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ANSI-B89.3.1, "Out of Roundness, Measurement Of," was adopted on October 3, 1994 for use by the Department of Defense (DoD). Proposed changes by DoD activities must be submitted to the DoD Adopting Activity: Commander, Naval Air Warfare Center, Aircraft Division (API Group), Systems Requirements Department (SR3), Highway 547, Lakehurst, NJ 08733-5100. DoD activities may obtain copies of this standard from the Standardization Document Order Desk, 700 Robbins Avenue, Building 4D, Philadelphia, PA 19111-5094. The private sector and other Government agencies may purchase copies from the American National Standards Institute, 11 West 42nd Street, New York, NY 10036.

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AMERICAN NATIONAL STANDARD

Measurement of Out-Of-Roundness

ANSI B89.3.1 - 1972
REAPPROVED '79

SECRETARIAT

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS

PUBLISHED BY

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS

United Engineering Center 345 East 47th Street New York, N.Y. 10017

FOREWORD

This Foreword is not a part of American National Standard Measurement of Out-of-Roundness, ANSI B89.3.1.

At the October 29, 1958 meeting of the American Standards B46 committee on "Surface Texture" a special subcommittee was formed to investigate the definition and usage of surface waviness specifications, particularly the application to round parts.

The subcommittee first met on February 19, 1959 and determined in this and subsequent meetings that the specification and measurement of out-of-roundness was the most important task.

Exploratory discussions and coordination of approaches were held at The American British Canadian Conferences on the Unification of Engineering Standards in June, 1960 and September, 1962.

In June, 1963, the ASA B89 Committee was formed to investigate and standardize the metrological aspects of dimension, geometry and form and the functions and personnel of the B46 subcommittee were transferred to the B89.3 Geometry Subcommittee Working Group 1 "Roundness".

At this point, an attempt was made to develop a unified approach to the centers and axis concepts for out-of-roundness measurement purposes and the similar concepts used for concentricity, effective size, and other feature characteristics being explored by other B89 Working Groups. However, after a considerable period of study, this approach proved to be impractical.

A series of draft standards were prepared beginning in 1965 in which the out-of-roundness characteristic and criteria are not necessarily related to other concepts. The British Standard 3730:1964 "Methods for the Assessment of Departures from Roundness" follows a similar approach.

The final draft of the proposal was approved by the ANSI B89 Sectional Committee by letter ballot, on November 19, 1971.

Upon approval by the sponsors, the final draft was approved by the American National Standards Institute on August 24, 1972.

Suggestions for improvement gained in the use of this standard will be welcome. They should be sent to the American National Standards Institute, Inc., 1430 Broadway, New York, New York 10018.

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CONTENTS

AMERICAN NATIONAL STANDARD

MEASUREMENT OF OUT-OF-ROUNDNESS

1 SCOPE

1.1 General

This standard covers the specification and measurement of out-of-roundness of a surface of revolution by the evaluation of a typical cross-sectional profile in terms of its radial deviations from a defined center. While this standard deals primarily with precision spindle instruments for out-of-roundness measurement and polar chart presentation, it is not the intent here to exclude other methods which will provide valid radial deviation data. This standard does not define the design requirements for roundness suitable for specific purposes, nor does it specify the manufacturing process for production of roundness.

1.2 Appendix Sections

The complexity of roundness measurements has necessitated the publication of a series of Appendix sections which describe other out-of-roundness indication methods, their applications and limitations. Other general information and specific examples of out-of-roundness measurement may be found in the Appendix, which the reader is urged to study. The Appendix sections shall not be considered a part of this standard.

2 DEFINITIONS

2.1 Surfaces vs. Profiles

Direct evaluation of a surface of revolution as a whole is normally quite difficult. However, a series of cross-sectional profiles will describe the surface sufficiently for a given function. Consequently, cross-sectional planes are usually specified and their profiles measured. Reconstruction of surfaces from cross-sectional profiles is described in Appendix paragraph E1.3.

2.2 Nominal Profile

Nominal profile is the intended cross-sectional profile, the shape and extent of which is usually shown and dimensioned on a drawing or descriptive specification.

2.3 Actual Profile

The actual profile is the cross-sectional profile of the part feature.

2.4 Measured Profile

The measured profile is a representation of the actual profile obtained by a particular measurement method.

2.4.1 Measured Polar Profile (Polar Chart). The measured polar profile is the measured profile which has been recorded about a center, or axis of rotation, wherein the central angles of the measured profile features do not differ significantly from those of the circular surface.

2.5 Ideal Roundness

Ideal roundness is the representation of a planar profile all points of which are equidistant from a center in the plane.

2.6 Out-of-Roundness

Out-of-roundness is the radial deviation of the actual profile from ideal roundness.

2.7 Out-Of-Roundness Value

The out-of-roundness value (OOR) shall be the difference between the largest radius and the smallest radius of a measured profile; these radii are to be measured from a common point, selected as one of the centers referred to in paragraphs 2.8 and 2.9. The unit of measurement shall be inches, unless otherwise specified.

2.7.1 Nicks, Scratches, Etc. Nicks, scratches, or other random flaws are not normally included in the assessment of the measured profile; special notes on the drawing or specification should be used to control these irregularities.

2.8 Centers for Out-Of-Roundness Measurement

The centers of the measured polar profile which may be used to determine the out-of-roundness value when specified are those related to one of the following alternative methods of out-of-roundness assessment:

2.8.1 Minimum Radial Separation (MRS). This center is that for which the radial difference between two concentric circles which just contain the measured polar profile is a minimum[1].

2.8.2 Least Squares Center (LSC). This center is that of a circle from which the sum of the squares of the radial ordinates of the measured polar profile has a minimum value.

2.8.3 Maximum Inscribed Circle (MIC). This center is that of the largest circle which can be inscribed within the measured polar profile[2].

2.8.4 Minimum Circumscribed Circle (MCC). This center is that of the smallest circle which will just contain the measured profile.[3]

2.9 Preferred Center

The center from which the out-of-roundness value shall be determined unless specified otherwise is the Minimum Radial Separation Center.

3 SPECIFICATION AND DESIGNATION OF OUT-OF-ROUNDNESS

3.1 Lack of Roundness Specification

Where no out-of-roundness value is specified, it shall be assumed that the surface profile produced is satisfactory. If the out-of-roundness of the surface is critical, the out-of-roundness value should be specified.

3.2 Roundness Statement and Symbol

An out-of-roundness specification statement, such as, "This surface must be round within - - - - inches," shall mean that any cross section covered by that specification shall be measured in a plane whose position is specified in paragraph 4.1, and shall have an out-of-roundness value as defined in this standard equal to or less than that specified.

3.2.1 Roundness Symbol. The symbol for roundness as shown in Fig. 1 and Fig. 2, is an extension of the geometric characteristic symbols used for feature control in American National Standard Y14.5–1966, "Dimensioning and Tolerancing for Engineering Drawings". Usually the proper measurement plane is obvious. Where the plane of out-of-roundness measurement is not obvious or must be controlled relative to a particular part feature, such as parallel to a shoulder surface or perpendicular to a specific axis, this specification must be added to the roundness symbol.

3.2.2 Symbol Interpretation

3.2.2.1 *Minimum Roundness Symbol.* The specification in Fig. 1 means the out-of-roundness shall not exceed 0.000025 inch. Since complete measurement conditions for a stylus type instrument[4] have not been specified here, it is understood that where such an instrument is used, the following shall be in effect:

Method of Assessment–Minimum Radial Separation (see par. 2.9)
Instrument Response–50 Cycles per Revolution (see par. 5.2)
Stylus Tip Radius–0.01 in. (see par. 5.3)

○	.000 025

FIG. 1 MINIMUM ROUNDNESS SYMBOL

3.2.2.2 *Complete Roundness Symbol.* This symbol shown in Fig. 2 is used when measured conditions must be specified.

[1] This is also known as the center for minimum Total Indicator Reading (TIR). The British Standards Institution publication 3730:1964 refers to it as Minimum Zone Center (MZC).

[2] This is also known as the plug gage center and is generally used for internal diameters.

[3] This is also known as the ring gage center and is generally used for external diameters.

[4] See Section 5, Instruments.

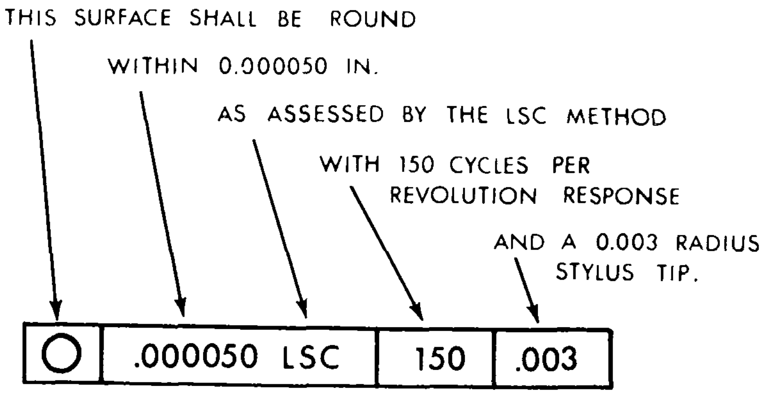

FIG. 2 COMPLETE ROUNDNESS SYMBOL AND INTERPRETATION

4 SELECTION OF MEASUREMENT POSITIONS

4.1 Angular Position of Profile Plane

The position of the measurement plane shall be determined by the related datum feature, e.g., perpendicular to a cylindrical surface or datum axis, or parallel with an end face or shoulder. An example of a properly and improperly positioned measurement plane is shown in Fig. 3.

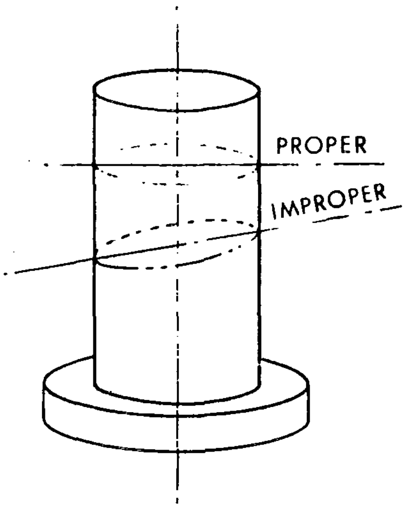

FIG. 3 ANGULAR POSITION OF MEASUREMENT PLANE

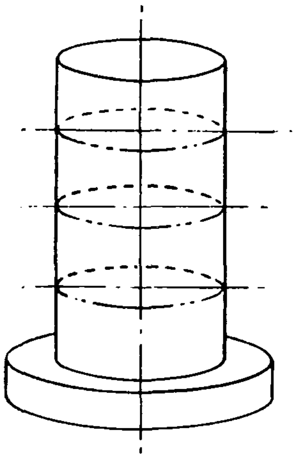

FIG. 4 AXIAL POSITIONS OF MEASUREMENT PLANES

4.2 Number and Axial Location of Profile Planes

The axial locations and the minimum number of out-of-roundness measurements that are required to define the surface of a three-dimensional body cannot be specified in this standard. Sufficient measurements should be taken to ensure that the measured profiles are typical.

4.3 Location of Part Center—Relation to Instrument Axis

Any eccentricity between the center of the part, as determined from the measured profile center of paragraph 2.7, and the rotational axis of the measuring instrument causes a distorted representation of the profile.[1] This distortion increases with increasing ec-

[1] See Appendix D2.1.

centricity. To reduce this distortion to a negligible amount and to properly center incomplete circular surfaces, the Center for Out-of-Roundness Measurement, as determined by paragraph 2.8 or 2.9, shall coincide with the rotational center of the polar chart within 0.1 inch plus 5 percent of the radial distance between the innermost profile point and the chart rotational center.[1]

5 INSTRUMENTS

5.1 General

Out-of-roundness as defined in this standard is usually measured by methods involving a stylus in contact with the part surface. Analog or digital techniques are used to reconstruct for graphical recording (usually on a polar chart) the magnified radial movements of the stylus, as either the stylus or the part is rotated around an accurately defined axis. This section of the standard is concerned only with this type of instrument. While this section deals with contacting stylus instruments, other non-contacting sensors which produce similar radial deviation data are not excluded from this standard.

5.2 Cycles Per Revolution Response

This term refers to the measurement characteristic of the instrumentation which limits the number of regularly spaced sine-wave shaped undulations of the actual profile that will be correctly represented by the measured profile[2]. For the purposes of this standard, the term Cycles Per Revolution response shall mean that number of cycles at which 70.7 percent of the amplitude data has been correctly transmitted through the instrument. The upper and lower response frequencies of the instrument shall correspond with the Cycles Per Revolution response values selected from the following:

0, 1.67, 5, 15, 50, 150, 500, 1500.

If no response figures are specified, the 0–50 values shall be assumed. If only a single response figure is specified, it shall be the upper response value and the lower value shall be zero.

5.3 Stylus Radius

Selection of the nominal stylus radius should be made with the part surface characteristics in mind[3], and should be chosen from the series shown in Table 1.

Table 1. Stylus Radius and Force Combinations

Nominal Stylus Radius in.	Max. Stylus Force – gms. Steel or Harder Mat'l.*
0.001**	0.5
0.003	2.0
0.010	5.0
0.030	10.0
0.100	20.0

Note: A stylus radius of 0.010 in. shall be assumed if no radius is specified.

* For materials softer than Rockwell "C" hardness of 20, the stylus force should be selected to prevent objectionable plastic deformation of the surface, yet should be high enough to reduce stylus bounce and produce repeatable traces.

** Fine surface irregularities, e.g. surface roughness, may be penetrated by a stylus of this or smaller radius, which may confuse and render difficult the interpretation of measured profiles as prescribed in this standard.

5.4 Tolerances on Stylus Radii

The actual range of stylus spherical radii shall be within 50 percent to 200 percent of the nominal value listed in Table 1.

5.5 Stylus Static Force

The appropriate stylus force[4] to maintain adequate contact with the part surface will depend upon the hardness, the flexibility, and the maximum compressive strength of the part material, the rotational speed and mass of the stylus assembly (for rotating stylus instruments), and the stylus tip radius. To minimize surface damage from high compressive stresses yet maintain a high contact pressure for consistent measured profiles, the maximum stylus force for each nominal stylus radius shall be determined from Table 1.

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[1] Based on a maximum allowable chart distortion of approximately 0.01 in. due solely to profile eccentricity.

[2] See Appendix C3 and D1.1 for further discussion of Cycles Per Revolution Response.

[3] See Appendix D1.2.

[4] See Appendix D1.3.

APPENDIX A

BASIC CONCEPT OF ROUNDNESS MEASUREMENT

A1 OBJECTIVE OF THE MEASUREMENT

The objective of roundness measurement is to evaluate form errors of components as opposed to feature size. Whenever one or more surfaces of a cylinder, cone, or sphere are required to have roundness of a high order, cross-sections of the feature must be measured to assure that the profile falls within the required form tolerance.

A1.1 Roundness Tolerance

Ideally all tolerances should be functionally derived, whether they be of form, size, texture, or other parameter. The tolerance on roundness should not be implied by related feature tolerances, such as size or surface texture.

A2 BASIC MEASUREMENT CONSIDERATIONS

The measurement of roundness is difficult to perform directly. It is usually necessary to measure and interpret a series of cross-sectional profiles assumed to be typical of the entire surface. These measured profiles are generally sufficiently accurate for functional evaluation and control.

[1]See Appendix D1.2.
[2]See Appendix D1.1.

A3 REDUCTION OF ROUGHNESS EFFECTS

Since the cross-section is of such importance, its selection must assure typicality. Also the measurement process should eliminate or minimize the effects of surface roughness, which occur in both the axial and circumferential planes. The effect of axial surface roughness should be reduced by the use of a sensor of relatively large effective area, e.g., a large radius stylus tip[1], either spherical or hatchet shaped.

The circumferential roughness effect should be reduced by the proper use of a large area sensor and a sufficiently low Cycles Per Revolution response value[2]. Unless surface roughness effects are reduced to a negligible amount, the roughness characteristics may cause a significant increase in the out-of-roundness value observed.

A4 UNIFIED MEASUREMENT PROCEDURES

Since out-of-roundness is determined by indirect means, and the part or work piece is judged by some measured representation, the results can be affected by the selection of the cross-sections, the instrument data-gathering processes, recorded chart distortions, and differences in interpretation. If the conditions defined in this standard and its appendices are applied, these variables will be reduced to tolerable proportions.

APPENDIX B

CAPABILITIES AND LIMITATIONS OF VARIOUS METHODS OF MEASUREMENT

B1 MEASUREMENT OF OUT-OF-ROUNDNESS

B1.1 Non-Standard Measurement Methods

Widespread usage throughout the metalworking industry of out-of-roundness measurement techniques by methods other than the use of precision spindle instruments prompts this discussion of their limitations. Although these secondary methods rarely yield accurate out-of-roundness values, the methods may be of value in comparison tests where functional or performance criteria have been related to geometric conditions based on that particular roundness measurement method. These techniques should be regarded only as a convenient, low investment approximation of the true out-of-roundness value.

B1.2 Out-of-Roundness Determined by Diametral Measurements

One of the most common methods of measuring out-of-roundness, not covered by this standard, is by the comparison of diameter measurements made in a common, cross sectional plane, such as those made by a micrometer, bore gage, or comparator stand. Two-point measurement methods can determine the out-of-roundness value only where the part is known to have an even number of uniformly spaced and uniformly sized lobes or undulations around its periphery. For this particular case, the difference in the diametral measurements will generally be twice the out-of-roundness value, due to the diametral vs. radial method of assessment.

B1.2.1 For parts having an odd number of lobes, the difference in diametral measurements generally will be smaller than the true radial out-of-roundness value and will diminish to zero for uniform symmetrically-shaped lobing. Parts having an even lobed surface will produce diametral out-of-roundness values larger than the true value.

B1.2.2 In any case where the diametral measurements are to be used as an indication of out-of-roundness, the lobing condition must be taken into account. There is no universal method for converting difference in diameter readings to out-of-roundness values as defined in this standard.

B2 OUT-OF-ROUNDNESS DETERMINED BY V-BLOCK MEASUREMENT

B2.1 Shapes with Odd Numbers of Lobes

As with diametral measurements, the accuracy of the roundness determination by V-block measurements is dependent upon the knowledge of the number and uniformity of the lobing. V-block measurements can be somewhat more useful than diametral measurements, however, as shapes with a known odd number of *uniform* symmetrically shaped lobes of equal size and uniform distribution can be related by a conversion factor to the out-of-roundness value when a V-block of proper included angle is used. These factors are tabulated below:

Table B1. OOR by V-Blocks

Number of Lobes	V-block Included Angle	Ratio: $\frac{\text{V-block Indicator Reading}}{\text{Out-of-Roundness Value}}$
3	60°	3.000
5	108°	2.236
7	128°34′	2.110
9	140°	2.064

There is no single V-block angle which will cover all numbers of odd-lobed parts.

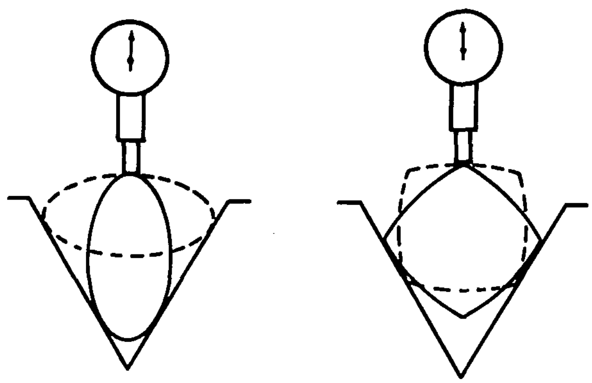

FIG. B1 EVEN-LOBED SHAPES IN 60° V-BLOCK

B2.2 Shapes with Even Numbers of Lobes

The V-block measurement system is not as useful for shapes with even numbers of lobes as the diametral method described in section B2.1. The V-block tends to diminish the total indicator readings of even-lobed shapes, sometimes to nearly zero. The two-lobed shape and the four-lobed shape in the 60° Vee, shown in Fig. B-1, will show only a slight variation in each total indicator reading.

B2.3 Usefulness of V-Block

The major disadvantage of the V-block method is that it is not sensitive to all types of lobing. Conversion factors are of value only when the part has a known number of *uniform* lobes. It may be of limited value to detect an out-of-roundness condition on a comparative basis among similarly machined parts, provided that sample parts are periodically examined by the standard circular profile method to verify the presence of the assumed type of lobing.

It should be mentioned also that V-block measurements are not 2-dimensional, but instead the part rides on its highest peaks along the contact length with the V-block surfaces.

One common failing of both the 2-point and V-block measurement methods is the lack of a fixed center.

B3 OUT-OF-ROUNDNESS DETERMINATIONS BY OTHER METHODS

B3.1 Radial Measurement on Centers and by Master Comparison

Other less commonly used methods for the determination of out-of-roundness include the radial measurement of the part as it is rotated on its own axis, i.e., on its own centers, and by the comparison of radial deviations with a master cylinder as both part and master cylinder are rotated on a common axis. In the former method, the shape, angularity, and alignment of the center holes, a secondary geometric feature, have a predominant effect on the accuracy of the measurement and must be controlled to a much greater degree than the roundness accuracy desired. Also, the indicated out-of-roundness will include the eccentricity of the measured cross section in relation to the axis of rotation, and the effects of bending. The master cylinder comparison method requires very accurate centering of cylinder and part but eliminates the troublesome effect of center holes as in the former method and is inherently more accurate.

B3.2 Other Commercial Gages and Instruments

There are also a number of proprietary gages available for out-of-roundness indication based on multiple chord measurements and other techniques. The manufacturer should be consulted regarding the capabilities and limitations of the measurements made with this equipment.

APPENDIX C

ASSESSMENT OF OUT-OF-ROUNDNESS BY PRECISION SPINDLE INSTRUMENTS

C1 REFERENCE CIRCLES ON MEASURED POLAR PROFILES

C1.1 Four Assessment Methods

The trace produced by a polar recording instrument is simply a graphical record, suitably magnified, of the displacement of the stylus of the measuring element, as either the stylus or the part rotates on the axis of rotation of the precision spindle. The out-of-roundness value can be assessed by the difference between the maximum and minimum radial ordinates of the profile measured from a specific center. Four ways in which such a center may be located are defined in this standard. They are:

1. Minimum Radial Separations (MRS)
2. Least Squares Circle (LSC)
3. Maximum Inscribed Circle (MIC)
4. Minimum Circumscribed Circle (MCC)

These are discussed in the following paragraphs.

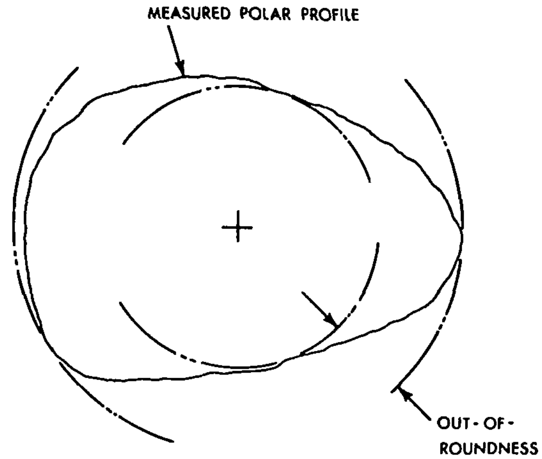

FIG. C1 MINIMUM RADIAL SEPARATION

C1.2 Minimum Radial Separation Method (MRS)

C1.2.1 In this method, two concentric circles are chosen so as to have the least radial separation and yet contain between them all of the polar trace, as shown in Fig. C1. This radial separation is the measure of the out-of-roundness value. The radial difference between concentric circles determined by this method is numerically unique, in that by definition a smaller value cannot exist.

C1.2.2 Practical Assessment – Graphical Methods (MRS). The proper location and size of the inscribed and circumscribed circles are most conveniently determined with engraved or printed circles on transparent templates. The radial separation can be noted from the engraved circles directly or measured from auxiliary concentric circles which can be drawn from the center located by the engraved circles. The radial separation measurement can be divided by the appropriate chart amplification factor to produce the out-of-roundness value. Trial-and-error methods with a bow compass can also determine the size and location of the boundary circles, but these methods generally are slower than those using transparent templates with engraved circles. By any method, however, at least two outer contact points and at least two inner contact points must occur alternately, but not necessarily consecutively, for one complete profile traverse.

C1.2.3 MRS Assessment by Meter Readings. Part out-of-roundness, as measured on precision spindle instruments, can be assessed by meter or indicator readings of radial deviations using MRS criteria. However, the centering between workpiece and instrument spindle axis must be done to a greater degree of concentricity than in the graphical polar chart methods to eliminate the effect of eccentricity on the out-of-roundness reading. The centering must be carried out such that the variation in the total meter or indicator reading is a minimum. This condition is reached (1) when the maximum excursions of the indicator needle reach at least two equal inward and two equal outward points, and (2) when two maximum outward points are separated by a maximum inward point and two maximum inward points are separated by a maximum outward point during one complete and continuous traverse of the profile. The total meter readings is then a correct indication of the out-of-roundness value by the MRS method.

C1.2.4 Characteristics of the MRS Method. The concept of the Minimum Radial Separation method is practical in nature since it resembles the conventional shop practice of seeking the position of the minimum total indicator reading (TIR) for the centering of circular parts. The relationship of reference axes, e.g., coaxiality, concentricity, etc., on a common part is simplified by the assessment of their datum surfaces by the MRS method, since both internal and external surfaces are treated alike. The axes of an internal surface and an external surface of a circular object having a constant wall thickness would coincide regardless of their profile shapes when the MRS method was used for determining their centers. Also natural polar chart distortions, which have their greatest effect on the extreme features of the polar profile, are reduced to a minimum by the MRS method, since this method centers the profile into an annulus of the least extremities.

C1.3 Least Squares Circle Method (LSC)

C1.3.1 In this method a theoretical circle is located within the polar profile such that the sum of the squares of the radial ordinates between the circle and the profile is a minimum. The out-of-roundness value would be determined by the sum of the maximum inward and maximum outward ordinates divided by the proper chart amplification factor.

C1.3.2 Determination of the Least Squares Circle and Its Center[1]. The position of the center of the least squares circle and the value of its radius can be calculated from simple approximate formulae. Referring to Fig. C3, the practical procedure is as follows: From the center of the chart draw a sufficient number

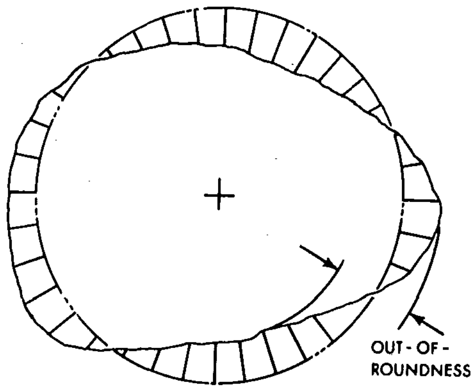

FIG. C2 LEAST SQUARES CIRCLE

of equally spaced radii. In the illustration they are shown, numbered 1–12. Two of these at right angles are selected to provide a system of rectangular coordinates –XX and –YY.

The distances to the points of intersection of the polar trace with these radii, P_1 to P_{12}, are measured from the axes –XX and –YY, taking positive and negative signs into account.

The distances a and b of the least squares center from the center of the paper are calculated from the following approximate formulae:

$$a = \frac{2 \times \text{sum of } x \text{ values}}{\text{number of ordinates}} = \frac{2\Sigma x}{n}$$

$$b = \frac{2 \times \text{sum of } y \text{ values}}{\text{number of ordinates}} = \frac{2\Sigma y}{n}$$

If desired, the distances from the center of the chart to the polar graph may be read and be used in the following alternate formulae along with the angle θ_i from the chosen +X coordinate. Therefore:

$$a = \frac{2}{n} \sum_{i=1}^{n} (R_i \cos \theta_i)$$

$$b = \frac{2}{n} \sum_{i=1}^{n} (R_i \sin \theta_i)$$

The radius R of the least squares circle, if wanted, is calculated as the average radial distance of the points P from the center, that is:

$$R = \frac{\text{sum of radial values}}{\text{number of ordinates}} = \frac{\Sigma R_i}{n}$$

[1] This section (a manual method for use with analog instruments) is abstracted from the British Standard 3730:1964, Assessment of Departures from Roundness, published by the the British Standards Inst.

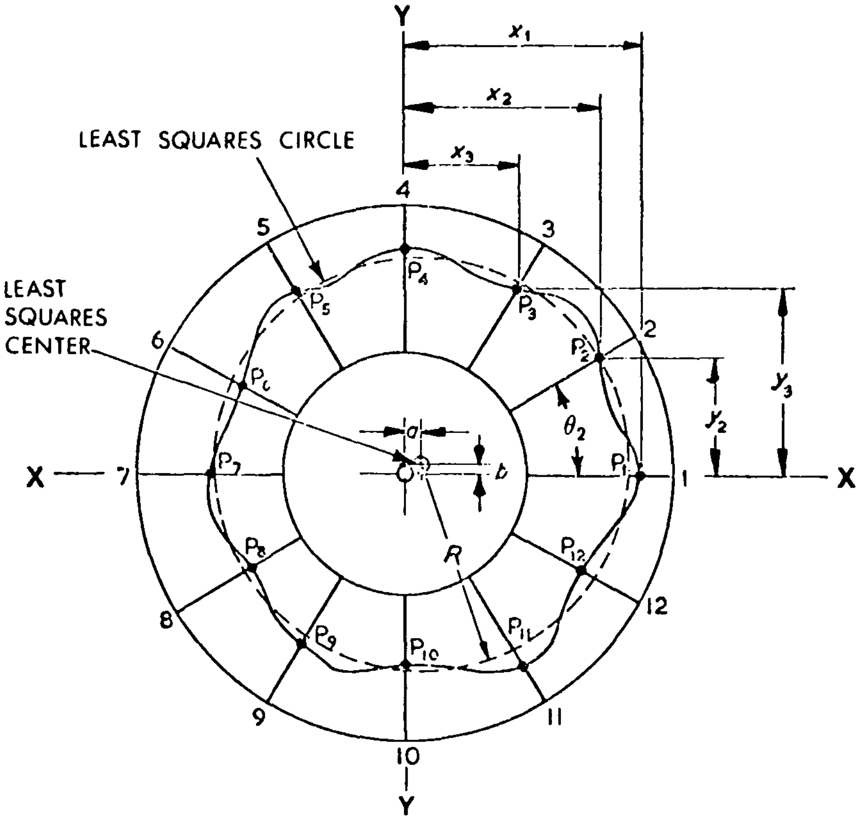

FIG. C3 DETERMINATION OF LEAST SQUARES CENTER AND CIRCLE

In practice, if it is required to know only the radial width of the zone enclosing the curve (the out-of-roundness), there is no point in finding R, and it is sufficient to draw the inscribing and circumscribing circles from the least squares center. See Fig. C2.

The accuracy of determination, both of the center and of the width of the radial zone, depends on the number of ordinates taken.

C1.3.3 Characteristics of the LSC Method. The least squares circle and its center are unique, since there is only one circle which meets the definition in paragraph C1.3.1. A mathematically precise statement of error can be obtained from this method. Since certain electrical instruments operate on a least squares principle, the least squares circle can be plotted and meter readings of error (radial deviations) can be displayed on such instruments. Manual graphical assessment can be tedious and time consuming but digital instruments and/or computers can greatly reduce the time and effort required for LSC evaluation.

C1.4 Maximum Inscribed Circle Method (MIC)

C1.4.1 This procedure determines the center of the polar profile by the center of the largest circle which can be fitted inside the profile.

This can be done graphically by trial-and-error with the aid of a bow compass or engraved circles on a transparent template. From this circle the maximum outward departure of this profile denotes the out-of-roundness. To determine the out-of-roundness value from meter or indicator readings alone the part must be centered to produce either two or three equal minimum readings, depending on the profile shape. If the overall figure is 2-lobed, i.e., oval or elliptical, proper centering will produce two minimum readings spaced at 180 degrees. All other figures should be centered to produce at least three equal minimum meter readings spaced over more than 180 degrees. Again the total meter reading will denote the out-of-roundness value. The MIC method is useful when the error is best interpreted as the radial deviations of an

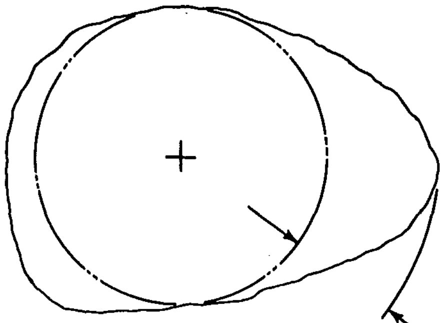

FIG. C4 MAXIMUM INSCRIBED CIRCLE

internal circular surface from the largest ideally round plug gage which can be fitted to it.

C1.5 Minimum Circumscribed Circle (MCC)

C1.5.1 By this method, the profile center is determined by the smallest circle which will just contain the measured profile. From this circle, the maximum inward departure of the profile can be measured; this maximum departure is the out-of-roundness. To determine the out-of-roundness value from a meter or indicator reading the part is centered to produce either two or three equal maximum readings, depending upon the profile shape. If the overall figure is 2-lobed, i.e. oval or elliptical, proper centering will produce two maximum readings spaced at 180 degrees. All other figures should be centered to produce at least three equal maximum meter readings spaced over more than 180 degrees. The total meter or indicator reading will denote the out-of-roundness value. The MCC method is useful when the error is best interpreted as the radial deviation of an external circular surface from the smallest ring gage which can be fitted to it.

C2 RELATION OF ASSESSMENTS TO EACH OTHER

C2.1 Changes in OOR Values with Center Selection

The smallest possible value for the out-of-roundness of a given profile is that determined by the MRS assessment, since by definition it places the profile within the minimum radial band. The LSC assessment in previous studies has provided out-of-roundness values which varied from less than 1 percent to more than 20 percent over those determined by the MRS

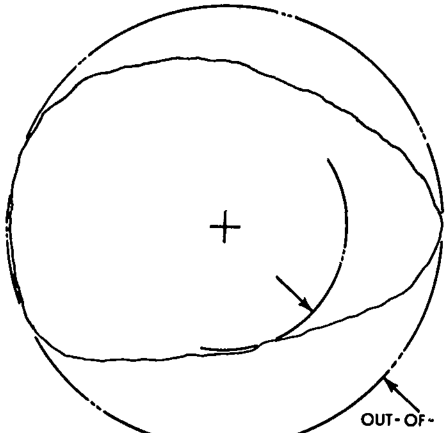

FIG. C5 MINIMUM CIRCUMSCRIBED CIRCLE

assessment. Values of out-of-roundness obtained by the MIC and MCC methods of assessment generally will be somewhat larger than those determined by the LSC method. Profiles which illustrate certain extreme cases of differing assessment values are shown in Fig. C6.

C3 EFFECT OF VARIATION IN CYCLES PER REVOLUTION RESPONSE

C3.1 Electronic Filters

If all of the radial deviations of a circular cross section were fully and completely represented by a measured profile, the presence of surface irregularities of high frequency could mask the lobing condition or the form of the profile. Since the lower frequency surface irregularities, i.e. waviness and lobing, may be of greater importance to the part function than the higher frequency irregularities, an electrical signal filter is commonly used for the suppression of the representation of high frequency radial deviations. Variations in the shape, size, and mass of the stylus, and the stylus pressure will act as mechanical filters to some extent, but generally the major attenuation will be done by the electrical filter on the signal coming from the stylus transducer. Filters are commonly denoted numerically by the frequency at which the sinusoidal amplitude is attenuated to the 70.7 percent transmission point of its peak value. In this standard, this filter point is termed the Cycles Per Revolution Response (see Para. 5.2), with frequency based on angular displacement rather than time. Thus, a Cycles

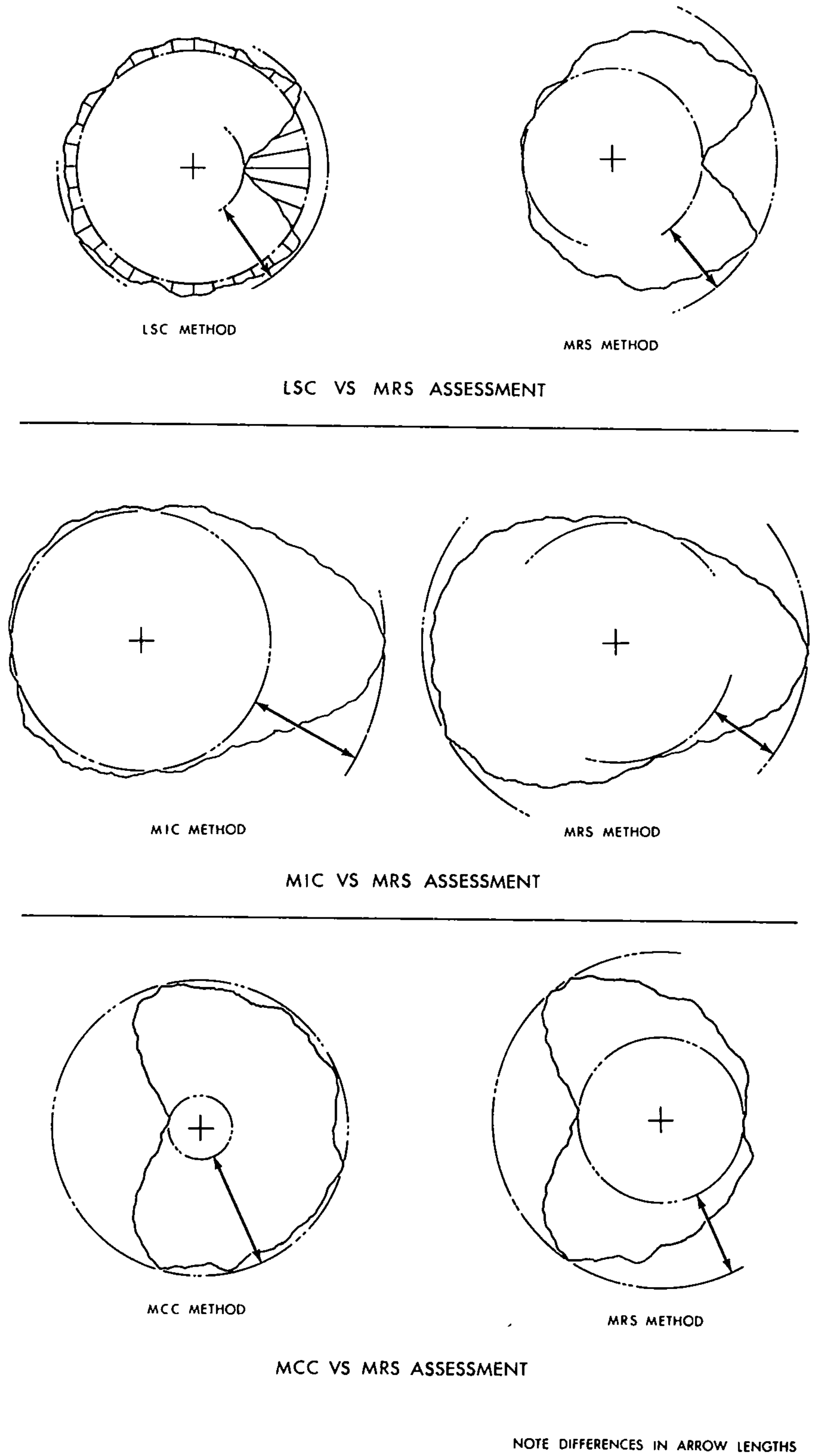

FIG. C6 COMPARISON OF POLAR PROFILE ASSESSMENT METHODS

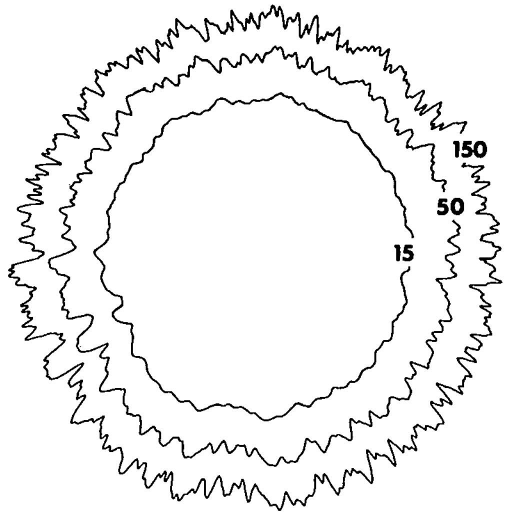

FIG. C7 POLAR PROFILES AT THREE DIFFERENT CYCLES PER REVOLUTION RESPONSE

Per Revolution Response figure of 50 means that the measured profile has been attenuated by a filter which has reduced by 30 percent the amplitude of the sinusoidal lobing which occurred at a regular interval of 50 lobes per revolution.

The character of the measured profile is primarily affected by the Cycles Per Revolution Response of the instrumentation. Reducing the number of Cycles Per Revolution Response will tend to smooth out the small scale irregularities. This is shown in Fig. C7. Here three profiles of a common part are shown at three different filter conditions. Surface profiles which are more inclusive of the total surface texture are represented by higher cycles per revolution response numbers.

C4 DISCONTINUOUS CIRCULAR PROFILES, ARCS, FILLET RADII

C4.1 Profile Distortion Due to Mis-Centering

The out-of-roundness of an arc, fillet, or any partial circular form encompassing less than 180 degrees, can be measured by noting the radial deviation of its profile, provided this profile is properly centered on the instrument axis. On precision spindle instruments, which record a polar profile, the problem is not one of assessment but of proper profile centering and recording. The ideal arc cross-section has a constant radius and can be readily centered. In actual practice, however, the measured profile of an arc is usually made up of a connected series of line elements having innumerable radii. The final centering movements of the part are guided by an attempt to make the recorded profile as circular in shape as possible. With the measured profile made up of multiple radii, without a coherent center, proper centering of the arc to make the measured profile fall within an optimum band is extremely difficult and may be quite subjective. This centering difficulty is further complicated by a chart distortion condition caused by unequal radial vs. circumferential magnifications. Under the unequal chart magnification condition, differences in centering may cause a given arc to be represented by any of the circular profiles shown in Fig. C8.

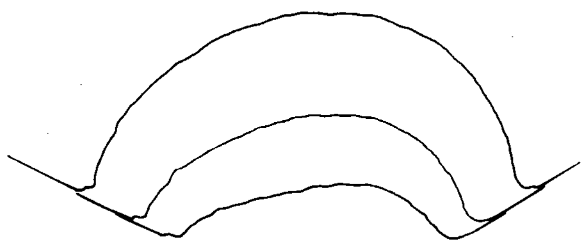

FIG. C8 ARC PROFILE DISTORTION CAUSED BY IMPROPER CENTERING

C4.2 Arc Centering by Minimum Radial Separation

The final centering adjustments prior to a profile recording or other radial deviation measurement of an arc can be accomplished directly by following the Minimum Radial Separation criteria. By this method the final adjustments are made so as to contain the measured profile within the narrowest possible annular band. This system provides a unique solution in that a smaller out-of-roundness value cannot be found. Also it provides a center from which radius (size) measurements can be determined. It eliminates the subjective personal judgment on the part of the instrument operator.

C4.3 Arc Centering Using a Reference Radius or Other Reference Parameters

C4.3.1 Reference Radius. When it is desired to measure radial deviations of an arc from a reference radius the stylus or other sensitive measurement element must be set accurately to this radial value. Variations of the profile from this radius can be plotted on circular or rectilinear chart paper, or can be read directly from a meter or indicator. It should be recognized that this is not a valid method for determining the out-of-roundness value as defined and prescribed in this standard, since the standard recognizes only four centers for radial deviation measurements. These four centers are determined by the part profile and no provision is made for recognizing a predetermined radial value.

C4.3.2 Other Reference Parameters. Centering of an arc can be accomplished by reference to three predominant surface features on the profile. The three features can be positioned to have either an equal maximum or an equal minimum radial value as denoted by a meter or indicator, depending on whether the surface is an exterior or interior arc, respectively. When recorded as a polar profile, these predominant features would define a maximum inscribed or minimum circumscribed circle, thus relating to the MIC or MCC method of profile assessment. The user of this technique must be warned that all arc profiles may not have three predominant features which can be adjusted (centered) to occur at a common radial value without seriously distorting the profile. Also, this method is subject to instrument operator judgment, and the values obtained can be influenced by chart distortions. This method is valid for the out-of-roundness assessment of measured profiles as described in this standard, so long as this method is specified.

APPENDIX D

GENERAL NOTES ON USE OF SPINDLE TYPE INSTRUMENTS

D1 SELECTION OF OPTIONAL PARAMETERS

D1.1 Choice of Cycles per Revolution Response

D1.1.1 Response Value. The selection of the Cycles per Revolution Response (CPR) figure should be based on the desire to reproduce graphically those elements of the circular surface which are most pertinent to the part function, or which fulfill the objective of the measured profile; and to reduce as much as possible the representation of all others. For example, if it is desired to specify and control low order lobing such as 3, 5, 7, 9 lobes typical of improperly adjusted centerless grinders, a response of 0 to 50 CPR would be adequate. The additional irregularities passed by the 0–500 CPR filter can actually make the assessment more difficult. Fig. D1 shows the measured polar profiles of a common part which have been recorded at 5 different response values as noted. While Fig. D1 illustrates typical attenuations at the response values, the final selection of the CPR figure should be based on the measured profiles of actual or sample parts made at various response values. It should be remembered that all measured profile undulations, whose frequencies are in the region of the selected response value and higher, are reduced by the action of the filter. The amount of this reduction is dependent on two factors as far as the filter is concerned:

1. The sinusoidal frequency which the undulation on the profile most closely resembles, and
2. The relationship of this frequency to the selected Cycles Per Revolution response value as shown by the attenuation curve.

D1.1.2 Filter Attenuation Curve. Electrical low-pass filters in common usage do not have an absolute cut-off at a given frequency. Instead, the transmission percentage falls off rather slowly until it reaches the frequency corresponding to the Cycles Per Revolution response value, and falls much more rapidly beyond this frequency. This roll off should produce a slope of −12 db per octave, equivalent to 2 unloaded RC networks in series. This characteristic is shown in Fig. D2, where the frequencies and corresponding amplitude transmission values in percentages are plotted for three response values selected from those listed in paragraph 5.2.

D1.2 Choice of Stylus Tip Radius

In general, the selection of the stylus tip radius from those listed in the standard is not critical with the exception of the 0.001 inch radius. The measured profiles of circular objects whose surfaces have been finished by common manufacturing processes, i.e., grinding, turning, honing, etc., do not change significantly unless the 0.001 in. radius stylus is used.

Where profiles of extremely fine surface detail are required, the smallest tip radius should be chosen, along with a high Cycles Per Revolution response figure. Larger radius styli should be used on materials softer than Rockwell "C" 20 to prevent plastic deformation of the surface resulting from high contact pressures.

D1.3 Selection of Stylus Static Force

For ferrous materials or materials having a Rockwell "C" hardness number greater than 20 the stylus force should be no greater than the value listed in Table 1 in this standard, to protect the part from excessive contact stress and subsequent permanent deformation. The stylus loads for softer non-ferrous parts whose surfaces must not be damaged should be selected so that the contact stress does not exceed the yield strength of the material. For critical surfaces[1]

[1] Low friction plastic or plastic coated styli are effective in reducing damage to highly polished or soft surfaces.

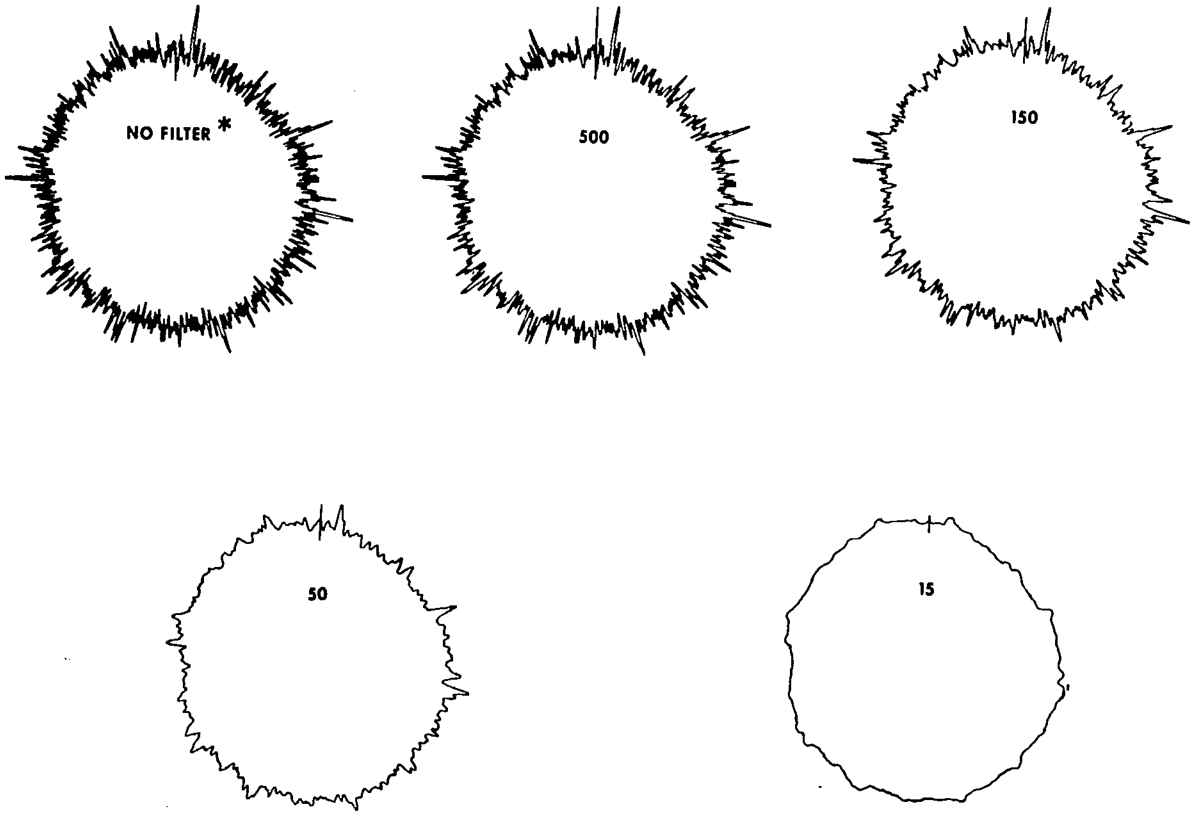

FIG. D1 POLAR PROFILES AT VARIOUS FILTER VALUES

*Actually each instrument analog or digital has a "built-in" mechanical and/or electrical filter characteristic, which may limit the true representation of the actual profile.

where the deformation effects of the stylus are known to be significant to part function, trial traverses should be made using the largest radius stylus consistent with the surface quality and the lightest available stylus force; and possible surface damage should be examined microscopically.

D1.4 Choice of Chart Magnification

Where a single measured polar profile is to be assessed for out-of-roundness, the magnification factor of the chart should be (1) the largest value available so that the profile is completely contained within the chart boundaries, or (2) the lowest value commensurate with the best assessment of the part features or tolerance. At the lowest magnification condition the distortion arising from various systematic causes will be minimized.

Where a series of measured profiles is needed, as for concentricity, taper, or other interrelated measurements, it is usually considered good practice to limit all the magnifications to the lowest value available within the series which will accomplish the measurement objectives. This facilitates profile comparisons. Increasing the magnification quite often requires re-centering of the part to reduce the profile mis-centering distortion described in Appendix section D2.1.

D2 SOURCES OF ERROR

D2.1 Mis-Centered Part

D2.1.1 Polar Profile Distortion. As mentioned in paragraph 4.3 any eccentricity between the part profile in the measurement plane and the axis of the

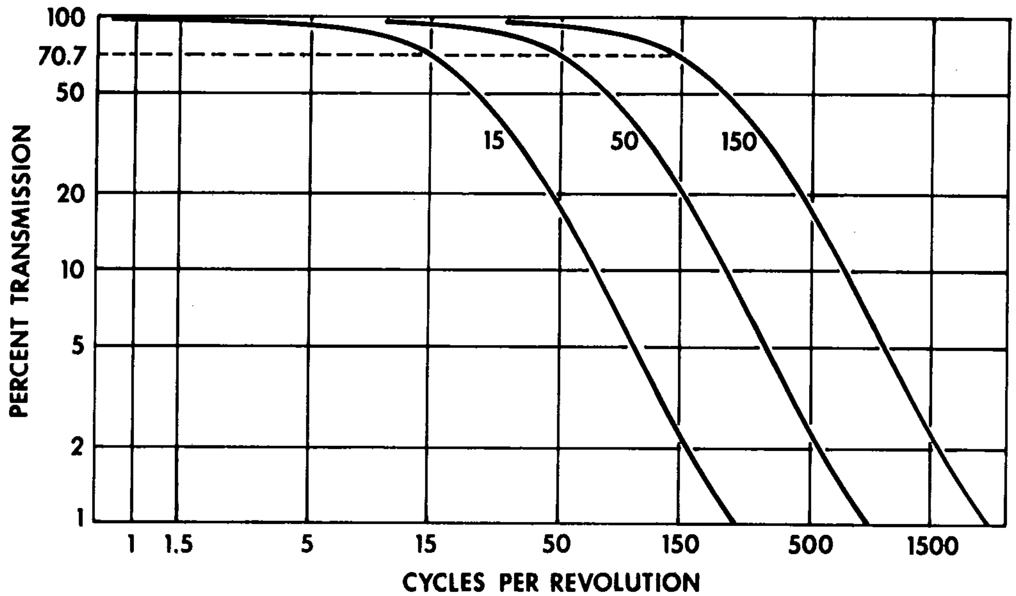

FIG. D2 THREE FILTER ATTENUATION CURVES

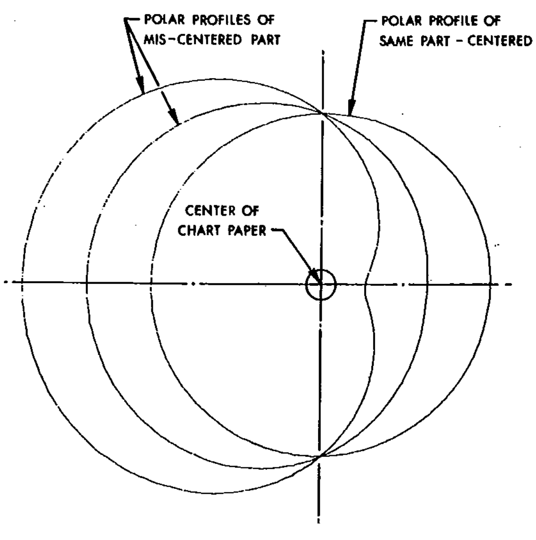

FIG. D3a POLAR PROFILES OF MIS-CENTERED PART

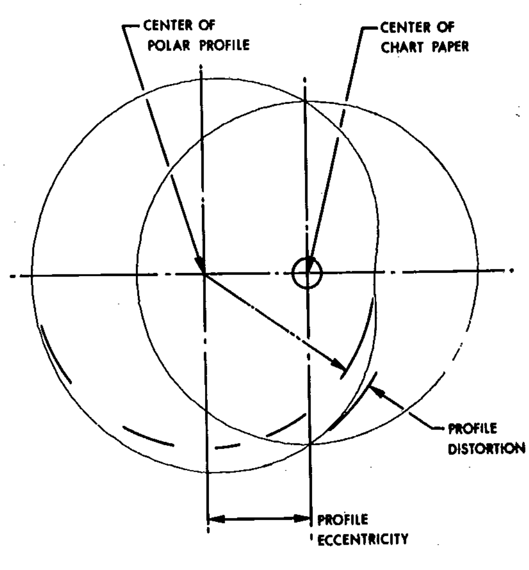

FIG. D3b MEASUREMENT OF PROFILE DISTORTION measuring instrument causes a distortion in the polar profile. The profile distortion of a mis-centered but nominally round part is shown in Fig. D3a and its assessment is shown in Fig. D3b. Distortion, or radial deviation error, becomes a maximum at an angular position 90 degrees from the direction of the eccentricity measured from the chart rotational center.

D2.1.2 Determination of Profile Distortion. The two parameters which affect the polar profile distortion the greatest amount are:

1. The amount of mis-centering or eccentricity.
2. The size of the polar profile, or more specifically the radial distance between the chart rotational center and the innermost profile point.

The manner in which these two characteristics determine the maximum amount of radial profile distortion of a perfectly round part is shown in Fig. D4 (measured by MRS assessment). From this graph an estimate can be made of the maximum profile distortion when the amount of profile eccentricity and the size of the profile have been determined.

Unless otherwise specified a maximum profile distortion of 0.01 inch is assumed for control purposes; and the formula for the maximum allowable eccentricity, as found in paragraph 4.3, is based on a straight-line approximation of the 0.01 inch profile distortion curve in Fig. D4.

D2.2 Effect of Misaligned Stylus

The stylus tip should contact the workpiece as close as possible to an axial plane through the center of the workpiece. The effect of any off-center contact is the increase in magnification by the factor sec θ as shown in Fig. D5. The stylus will move through the distance $\Delta r \cdot \sec\theta$ as it contacts the protuberance, whereas the actual radial deviation is only Δr. Holding the angle of misalignment, θ, to less than 10 degrees will increase the magnification less

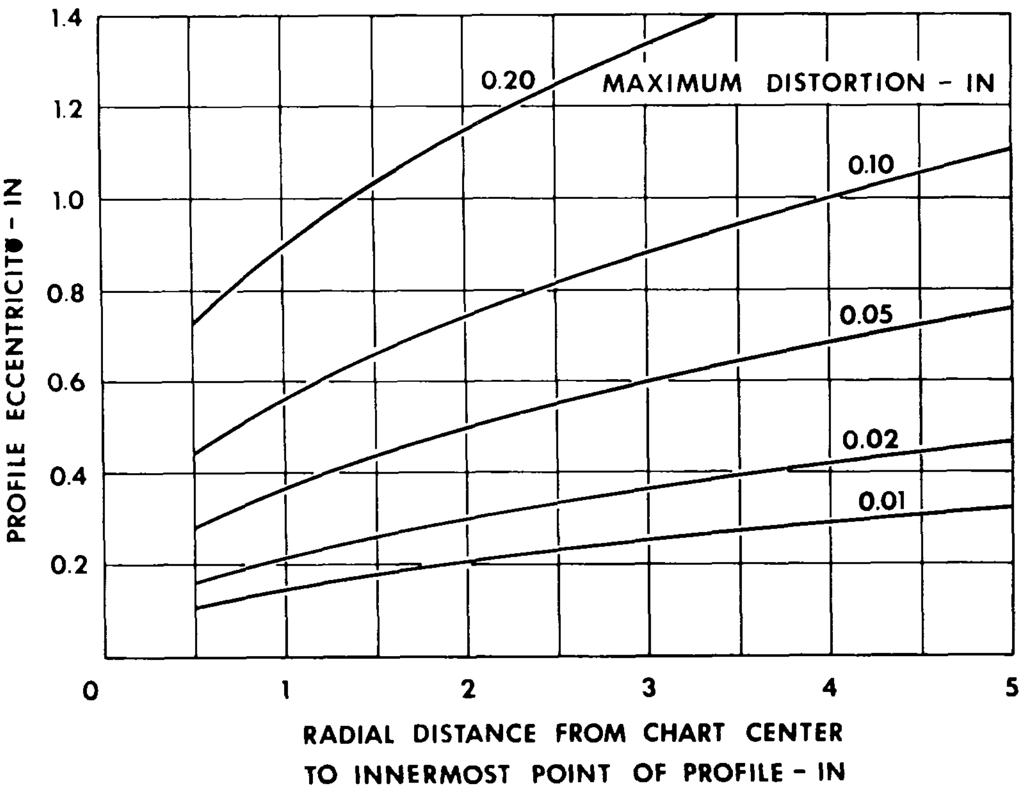

FIG. D4 POLAR PROFILE DISTORTION (OOR)
FROM MIS-CENTERED PART

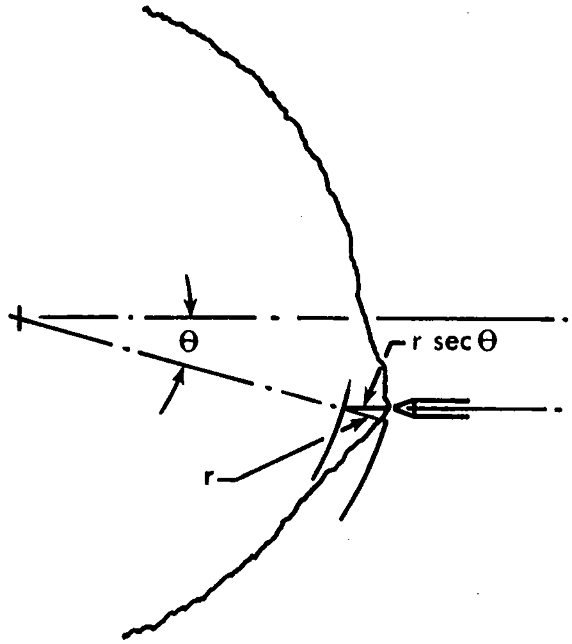

FIG. D5 STYLUS MISALIGNMENT

than 2 percent. This form of misalignment should be carefully checked for parts having small internal or external diameters where a slight amount of stylus offset can produce appreciable misalignment angles. Similar errors can occur with a stylus misaligned in an axial plane, i.e., a plane perpendicular to that of Fig. D5.

D2.3 Angular Distortion of Polar Profiles

Several illustrations of profile distortion have been cited previously, i.e., Figures C7 and D3, where part mis-centering can cause a flattening of an arc profile or an enlargement of a complete polar profile. Another form of profile distortion due to part mis-centering is the angular distortion of circumferential features, as shown in Fig. D6.

The properly centered profile on the left shows that the part is essentially round and has 12 equally spaced radial deviations. The profile of the mis-centered part made at the same magnification is shown on the right. Mis-centering causes not only a distorted circular shape but an angular misrepresentation as well. Lines drawn through the centers of the notches located 180° apart intersect at the rotational center of the chart, indicating that angles are properly represented from the chart center and not from the polar profile center defined in paragraph 2.8. Furthermore, the measurement of chart distances between the bottoms of opposite notches (through the chart center) shows that these values are alike, as they are on the correctly drawn profile of the centered part. Thus, angular relationships and diametral distances can be read from mis-centered part profiles by using the chart center as reference. Best measurement practice would dictate that the part be centered to the tolerances defined in paragraph 4.3.

D2.4 Part Cross-Section Uniformity Limitations

Many circular parts have a surface texture pattern of helical grooves caused by the axial feed of the cutting tool which produced the part. The roundness measurement made with a sharp stylus will present a rather accurate cross-section, one which may cross multiple peaks and valleys of the helical pattern. If the part function is such that this cross-sectional representation may be misleading it is suggested that a stylus be selected whose tip radius will prevent it from entering these valleys. A large radius stylus or a hatchet-type stylus will produce a measured profile more representative of the part's exterior envelope, and where the part profile envelope is more important to the part function than a true cross-sectional profile, a stylus of larger radius should be used.

D2.5 Spindle Errors

D2.5.1 Introduction. Radial motion of the spindle axis[1] in the sensitive direction (along a line connecting the spindle axis and the stylus tip) will cause a direct error in the measured part profile. This error can be measured directly if a 'master round' is available which has a negligible roundness error. For cases where it is uncertain what portion of the measured profile is due to the spindle and what portion is dures described in the following section can be used to separate these two errors. It must be emphasized that
separate these two errors. It must be emphasized that
the procedures of the following section assume that the spindle errors repeat exactly from one revolution to the next.

[1] The testing of axes of rotation will be covered more completely in the forthcoming American National Standard ANSI B89.3.4, Axes of Rotation.

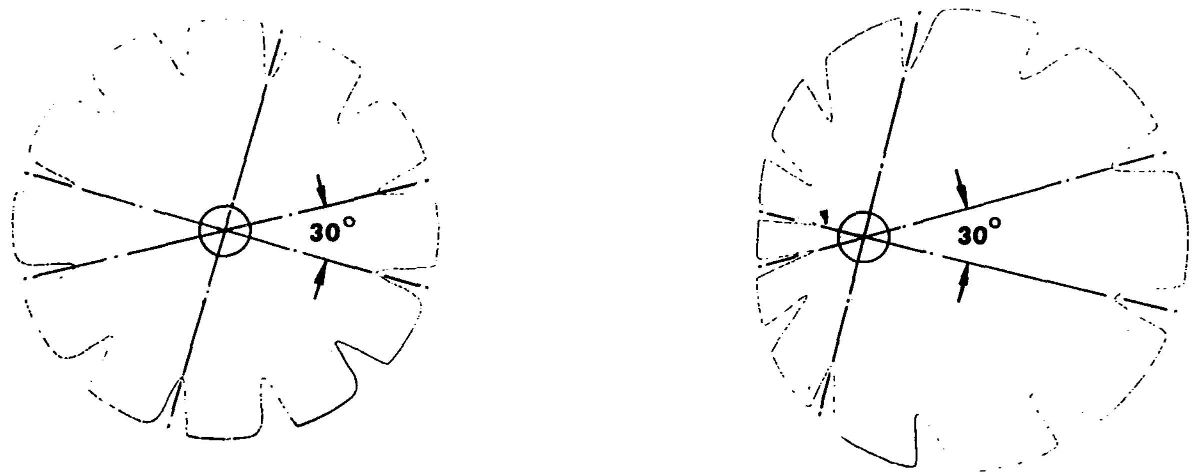

FIG. D6 ANGULAR DISTORTION

D2.5.2 Profile Averaging Method. The present method consists of two procedures. Procedure P yields the Part profile $P(\theta)$ while procedure S yields the Spindle radial motion error $S(\theta)$, where θ is the angle of rotation.

D2.5.2.1 *Procedure P.* Procedure P begins by recording an initial profile $T_1(\theta)$. The arbitrary initial positions are marked as $\theta = 0^\circ$ by coincident marks on the part, spindle shaft and spindle housing at the stylus position as shown in Fig. D7A. At each angle θ, the recorded value $T_1(\theta)$ is the sum of the part profile $P(\theta)$ and the spindle radial motion $S(\theta)$, so that

$$T_1(\theta) = P(\theta) + S(\theta)$$

It is assumed that the normal sign convention is used, so that hills and valleys on the chart correspond to hills and valleys on the part. For procedure P, the second step consists of taking a second record $T_{2P}(\theta)$ with the setup shown in Fig. D7B, in which the spindle shaft and housing marks are coincident at 0°, but the part and stylus positions are reversed (rotated 180°). The same sign convention must be used as for $T_1(\theta)$. Comparison of Figs. D7A and D7B shows that the part errors are recorded in the same manner, since the relative position of the stylus and part is unchanged. However, the spindle errors are recorded with a reversed sign in Fig. D7B, since a movement of the spindle toward the stylus in Fig. D7A becomes a movement away from the stylus in Fig. D7B. Expressed as an equation,

$$T_{2P}(\theta) = P(\theta) - S(\theta)$$

If the above two equations are added, $S(\theta)$ cancels, and solving for $P(\theta)$ gives

$$P(\theta) = \frac{T_1(\theta) + T_{2P}(\theta)}{2}$$

This equation states that the part profile $P(\theta)$ at any particular angle θ is the average of the two recorded profiles $T_1(\theta)$ and $T_{2P}(\theta)$ at the same angle θ. By recording $T_1(\theta)$ and $T_{2P}(\theta)$ on the same polar chart, the part profile $P(\theta)$ is obtained by drawing a third profile halfway between the first two as indicated in Fig. D8A.

D2.5.2.2 *Procedure S.* Procedure S also begins by recording an initial profile $T_1(\theta)$. The second step of procedure S differs from that of procedure P only in that the sign convention must be reversed compared to that used for $T_1(\theta)$ and $T_{2P}(\theta)$. Calling this record $T_{2S}(\theta)$, it follows that

$$T_{2S}(\theta) = -T_{2P}(\theta) = -P(\theta) + S(\theta)$$

If the equations for $T_1(\theta)$ and $T_{2S}(\theta)$ are added, $P(\theta)$ cancels, and solving for $S(\theta)$ gives

$$S(\theta) = \frac{T_1(\theta) + T_{2S}(\theta)}{2}$$

This equation states that a third profile drawn halfway between the $T_1(\theta)$ and $T_{2S}(\theta)$ profiles will be the spindle radial motion profile $S(\theta)$ as shown in Fig. D8B. This profile is the apparent out-of-roundness record that the spindle would produce for a perfectly round part.

The following table summarizes the above procedures:

Procedure	Reverse for Record 2	Average
P	Part, Stylus	Part Profile
S	Part, Stylus, Sign	Spindle Error

No mention was made as to whether the part or the stylus rotates with the spindle, and the above procedures are equally valid for both types of instrument. In some instruments it may be more convenient to *reach across* with the stylus to the opposite side of the part without physically reversing the indicator position, which is satisfactory providing that proper account is taken of the sign reversal which this causes. Many instruments are provided with electrical polarity reversal switches which simplify the execution of procedures P and S.

D2.5.3 Practical Considerations. Several observations can be made regarding the polar charts obtained in procedures P and S. First, different centering errors can be present for the two profiles of Fig. D8A or D8B without influencing the results, subject to the usual polar distortion considerations for each profile as discussed in Section D2.1. Secondly, there is no effect from zero shifting the polar recorder between the first and second records (other than a small change in polar distortion) and it does not matter which record has the larger diameter or if the records overlap. Third, all averages and radial distance measurements should be taken along radial lines from the chart center (see paragraph D2.3). Finally, it should be noted that values for out-of-roundness or spindle error (obtained by one of the assessment methods of Section C1) cannot be added and subtracted in the same way as the $P(\theta)$ and $E(\theta)$ errors can at a particular angle θ. For example, if a two microinch OOR value is obtained for a particular part on a spindle with a one microinch error value, it cannot be concluded that the part has a one microinch OOR value. This is because the part and spindle errors can tend to cancel as well as add, so that the part OOR value can be anywhere between one and three microinches. Thus, the spindle radial motion error value becomes a plus-or-minus uncertainty on the measured OOR value of a part. To obtain the exact part OOR value, the error separation procedure must be carried out in detail.

Since the equations are based on the assumption

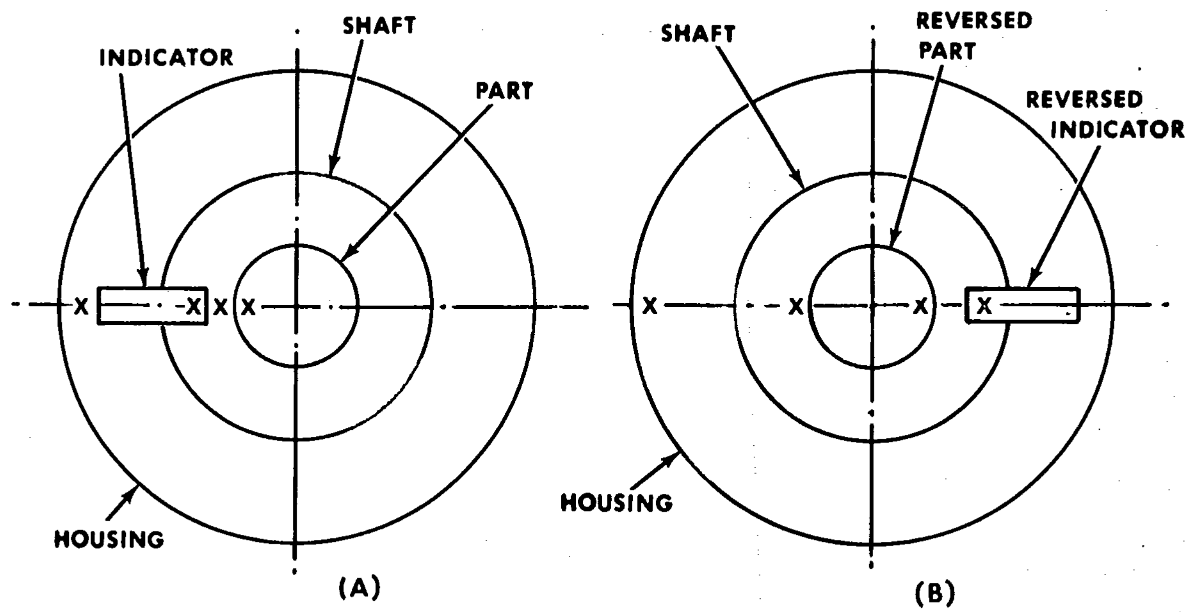

FIG. D7 PART-INDICATOR REVERSAL SCHEMATIC

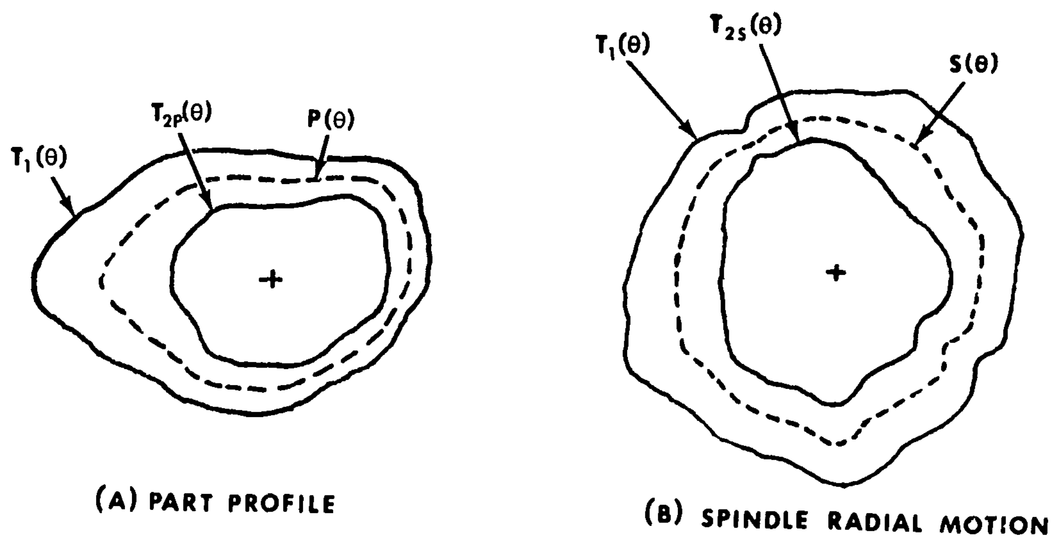

FIG. D8 PLOTTING TRUE PART PROFILE AND SPINDLE ERROR

that the part and spindle errors are repeated exactly in the various measurements, the above tests cannot deal with errors which do not repeat from revolution to revolution. The basic level of repeatability of the instrument can be obtained by recording several successive profiles with a single setup. If the failure to repeat consists of a *cloud band* about an average profile (as might occur due to building vibration or electrical noise), then the part out-of-roundness can be separated from the average spindle radial motion error by use of procedures P and S. However, if successive profiles consist of a spiraling pattern (usually due to a changing temperature condition), then the error separation procedures should not be attempted.

A spindle radial motion error profile should be associated with the axial position at which it is measured. The profile will vary with axial position since the spindle axis can exhibit angular motion as well as pure radial motion (parallel displacement). Angular motion is the difference of two axially separated radial motion errors divided by the axial distance.

D2.5.4 Spindle Errors in Checking Flats and Cones. Roundness measuring machines are also used with the indicator sensing axially to measure circular flatness (deviations from flatness around a circular path on a nominally flat part). Such measurements are influenced by a spindle error called face motion, which is defined as motion parallel to the axis of rotation and at a specified radius from it. The special case of zero radius is called axial motion, which can be measured by carefully centering the indicator in line with the axis of rotation. Since face motion can arise from both axial motion and angular motion, larger spindle errors can occur in circular flatness measurement than in the axial motion test.

The most general case occurs when checking cones and other shapes involving a surface at an angle α between the spindle axis and the tangent to the part surface. The spindle error will involve a contribution from the radial motion at that axial location (proportional to cos α) and a contribution from the face motion at that radius (proportional to sin α).

D2.6 Errors from Improper Mounting–Misalignment of Axes

When the axis of any non-spherical body of revolution, i.e. cylinder, cone, torus, etc., is misaligned angularly from the axis of rotation of the measuring instrument the profile cross-section defined by the contact traverse of the stylus will be elliptical in shape. The deviation from true roundness, or out-of-roundness as defined in this standard, for an angularly misaligned cylinder is shown in Table D1.

Table D1. Radial Error

Tilt A In. Rise Per In. Base Diam.	Radial Error (OOR) Microinches/In. Part Diameter
0.0010	0.25
0.0020	1.0
0.0040	4.0
0.0060	9.0
0.0080	16.0
0.0100	25.0
0.0150	56.2
0.0200	100.0

The misalignment angle A is listed in terms of the deviation in inches per inch of axial length of the misaligned axes, or the rise in inches per inch of diameter of the part's perpendicular base as shown in Fig. D9. This table indicates the required accuracy of perpendicularity of the instrument's base when the tolerance for this error is specified or implied.

A rule of thumb for angular misalignment error is given by:

$$\text{OOR (in microinches)} = \frac{\text{Part Dia. (in.)} \times [\text{Tilt error (mils/inch)}]^2}{4}$$

Measurement errors may be introduced by the method used to clamp or fasten the part to the instrument table. Care should be taken when fastening the part to insure that the restraining stresses do not cause any strains in the cross-sectional profile.

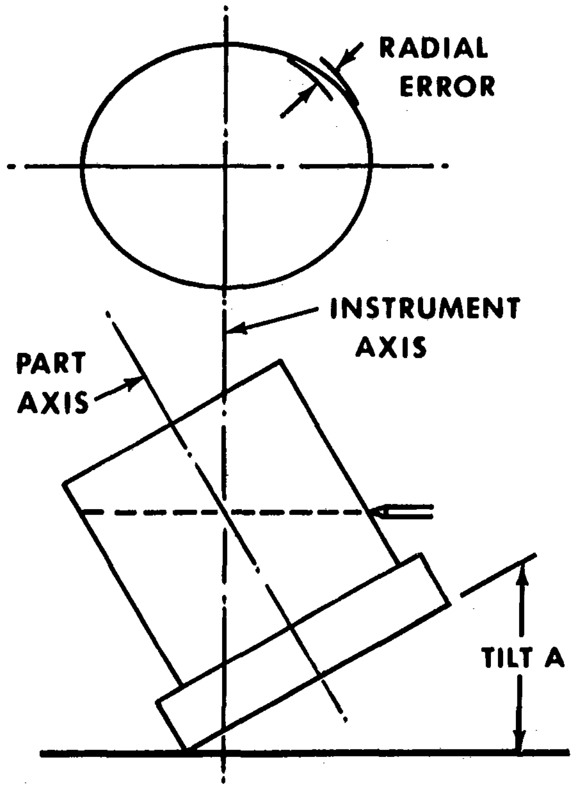

FIG. D9 ANGULAR MISALIGNMENT ERROR

APPENDIX E

E1 RELATIONSHIP OF ROUNDNESS TO OTHER MEASUREMENTS

E1.1 Roundness Tolerance

According to the American National Standard Y14.5-1966, Dimensioning and Tolerancing for Engineering Drawings, all form (including roundness) tolerances are within feature (cylinder, sphere, cone, etc.) tolerances. Therefore, a roundness tolerance does not increase or decrease the tolerance envelope which is controlled by the Maximum Material Condition (MMC) size limit. All individual part features must have perfect form at MMC. Roundness imperfections must occur within the boundaries defined by perfect form at the Maximum Material Condition and the line or surface separated from the MMC surface by the size tolerance.

E1.2 Relationship of Roundness to Effective Size

The effective size of a circular feature is the size of the mating feature of perfect roundness that will fit the circular feature with zero clearance; this size is that associated with the concept of plug and ring gages. The usual size determination of parts whose cross-section is predominantly circular is performed by a two-point diametral measurement technique, as described in Appendix B, paragraph B1.2. The sketches in Fig. E1 illustrate the fact that parts may not be round even though there is no variation in diameter. The circumscribed and inscribed circles graphically illustrate that the effective diameter of a lobed constant diameter shaft or hole is not the same as the measured (indicated) diameter.

E1.3 Axis Considerations

The geometric axis of a circular part is defined here as the line connecting the centers of the part cross-sections. For a given part this geometric axis can have several forms depending on which method of profile center determination (as described in paragraph 2.8) is selected to define the center of the part cross-section. This is shown in Fig. E2 where two cylinders having similar polar profiles are shown to have two different geometric axes when two different methods are used to determine their polar profile centers. The choice of the polar profile center for location of the geometric axis should be based on part function.

E1.4 Concentricity-Eccentricity

Superimposed polar profiles, made by maintaining the measuring instrument axis constant with the part during the measurements, can be used to evaluate concentricity. The distance between the centers of each polar profile divided by the instrument magnification is the eccentricity at that measurement plane. Again the selection of the polar profile center from those described in paragraph 2.8 will affect the eccentricity value. This center selection, therefore, should be based on functional requirements. Where profiles are recorded at different magnifications the eccentricity should not be measured directly, but should be determined trigonometrically from individual measurements between each profile center and the chart paper center.

E1.5 Datum Axis

The effective datum axis, for roundness measurements defined in this standard, is the axis of the measuring instrument. On a measured polar profile (circular chart) the intersection of this axis with the measurement plane (axis center) is represented by the center of the chart paper and not the center of the profile. Confusion between this axis and the geometric axis may arise when measurements involving concentricity or coaxiality are related to this datum axis. Measurements of concentricity and coaxiality, as described in previous paragraphs, are dependent on their profile centers. To reduce this double-axis confusion it is recommended that where possible the circular profiles be recorded such that their profile centers are coincident with the chart center to a practical degree of accuracy.

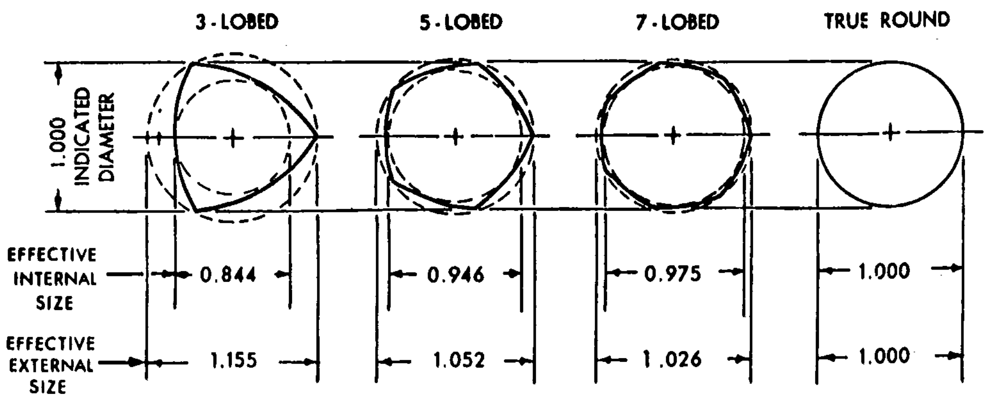

FIG. E1 EFFECTIVE SIZES OF CONSTANT DIAMETER SHAPES

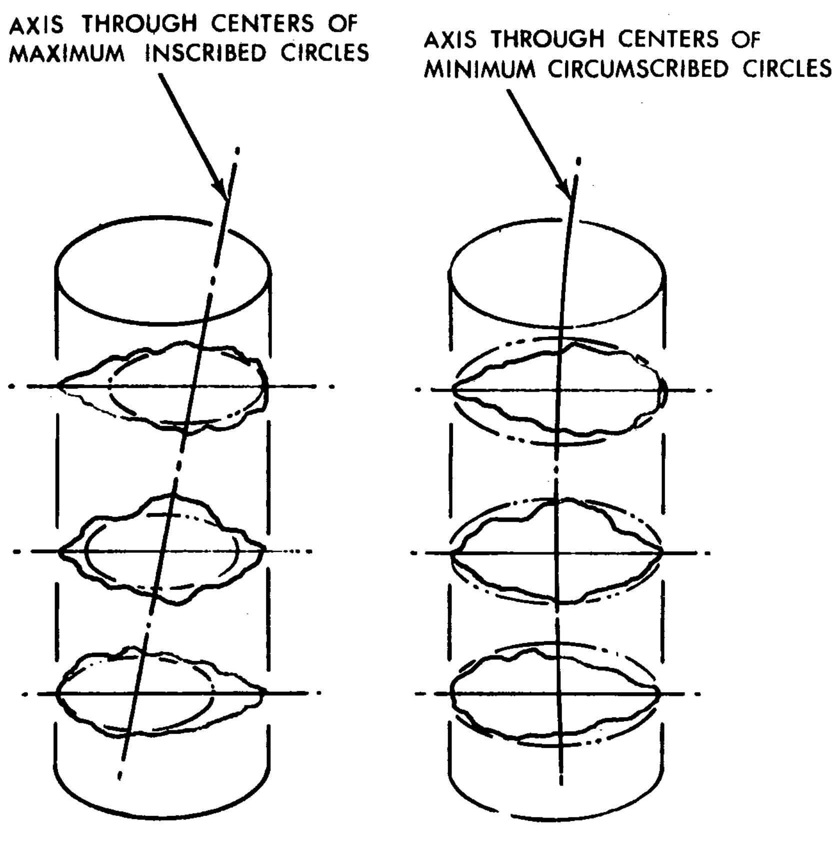

FIG. E2 LOCATION OF GEOMETRIC AXIS BY POLAR PROFILE CENTERS

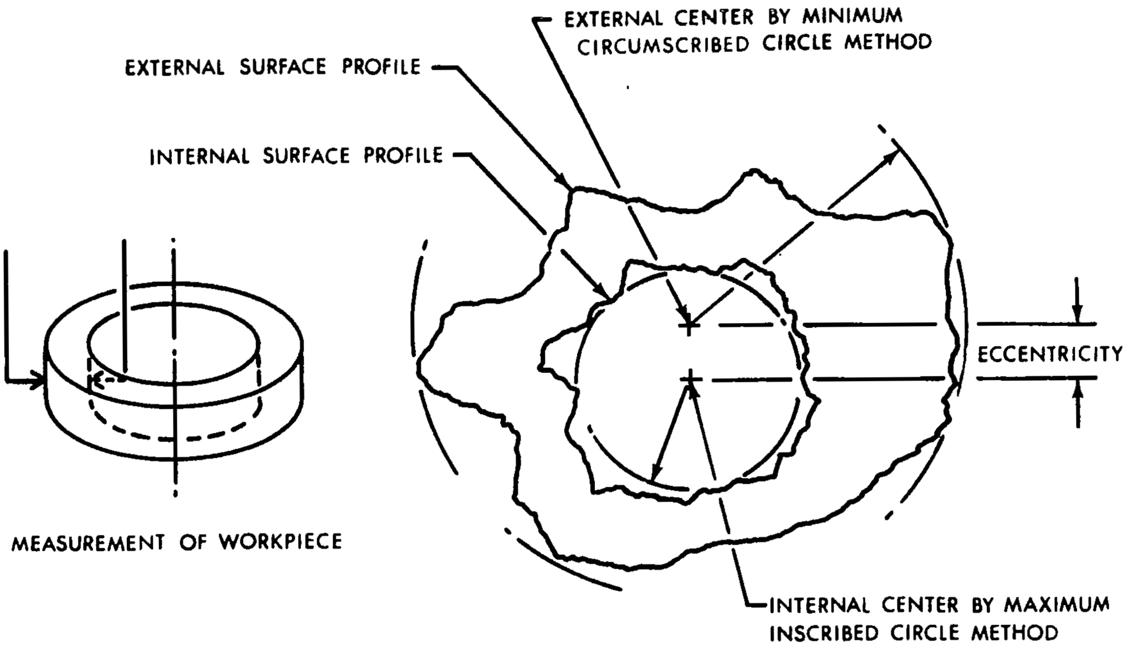

FIG. E3 ECCENTRICITY DETERMINATION BY SUPERIMPOSED POLAR PROFILES

The datum axis is particularly useful in concentricity and axial straightness studies where profiles are often superimposed at different radial magnifications. Here the amount of eccentricity or misalignment must be determined by initial measurements between the datum axis (chart paper center) and each profile center. These distances, when divided by their respective magnifications, are used in trigonometric calculations (Cosine Law) to determine actual distances between profile centers.

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