XIII. NEUROPHYSIOLOGY*

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A. FIBER OPTIC PROXIMITY PROBE OF NOVEL DESIGN

The fiber optic proximity probe is an important device for the measurement, without contact, of small mechanical displacements.[1,2] In an earlier report, we have shown that such a device can also be adapted to the determination, with considerable accuracy, of the location of the focal plane of a lens.[3,4] The usual form of such a device makes use of a bifurcated, randomly intermixed fiber optic light guide, as follows: Two sets of approximately equal numbers of small diameter glass light conducting fibers are fitted with terminations at their proximal ends so as to couple to a light source and a photocell. These sets of fibers are now joined, that is, randomly woven together, and share a common termination at their distal end. The polished, flat distal termination forms the proximity probe, which faces a first-surface mirror attached to the moving object, located a few thousandths of an inch away. The distance from the probe to the mirror is seen to determine the degree of spreading of the beams of emergent light before reentering the fiber bundle. The result is that the light received by the photocell is a sensitive monotonically increasing nonlinear function of the separation of the probe and the mirror.

The commercial success of this idea is due to the choice of a random intermixing in preference to a more ideally ordered array of the elements of the two sets of fibers that cannot, at present, be manufactured economically. We have tested several such randomized bifurcated light guides and found that some operate exceedingly well. Unfortunately, the required degree of random intermixing is not always achieved, and especially with fiber diameters smaller than 3 mils it is very difficult in the assembly process to effect complete randomization – the separate sets of fibers understandably tend to remain together in large clumps. Tests at our workbench with 3-mil fibers confirm the extremely taxing nature of the randomization operation, which, lacking some sort of computer control must remain an art rather than a science. It is for these reasons that

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we seek a different solution to the problem.

The method that we describe here should make it possible, in principle, to use an ordinary fiber optic light guide comprised of fibers of any practical size as a proximity probe. The method depends on the possibility of exciting two different modes of transmission in each fiber of the bundle depending on whether the light, as it is multiply reflected, spirals down the fiber in a clockwise, or counterclockwise direction, as illustrated in Fig. XIII-1. Here we show a single fiber of the bundle, which

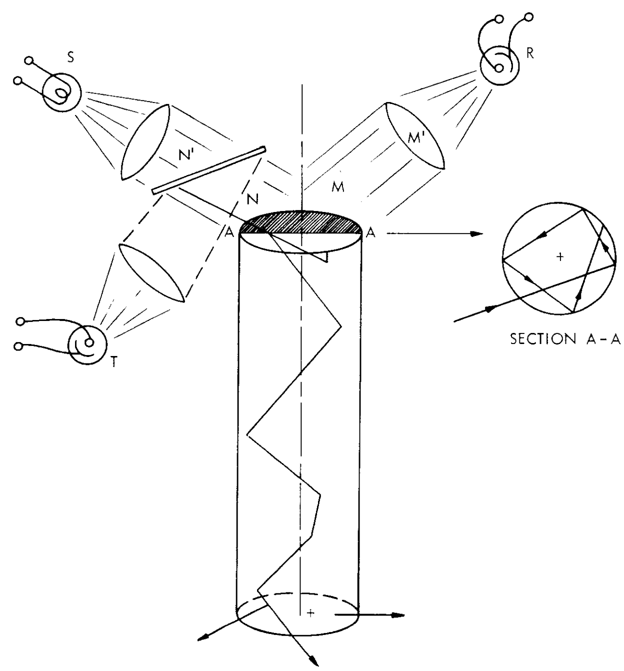

Fig. XIII-1. Arrangement of illumination, semicircular mask, and light-guiding fiber to illustrate spiral modes of light transmission through a fiber.

has been fitted at the proximal end with a semicircular aperture mask, oriented as shown, and obliquely illuminated from the direction N'N. In the cross section AA we show in an end view several successive reflections of an entering ray, as it passes down the fiber. The point to note is that the axis of the fiber lies always to the left of the ray on its downward passage,and this must remain the case even following several thousands of internal reflections that occur in each foot of light guide.

Now let us suppose that there is a mirror in contact with the far end of the fiber which reflects the light directly back. In the view of cross section AA, this light will appear to spiral in the same sense (counterclockwise), but when it emerges from the fiber, under the assumption that it is not stopped by the aperture mask, it will emerge in a direction which is, on the average, directed away from the light source. These emergent rays will form a cone of illumination, with maximum intensity in the direction MM', and minimum in the direction NN'.

Next, we consider the action of a bundle of light-transmitting fibers, each of which is equipped with its own semicircular mask, as shown in Fig. XIII-2. We have included a simple measurement test apparatus whereby we are able to adjust the location of the mirror, here the polished end surface of a micrometer shaft, relative to the polished, flat distal end of the fiber bundle. The source S provides oblique illumination, as before.

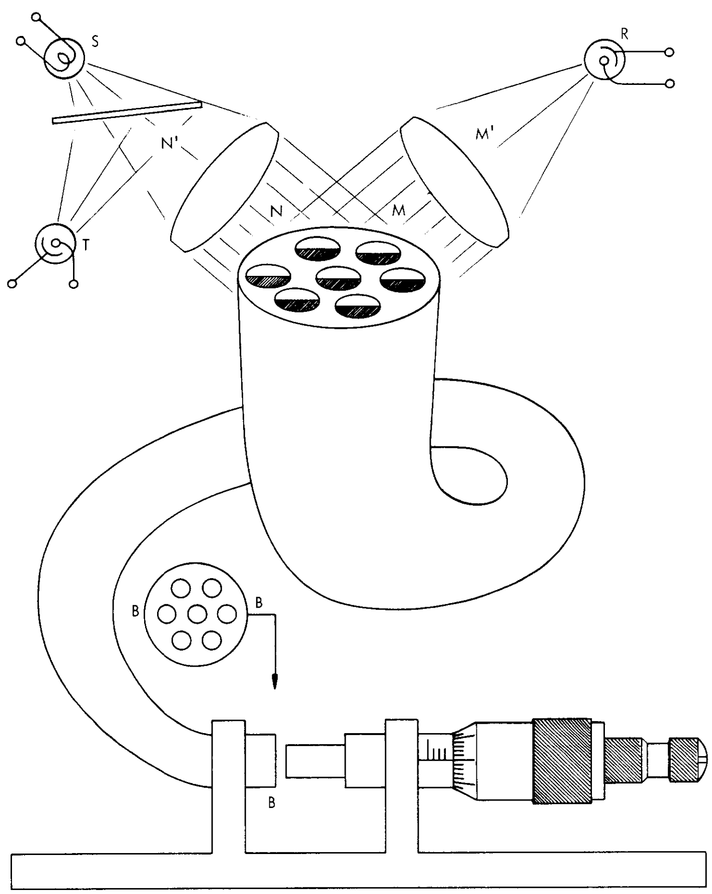

Fig. XIII-2. Arrangement of fiber bundle, photographic aperture mask, light sources, photocells, and movable mirrored surface to illustrate the method of proximity detection.

Two photocells, R and S, monitor the intensities of the cone of illumination exiting the fiber bundle in the directions MM' and NN'. Note that the distal surface of the bundle shown in cross section BB' is unmasked; furthermore, we do not postulate any coherent ordered relation between fibers at the two ends of the bundle.

The operation of the method now becomes clear: If the mirrored end surface of the micrometer is in contact with the distal end of the fiber bundle, light spirals directly back through each fiber in such a way as to emerge predominately in the direction MM', regestering on photocell R, as before. If we now move the mirror a short distance from the end of the bundle, at least some of the light will exit from the fibers and re-enter other fibers so as to spiral back with the opposite sense as before, thereby causing some finite illumination to exit in the direction NN' and register on photocell S. In the limiting case, the light intensities returning by each spiral mode of transmission will be equal. The ratio of light intensities recorded by photocells S and R is thus seen to be a sensitive measure of the distance from the surface of our probe to the mirrored surface that it opposes.

This new method (which we have not had a chance to test) has several possible advantages over the randomly intermixed fiber optic probe: (a) There will be less uncertainty in the preparation of the critical element, which is the collective semicircular aperture mask. The task of preparing this mask is within the capabilities of apparatus routinely available for microelectronics fabrication. (b) It should be possible to extend the sensitivity of the method with the use of smaller glass fibers than are practical with the randomly intermixed light guide. (c) Photographs of the cross section of fiber optic light guides show a high degree of ordering of the individual fibers, which tend to arrange themselves in hexagonal groups. Thus, we may expect that random differences in the fabrication of the original bundle will not manifest themselves as large differences in performance of the unit as a whole.

B. Howland

References

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3. B. Howland and A. F. Proll, "Apparatus for the Accurate Determination of Flange Focal Distance," Quarterly Progress Report No. 92, Research Laboratory of Electronics, M.I.T., January 15, 1969, pp. 441-445.
4. B. Howland and A. F. Proll, "Apparatus for the Accurate Determination of Flange Focal Distance," Appl. Opt. 9, 1247-1249 (1970).

B. KINEMATIC THRUST BEARING, PART II

In a previous report,[1] we described a novel form of thrust bearing which gave promise of improved accuracy and the possibility of correction of periodic errors when used in conjunction with worm gear drives. We shall now report a new version of the kinematic thrust bearing which is simpler to construct and assemble, and has the added advantage that the configuration is tractable to mathematical analysis, using a computer.

In Fig. XIII-3 we show a cross-sectional drawing of the device, which requires two sets of balls of two sizes. The outer race is constructed in two pieces, with provision for decentration of the outer segment by means of 3 set screws, in the manner of a three-jaw lathe chuck. Not visible in this drawing is the small eccentricity of the inner race, which fits on the shaft with a hole drilled 4 mils from its geometric center. Additional conventional ball bearings cause the shaft to run concentric with the inner section of the outer race.

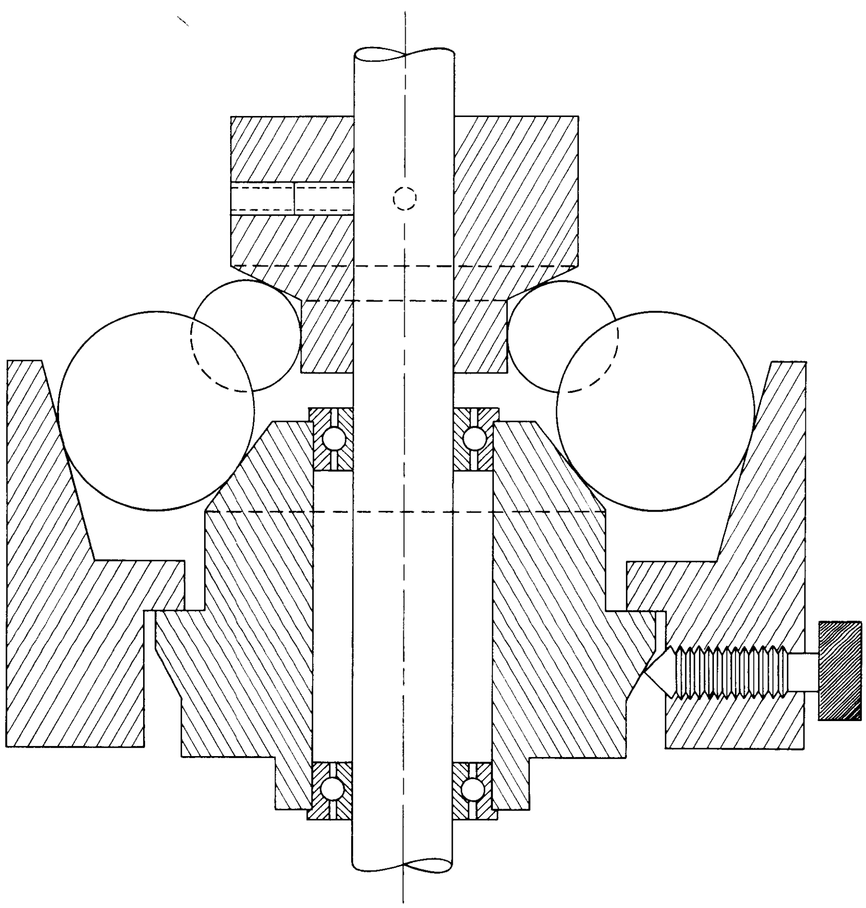

Fig. XIII-3. Cross section of kinematic thrust bearing for the case N = 6.

In Fig. XIII-4 we show the finished prototype model of the bearing with 6 pairs of balls, together with a gauge block and electronic indicator head that permits us to measure the axial displacement of the shaft to 5 microinches. (Not shown is a small

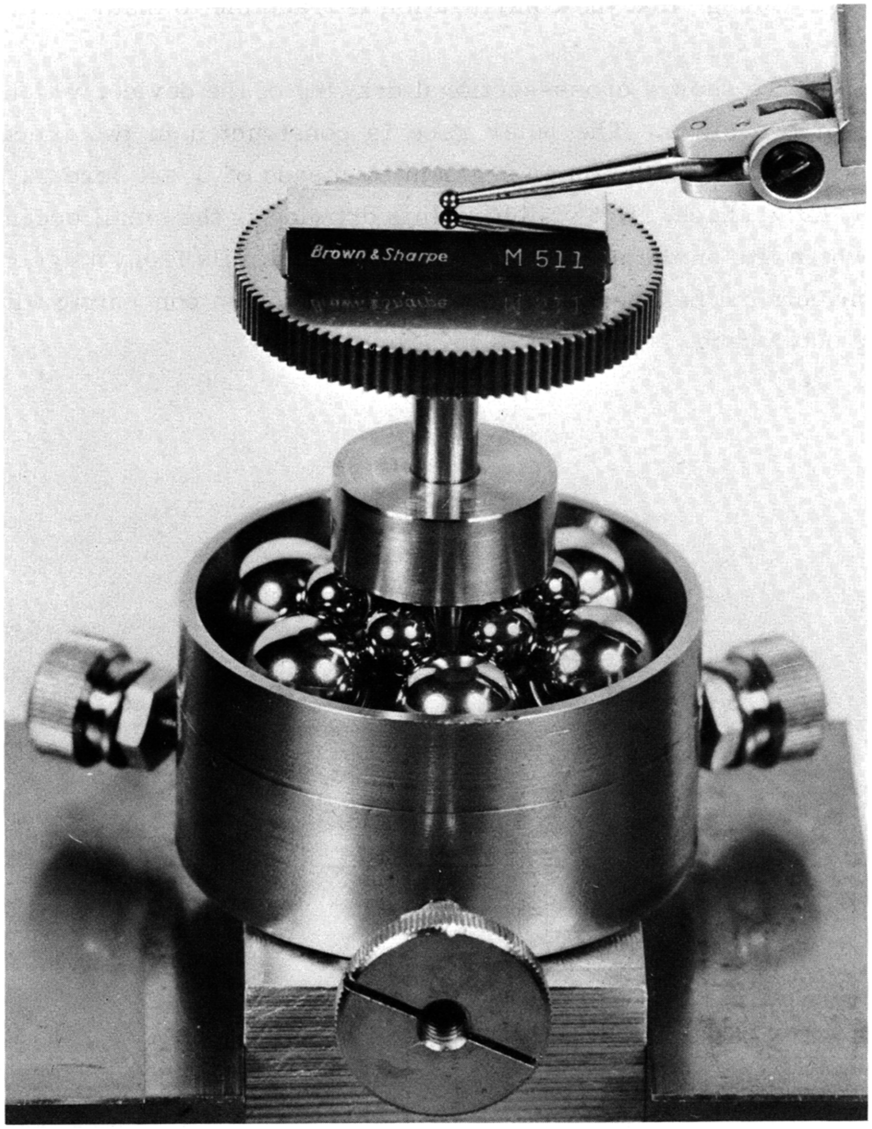

Fig. XIII-4. Photograph of kinematic thrust bearing with test apparatus to measure axial cam motion.

electric motor and gear drive that enables rotation of the bearing with minimum disturbing forces.)

The parts for this model were somewhat inexpertly machined on an old South Bend lathe, from stainless steel, and were then polished with fine emery paper. The balls were 10 microinch sphericity grade from Industrial Tektonics, made of high-speed steel. After adjustment of the screws for minimum axial runout, we measured an axial motion of between ±10 and ±15 microinches displacement, which is far better than the accuracy of the machined elements of the bearing. This result we take to be encouraging.

The cooperative action of the elements of this bearing is such as to cause the shaft to run smoothly as the inner shaft rotates, with the possibility of a very nearly sinusoidal axial camming motion, which is adjustable in phase and magnitude by means of the screws that center the outer race. We have verified this conjecture by decentering the outer race 20 mils, and measuring the axial motion, which when plotted as a function of shaft angles within the accuracy of the measurement was a sinusoidal motion having peak-to-peak amplitude of approximately 2 mils.

A second attack on the problem was performing a numerical computer analysis of the behavior of the device with different eccentricities, phases of rotation of the shaft, phasing of the balls, and so forth. To make this task feasible, we decided to change the shape of the two segments of the outer races to spherical, rather than conical. The result of this is that the track of the centers of the outer balls is always a circle, displaced and inclined to the plane of the inner balls, and very slightly diminished in size with large eccentricities. Since the machined model is made of cones that are tangent to the spheres in the mathematical model, the differences in performance for small relative eccentricities is expected to be minimal.

With this mathematical model, we wrote a computer program that successively approximates the state of the model as follows: First, we choose a trial value for axial position of the inner race. Next, we place the first ball at an arbitrarily chosen starting

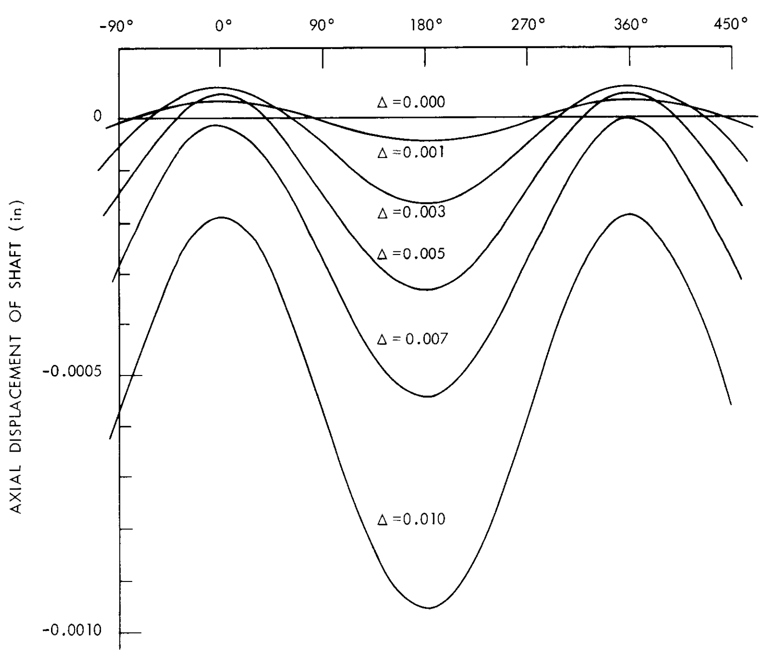

Fig. XIII-5. Computed axial cam action for different degrees of decentering of the outer raceway.

phase, and then, again using a simple iterative scheme, fit the balls in place around the circles, adding, for good measure, an $(n+1)^{th}$ ball. Now, the position of this supernumerary ball is compared with the position of the starting ball, and adjustments are made in an outer loop to iteratively adjust the axial distances so that, after a number of iterations the $(n+1)^{th}$ and the first balls coincide to the limit set by an error criterion. The axial position is then determined for a new set of input conditions.

With this program, we have been able to verify that the axial motion of our computer model (based on spherical races) is indeed similar to that which we observe with our physical model.

In Fig. XIII-5 we show the computer results for the case of an inner race eccentricity of 4 mils. We have plotted here the axial displacement as a function of shaft angle for various amounts of decentration of the outer race, with values in mils marked on the curves. The phase of this displacement is determined by the direction in which the outer race is perturbed. The shape of these curves is sinusoidal, with maximum value of harmonic distortion of 0.2%. Furthermore, even with these large displacements, the errors in axial displacement caused by random changes of phasing of the balls amount to less than 10^{-8} in. displacement. Further experiments will be required to establish the optimum proportions for the design of this device.

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