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PROBLEMS OF MILLIPOUND THRUST MEASUREMENT

The "Hansen Suspension"

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Abstract

The system considered is the so-called "Hansen Suspension" by which the best measurements to date of millipounds of thrust have taken place. Measurements of thrust in the millipound region with a sigma of 1% have been found repeatable and practical.

Considered in detail are problems which led to the need and use of the "Hansen Suspension". Also discussed are problems which are likely to be encountered in any low level thrust measuring system. The methods of calibration and the accuracies involved are given careful attention. With all parameters optimized and calibration techniques perfected the system was found capable of a resolution of 10 μ lbs.

A comparison of thrust measurements made by the "Hansen Suspension" with measurements of a less sophisticated device leads to some surprising results.

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1. This paper reports work accomplished by the author while a summer employee in the Advanced Propulsion Engineering Section at the Jet Propulsion Laboratory during the summer of 1962.

2. Named for Dr. Siegfried Hansen, Hughes Research Laboratory, Malibu, California.

3. Graduate student at California Institute of Technology, Pasadena, California.

I. Introduction

Because of superior payload capabilities and availability of large quantities of supplementary electric power, it appears likely that planetary missions of the near future will be performed by electric propulsion systems. Before such systems can get off the ground, however, some means must be available for ground evaluation. Since the thrusts of present day electric propulsion motors are in the one to one hundred millipound region, techniques peculiar to small force measurements are necessary.

This brief paper discusses some of the problems encountered in thrust measurement by the Advanced Propulsion Engineering Section of the Jet Propulsion Laboratory, a review of possible thrust measuring systems, and the system currently in use at JPL.

II. Measuring Systems

Two general classes of thrust measuring devices are possible; direct and indirect. A direct measurement is an absolute measurement in pounds or alternately calibrated in pounds taken by some device physically linked to the motor. An indirect measurement is based on a calculation using given accelerating voltages and ion beam current information collected somewhere downstream from the motor.

The latter we temporarily put aside because of uncertainty as to beam neutralization, collector efficiency, collector secondary electron emission, etc. Its usefulness can best be determined by a comparison with direct measurements. A hybrid indirect-direct system, where the force experienced by a beam collector is measured, is similarly disregarded as being another step removed in uncertainty.

The problem is then reduced to finding a reasonable configuration for a direct force measurement.

III. General Considerations

Before trying to evaluate the merits of any particular configuration let us first examine what constraints exist to limit our choice.

The basic constraint of any system will be the necessity of being mechanically self-contained and capable of working in a high vacuum environment--the conditions under which today's motors must be tested. A second important constraint will be the dynamic weight of the motor and its mount, a weight which will vary roughly from twenty to fifty pounds. This constraint, as shall be demonstrated, introduces a myriad of problems. Another constraint will be the necessity of electrically tying into the system without introducing mechanical forces which disturb its operation. Other considerations, not so much constraints but desirous properties, will be the ability to give continuous thrust readings and instant calibrations at any stage of operation.

We now ask ourselves the question: Given the constraints, what means do we have of measuring force? Because of the small forces involved and the inaccessibility of the system, we pass up the absolute force measurement and consider only a semi-direct approach. Here some analogue of force such as displacement or voltage is measured and by some calibration procedure is translated into force readings.

The dynamic weight constraint leads to a further reduction in flexibility. Since it is much easier to measure millipounds than to resolve millipound increments over fifty pounds, we require some method of "neutralizing" the dynamic weight. This can be done by either a topside (pendulum) or underside type of suspension. The "Hansen Suspension" is of the latter type.

IV. The "Hansen Suspension"

A. Theory of Operation

The "Hansen Suspension", conceived by Dr. Siegfried Hansen of Hughes Research Laboratory, employs first a platform upon which the motor to be tested is rigidly mounted. This platform in turn is mounted to a rigid base by three water-thin flexures. Two of the flexures are mounted near corners of one end of the platform, and one in the middle of the other end. A gap of about two inches separates platform and base. The dynamic weight is then "neutralized" by loading the platform until the flexures are almost in a collapsed mode.

With thrust turned off the spring system of flexures and platform will reach some equilibrium position. When thrust is introduced, the platform will seek a new equilibrium, and the magnitude of the thrust could be measured by using some type of calibrated proximity detector. The "Hansen Suspension", however, goes one step further. An inverse feedback mechanism detects the motion and introduces a negative force almost cancelling the applied thrust. Thrust is measured as a function of current in the feedback loop.

Because any thrust applied is almost completely cancelled, the platform displaces very little. Thus, there is little problem with mechanical non-linearities which might well be serious for large displacements since the flexures are nearly in a collapse mode. Although we might also expect oscillations to be troublesome, the "Hansen Suspension" configuration allows us to circumvent this problem by introducing an electrical dampening mechanism in the feedback loop (assuming thrust is essentially a D.C. variable).

B. Description of Equipment

The Jet Propulsion Laboratory uses the following basic equipment: A thrust platform, a base, three flexures, a differential transformer, two voice coils, a D.C. preamplifier-amplifier, and a recorder.

C. Assembly

1. The thrust platform is attached to the mount by means

of the flexures, two at one end, one at the other.

2. The two voice coils and the differential transformer, each of which has two components, are attached as in Fig. 1.

3. The motor to be tested is mounted upon the thrust platform.

Since the forces we are trying to measure are small, special measures must be taken in attaching the electrical leads to minimize the restoring force exerted on the table by the leads.

4. The motor leads are attached to high voltage stand-offs on the thrust platform so that except for the flexures, the platform, motor, and leads are isolated.

5. The motor leads are attached from the platform stand-offs to similar stand-offs on the base by #16 nickel-plated copper wire coiled in the form of a spring.

6. Necessary connections are made to stand-offs on the base. The completed assembly is shown in Fig. 2.

D. <u>Preliminary to Operation</u>

The platform with all paraphernalia attached is leveled and then weighted down until the desired spring action is achieved. Considering the flexures alone, as the weight upon them is increased, a point is reached where the platform tends to fall to one side or the other rather than be supported; this is where the spring constant changes from positive to negative i.e., restoring to antirestoring. As the spring constant approaches zero, the period grows longer. At the exact zero spring constant point, the table can be placed anywhere in the equilibrium region, and it will remain stationary, i.e., the period becomes infinite. For negative spring constant the table no longer restores.

With motor lead coils attached, there is an additional positive spring constant so that to obtain a zero constant for the platform assembly the flexures must be operated in the negative region. In actual operation the entire assembly is brought to the zero constant level and then unweighted to be in the positive region by about two pounds. (This was found empirically to be a good operating region).

E. Summary of Operation

Thrust measurement is performed in the following manner: The platform assembly is allowed to reach equilibrium in the two pound positive constant region. When thrust is applied, the platform will seek a new equilibrium. A displacement is sensed in the differential transformer which sends a signal to the preamplifier-amplifier. The amplifier sends an appropriate signal to a position coil which exerts a force opposing the excursion. The magnitude of the primary thrust is proportional to the D.C. current necessary to halt the excursion. This current is measured by using the voltage drop across a resistor in series with the amplifier output as input into a recorder. The recorder displacement is calibrated to thrust by the use of a calibration coil.

F. Details of Operation

1. The Differential Transformer

The differential transformer is illustrated in Fig. 3 and 4. The primary of the differential transformer is excited by a 400 cps source. The secondaries are so connected that the induced voltages are bucking. The output to the preamplifier is taken from the two remaining secondary leads.

With the above connections, when the movable slug is centered, the two secondaries have equal and opposite voltage outputs, giving zero net result to the preamplifier. When the slug is displaced in either direction, one secondary sees less of the slug and hence picks up less of the primary excitation. This gives a net input into the preamplifier, the phase of which is determined by which way the slug moved; the two possible phases being 180° apart.

2. The Basic Signal Path

The 400 cps differential transformer output is amplified by the preamplifier and rectified by a mechanical chopper synchronized to the 400 cps source. The resulting D.C. voltage, which may be of positive or negative polarity, is then sent to a D.C. power amplifier which supplies restoring current to the position coil. The current sent to the position coil, the magnitude of which indicates thrust, is recorded as a function of the voltage drop across a 1 ohm series resistor. Because it was found that under some circumstances the amplifier damping could not sufficiently reduce oscillations, a ladder filter network which sharply attenuated the A.C. ripple component was provided as shown in Fig. 5.

3. Calibration

Thrust measurement accuracy is basically a function of how well the recorder deflection can be calibrated. The calibration coil consists of a permanent-magnet pole piece and a cylindrical drum wound with #40 wire. This is illustrated in Fig. 6. With the pole piece on one arm of an analytic balance and the drum rigidly suspended in the gap, the magnetic interaction force as a function of current into the drum winding was calibrated.

4. Accuracies

There are three main areas which we must consider for a statistical evaluation of the errors involved; the differential transformer, the amplifier-recorder system, and the calibration coil. Although it is not necessary that thrust be linear over the scale of the recorder, it would simplify readings significantly if this were the case. The accuracies of the first two are given by their manufacturers as linear to ¼% and ½% respectively. Calibrations of the calibration coil gave straight lines to a sigma of 0.8% or less.

A more important consideration, however, was found to be a 1.5% variance of calibration lines with different placements of the coil in the gap. This meant that for better accuracy than 1.5% we needed some other means of calibration. The above approach did prove useful though, since it told us that once the coil is held rigidly in one gap position, the calibration line is linear to within 0.8%.

The calibration was then accomplished to ½% by use of a gold chain-catenary method similar to that used for fine adjustments of an analytic balance. Calibration points were taken by using the chain force to null a force injected by a known current into the calibration coil.

An empirical check on the entire system linearity was made by halving the current causing a full scale deflection on the recorder. The new recorder deflection read half scale to within 1%.

For the coils used, the upper limit of thrust calibration was 20 mlb. Larger coils could be used if measurement at higher levels were desired. One approach, however, to extend with confidence the region of usability to twice the calibration limit (40 mlb in our case) is to use the calibration force to oppose motor thrust. In this mode 38 mlb would read as 18 mlb.

In addition once the calibration line is known one could blindly extrapolate it to higher values where we have no information on accuracy. The error, however, should not exceed the 1% by very much, if we do not exceed the limits of linearity of the system. Under present operating conditions the differential transformer output would be linear to the equivalent of 3 lbs., and the amplifier to 500 mlb. The only problem remaining is the linear range of the flexures, which will depend on loading and on composition. Although it has not been tried, it appears likely to this author that a theoretical 500 mlb limit can be achieved with no change of configuration. A spot check with a larger catenary chain could easily verify the above statement.

Larger thrusts can be coped with by running the flexures with less weight, relying more on spring forces to oppose thrust. Calibration systems for these higher thrust levels would have to be considered.

V. Problems

There are three main problem areas related to "Hansen Suspension": vibration, heat, and level changes. The last two are often related, a temperature gradient causing differential expansion of parts producing a change in level.

At JPL gross problems in vibration and level changes are avoided by mounting the vacuum tank on a 10 ton seismic mass with negligible coupling to the building. The seismic mass along with amplifier damping and recorder input filtering essentially solved the oscillation problem.

That level changes are important is not hard to see; a level change of one second with a dynamic weight of 40 lbs. produces a lateral force of 0.2 mlb. This sensitivity made it necessary to install a differential screw to make the fine level adjustments required to bring the mechanical equilibrium into correspondence with the electrical null of the differential transformer.

Heating can also be a real problem. Typical electrical propulsion motors have parts which operate at temperatures in excess of 1000°F. Except for radiated heat, the platform assembly can only dispose of excess heat by conduction through the flexures and lead coils. But as previously noted, a temperature gradient in the flexures can severely affect the platform level.

Radiated heat is kept off the platform by a shield interposed between it and the motor. Conduction heat is minimized by mounting the motor on an insulator (which also provides the electrical isolation sometimes necessary). Even with these precautions, the heat problem was found to produce sufficient drift to render continuous measurements for more than an hour impractical. Instantaneous measurements have a resolution of roughly 8 μ lbs when the recorder reads 0.4 mlb full scale. The practical limitation, however, is an approximate drift of $\pm 3\mu$lb/min due to heating effects.[4]

Some minor problems arose from unusual sources. Tank distortion during the evacuation process introduced a systematic drift in level which rendered the system useless for continuous measurements during the first six hours. To realign the level under vacuum conditions the differential screw was made accessible to the outside by means of a vacuum feedthrough.

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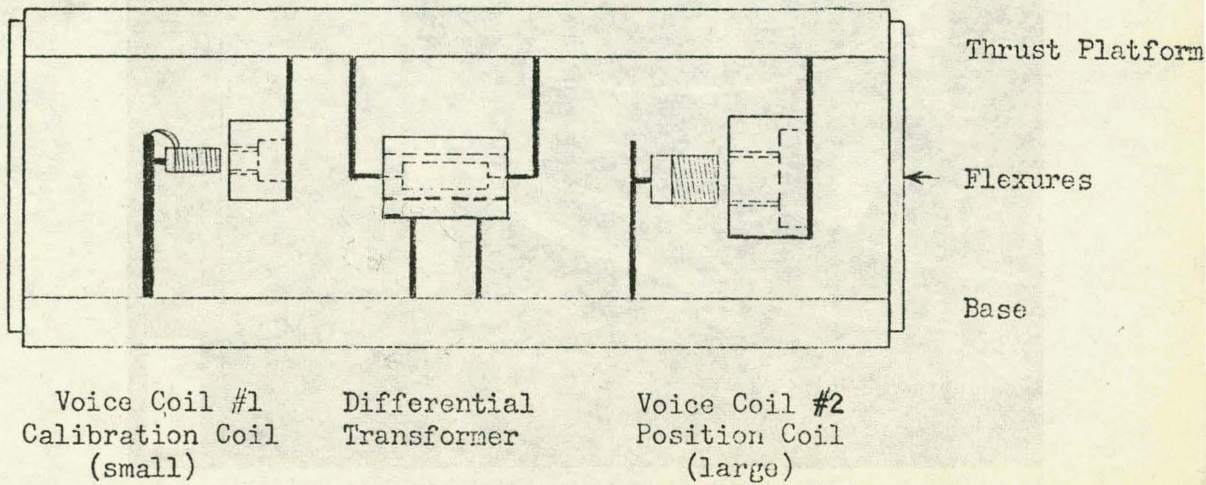
[4] A way suggested to handle the heat problem is to submerge the platform assembly up to the top of the platform in a water-cooled oil bath. This has yet to be tried.

Fig. 1. Side view. Schematic only; heavy lines are supports.



Three materials were tested for use as flexures. The first two tried, stainless steel and Invar (zero temperature coefficient of expansion), exhibited mechanical hysteresis properties when critically weighted. The material finally used was spring steel.

VI. Conclusions

The first conclusion is academic. Millipound thrust measurements to 1% accuracy are possible and practical. A second conclusion gives a very pleasant surprise. When "Hansen Suspension" measurements were compared with those of beam collector currents, the agreement was to within 2%. Thus, if one is interested in no more than 2% accuracy, one can simply collect beam currents, bypassing heat, level, and vibration problems.

VII. Acknowledgement

The author wishes to acknowledge the valuable assistance of Kenneth L. Geiler of JPL from whom many suggestions and helpful comments originated and Dr. Siegfried Hansen of the Hughes Research Laboratory who originated the basic thrust measurement concept described in this paper.

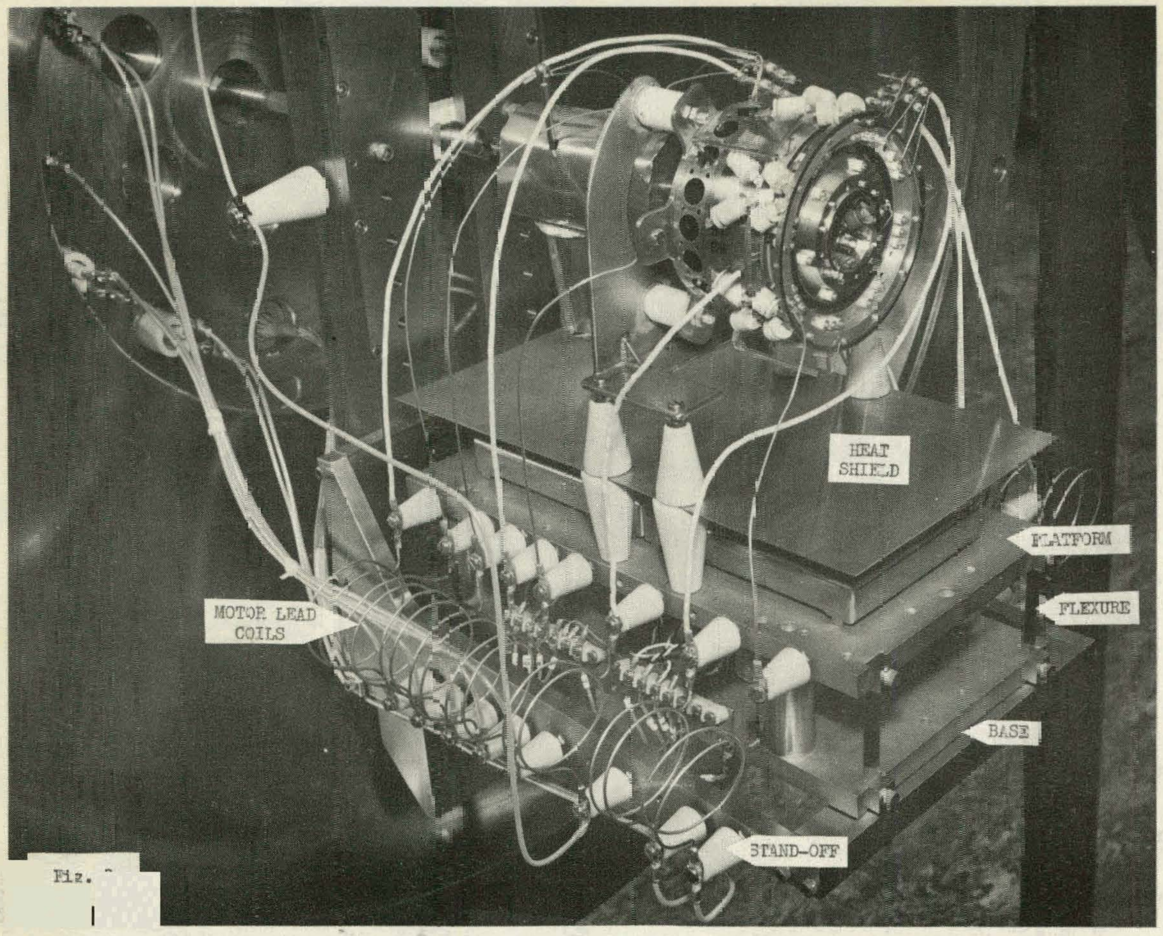


Fig. 4. Differential Transformer Schematic

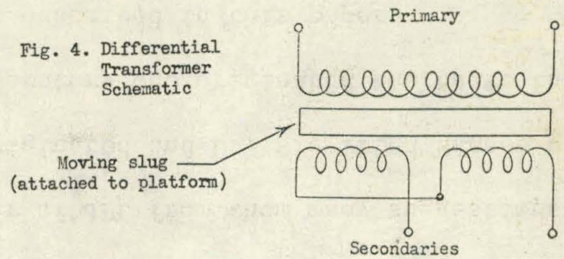
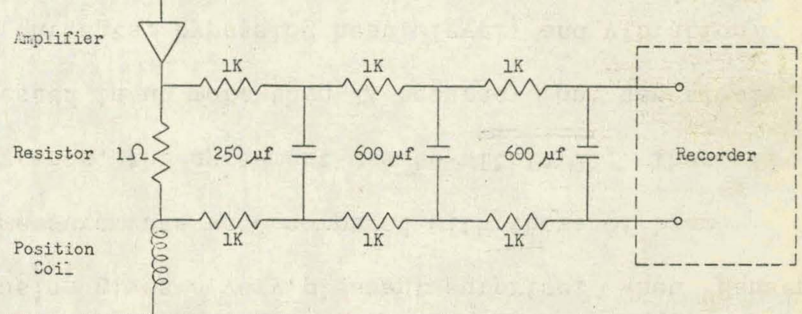


Fig. 5. Filter Network.



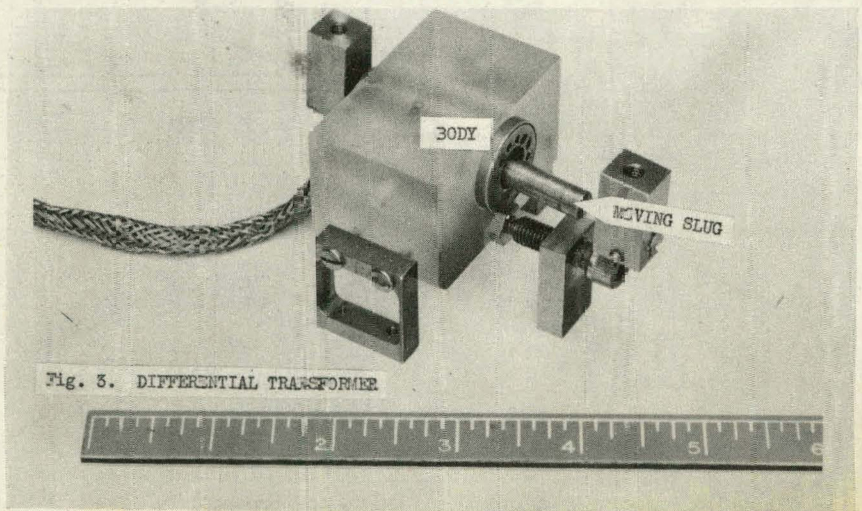


Fig. 3. DIFFERENTIAL TRANSFORMER

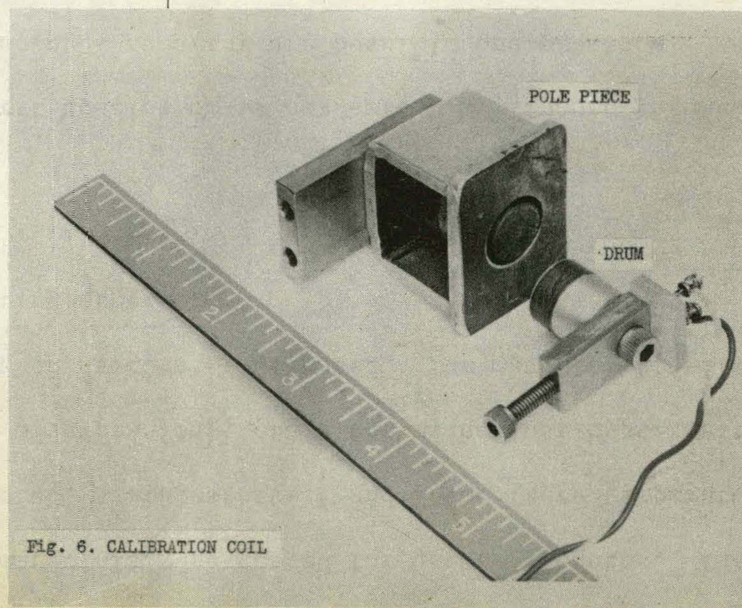


Fig. 6. CALIBRATION COIL

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