^{-1}K - \frac{R^2}{4M^2}\right) \quad \& \quad T^2 = \left[4\pi^2\left(KM^{-1} - \frac{R^2}{4M^2}\right)\right]^{-1}$$

~~for~~ For signicant values of R there is deviation from the 'natural' or undamped period as in Fig 3.

<u>Nature of masses to be measured</u>: depending upon accuracy desired, in addition to resistance, a number of other characteristics of the unknown ~~may~~ mass may affect its measurement including:

a. non rigidity which can produce deformation and change in ~~a~~ shape and center of mass, or in the case of an oscillating system may oscillate in resonant modes of its own.

~~An~~ extreme examples of ~~shape change can see~~ these are mixed gas + liquids in W where liquid drops may separate + float and also where gas bubbles (Fig. 4) in a (Pix?) closed container

~~allow~~ produce an oscillating system. In living systems ~~forces~~ there are many resonant systems, e.g. thoracoabdominal viscera, and many force producing systems, e.g. heart and lungs which can produce regular or random forces into the ~~sys~~ measurement equations and systems. Fig 5

Fig. 4 a. water drops in W̄
b. air " " "

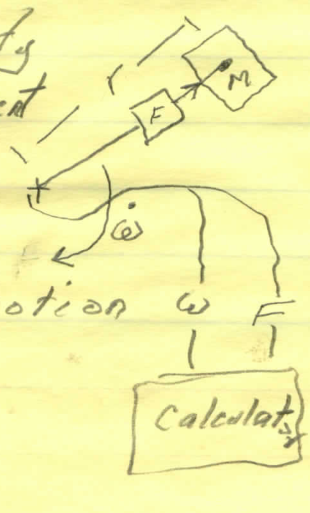
Fig. 5 a. Human Mechanical Analogy
b. " BCG –

The most simple & direct approach is to minimize these effects where possible.

II. Rotating inertial systems:

Centrifugal forces ~~immediately~~ may be employed as in Fig 6.

ω = angular velocity
F = Force Measurement
M = Unknown mass
r = radius of motion



$$F = \frac{\frac{1}{2} m V^2}{r}$$

$$= \frac{\frac{1}{2} m (r \cdot \omega)^2}{r}$$

$$= \frac{1}{2} m r \omega^2$$

~~A major problem~~ This is a simple system ~~so long as~~ for ω and F are reasonably easy to measure however the center of mass

CM must be accurately known or else variations in the CM, Δr, must be neglegible c̄ respect to the radius, r. Such a system might be of particular value of measuring liquids of known density ~~in~~ for an ullage is performed by the centrifugal force and ~~at the~~ if ~~same time~~, a regular known ~~volume~~ container is used variations in depth could be accounted for. ~~Then~~

~~An alternative is to use a centrifuge c̄~~

Practice: developing non-gravimetric mass

Difficulties in a practical measurement systems ~~vary~~ vary as an ~~inverse~~ exponential of required accuracy and also depend upon the mechanical nature of the object. It is relatively simple to reach accuracies of ±1% c̄ a variety of systems however reaching ±.05% for human mass required a year's major effort and a relatively complex device. While the linear spring mass ~~& pendular~~ oscillators are the only devices in use today the following is a brief resumé of known work to date including results and a comment & on promising candidate methods.

Linear acceleration.

There are three major problems areas here;

1. constraint to linear motion 2. provision of known or ~~cons~~ stable acceleration force and 3. measurement of

M M W̄

acceleration. ~~We were unable to find accel~~ &

Other problems include:

4. ~~volume~~ space required for acceleration
5. acceleration level and resulting velocity
6. non ~~rigidity of~~ rigid masses
7. ~~masses c̄~~ force generation by masses
8. air resistance

~~Constraint to linear~~

A simplified practical arrangement is shown in Fig. 7

A pulley P ~~is~~ has a torque applied by a precision coil spring S which will apply a force F to a flexible cable C producing acceleration, Ẍ. The mass shown is ~~x~~ non rigid and for an initial period over the distance X_o will has transients. Over the incremental travel distances ΔX will be measured and by a scale Sc + optical detector. The computer Co will then derive velocities ~~of the~~ over the increments ΔX and with known force analytically fit an ~~curve~~ acceleration curve from which ~~x~~ Ẍ and then mass will be derived.

Reducing this to a system which ~~will~~ can

To measure human mass to ±0.1 lbs over the range of 100 to 225 lbs, requires careful attention to many details.

1. Constraint to linear motion

If the center of mass, CM, ~~shuf~~ acquires linear or angular movement ~~rotation~~ in directions other X, ~~either linear~~ this will a. alter the ~~center of~~ CM position and b. alter the basic force relations. An unanswered question is whether the force can be applied through the CM and mechanical constraints avoided in W.

DTD Provision of frictionless mechanical constraints for a distance of 2 feet or more is ~~a s~~ not simple ~~& to move~~ for tolerances of a few thousandths of an inch will be required; ~~and c physical contact to prevent friction forces~~. At the same time appreciable physical forces must be supported. Magnetic or air bearings seem to be the required here.

2. Measurement of linear acceleration to the accuracies required could not be achieved by practical available accelerometers but ~~and the curve fitting scheme~~ a series of velocity + derived accelerations over ~~the~~ a number of distance increments can provide the requisite accuracy.

3. Generation of known linear forces to the required resolution and repeatability is also difficult. While a number of methods are ~~po~~ possible including servo controlled motors, a precision spring ~~has~~ c a pulley and cable has many advantages. Mechanical tolerances are not a problem but the spring characteristics must be carefully

$\cancel{\frac{2\pi}{T}}$ $\omega = 2\pi f$

$\omega^2 = \frac{K}{M}$

$f = \frac{\omega}{2\pi}$

$T = \frac{1}{f}$ $T = \frac{1}{f}$

$f = \frac{1}{T}$

$\frac{1}{T} = \frac{\omega}{2\pi}$

$T = \frac{1}{\frac{\omega}{2\pi}}$ 1 2

$T = \frac{1}{\frac{2}{2\pi}}$ $\frac{1}{\pi}$

$T = \frac{2\pi}{2} = \pi$

controlled. Such an arrangement will produce a variable force c̄ displacement, and this variation must be known and accounted for in computations.

4.&5. There are complex tradeoffs between safety and operational limitations on a space craft and measurement system requirements. ~~Generally~~ interior space is at a premimum such that the minimum acceleration distance possible is ~~desirable~~ mandatory ~~and~~ ≡ this also results in minimum velocities for the test masses including humans.

6. Non rigid masses may shift their C.M. or even oscillate under acceleration. This is a special problem c̄ the human body. ~~However~~ ≡ application of a continued relatively constant force will tend to produce a stable condition, however time must be allowed for this to happen. Under these circumstances the first part of this measurement cycle for non-rigid masses may be considered an ullage maneuver while the actual measurement occurs during the latter part.

7. Living organisms, especially the higher animals, all produce ~~under~~ various internal forces c̄ both internal and external mass displacements which can result in unknown disturbing forces and errors in measurements here. In the human body they include external body movement, respiratory and cardiac forces (ballisto cardiogram). The first two may be voluntarily controlled by the subject but the latter is unavoidable and has sufficient force to significantly

affect measurements - BCG forces are directional (Fig-8 BCG tracing) and ~~by~~ may be minimized by orientation of the body ie. the prone posture shown in Fig— may not be optimum. External effect of this force is zero over one or more complete cardiac cycles ~~#~~ and ~~if~~ the mass measurement ~~is~~ may be restricted to such periods ~~a in comp~~ by timing from the EKG signal.

8. Wind or other resistance effects ~~may be redu with disturb~~ is not covered by the basic equations of motion. If velocity is low it may be neglected, however large frontal areas may make correction neccessary.

Results -

A program ~~was~~ using this principle was started at JSC in Sept. 1993 ~~and~~ to provide a practical MMD for use ~~on~~ in Shuttle Operations and research.[1] ~~The A supporting contractor was let to~~ Ground work to date ~~has~~ includes demonstration and feasibility of the basic concept.

[1] The supporting contractor ~~was~~ is Lockheed Missile and Space Co and project engineer is ~~Dr~~ Damon Smith, Phd.

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Spring mass oscillators were the first successful devices developed in 1965, first flown in 1974 and remain the only devices in current use. An alternative arrangement of this method was flown by the USSR in . Development of a replacement for the U.S. (human) body mass measurement is in work in NASA and possibily ESA.

Basic Theory:

Inertial forces of a mass are indistinguish able from gravitational and offer an alternative measurment method by accleration or momentum. If densities are known volumetric methods, especially with liquid might be considered as may radiation absorption methods, however inertial methods are generally simplier. and will be treated here

An almost endless ineration of metodologies are possible and some classifcation scheme is useful. A first order classification of inertial methods might be:

I. Linear Acceleration
II. Angular Acceleration
III. Momentum

Various basic arrangements may be grouped under these headings.

A. I. linear Acceleration.

A. F=MA system

Newtons first law provides the simplest theoretical method.

Force = Mass Acceration and M= FA-1 Egn. 1

(Fig. 1)

A measurement system then requires:

1. A constant or known force
2. Means of measuring acceleration
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In practice the need to impart acceleration and velocity to the object requires both space and safe means od deceleration.

Advantages are that nonrigid masses including liquids may be measured by allowing the initial acceleration to be an ullage manuever to seat or settle the mass into a single system and then making the measurment during continued acceleration.

Comparison of the forces produced by two masses subjected to the same accelration is a variant of the preceding which avoids measurment of accleration.

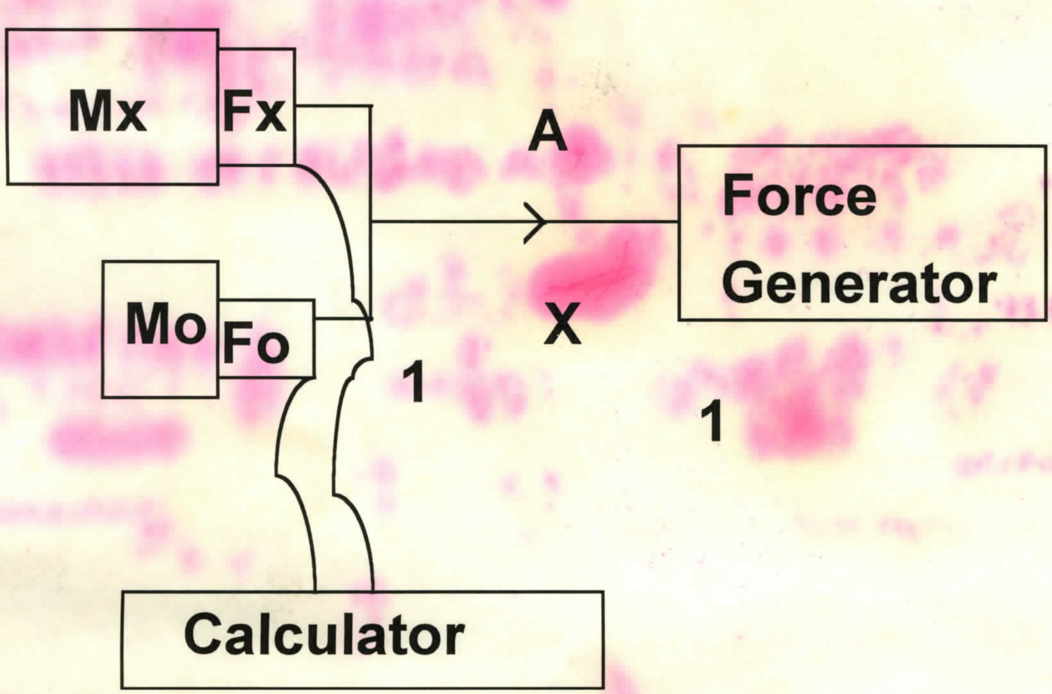


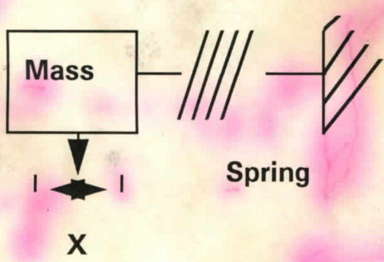
Fig 2.

Here MxFx = A= MoFo

and MX = Fx Fo Mo Eqn. 2

1. one can plausibly argue that acceleration is frequently measured from/the force produced by acceleration of a known mass i.e. MoFo is an accelerometer. If friction such as air drag is present Eqn. 1 becomes F=MX+RX Eqn. 1A where force, resistance = Resistance Velocity (X) and must be accounted for.

3. The spring-mass oscillator is another variant of linear acceleration which allows measurement of a single variable in time our simplest and most accurate measurement domain.



Mass Acceleration = Force
Displacement (X) Spring
Constant (S) = Force
and Mx = Sx Eqn. 3

Fig. 2

If the mass is constrained to linear motion (translation), displaced from rest position and allowed to oscillate it will do so at a characteristic frequency given by solution of Eqn 3:

W =

Eqn. 4

with stable springs then mass may be determined from:

K = constant M = KT2 Eqn. 8

and the constant K may be determined by calibration of the sytem may be accomplished by measuring the perio dof the system with a known mass Mo as in Fig. 3.

In practice there are other affects which modify this response.

If any friction or other damping, such as air drag, is present Eqn. 3 becomes where

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Fig. 4 a. water drops in weightlessness
b. air drops in weightlessness

Fig. 5 a. Human Machanical Analogy
b. Human BCG

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