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Capacitive Transducer for Relative Position Error Galvo Mirrors

Joshua C. Harrison

Abstract—**A transducer was designed to sense small angular displacements of servo-controlled galvo mirrors in rotary optical storage devices. The transducer is differential in nature, and operates on the principle of linear electrical capacitance variation with area overlap of uniquely shaped capacitor plates. These capacitive plates lie in planes normal to the axis of rotation, and consist of many electrically connected wedge-shaped projections aligned radially to the center of rotation. A prototype was fabricated and tested. For optical storage devices, experimentally determined characteristic curves show sufficient linearity and repeatability for relative position error (RPE) feedback applications, at plate spacings of 0.15 mm or less. A design change, for further extending the linear range of the characteristic curve of the transducer beyond RPE feedback requirements, is described. A circuit design to produce voltage variations proportional to differential capacitance changes in the transducer is discussed, and peak-to-peak signal-to-noise ratio is conservatively approximated at 2×10^4 with 10 kHz bandwidth.**

NOMENCLATURE

A	Area of plate overlap.
C	Capacitance.
d	Plate spacing.
$i_{\rm rms}$	Root mean squared current.
S/N$_{\rm rms}$	Ratio of $v_{\rm rms}$ of signal to $v_{\rm rms}$ of noise.
$v_{\rm rms}$	Root mean squared voltage.
ΔX_c	Capacitive reactance variation.
β	Stationary plate design modification angle.
ε_0	Permittivity of air.
θ	Angular linear range from nominal position of transducer characteristic when $\beta = 0$.
ϖ	Bandwidth in Hz.

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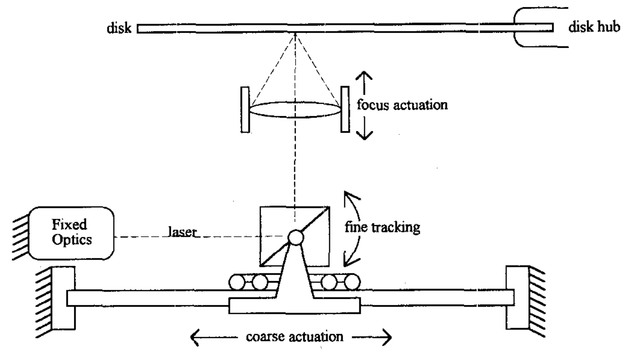


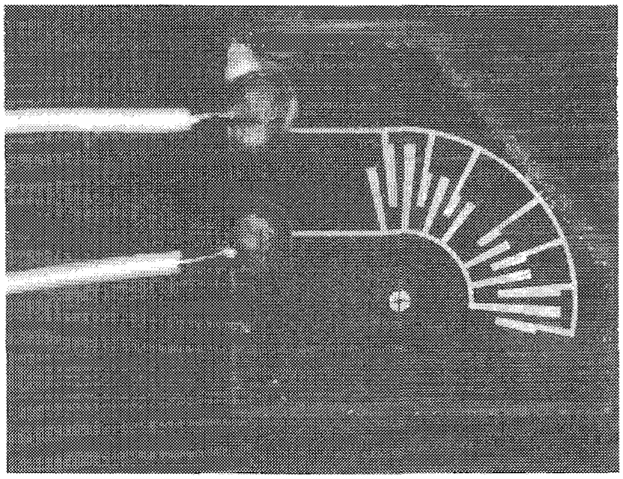
Fig. 1. Schematic drawing of optical storage fine tracking with galvo mirror mounted on the coarse actuator.

I. INTRODUCTION

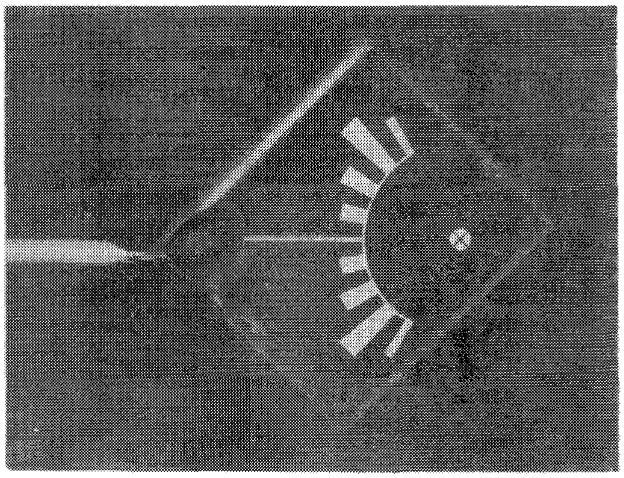
The radial position of the objective lens in rotary optical storage devices must be actively controlled with respect to the disk in order to follow closely spaced tracks of information as the disk spins. The objective lens position normal to the disk is also servo controlled to maintain focus with disk runout. The focus actuator increases the mass which the track-following actuator must move, without reducing its bandwidth requirement. Therefore, the task of radial position control is usually divided between two actuators: a coarse actuator with large stroke but small bandwidth, and a fine actuator with larger bandwidth but small stroke.

The fine actuator position is fed back to the coarse actuator controller so that the coarse actuator will move in such a way that the fine actuator does not need to exceed its small stroke. This requires a transducer for the instantaneous position of the fine actuator, with output proportional to the displacement of the fine actuator from its nominal position. This output is fed back to the coarse actuator as an error signal to be minimized. This feedback is commonly called "relative position error" (RPE) feedback. For galvo mirror-type fine-tracking actuators, such as the ones used in the Pioneer U7001 and Hitachi 112-1 optical storage products, the RPE transducer must sense the angular position of a small mirror or prism. A typical application of galvo mirror fine-tracking actuation is shown in Fig. 1. While Fig. 1 shows the galvo mirror placed underneath the focusing lens and traveling with the coarse actuator, the galvo mirror can also be mounted off the coarse actuator with other fixed optical components [1]. This design choice does not affect the angular range requirement on the galvo mirror, which for a typical value of focal length (3.9 mm) and fine-tracking range (± 30 tracks $\approx 50 \mu$m), is approximately $\pm 0.73°$.

Several methods for sensing RPE have been used or proposed. One such method requires a light-emitting diode, two carefully positioned photodiode detectors, and a mirror with a shadow stripe which is deposited on the moving part. The output from the stationary photodiodes is modulated by the motion of the shadow, which moves due to rotation of the moving part. This method relies on more active components than the capacitive method presented by this paper, and therefore is more expensive, requires more space, and is less reliable. Another method utilizes the voice coil current driving the galvo mirror against a mechanical restoring force as a measure of RPE. This method, however, does not provide a differential output, and therefore is sensitive to thermal changes and drift.



(a)



(b)

Fig. 2. Prototype of transducer capacitive plates.

II. DESIGN

A capacitive transducer was designed to sense the angular displacement of servo-controlled galvo mirrors in rotary optical storage devices. The capacitive element consists of a total of three conducting plates. The plates lie in planes normal to the axis of rotation, and consist of many electrically connected wedge-shaped projections aligned radially to the center of rotation. Two of these plates remain stationary, and are shown in the top photograph of Fig. 2. The third plate rotates with the galvo mirror, and is shown in the bottom photograph of Fig. 2.

The change in capacitance between the plates due to rotation is brought about by a linear change in the area of overlap between the plates, rather than by a change in the plate spacing. As the capacitance between the moving plate and one stationary plate increases with rotation, the capacitance between the moving plate and the other stationary plate simultaneously decreases. Thus, the capacitive element of the transducer is differential in nature so that many disturbances to the system, such as thermal effects, contamination, and variations in plate spacing, are common to both plate pairs and thus are self-cancelling. Such disturbances, therefore, do not result in a shift of the transducer nominal position, although they may affect transducer sensitivity.

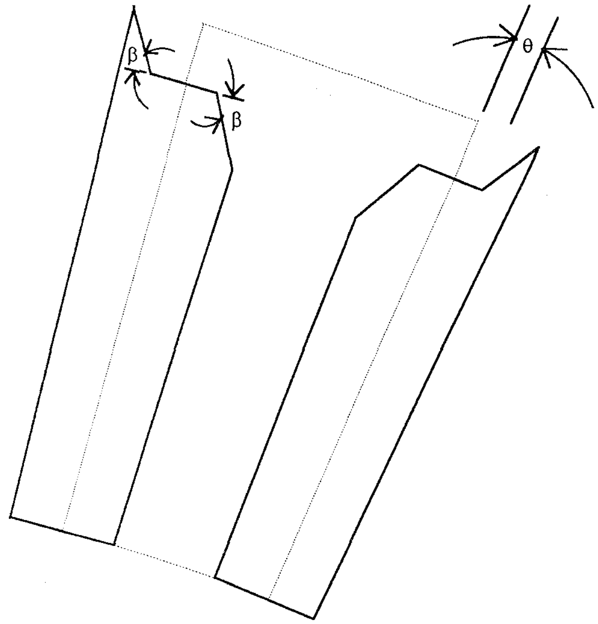


Fig. 3. Design change for extension of the transducer linear range (not to scale).

Angular position transducers based on capacitive plate overlap have been previously investigated. Many designs which have been documented have either been too large or insensitive for RPE-sensing applications [2], or cannot meet the RPE-sensing bandwidth requirement due to utilization of a direct current source [3], [4]. In the present design, the capacitive element is designed such that the moving plate requires less than a 2 mm by 6 mm rectangular area on the side of the rotating part. The wedge-shaped areas of overlap are narrow in the nominal position to increase output sensitivity to small angular displacements.

Since the capacitive plates are formed by photolithographic methods, it is possible to modify the shape of the stationary plate wedges in such a way that the linear range of the transducer characteristic curve is increased. One such modification is proposed in Fig. 3. Here a single group of projections of the modified capacitive plates is shown in the nominal position. Angle $\pm\theta$ represents the angular range for which the transducer was linear before the design change. The length of the stationary plate projections is held constant in this range to preserve linearity. The length of the stationary plate projections increases (with increasing overlap) outside of this range in order to compensate for sensitivity roll-off in the original design. The amount of compensation increases with increasing values of design angle β until linearity is achieved (although with lower overall transducer sensitivity than without the design change). The capacitive plates fabricated for this study did not incorporate the design modification proposed in Fig. 3, and so further photolithographic fabrication and experimental testing would be necessary to confirm the hypothesized increase in linearity (and decrease in sensitivity) associated with such a modification.

III. ANALYTICAL PREDICTIONS

Capacitance variation predictions can be made for the transducer design using the equation

$$C = \varepsilon_0 A/d. \tag{1}$$

This equation ignores capacitor-plate edge effects, which for the designed transducer introduce a sensitivity roll-off at angular dis-

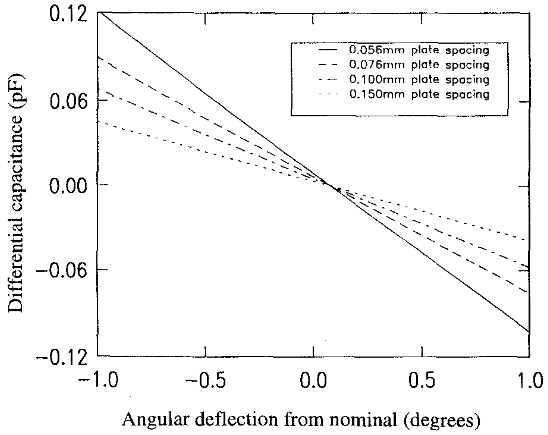


Fig. 4. Differential capacitance versus angular deflection.

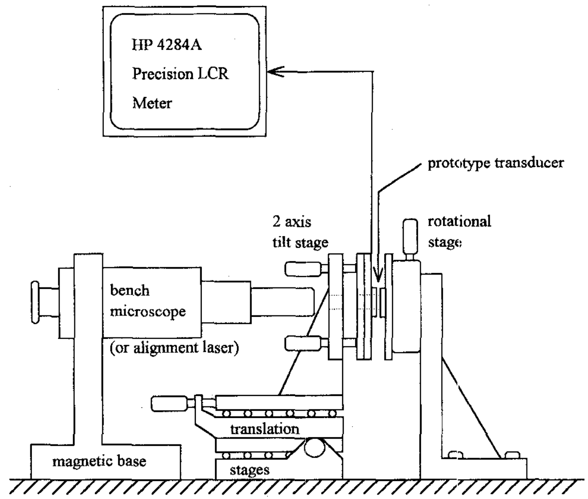


Fig. 5. Schematic drawing of experimental test apparatus.

placement extremes and cause a nominal capacitance increase. However, the application of this formula lends insight into the qualitative behavior of the transducer in its operating range.

The transducer output is proportional to the difference between the individual capacitances, and this difference will hereafter be called the "differential capacitance." The predicted relationship between differential capacitance and angular displacement (for the transducer with $\beta = 0^\circ$), and the effect of plate-spacing changes on this relationship, are shown in Fig. 4. The angular deflection associated with the nominal output of the transducer is not affected by increases in plate spacing, due to the differential nature of the transducer. Thus, using this transducer, steady-state error can be avoided when the error-minimizing control system design is robust to anticipated sensitivity fluctuations. Note that the intersection of the capacitance curves is shifted slightly to the right in Fig. 4 due to a constant capacitance addition from the overlap of the electrical connections over one of the stationary plates.

IV. Prototype Fabrication and Experimental Apparatus

A prototype of the transducer capacitive element was fabricated in order to determine the actual sensitivity and usable linear range of the transducer in light of edge effects and to determine a practical plate spacing. Photolithography was used to produce gold-on-glass prototype parts from chrome-on-glass masks of the plate designs. The gold layer was 0.03 mm to 0.04 mm thick and was deposited on clear glass wafers of 4 mm thickness. Clear glass was chosen in order that optical methods could be used to align the plates during testing. Wire bonding to the plated leads was accomplished using Epo-Tek H20E silver epoxy glue, and the measured resistance across the bonds was less than 2 Ω in all cases.

The moving capacitor plate was mounted on a rotational stage with 0.01° resolution, such that its origin was in approximate alignment with the center of rotation. The stationary plates were mounted on a two-axis tilting stage, which was itself mounted on a three-axis translation stage. A laser was used to align the plates parallel, and a bench microscope was used to align the origins to be coincident. Realignment of the plate origins was necessary after each rotation of the moving plate, since its origin was not exactly coincident with the center of rotation.

Capacitance was measured using an HP4284A Precision LCR Meter with 0.000 01 pF resolution and $\pm 0.05\%$ approximate error. The effect of stray capacitance was reduced by providing a dual-coaxial-wire connection to each plate, and grounding of the stages and shields. A schematic drawing of the experimental apparatus is shown in Fig. 5.

Zero spacing was defined as the spacing at which the electrical resistance between the gold capacitor plates abruptly dropped to a near-zero value. Since slight plate misalignment would cause glass corner contact of the prototype parts to occur prior to electrical contact, electrical contact only occurred when the position stages resisted a contact pressure. This introduced a ± 0.005 mm uncertainty in plate spacing (due to flexibility of the position stages and mounting material), and was the largest source of experimental error.

V. Experimental Results

Measured values of the previously defined "differential capacitance" are plotted versus angular position in Figs. 6 and 7, for nominal plate spacings of 0.056 mm and 0.076 mm, respectively. These plots show the behavior of the characteristic curve over a $\pm 1^\circ$ range of angular position, although only the inner $\pm 0.75^\circ$ is important in most RPE applications. The characteristic curves are sufficiently linear in the range of interest. Note that two separate sets of experimental data are plotted here to illustrate experimental repeatability. In all cases, the plotted data is linear to within 7% of the slope at zero deflection. The value of the slope is seen to decrease with increasing plate spacing, as expected from (1).

The change in measured differential capacitance due to 1° angular displacement (the slope of the differential capacitance versus angular displacement curve) is a measure of transducer sensitivity, and is plotted versus plate spacing in Fig. 8. The corresponding values expected from (1) are plotted as a continuous curve on the same graph. Both the experimental data and predicted curve show a nonlinear decrease in transducer sensitivity with increasing plate spacing, and these decreases are of the same general form. However, the experimental data seems to have an origin which has been shifted toward greater plate spacing when compared to the predicted curve. The reason for the apparent origin shift is twofold. First, although edge effects cause a sensitivity roll-off at extreme angular displacements, edge effects also increase the nominal capacitance of each plate, and therefore also increase the nominal capacitance shift due to rotation in the linear range. A second contributor to the apparent origin shift was that the stage micrometer required turning beyond the initial physical contact to establish the pressure necessary for electrical contact (see the aforementioned experimental definition of zero plate spacing).

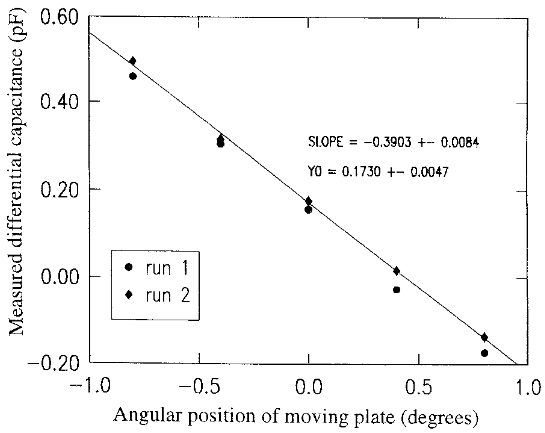


Fig. 6. Measured differential capacitance versus angular displacement (d = 0.056 mm).

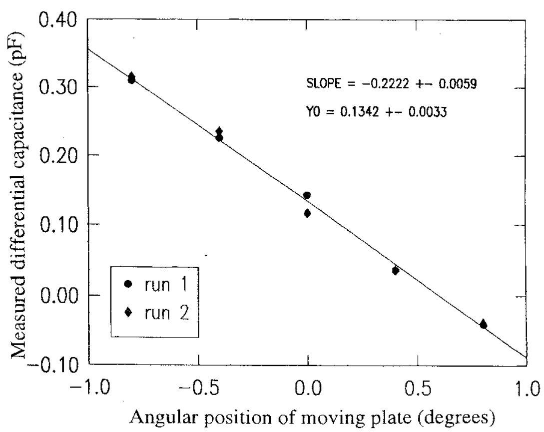


Fig. 7. Measured differential capacitance versus angular displacement (d = 0.076 mm).

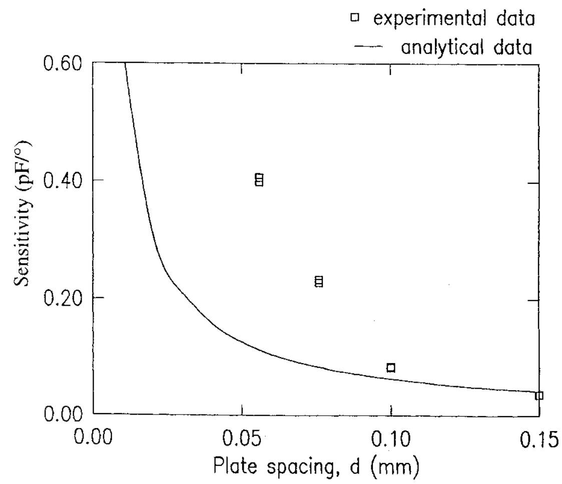


Fig. 8. Measured and calculated transducer sensitivity versus plate spacing.

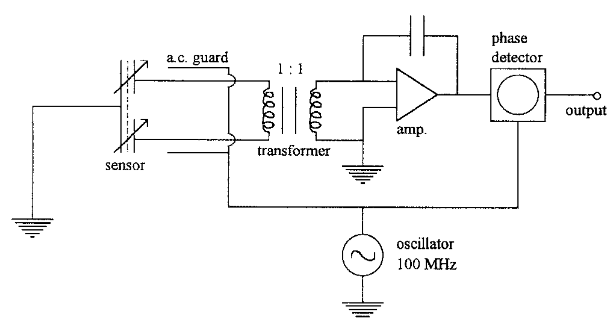


Fig. 9. Capacitive detection circuit assumed in SNR approximation.

VI. Suggested Circuit and Approximate S/N

A. Circuit

Many high-resolution capacitive detection circuit schemes are currently available, including those which convert capacitance changes to changes in output frequency [5] or phase [6]. The use of such a phase-based detection circuit can be assumed for the approximation of the transducer signal-to-noise ratio (S/N). Such a circuit is shown in Fig. 9. It is noteworthy that at least one circuit which measures extremely small variations in capacitance as a means for data encoding, storage, and retrieval, has appeared in a consumer electronics product before. The RCA VideoDisc product, announced in 1977, utilized a resonant circuit which could resolve 0.0001 pF peak-to-peak capacitance variations over a standing capacitance of 0.5 pF with over 3 MHz bandwidth [7]. The circuit S/N was reported to be 10 dB below that of the system's recording media, which had a reported S/N of 50

−60 dB with 30 kHz bandwidth. Although this resonant circuit design featured outstanding sensitivity and S/N, the circuit of Fig. 9 has the potential for similar performance with higher dc stability.

B. Signal

Plate rotation ($\pm 1^\circ$) produces a 0.14 pF measured capacitance variation at 0.1 mm plate spacing. The resulting capacitive reactance variation is $\Delta X_c = 71.4$ kΩ, for an oscillator frequency of 100 MHz. If the transformer used in the circuit of Fig. 9 is an MCLT1-1, its parallel impedance is 400 Ω. These two impedances act as a voltage divider, with the voltage across the transformer input to the amplifier. Thus, if the oscillator output voltage is 1.0 V_{rms}, then the signal into the amplifier is 5.57 mV_{rms}.

C. Noise

The main noise-producing component in the circuit shown in Fig. 9 is the amplifier. If the amplifier used is a Comlinear CLC401, then its internal noise is given as

$$v_{\mathrm{rms}} \approx (2.4 \text{ nV})(\varpi)^{0.5} \tag{2}$$

$$i_{\mathrm{rms}} \approx (3.8 \text{ pA})(\varpi)^{0.5} \tag{3}$$

$$(i_{\mathrm{rms}} \times 400\ \Omega) \approx (1.5 \text{ nV})(\varpi)^{0.5}. \tag{4}$$

These two internal noise values combine as the root sum of squares

$$v_{\mathrm{rms}} \approx (2.8 \text{ nV})(\varpi)^{0.5}. \tag{5}$$

D. Signal-to-Noise Ratio (S/N)

Thus, S/N can be conservatively estimated as

$$\text{S/N}_{\mathrm{rms}} \approx (2.0 \times 10^6)/(\varpi)^{0.5} \tag{6}$$

so that $\text{S/N}_{\mathrm{rms}} \approx 2.0 \times 10^4$ for a 10 kHz bandwidth. This S/N can be substantially improved by appropriate circuit component substitutions (e.g., lower noise amplifier or transformer).

VII. Conclusion

A differential capacitive angular position transducer was designed to sense the angular displacement of servo-controlled galvo mirrors in rotary optical storage devices. A prototype was fabricated and tested. Experimentally determined characteristic curves show sufficient linearity and repeatability for relative position error (RPE) feedback applications, at plate spacings of 0.15 mm or less. A possible design change, for further extending the linear range of the characteristic curve of the transducer beyond RPE feedback requirements, is discussed. Peak-to-peak SNR is conservatively approximated at 2×10^4 with 10 kHz bandwidth. The transducer senses angular position with passive parts and has only two active subcomponents: an oscillator and an amplifier. One of these, the oscillator, may be eliminated if the transducer is driven by a "clock" signal already present in the direct access storage device.

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A Capacitor-Based Device for the Measurement of Shaft Torque

Anthony Falkner

***Abstract*—This paper describes a capacitor technique for the measurement of torque in a rotating shaft. The passive rotating part incorporates a capacitor bridge which is connected capacitively to the static part. This device is simple in operation and is relatively easy to manufacture.**

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I. Introduction

This paper is concerned with the measurement of torque in a rotating shaft without direct electrical contact. A typical application lies in an electric power-assisted steering system for an automobile where the torque exerted by the driver forms the error signal of the servo system. Other workers have developed a device for this purpose, using gauges mounted on the shaft to measure the strain and hence determine the torque [1]. There are optical methods also [2], [3]. Following earlier work on the measurement of force and torque in static situations using capacitor techniques [4], this paper reports an improvement in which the signals are coupled to a rotating part capacitively. Fig. 1 shows a conventional capacitor bridge and a modified bridge using capacitors to couple to the three electrodes. Each of these coupling capacitors has an electrode on the rotor and an electrode on the stator and remains effective during rotation. Thus, there is electrical contact without physical contact. The main advantages of this are simplicity and low fabrication cost. The same electronics, as established earlier in the overall program, is applicable here [5]. This requires low power and makes electronic integration feasible, these features having been demonstrated in a circuit designed for the static-torque device [5]. The design and development of a prototype device with experimental and theoretical results are discussed here.

II. Prototype Design

A. Mechanical Design

It is necessary that the shaft show strain in a well-defined way when axial torque is applied but that there be no response to torque about either of the other two axes, or to a force in any direction. Fig. 2 shows the basic element which achieves this, the design being based on that developed for the static torque device. Details of the theory are given elsewhere [4]. The axial torque applies forces to each leaf perpendicular to its large faces so that the leaf flexes easily. If any other torque or force is applied, the device appears stiff because some or all of the leaves are subject to forces which are longitudinal or are perpendicular to the small faces. It is possible that a thin section of shaft would perform satisfactorily in many practical applications because the axial torque would dominate, but for the initial experimental work the proven configuration has been chosen. The capacitor values are more sensitive to relative electrode motion perpendicular to their faces, changing the spacing, than to lateral motion changing the area. In Fig. 2 one pair of capacitor plates is inserted in the gap 'B' and the other pair in a gap diametrically opposite, thus forming C_1 and C_2 of the bridge. Application of the torque in the sense shown reduces the gap in C_1 and increases that in C_2. This increases the value of C_1 and reduces that of C_2. For the dimensions of Fig. 2 the motion at each capacitor is given by

$$\delta g = (r_2/r_1^2)(h^3/4Et^3q)T_z \tag{1}$$

where E is the modulus of elasticity, and T_z is the applied torque. h, t and q are the leaf dimensions as shown; r_1 is the mean radius of the hollow cylinder, and r_2 is the radius to the center of the capacitor plates. The dimensions chosen to give a range of ± 0.9 N·m corresponding to a motion of ± 13.1 μm are

$$\text{leaf thickness } t = 1.18 \text{ mm}$$
$$\text{leaf width } h = 10.0 \text{ mm}$$
$$\text{leaf length } q = 7.0 \text{ mm.}$$