NASA TM X-1209

# FORCE MEASUREMENT IN A VACUUM ENVIRONMENT BELOW $10^{-6}$ TORR

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## SUMMARY

A capacitance force transducer is described which was developed to measure the torque of a rolling-element bearing with both transducer and bearing in a vacuum environment ($10^{-7}$ torr ($1.33\times10^{-5}$ N/m$^2$)). The transducer is capable of measuring forces from $2.2\times10^{-3}$ to 1.32 pounds ($9.807\times10^{-3}$ to 5.884 N) and can be calibrated statically for vacuum operation at atmospheric pressure.

Author

## INTRODUCTION

The problems in equipment testing under simulated space conditions involve not only the production of the required high vacuum and other environmental conditions but also the observation and measurement of the test quantities of interest under these conditions. A high-vacuum environment frequently imposes severe demands on the instruments required to make these measurements. This type of problem is encountered in research on rolling-contact bearings operating in a vacuum environment where it is desired to measure speed, load, torque, and temperature of the test bearing in operation.

A schematic of the bearing test configuration used in the studies reported herein and in reference 1 is shown in figure 1. A severe problem arises in measuring the test bearing running torque which requires the use of a force transducer at some radial distance from the center of the bearing shaft. At the start of the program an unbonded strain-gage force transducer was used. The excitation voltage on the strain gage produced heat in the wires. Since a great portion of this heat can be transferred only by radiation in a vacuum environment, the elements in the unbonded strain gage soon heated excessively and burned out. This failure was verified by microscopic examination of the strain-gage wires. The excitation voltage can be reduced to obtain a longer transducer life, but this reduces the output of the strain-gage bridge significantly since output is directly proportional to impressed voltage. Bearing torque sensitivity is, therefore, appreciably diminished.

Although the unbonded strain gage is inadequate for this application, other types of transducers for measuring forces in a vacuum seem to be more attractive. One such force transducer is of the capacitive type. Capacitance transducers have some advantages (ref. 2): (1) They can measure extremely small mechanical displacements with a force of the order of several dynes on the test object; (2) they can be made extremely small; (3) many applications do not require mechanical or electrical connections to the test object; (4) the test object (plates) can be designed with very little mass, which results in desirable dynamic response characteristics; (5) dimensional stability is not a severe problem because materials with low coefficients of thermal expansion can be used; (6) the capacitive transducer can be shielded from stray electric fields and is not affected by magnetic fields; and (7) negligible heat is generated by the transducer during operation.

The object of this report is to verify the merits of a capacitance force transducer by measuring rolling-element bearing torque in a vacuum.

## APPARATUS

A capacitance force transducer normally consists of two metal plates with parallel surfaces separated by a suitable dielectric gap. One plate remains fixed, while the other is attached to the end of a spring and is deflected by the force to be measured. The force thus varies the gap between the plates so that the capacitance change is a function of the applied force. It is desirable to provide a linear relation between the force and the gap. The deflection at the end of a cantilever beam is directly proportional to the force applied. Therefore, this beam can perform the function of a spring in a force transducer.

The force transducer described herein (fig. 2) employed an accurately machined, 17-4 PH stainless steel cantilever beam which was hardened to a Rockwell hardness of C-45 and measured 1.75 by 0.443 by 0.0738 inch (4.44 by 1.125 by 0.1874 cm). In addition to performing the function of the spring, this beam was one of the capacitance plates. When the capacitance force transducer beam was designed, the sensitivity and capacity were selected on the basis of previous requirements established in earlier bearing studies in which the unbonded strain gage was used (ref. 1).

Several circuits can be used to convert an unknown or varying capacitance to an output voltage. The commercial type which was used in this investigation employs a high-gain amplifier with the capacitive transducer in a feedback loop (fig. 3). This results in a voltage output directly proportional to the capacitor plate separation (linear output). This type is desirable for the capacitance force transducer in that the voltage output is directly proportional to the applied force (if the separation, or displacement, is directly proportional to the applied force).

As shown in figure 4, the output signal from the amplifier in the capacitance meter was filtered with a low-pass filter to eliminate the carrier frequency, recorded on a strip chart recorder, and observed on an oscilloscope.

The capacitance probe is shown in figure 5. The probe is the fixed plate on the force transducer and consists of three concentric metallic elements separated from each other by a dielectric. The inner element is the active probe plate. The inner cylinder is the guard cylinder, which provides a uniform electrostatic field between the probe and the beam (and may not be grounded). The outer cylinder is an insulator shield that may be clamped to ground for mounting. References 3 and 4 give data on insulation materials which are suitable for operation in vacuum to $10^{-6}$ torr ($1.33\times10^{-4}$ N/m$^2$) and 170° F (76.4° C). The insulation material used in the capacitance probes described herein was a high-temperature (400° F) epoxy resin which has operated very satisfactorily at a pressure of $1\times10^{-7}$ torr ($1.33\times10^{-5}$ N/m$^2$) and 100° F (37.8° C). Glass bonded mica, aluminum oxide ($Al_2O_3$), beryllium oxide ($BeO$), and zirconium oxide ($ZrO_2$) can be used as dielectric materials for pressures lower than $10^{-6}$ torr ($1.33\times10^{-4}$ N/m$^2$), and all organic materials can thereby be eliminated from the vacuum test chamber.

## PROCEDURE

One of the advantages of the capacitance force transducer described is that it can be statically calibrated in air at atmospheric pressure. The transducer was calibrated in this manner, and the results are shown in figure 6. Also, the resonant frequency and damping coefficient for the complete torque measuring system were determined experimentally and found to be 68 cps (Hz) and 0.67, respectively.

After the force transducer was calibrated, the bearing test apparatus was operated in vacuum. Figure 7 is a typical torque waveform recorded while a self-lubricating rolling-element bearing was being run. The inner race of the bearing was rotating at 3600 rpm.

## RESULTS

Experiments to measure the running torque of rolling-element bearings with the bearing and a capacitance force transducer in vacuum are described in reference 1. Previous bearing tests were performed with an unbonded strain-gage transducer, which resulted in the failure of the strain-gage wires by excessive heating. The capacitance transducer, however, generates a negligible amount of heat and operates satisfactorily in a vacuum environment. During the 100 hours of bearing tests, the capacitance transducer has not experienced any difficulty or malfunction. Bearing torque amplitude, torque oscillations, and torque waveforms have been observed, since static and dynamic forces from $2.2\times10^{-3}$ to 1.32 pounds ($9.807\times10^{-3}$ to 5.884 N) can be measured. The elements of the capacitance probe used in the transducer were insulated with a high-temperature epoxy resin. However, a capacitance force transducer can be fabricated without incorporating any organic materials. The dielectric constant for air (1.0006) is very nearly that in vacuum (1.0000). Therefore, for vacuum operation, the transducer can be calibrated in air at atmospheric pressure.

## SUMMARY OF RESULTS

An investigation of force measurement on a rolling-element bearing in a vacuum produced the following results:

1. A capacitance force transducer used to measure rolling-element bearing torque has been designed and fabricated that will measure static and dynamic forces from $2.2\times10^{-3}$ to 1.32 pounds ($9.807\times10^{-3}$ to 5.884 N) in a vacuum environment to $10^{-7}$ torr ($1.33\times10^{-5}$ N/m$^2$).

2. In vacuum, the capacitance force transducer does not generate heat and fail as did the strain-gage transducer.

3. The rolling-element bearing torque amplitude, torque oscillation, and torque waveform have been observed by the capacitance transducer system.

4. Capacitance force transducers for vacuum operation can be fabricated without incorporating organic materials.

5. The capacitance force transducer can be calibrated for vacuum operation in air at atmospheric pressure.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 3, 1965.

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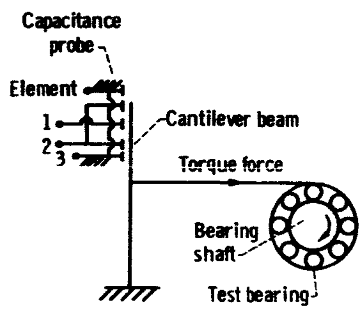


Figure 1. - Vacuum bearing test apparatus.

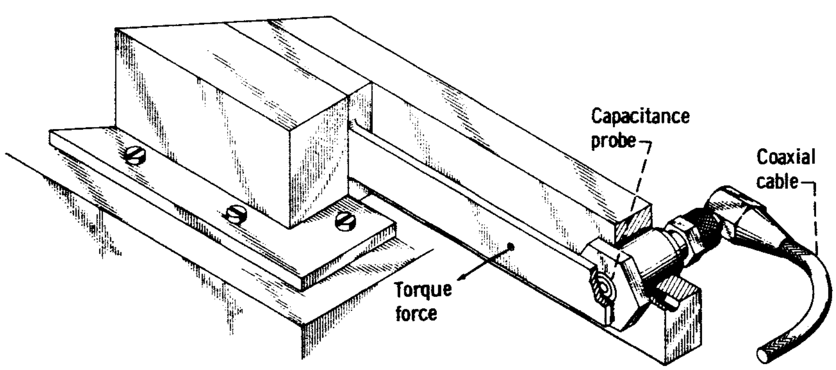


Figure 2. - Capacitance force transducer.

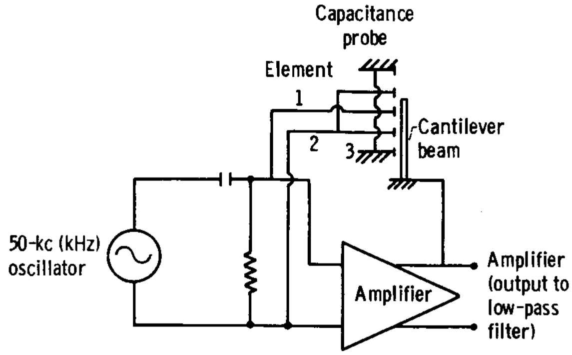


Figure 3. - Capacitance meter circuit.

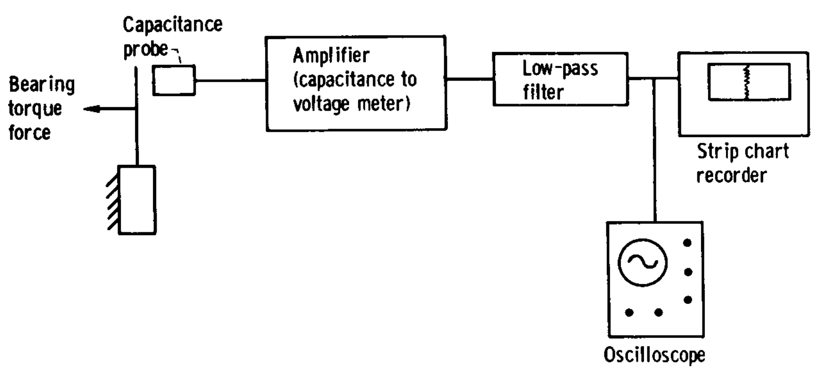


Figure 4. - Block diagram of capacitance transducer system.

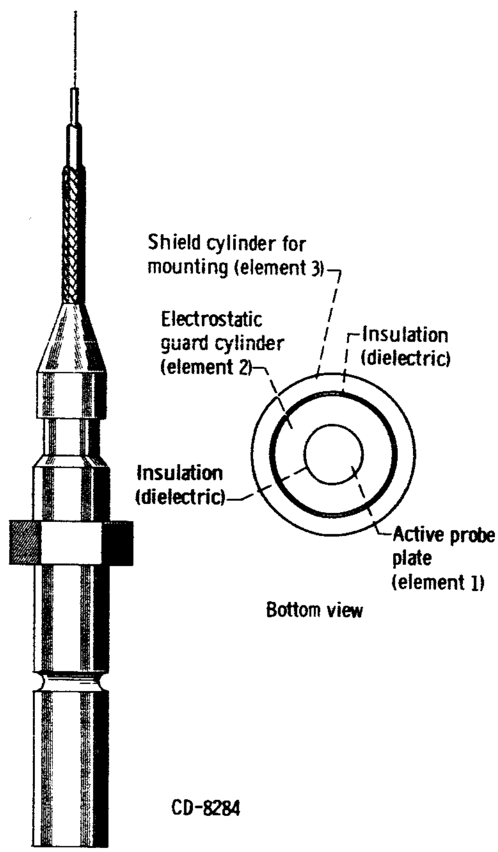


Figure 5. - Three-element capacitance probe.

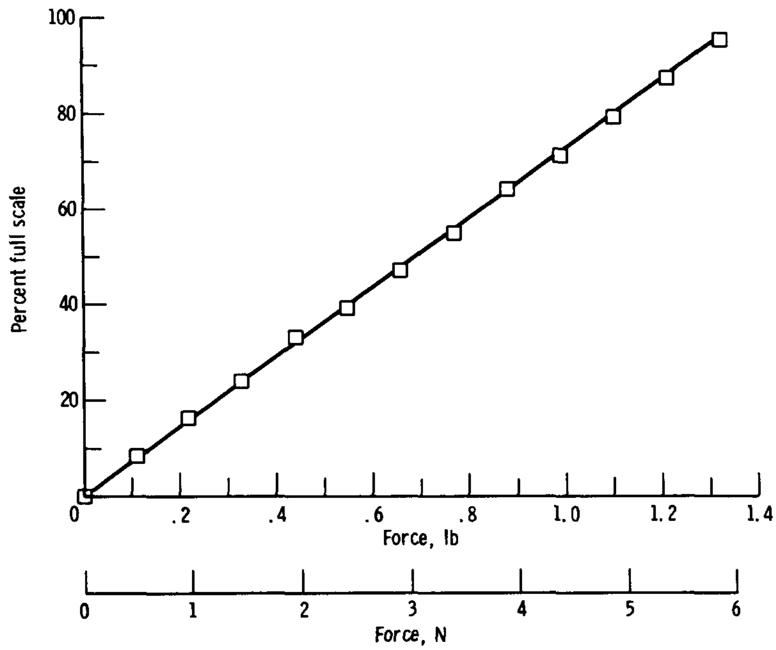


Figure 6. - Calibration of capacitance force transducer with 17-4 PH beam and 0.010-inch (0.0254-cm) probe.

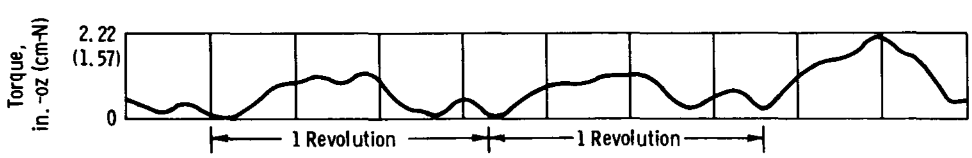


Figure 7. - Typical rolling-element bearing torque waveform produced by capacitance force transducer. Pressure, $10^{-7}$ torr ($1.33 \times 10^{-5}$ N/m$^2$); self-lubricating bearing operating at 3600 rpm.



NASA-Langley, 1966 E-3246