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THE PRESENT WATT BALANCE: A MEASURE OF ITS RESOLUTION†

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Abstract

It was possible to operate the watt balance in the normal mode, but with the magnetic field reduced by more than six orders of magnitude. This mode of operation allowed the investigation of possible sources of systematic errors not specifically connected with the magnetic field, but rather with the balance environment. This measurement revealed a general lack of environmental effects and indicated an upper limit of resolution less than thirty parts per billion for a potential watt evaluation.

Watt Balance Experiment

Introduction. The watt balance experiment [1] normally consists of measuring the ratio, $a + b$, where a is the force divided by current needed to statically balance a mass with a current-carrying coil in a magnetic field, and b is the voltage divided by velocity generated by the coil moving in the same field. In the voltage measurement, the major portion of the voltage signal is normally canceled out with a 1 V source so that only the difference is measured to obtain high resolution in the sub-parts per 10^6 (ppm) range. For this experiment, the static magnetic field provided by the superconducting magnet was reduced by over six orders of magnitude (turned off), so no voltage source was needed. This also reduced environmental uncertainty components for the force (air buoyancy) and velocity (air index of refraction) measurements, while retaining most of the voltage uncertainty components affecting the reproducibility. All of the normal functions of the watt balance and measurements were otherwise the same. The results provided a gauge of other effects of the local environment as well as the operational noise of the watt balance on the measurement of the watt.

The Voltage + Velocity Measurement. Normally, the velocity of the suspended coil's motion up and down through the superconductor's field is servo-controlled to induce one volt across the coil. For this experiment, the velocity was maintained constant via measurements with a laser interferometer. Even though the superconducting magnet was not turned on, there was the earth's magnetic field across the suspended coil. This was enough to induce an emf in that coil of about 1 μV as it moved vertically at the normal velocity of two millimeters per second.

By measuring the ratio of voltage induced in the suspended coil to its vertical velocity, a "velocity profile" was compiled. This velocity profile is just the gradient of the ambient magnetic field in the vertical direction. Ten sets of measurements were made. Each set consisted of five subsets of nine "up" velocity and nine "down" velocity passes. Each pass lasted about thirty seconds while six measurements of voltage, position, and time were recorded every second.

The Force + Current Measurement. Since there was almost no magnetic field to produce a vertical force while there was current in the suspended coil, the linear motor on the counter mass side (CMS) was used to servo-control the suspended coil at selected vertical positions. The control current in the CMS linear motor was calibrated by temporarily placing a 200 mg mass onto the suspended coil. This calibration was made at a number of vertical positions of the suspended coil.

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While the residual earth's magnetic field was about six orders of magnitude below the normal field, a current of 20 mA flowing in the suspended coil still produced a finite vertical force. For each current reversal, the current in the CMS linear motor was measured, and from the above small mass calibration, the vertical force produced by the current in the suspended coil was deduced. For each current direction the magnitude of the current was measured by averaging for thirty five seconds. For each vertical position, there were twenty current reversals. From these measurements, a "force profile" along the range of coil motion was deduced.

The Watt. Normally, the ratio of the force profile to the velocity profile provides the calculation of the watt. In this case, the precision of the measurements is the important point to note from the data for each profile shown in figure 1 (as calculated from the known relation of the force divided by current being equal to voltage divided by velocity). The filled squares, accompanied by one sigma standard deviation dotted lines, are the results of the force measurements, while the open circles with one sigma standard deviation bars, are the results of the velocity measurements. The standard deviation is the Type A uncertainty of the measurements. The accuracy of this particular experiment is not significant because the low level magnetic field generates less than 1 μV across the coil. However, the overlap of both profiles provides a test of the sensitivity limit for our voltage and force measurements. When the magnet is fully energized, the signal would be 1 V, making this data's error contribution to calculations of the watt less than 50 parts in 10^9, as shown by the high field scale indicator in figure 1.

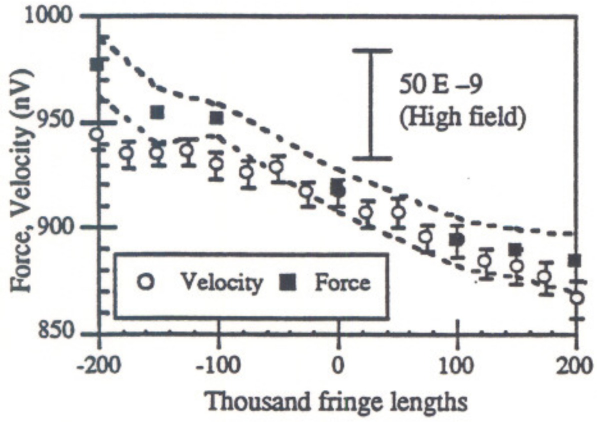

Fig. 1 The force divided by current and voltage divided by velocity profiles along the motion axis. Fringe lengths are units of 1/4 wavelength along the motion path, about 150 nm each.

This low field experiment was also a test for certain types of potential systematic errors. For example, any forces due to ferro- or diamagnetic material can be evaluated at the 30 parts per 10^9 level in the watt. Errors that might be caused by background fields at the power line frequency can be tested.

Conclusion

In general, the resolution looks promising for a lower limit of about 30 parts per 10^9. There is still much work to be done on improving the accuracy for the high field operation of the watt balance. The three most difficult tasks are: 1) Improve velocity measurements (factoring in limitations from the air index of refraction). 2) Align the superconducting and room temperature coils with respect to gravity. 3) Improve the determination of the coil emf in relation to the Josephson array voltage standard.

References

[1] T. P. Olsen, W. L. Tew, E. R. Williams, R. E. Elmquist, and H. Sasaki,, "Monitoring the Mass Standard via the Comparison of Mechanical to Electrical Power," IEEE Trans. Instrum. Meas., Vol. IM-40, No. 2, pp. 115-120, April 1990.