SOUTHWEST RESEARCH INSTITUTE

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Aerospace Medical Division (AFSC)
Attn: AMRV
Brooks AFB, Texas 78235

Subject: Contract AF 41(609)-2715
SwRI Project 16-1872-01

Gentlemen:

This letter constitutes the final report on the subject project, the purpose of which was to investigate the properties of two existing pendulum mass measuring devices.

1. The smaller of the two pendulums investigated consists of an air-bearing supported weighing pan suspended so that it can be oscillated by a pair of helical springs, one on each end of the pan. An optical system at one end of the weighing pan consists of a light source and a photo-electric cell arranged so that at the zero-crossing (or equilibrium) point of each cycle of oscillation the light beam is cut off by the edge of a razor blade. An electronic timing system then reads out and records the time interval between zero-crossing points in a cycle, that is, the period of oscillation.

In operation, mass to be measured is firmly attached to the weighing pan, the pan and mass are displaced from the neutral position a fixed distance, and temporarily held there by a sear device. The sear device is activated manually to release the pan and mass, and the system oscillates in free vibration. A record is made of a series of periods, and from these the mann can be calculated from the formula:

$$T = 2\pi\sqrt{\frac{M}{K}}$$

where

T = length of period (seconds)

M = mass $\left(\frac{\text{pounds} \cdot \text{seconds}^2}{\text{inches}}\right)$

K = spring constant (pounds/inch)

During the tests made with this pendulum, the following conditions were held:

a. Precision isoelastic helical springs, each with a spring rate of 5 lbs/inch were used to oscillate the masses.

b. The length of each spring when extended, with the weighing pan in the zero-crossing position, was 2.08".

c. The sear was set so that the initial displacement of the weighing pan before oscillation was 0.38".

d. The base of the air-bearing was leveled by disconnecting the springs from the weighing pan, turning on the air, and allowing the weighing pan to float. When the weighing pan did not drift toward one end or the other, the system was considered level. This proved to be a more accurate method than using a precision level on the air-bearing surface.

e. Air-bearing pressure was 190 mm Hg.

f. Ambient temperature was recorded twice daily.

g. All equipment was allowed to warm up one-half hour each day before testing.

h. An enclosing light shield was placed over the pendulum during test runs to prevent stray light from affecting the optical system.

i. Walking around or other possible sources of vibration in the pendulum laboratory were not allowed during a test run.

j. A set of six brass cylinders of various sizes were used for the test masses. Together with the unloaded weighing pan, this made seven different test masses that were measured. The brass cylinders were kept clean and were handled only with rubber gloves.

k. Records of test runs were numbered consecutively and dated. In addition, daily entries of pertinent information were made in a notebook.

2. Initial fixed-mass tests on the small pendulum had been essentially completed before the project was initiated. The remaining test involving fixed (solid) masses was a stability test to determine how repeatable the system would be over a period of several days.

To accomplish the stability test, each of the seven masses was oscillated consecutively twice a day. Records of approximately 150 consecutive periods for each mass were made. Twenty such test series were run making a total of 140 records.

Familiarization with equipment and instrumentation, calibration and installation of an air regulator were accomplished before the stability test began. Some delay was experienced because of erratic operation of the digital printout equipment during the early part of the test, but this was corrected for later tests.

Only minimum data reduction was done during the stability test. A twice-daily average of ten consecutive periods for each mass was calculated and plotted in order to detect any major deviations. The only significant deviation noted was a reduction of the period of oscillation for all seven masses during one morning's run when the ambient temperature was about 5 °C below normal.

The data from the stability test was turned over to the Biometrics group at SAM for analysis. At their request, an additional series of eight test runs of approximately 80 successive periods for each of the seven masses was run during one afternoon. This was a control to test the effect of temperature on period of oscillation, because the temperature change during one afternoon was relatively small. This data was turned over directly to Biometrics with no data reduction being done by the observer.

On the basis of direct observation and the minimum data reduction carried out concurrently with testing, the stability of the small pendulum appears to be very good. Total variation in the average period was not more than ±2 or 3 microseconds for the smaller masses, up to ±4 or 5 microseconds for the larger masses, except for the one morning when the ambient temperature was lower than normal. Actual periods of oscillation for the masses tested were from about 0.2 second to about 0.5 second.

A modified weighing pan for use in measuring the masses of liquids and some solids was designed, but fabrication was not completed in time to make tests with it. This weighing pan is basically a hollow box with a removable glass lid. The mass to be measured (such as a liquid-filled plastic bag) is to be placed in the weighing pan, with an inflatable bladder beneath it. The glass lid will be put on, and the bladder inflated to press the mass upwards against the glass and to hold it as much as possible in a fixed position. If sloshing is evident with this system, the bladder is to be replaced with fabric straps for holding the mass.

3. The second pendulum is similar in design to the small pendulum but is much larger. It uses an air-bearing, helical springs, and the same optical and electronic systems as the small pendulum.

This pendulum was leveled using the same methods as those for the small pendulum. Precision 10 lb/in. isoelastic springs were installed on it, and the optical system was adjusted and calibrated.

Preliminary test runs were made with fixed masses of from 60 lbs to 250 lbs and the period for each mass remained essentially constant, showing a resolution of about 10 microseconds in the period of oscillation, and a repeatability of about 5 microseconds based on averages of ten consecutive periods taken from successive test runs. These figures are not final because a detailed analysis of this data has not been made. It was noted that a variation in period of as much as 200 microseconds (normal period of about one second) could result from moving the fixed masses off the center of the weighing pan by approximately 9 inches. This factor should be considered in making mass measurements of the human body, but it is unlikely that the mass center would be off more than about 2 inches. In a later test series one of the subjects got off the weighing pan and back on between successive tests and the length of the period did not vary appreciably. Also, the fixed test masses were removed and put back on the weighing pan in approximately the same position, as judged by visual observation. These tests again did not show significant differences in the period of oscillation.

Another series of tests on the large pendulum was made with a fixed mass and a mechanical harmonic oscillator attached to the weighing pan. The harmonic oscillator consisted of a DC motor with an unbalanced mass attached to the motor shaft. The pendulum was allowed to oscillate while the harmonic oscillator was run at several different speeds. This had the effect of superimposing one oscillating system upon another. Data gathered on these tests were the usual record of successive period lengths, accompanied by a matching record made on a Sanborn strip chart recorder. Signals fed into the Sanborn recorder consisted of: (1) the zero-crossing signal from the pendulum, and (2) a signal generated by a contact on the mechanical oscillator which was activated once each revolution. The record then appeared as a series of square waves corresponding in length to the period of oscillation of the pendulum with small pips appearing as distortions of the square wave. The distance between the pips indicates the time interval for one revolution of the mechanical oscillator. Data from this test series will be analyzed by others.

A third test series was run to measure the effect of viscous damping on amplitude of oscillation. The weighing pan was loaded with a fixed mass and an aluminum paddle was attached to one end of the weighing pan. A can containing 2" of motor oil was set on the base of the pendulum so that the paddle would move through the oil. A second light source, photo-electric cell, and blade were set up on the pendulum. This is similar to the zero-crossing detector used to measure the period of oscillation, except that in this case as the amplitude of the pendulum decreases, the strip chart record shows the amplitude as a decreasing function of the height of successive recorded pulses. The data for these tests will be analyzed by others also.

The final series of tests on the large pendulum was concerned with measuring the mass of man. A flat lightweight platform was attached to the weighing pan, and the subjects lay on this platform during mass measurement tests. Fixed masses equal to each man's weight were put on the platform in equivalent tests to check the relative accuracy of measurement.

Tests were made with the subjects (1) relaxed and breathing regularly, (2) relaxed but holding their breath, (3) tensing their muscles and holding their breath, (4) gripping the edge of the platform, tensing muscles and holding breath, and (5) holding the feet against a footrest, gripping platform, tensing muscles, and holding breath. Periods of oscillation of the man and periods of oscillation of the equivalent fixed mass became more nearly equal as the tests progressed from (1) through (5). For example, the relative error in test (1) above was as high as 5%. Tests (2), (3), and (4) all showed improvements and in test (5), the relative error for three subjects averaged about 1-1/2%.

All of the above tests were made with precision 10 lb/inch springs and the resulting period of oscillation with a subject on the platform was about one second. The 10 lb/in. springs were replaced by 5 lb/in. springs with a resulting period of about 1-1/2 seconds. This increase in period (decrease in frequency) immediately improved the accuracy to around 3/4 of 1% error, with all other conditions remaining the same.

Additional springs having lower spring rates had been ordered, but were not received by the end of the contract period. Accessories for the platform to provide for restraining the subject are now being fabricated and it is felt that with more restraint the accuracy of measurement will increase. A concept for a contoured honeycomb couch with restraining tie-downs to fit the large pendulum has been developed and can be fabricated at any time. It is felt that more tests should be run on the existing platform using temporary restraints at various points on the body before final details on the contoured couch are formulated.

4. Conclusions and recommendations at this time are:

a. The small pendulum is capable of accurate measurement of fixed masses and its stability over a period of time is good. It appears to be rather temperature-sensitive, but the final decision on this cannot be made until the data are reduced and analyzed.

b. Testing the small pendulum with liquid and semisolid masses should be carried out.

c. The accuracy of measurement of man's mass can be improved by lowering the frequency of oscillation and by restraining the man as much as possible. Further experimental work is needed to determine what accuracy can be obtained.

d. The air supply to the air bearings needs to be clean and dry. Deposits of oil from the air onto the bearing surfaces result in system damping.

5. Attachments A and B are comments on two papers pertaining to this method of mass measurements. These papers were furnished by the Sponsor for evaluation.

Yours very truly,

Douglas N. Travers

Douglas N. Travers, Director
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ATTACHMENT "A"

COMMENTS ON PAPER BY DR. THORNTON ENTITLED "DESCRIPTION OF A PLANNED DEMONSTRATED OF MASS DETERMINATION BY AN OSCILLATING MASS/ SPRING SYSTEM"

1. The theory presented, the conclusions drawn, and the design concepts and details evolved appear to be sound.

2. Some refinements in the theoretical approach might be considered, although these are not felt to be critical since it is the variation of certain quantities that will affect the results rather than absolute magnitudes (within limits, of course). That is, it is presumed that initial calibrations can be performed under sufficiently representative conditions such as to account for gross effects.

3. One refinement concerns the calculations of air drag. For low velocities and where the displacement amplitude is small compared to the dimensions of the body, the drag coefficient in the expression $1/2 \rho V^2 C_d S$ can be as high as 10 to 12 or so. See references (1) and (2).

4. Second, the linear theoretical treatment is of necessity based on the premise that the resistance force, R, is constant, independent of velocity or amplitude. For cases where the effective damping ratio is less than 0.2 or so, it is valid to assume that the system is linear though R is not independent of velocity. But it is then necessary to develop an expression for the equivalent linear R in terms of the actual resistance force. The technique is to assume a purely sinusoidal oscillation and find an equivalent R that results in the same energy dissipation as the actual resistance force, to wit

$$\text{Assume} \quad x = x_o \sin \omega t$$

$$v = x_o \omega \cos \omega t$$

Let E be the energy dissipated per half cycle,

$$E = \frac{1}{2} \rho C_d S \int_0^{\pi/\omega} v^3 dt = \frac{1}{2} \rho C_d S X_o^3 \omega^3 \int_0^{\pi/\omega} \cos^3 \omega t \, dt$$

$$= \frac{1}{3} \rho C_d S X_o^3 \omega^2$$

But we also set

$$E = R\int_0^{\pi/\omega} v^2 dt = RX_o^2 \omega^2 \int_0^{\pi/\omega} \cos^2 \omega t \, dt$$

$$= \frac{1}{2} RX_o^2 \omega \pi$$

Equating these two energy terms and solving for R gives

$$R = \frac{2 \rho C_d S X_o \omega}{3 \pi}$$

Note that this is a function of the resulting amplitude and frequency of oscillation which are assumed fixed for a given case.

5. A third point deals with the additional virtual or apparent mass associated with the displacement of the atmosphere due to motion of the oscillating mass. This effect (or at least its variations from calibration conditions) should be negligible.

6. A last point concerns the effect of the mass of the spacecraft itself (page 8). The analysis presented is valid only if the line of oscillation of the mass passes through the c.g. of the spacecraft. If it does not, then account must be taken of the rotational reaction of the spacecraft about its c.g. Since actual rotational motion of the spacecraft will probably be small, this effect can be approximated by using an equivalent mass in place of M_s as derived in the paper. The equivalent mass M_e is given by

$$M_e = \frac{J_{c.g.}}{d^2}$$

where $J_{c.g.}$ is the mass moment of inertia of the spacecraft about its c.g. (neglecting the oscillating mass under test) in the plane defined by the c.g. and the line of oscillation of the mass, and d is the least distance from the line of oscillation to the c.g.

7. From the mechanical impedance data for the human body presented by Coermann, et al, it appears entirely valid that non-rigid body effects should be negligible for oscillation amplitudes of less than about 1" and for frequencies less than about 1 cps. To avoid possible anomalous results due to heartbeat effects, the oscillation frequency should be sufficiently low as to preclude resonance with the lowest possible heartbeat frequency. Such conclusions

are based upon the accuracy and sensitivity of Coermann's data. Indeed, some recent test results indicate that non-rigid body effects are sufficiently great at 1 cps such as to lead to unacceptable errors in mass measurement. Proper restraint and condition of the human subject is perhaps the overriding consideration in attaining the requisite accuracy.

REFERENCES

(1) "Forces on Cylinders and Plates in an Oscillating Fluid," Keulegan and Carpenter, Research Paper 2857, Journal of Research National Bureau of Standards, Vol. 60, No. 5, May 1958, pp. 423-440.

(2) "Drag Coefficient of Flat Plates Oscillating Normally to Their Planes," Ridjanoric, Schiffstechnik, BD.9, Heft/15, 1962.

ATTACHEMENT "B"

COMMENTS ON PAPER BY DR. PETERSON ENTITLED "THE ERROR IN MASS MEASUREMENTS OF A NON-RIGID BODY WITH AN OSCILLATING SPRING TECHNIQUE"

1. The paper presents some interesting mathematical analyses of the non-rigid body mass measurement problem. However, it appears that it would be rather difficult, and perhaps tedious, to instrument a physical system to check these theories out to the desired order of accuracy.

2. It does not appear that the treatment discloses or infers any new or better way to approach the measurement of a non-rigid oscillating mass. Rather, it is inferred, because of the rather unpredictable "non-rigid" characteristics of the human body, that reduction of the frequency of oscillation is probably the approach to follow. The question: "How low should the oscillation frequency be to produce results of the desired accuracy?" can probably best be answered by experiment.