ESTIMATION OF BEARING CONTACT ANGLE IN-SITU BY X-RAY KINEMATOGRAPHY

by Peter H. Fowler* & Frank Manders**

The DSCS II Satellite consists of an earth-pointing platform carrying the transponder and antenna farm, mounted on a spinning section providing power and command. Attitude control and pointing are performed entirely in the spinning section. The whole satellite weighs about 650 kg.

The two sections are joined by the "despin mechanical assembly" (DMA), consisting of drive motors, slip rings, and a pair of ball bearings on which the spinning section revolves, all enclosed in a load bearing case (Fig. 1). The system is required to maintain precise earth pointing for at least five years at 60 rpm.

The need arose to measure the bearing contact angles in assembled units which had completed acceptance test. The usual bench methods of estimating contact angle are not applicable to a bearing assembled in an opaque case, and in any case the contact angle as assembled includes the effects of preload and assembly tolerance. Dismantling a flight-accepted unit is both costly and introduces program risk.

The usual methods of measuring bearing contact angle are the Turns method and by measuring internal clearance.

The Turns method is the most popular since it is fairly accurate, requires simple tooling and it can be performed in a relatively short time. This method provides free bearing, preloaded contact angle data. Three marks are located on the outer ring, inner ring and ball cage. These marks are initially aligned. The outer ring or inner ring is rotated a predetermined number of revolutions with the other ring restrained from rotation. The number of ball cage rotations is measured (whole number plus the fraction). The contact angle is then calculated by using the following equation:

$$\beta = \text{arc cos} \ \frac{E}{d} \left(1 - \frac{2N_E}{N_i}\right)$$

or

$$\beta = \text{arc cos} \ \frac{E}{d} \left(1 + \frac{2N_E}{N_o}\right)$$

where β is bearing contact angle
E is bearing pitch diameter
d is bearing ball diameter
N_E is number of ball cage revolutions
N_i is number of inner ring revolutions
N_o is number of outer ring revolutions

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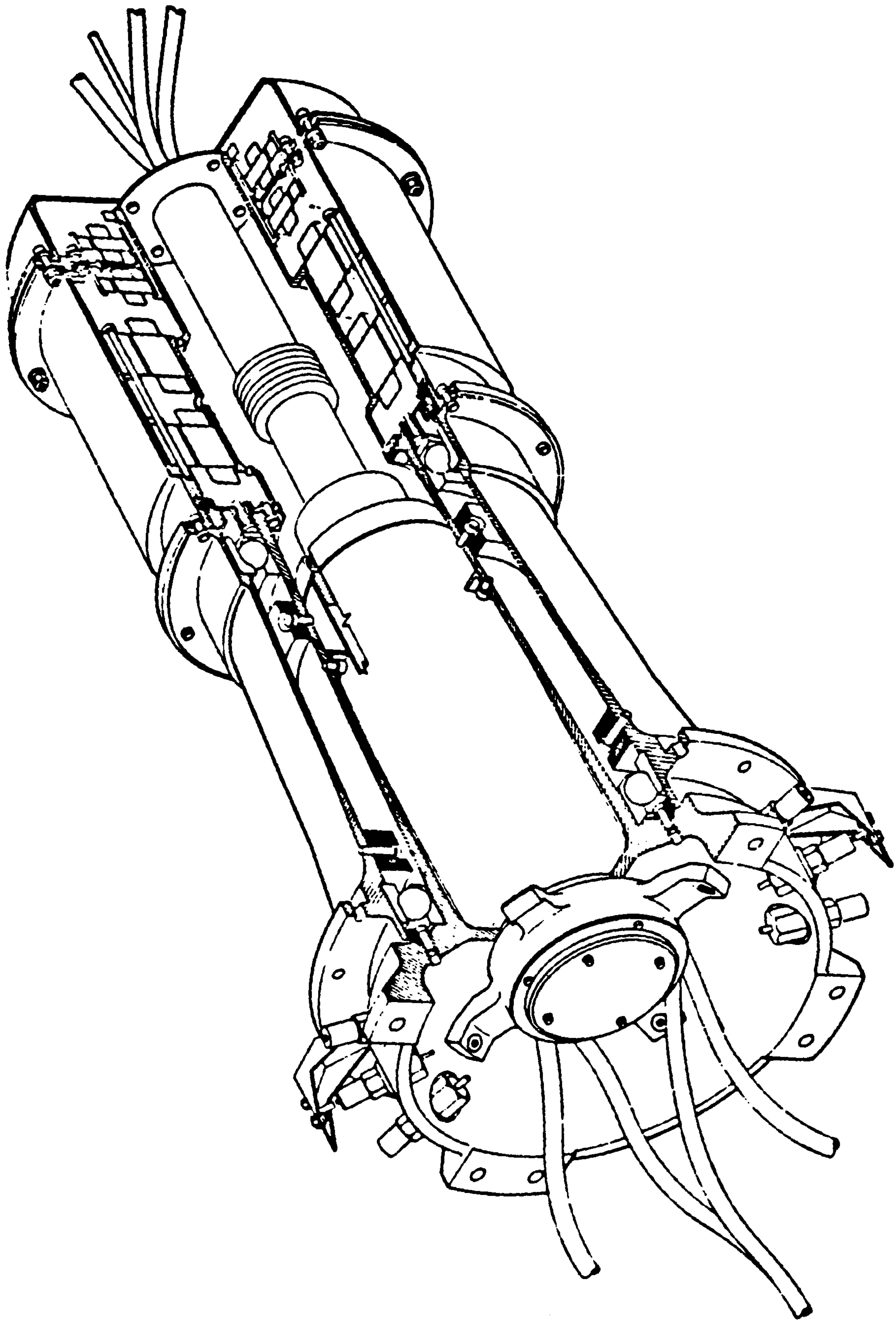


Figure 1. DMA Cutaway View

The internal clearance measurement determines the free bearing, unloaded contact angle. This method is generally used in small bearing production lines since it requires the least amount of time. The outer ring is held, while the inner ring is moved to its extreme radial positions. This motion (C) is measured and the contact angle is calculated by the following equation:

$$\beta = \text{arc cos} \left(1 - \frac{C}{2Bd}\right)$$

here C is the total diametral measurement (called radial clearance)
B is the total curvature constant = $f_o + f_i - 1$

f_o is the ratio of outer race radius to ball diameter

f_i is the ratio of inner race radius to ball diameter.

If, during installation on the shaft and in the housing, the bearing interfaces are slip fits and the bearing preload is equal to the gaged load of the free bearing measurement, the installed bearing contact angle will be as measured by either method. If, however, the bearing is installed with either or both of its interfaces press-fit and/or the preload is different from the gaged load, the mounted, preloaded contact angle is different from any free bearing measurement.

To complicate the situation, in most cases the bearings are not visible after installation in a device. Analysis can be performed to approximate the mounted preloaded contact angle, but this may result in errors of several degrees.

Our problem was to attempt to measure the mounted, preloaded contact angle of the structural bearings in the already assembly DMA.

Initially, it occurred to us that the contact angle could be measured by counter-rotating the inner and outer races at such a speed that the ball train is stationary, hoping to determine this point by x-ray observation.

The free bearing, preloaded contact angle can then be calculated from:

$$\beta = \text{arc cos} \; \frac{E}{d} \; \frac{(R_i - R_o)}{(R_i + R_o)}$$

where R_i is the speed of the inner ring

R_o is the speed of the outer ring.

This method is not normally used because the individual speeds or the speed ratio must be known to a high degree of accuracy (on the order of 50 parts per million) for reasonable ($\pm 0.25^o$) accuracy.

We proposed to construct a rather complicated device to counter-rotate the DMA shaft and housing and use this method to calculate the required contact angle.

We located an x-ray facility with a manipulator capable of mounting a DMA and with kinematic display capability. The facility is owned by Test Equipment Distributors, in Detroit. Not being familiar with the state of the art of this type of equipment, we were surprised at the clarity and definition with which moving parts could be seen. Figure 2 is a print of one frame of a video tape of the DMA in motion. The ball positions can clearly be determined with accuracy, even though, of course, the phenolic retainer position cannot be seen. A less complicated modification of the Turns method appeared practical.

Contact angle can be estimated by counting the number of balls passing a given point as a function of number of turns of the shaft. The Turns method is then modified as follows:

The angular distance between the leading edge of one ball and the leading edge of the following ball (ϕ) is:

$$\phi = \frac{360}{n} \text{ (degrees)}, \quad \frac{2\pi}{n} \text{ (radians)}$$

where n is the number of bearing balls.

The total angle for ball train motion depends upon the number of balls observed passing a stationary point or:

$$\Theta_E = N\phi = \frac{360N}{n}$$

where N = the number of balls observed passing a stationary point.

The contact angle equation then becomes:

$$\beta = \text{arc cos } \frac{E}{d} \left(1 - \frac{720N}{n\Theta_i}\right)$$

where Θ_i = the shaft angle rotation in degrees.

Using this technique and estimating the bearing individual errors (d, E, Θ_E, Θ_i) the test accuracy can easily be determined.

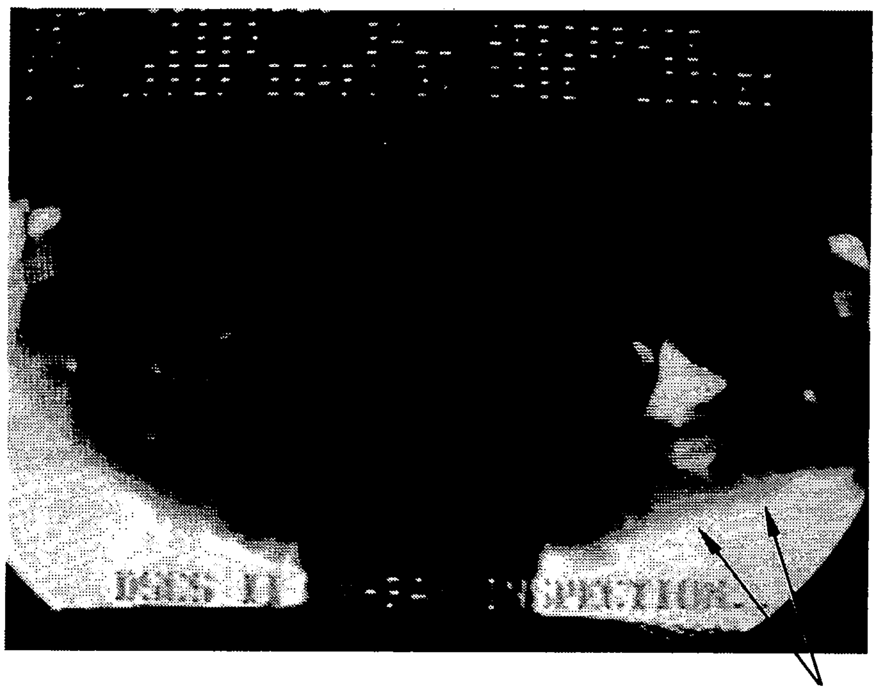
For the purpose of illustration, let us use one of the DMA bearings as an example. The basic bearing parameters are:

d = 0.5 inch[1]
E = 5.14 inches
β = 15 degrees
n = 23 balls

Ball Diameter Variation

The selection of ball diameter is one of the primary methods of setting free-bearing gaged preload. Ball diameter variation for bearing of the approximate size as the example can vary by ± 0.001 inch. The total variation within a single bearing, however, is 0.00001 inch. In our example, we have measured the basic ball size and therefore have knowledge to 10 microinches.

[1]Bearing dimensions and tolerances are given in inches, since the design and specifications were pre-SI and an arbitrary translation reduces clarity.



BALLS

Figure 2. Bearing Appearance on Video Monitor

Pitch Diameter Variation

Pitch diameter variation is the most difficult dimensional parameter to determine, since it is made up of several other dimensions which are not normally known by an aerospace applications engineer. For bearings of this size and quality, the range is ±0.001 to ±0.005 inch. For our bearing, the lower figure was used in the error analysis.

Ball Train Uncertainty

If we assume knowledge of the ball in the raceway to ±0.01 inch, the resulting error in ball train angle is about ±0.2 degree.

Shaft Angle Uncertainty

The interface fixture design will dictate the accuracy of shaft angle. If an optical encoder is used, the shaft angle error will be a small part of one degree. For our test, assume a reasonable potentiometer with a readout error of about ±0.25 degree.

Figure 3 shows the contact angle total error for the four parameters using our example bearing, counting 100 balls. This figure shows for equal uncertainty the ball position error is the more critical angular parameter and the ball diameter variation is the more critical dimensional error.

Figure 4 shows the total contact angle error as a function of the ball count and contact angle, for the expected parameters for the example bearing.

As can be easily seen, the contact angle accuracy improves with an increase in ball count and as the contact angle increases.

If we count 300 balls, the calculated contact angle will be accurate to approximately ±0.2 degree. If we increase the count to 700, the error will decrease to about ±0.1 degree. We are thus able to estimate the assembled bearing contact angle with excellent accuracy.

The measurement is made by mounting the assembly shaft on a rotating table, as shown in Figure 5. The x-ray source and imaging system are arranged to view the bearing at a convenient angle so that the balls can be tracked individually. Note that ideally the x-ray axis should be tilted rather than the device axis, as having the weight off-center alters the net preload and side-loads the bearings.

A ball position is marked on the viewing screen, and the shaft rotated slowly some preset number of times. The number of balls is counted, including the fraction. Alternately the shaft may be rotated until some preset number of balls has passed, and the total shaft angle read off. In principle the counting could be automated, but for an occasional measurement on a high-value device this is not worthwhile.

Using a modern image multiplier, the total x-ray dose is very small, insignificant compared with the energies and integrated fluxes of a life in orbit. Radiation damage to lubricant and other parts is thus not a factor in the measurement.

The DMA has a beryllium housing and shaft, with stainless steel balls and races. The x-ray source for clear viewing of the ball positions is about 1 mA at 50 kV. A sharp focus x-ray source and imaging system is capable of showing ball position when the ball is as little as 2% of the total x-ray density. Thus, the measurement could be made as easily if the case and shaft were also stainless steel.

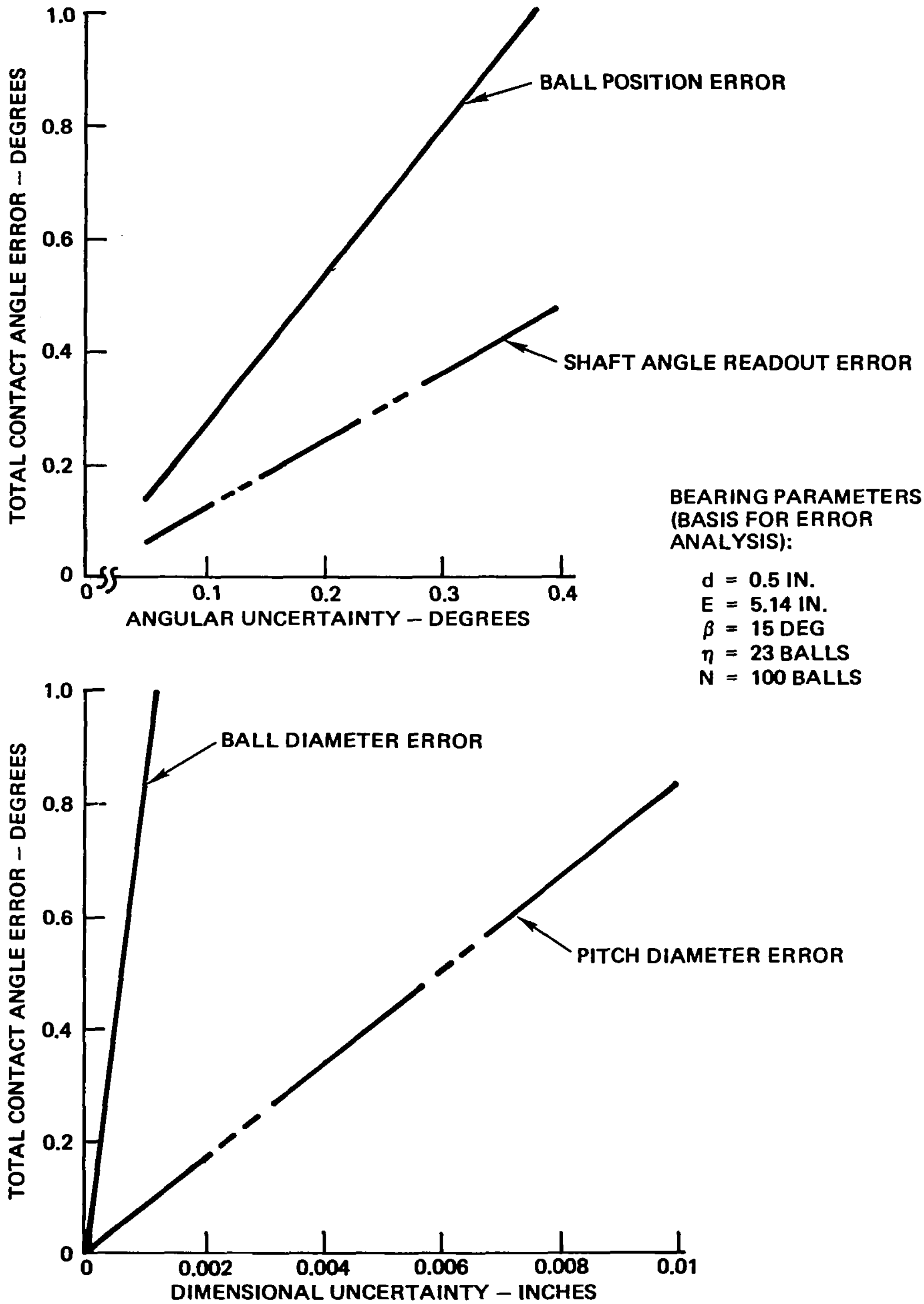


Figure 3. Effect of Measurement Uncertainty on Contact Angle Calculations

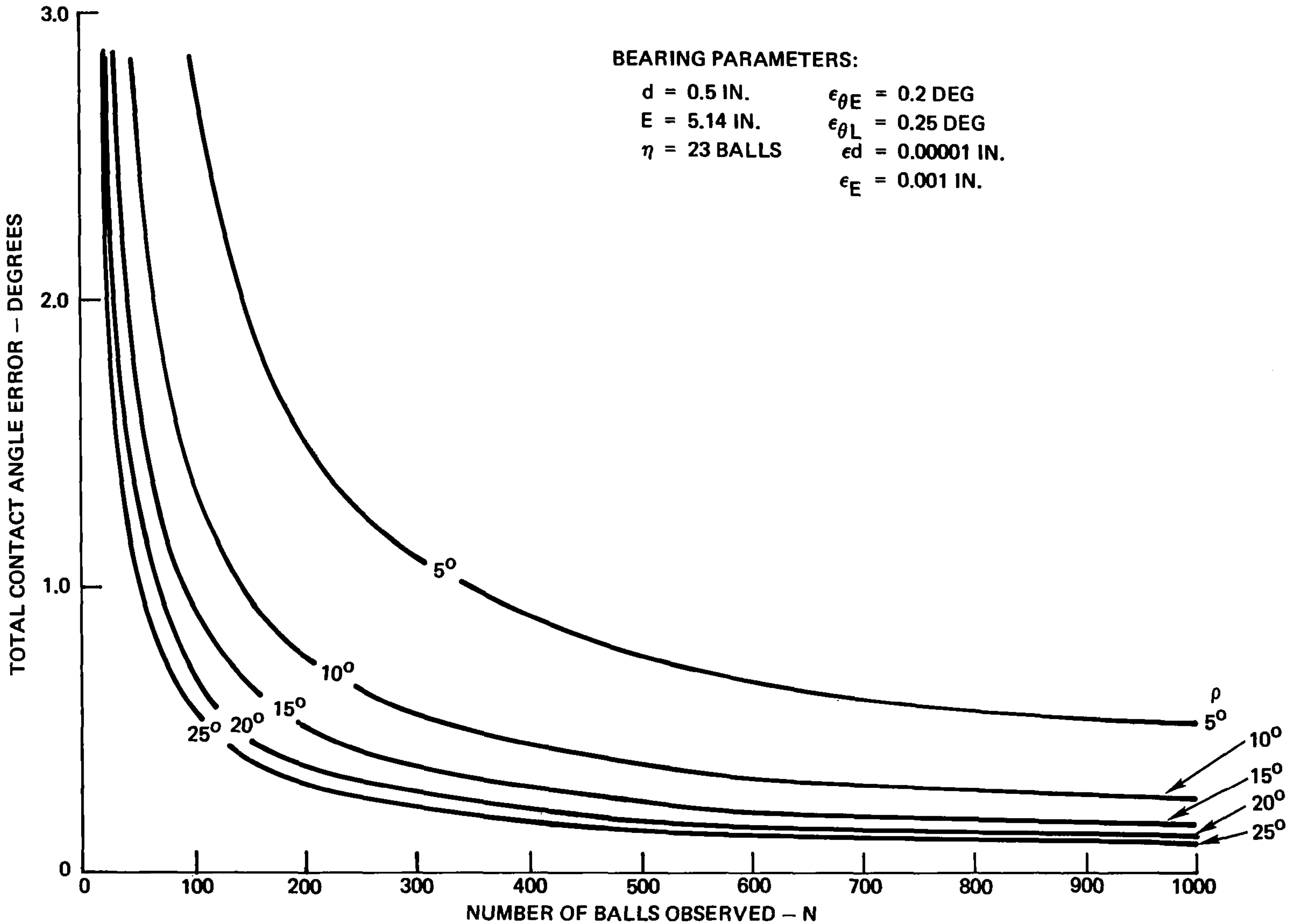


Figure 4. Effects of Ball Count on Contact Angle Calculations

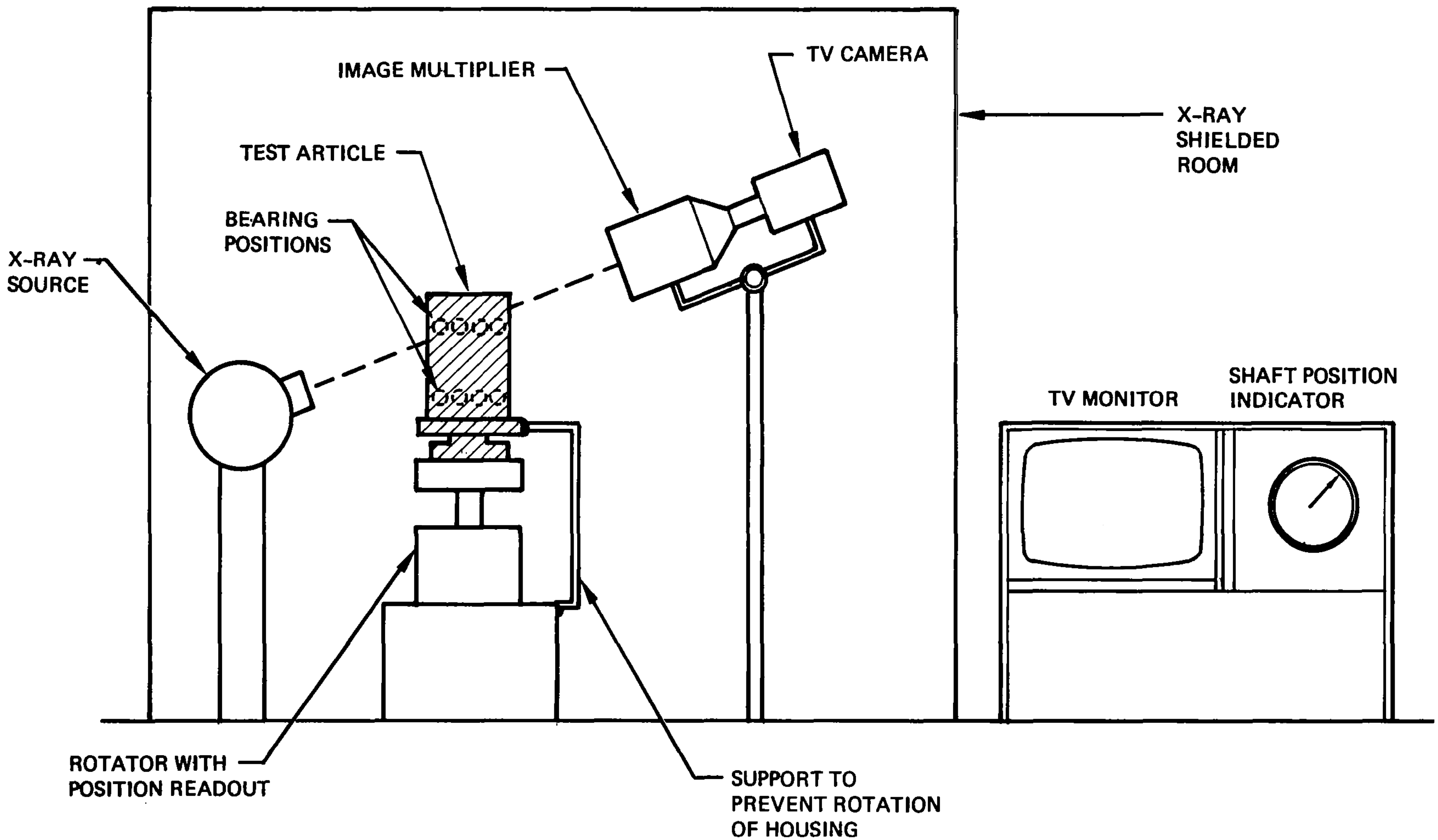


Figure 5. Measurement System

For the DMA, and other comparable-value equipment, it is good practice to make a simultaneous video tape of the monitor as this provides a record of the correctness of the ball count. Since the DMA has a large wire bundle coming out of each end and other connections with opportunity for interference, it is also wise to lock the case with tape or similar easily broken connection. If something hangs up, the case will then pull free and only the measurement is lost.

We suggest that the method described is useful in confirming capability of assembled units, and facilitates in-situ adjustment of preload to obtain a defined contact angle.

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Mr. Fowler was educated in England, emigrating to the United States in 1957. He is currently System Engineering Subproject Manager for the Defense Communication Satellite Phase II. Previous responsibility at TRW includes Assistant Project Manager for the Viking Lander biology and meteorology experiments. Prior to joining TRW in 1967, he worked on test equipment design, communication system design, and launch vehicle reliability. He holds patents on a temperature-compensated accelerometer and a pneumatic shock machine. In addition, Mr. Fowler has written papers on wideband shaker design, system pathology, and orbital experience with TWTA reliability.

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