TEXTBOOK NO. 7021 ⑥

Roundtest
Roundness Measuring Machine

TEXTBOOK

Mitutoyo

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1. INTRODUCTION

When a cross section of a cylindrically machined part is measured by magnifying the irregularities in the radial direction, it may take the form of an ellipse, a triangle, or a non-geometric shape. The function and form accuracy requirements of each component must be assessed to ensure product reliability, durability, and performance. Strict roundness control is especially important for rotating shafts and bearings of machine tools, airtight systems, and components of constant-speed feed devices.

2. DEFINITION OF ROUNDNESS

According to JIS (B0621-1984), "roundness (circularity) is defined as the amount of deviation of a circular feature from a geometrically exact circle". Here, a circular feature is "a feature that is specified to be a circle from the functional point of view; for example, a circle as a plane figure or a circular cross-section of a rotational surface." Roundness is determined by the difference between the radii of two concentric circles, which enclose the circular feature being considered. When the distance between the two circles is minimized, the roundness is expressed as "roundness ○mm" or "roundness ○ um".

3. ROUNDNESS MEASUREMENT METHODS

The three conventional methods for measuring roundness, the diameter method, the radius method, and the 3-point method, are described in the following sections:

3.1 Roundness Measurement Using the Diameter Method

The diameter of a circular profile is measured using a micrometer at several different angles around the central axis of the workpiece. Roundness is expressed as the difference between the maximum and the minimum measured diameters (see **Fig. 1**). The roundness of a hole can be determined in the same manner using an inside micrometer. This is a simple and effective method to measure ordinary machined parts. Since new definitions of roundness are being introduced, this evaluation parameter should be referred to as the uniformity of the diameter.

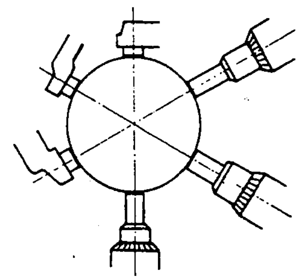


Fig. 1 Roundness measurement using the diameter method

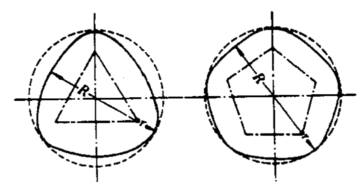


Fig. 2 Lobed circle

The diameter method will not provide accurate roundness measurements for some workpiece profiles. A lobed circle having a uniform diameter which is illustrated in **Fig. 2**, shows a workpiece profile that has no difference in diameter.

3.2 Roundness Measurement Using the 3-point Method

Roundness measurements made using the three-point method, require a V-block, a saddle gage, or a tripod gage, as shown in **Fig. 3**. In diagram (a), the workpiece is supported at two points by a V-block. The dial indicator touches the workpiece at the bisection of the angle formed by the two faces of the "V" shape of the block. (The angle of V-blocks are typically 90° or 120°.) The workpiece is rotated, and the roundness is defined as the maximum difference between the indicator readings. Saddle gages are used to measure large diameter workpieces, and tripod gages are used for inside diameters. However, the accuracy of the 3-point measuring method depends on the angle of the V-block, and the shape of the workpiece profile.

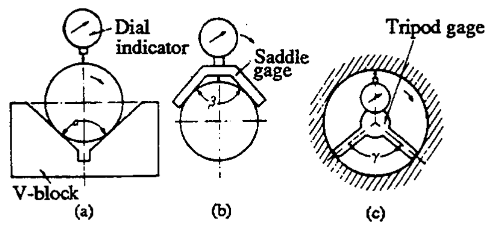


Fig. 3 Roundness measurement using the 3-point method

Note that the 3-point method may not provide accurate measurements if the workpiece profile is in poor condition (i.e. ellipse, triangular, rectangular, etc.) or if the angle of the V-block is unsuitable.

3.3 Roundness Measurement Using the Radius Method

The workpiece is mounted on a center support along its central axis and rotated. A dial indicator measures the displacement of radii of a cross-section at specific angular intervals. The roundness is determined as the difference between the indicator readings. (See Fig. 4)

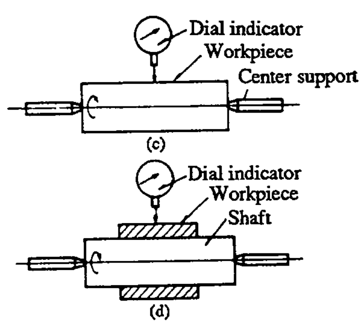


Fig. 4 Roundness measurement using the radius method (Workpiece with center holes)

Other types of radius measurement methods include:
Turntable type: The workpiece is mounted on a turntable and a fixed detector measures radial displacement.
Rotation detector type: The workpiece is fixed and the detector rotates around the workpiece to measure its radial displacement.
When these methods are used, the measured workpiece profile is usually recorded by a polar recorder.

4. ROUNDNESS EVALUATION METHODS

The majority of roundness measuring machines currently on the market employ a radius method to determine the roundness of workpieces. The magnified deviation of the measured workpiece profile is recorded on polar graph paper. As described above, the radius method determines roundness in terms of the difference between the maximum and the minimum radii of the measured workpiece profile. There are four methods for determining the center of the workpiece profile. The roundness value obtained varies in each case.

4.1 Minimum Circumscribed Circle Method (MCC)

The minimum circumscribed circle that touches three points of the measured profile is determined. The center of this circle is defined as the center of the measured profile, and an inscribed circle is determined based on this center point (See **Fig. 5**)
The roundness of the measured profile is defined as the difference between the radii (R_{max} - R_{min}) of these two concentric circles.

4.2 Maximum Inscribed Circle Method (MIC)

The maximum inscribed circle that touches three points of the measured profile is determined. The center of this circle is defined as the center of the measured profile. (See **Fig. 6**)

4.3 Least Square Circle Method (LSC)

The center of the least squares mean circle is defined as the center of the measured profile. The least squares mean circle of the measured profile is determined so that the sum of the squared deviations of the profile from the mean circle is minimized. (See **Fig. 7**)

4.4 Minimum Zone Circle Method (MZC)

Two concentric circles (circumscribed and inscribed circles of the measured profile) are determined so that the difference between the radii of these circles are minimized. The center of these circles is defined as the center of the measured profile. (See **Fig. 8**)

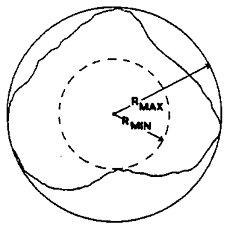


Fig. 5 Minimum circumscribed circle method

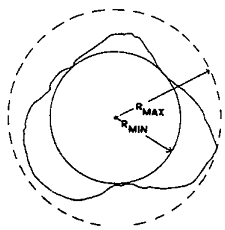


Fig. 6 Maximum inscribed circle method

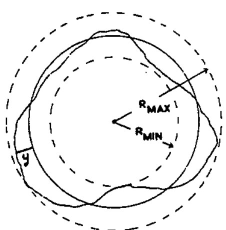


Fig. 7 Least square circle method

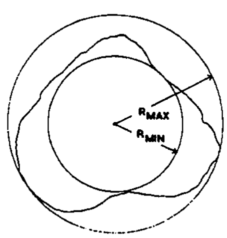


Fig. 8 Minimum zone circle method

5. ROUNDNESS MEASURING MACHINES (Turntable and rotation detector types)

There are two types of roundness measuring machines available on the market; (1) the turntable type, which has a turntable with a fixed detector, (2) the rotation detector type, which has a fixed table with a rotation detector. Roundness is determined from the recorded workpiece profile or by computer analysis of the measured data.

5.1 Turntable System (Fig. 9)

The workpiece is placed on a high-precision turntable. The turntable rotates and a detector fixed to a column by an arm is made to contact the surface of the workpiece to measure its radial displacement. A turntable rotation system has several advantages over a rotation detector system. The advantages are:

(1) Complex-shaped workpieces can easily be measured by setting the detector at an appropriate position.

(2) The profile of more than one cross section of different diameters at different heights of the workpiece can be measured without having to change the workpiece setup on the turntable. This feature is particularly useful when measuring coaxiality, parallelism, or perpendicularity because errors due to the change in workpiece setup are not produced. (This measurement is also available using the rotation detector system by shifting the spindle or the worktable vertically. However, a shift in the orientation of the rotational axis may occur, resulting in errors.)

(3) Any part of the workpiece can be measured.

(4) There is no specific limitation to the maximum height of a workpiece that can be measured. By using a tall detector column, workpieces such as crankshafts can be measured.

(5) The length of the stylus arm does not need to be changed when measuring the roundness of the lower section of a tall workpiece. (However, with the rotation detector system a longer arm is required in order to reach the lower section (see **Fig. 10**). A long stylus arm is more susceptible to vibrations and less sensitive than a short arm).

(6) The maximum measurable workpiece diameter depends on the distance between the turntable and the detector column. If the turntable and detector column are not integrated into a single unit the diameter is not restricted. (In the rotation detector system the maximum measurable workpiece diameter is determined by the distance between the detector spindle and the column.)

(7) A compact and portable system can be manufac-

tured.

(8) More than one detector can be used simultaneously to various types of application measurements.

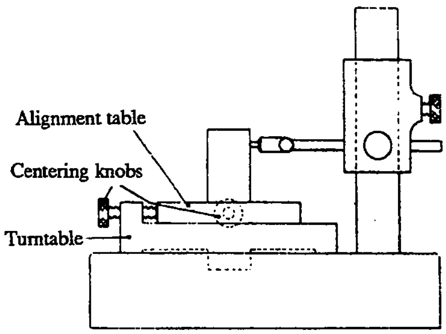


Fig. 9 Turntable system

5.2 Rotation Detector System (Fig. 10)

The workpiece is fixed in position on the worktable, which is provided with X- and Y-axis fine adjustment. The detector is attached to a spindle which rotates around the workpiece to measure its displacement in the radial direction. The advantages of this system over the turntable system are:

(1) The worktable remains fixed in position throughout measurement, so heavy workpieces will be measured under the same conditions as light workpieces.

(2) Measurements will not be affected if the axis of the measured section does not coincide with the center of the workpiece.

(3) Measurements are taken under a constant load (the weight of the detector head) that is put on the rotating section.

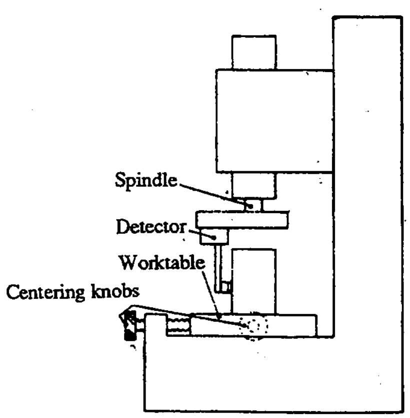


Fig. 10 Rotation detector system

6. MITUTOYO ROUNDNESS MEASURING MACHINES

Mitutoyo offers six types of roundness measuring machines, under the "Roundtest" series name.

6.1 Roundtest RA-112/RA-122 (Photo 1)

These are small, lightweight roundness measuring machines designed to measure small, high-precision parts. They are easy-to-use, high-performance instruments that incorporate the latest technological developments.

Main features:

- Digital display of measurement results for any or all of the following evaluation methods: Four roundness evaluation methods; LSC (Least Square Circle method), MIC (Maximum Inscribed Circle method), MCC (Minimum Circumscribed Circle method), and MZC (Minimum Zone Circle method).
- Automatic off-center and tilt compensation (standard functions).
- A built-in printer that outputs measurement results in the form of numerical data and polar graph.

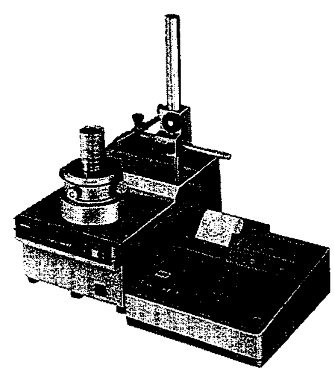


Photo 1

6.2 Roundtest RA-211 (Photo 2)

This is the standard machine of the Roundtest series. It is easy to operate and uses a precision air bearing system which ensures highly accurate measurements.

Main features:

- Digital display of measurement results
- Turntable rotational accuracy: 0.04 µm
- Maximum recording magnification: 20000 X

- Maximum workpiece weight: 25 kg
- Automatic off-center compensation
- Four roundness evaluation methods; LSC, MIC, MCC, and MZC.

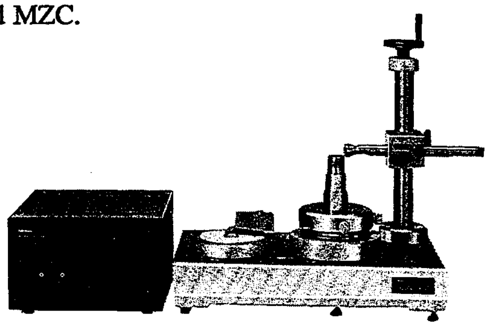


Photo 2

6.3 Roundtest RA-221 (Photo 3)

This is an enhanced version of the RA-211. The basic configuration is the same, except that the RA-221 can perform two-axis measurements by using two detectors.

Main features:

- Automatic tilt compensation (efficient for measuring long shafts)
- Selection and display of measurement mode

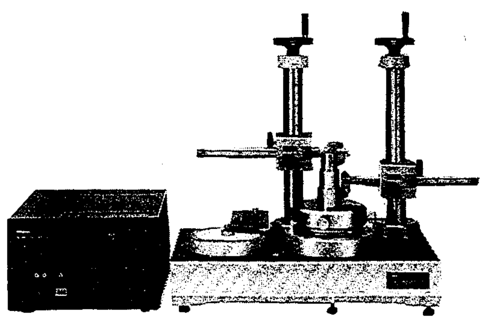


Photo 3

6.4 Roundtest RA-7 (Photo 4)

This is a high-precision model, with a column having a certified straightness. It is particularly suitable for cylindricity (by spiral tracing) and straightness measurements.

Main features:

- Turntable rotational accuracy: 0.04 μm
- Maximum recording magnification: 20000X
- Maximum workpiece weight: 60 kg
- Spiral tracing

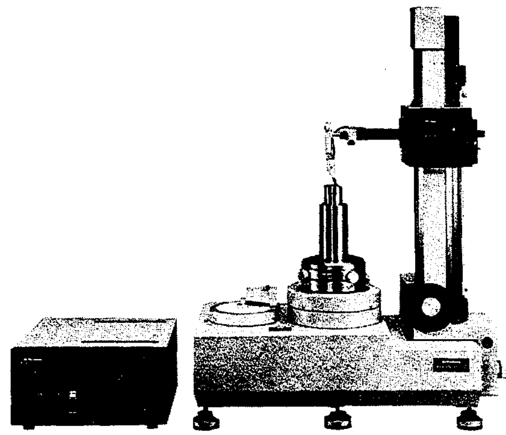


Photo 4

6.5 Roundtest RA-711 (Photo 5)

This is an enhanced version of the RA-7. It incorporates an automatic centering function, making manual centering unnecessary. This function allows measurements to be made by even a novice operator.

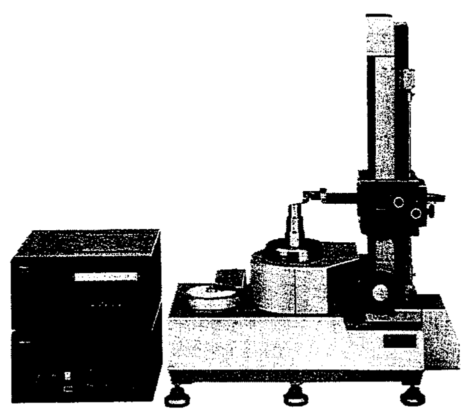


Photo 5

6.6 Non-contact Roll Measuring System RA-801 (Photo 6)

This is a non-contact measuring system that measures roundness, cylindricity, straightness, external diameters, incorporating a Mitutoyo Laser Scan Micrometer. Since no mechanical contact is involved in measurement, the RA-801 is suitable for measuring delicate workpieces such as rubber products, thin wall pipes, products with mirrored surfaces and other workpieces that are subject to scratches or deformation.

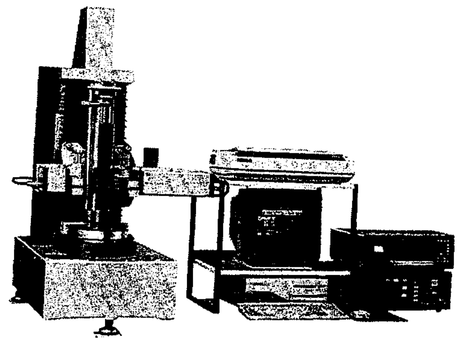


Photo 6

7. OUTLINE OF THE MITUTOYO ROUNDTESTS

This chapter outlines the Mitutoyo Roundtests, exemplifying with the RA-211 and RA-221.

7.1 Features

(1) The roundness is displayed digitally. This eliminates the complex task of analyzing the recorded profile using an overlay template, thus ensuring error-free readings.

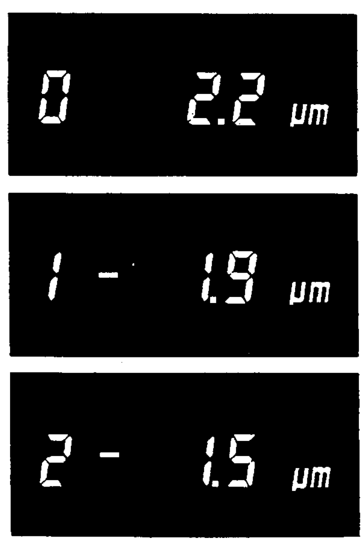


Photo 7

(2) The off-center compensation function automatically centers the measured workpiece profile for recorder output. The mean circle, the maximum circle, and the minimum circle can also be drawn.

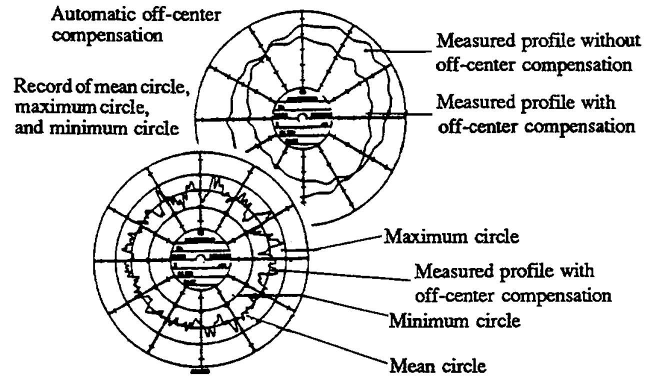


Fig. 11 Examples of recorder output

(3) The turntable has a high rotational accuracy (0.04 µm).

(4) The main unit, which consists of a turntable, a recorder, and a column, is very compact. The detector allows fine adjustments for easy operation.

(5) The turntable and the recorder have synchronized rotation.

(6) The detector mounting fitting has been designed to allow the detector maximum flexibility so that it can be orientated to measure all types of workpieces.

(7) The two-axis measuring system simplifies the alignment procedure. When this is used in conjunction with the automatic tilt compensation function, it is particularly useful for measuring from errors of multiple-section workpieces.

(8) Roundtests can accommodate a wide range of applications, including the measurement of notched workpieces, coaxiality and mean line average departure measurements, and other types of measurements using parameter calculation programs.

7.2 Standard System Configuration

Typically, Mitutoyo Roundtests consist of a turntable, a detector and its support column, a recorder, an amplifier/indicator unit, and an air supply unit.

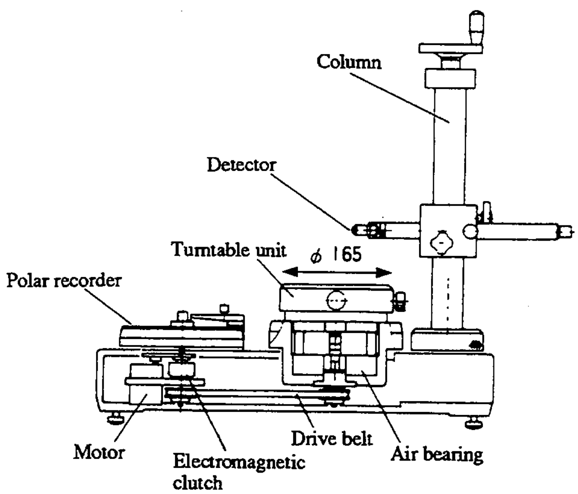


Fig. 12 Drive mechanism of Roundtest (RA-211)

7.2.1 Turntable

The turntable unit consists of an alignment table for centering and leveling a workpiece, and a turntable and air bearing (static pressure) for supporting the rotor. The air bearing is the most important part of the turntable unit, and has the following characteristics (RA211/221).

(1) Maximum workpiece weight is 25 kg.
(2) There is no abrasion on the non-contact air bearing so it retains its initial accuracy over long periods of time.
(3) The turntable does not require a "breaking-in" period.
(4) Lubrication is not required, which simplifies maintenance.
(5) Damage to the air bearing does not result from manually turning the turntable in the reverse direction.
(6) An air layer of the bearing dampens and absorbs shocks to preserve the accuracy of the turntable rotation.

7.2.2 Detector and column

A differential transformer and leaf spring are used in the lever-head type detector. It is mounted on the column at the required height and orientation. A fine adjustment mechanism is used to position the detector for high magnification measurements.

7.2.3 Polar recorder

The polar recorder is located next to the turntable and a thermal pen is used to record workpiece profiles. The polar recorder's rotation is synchronized with the rotation of the turntable.

7.2.4 Amplifier/indicator unit

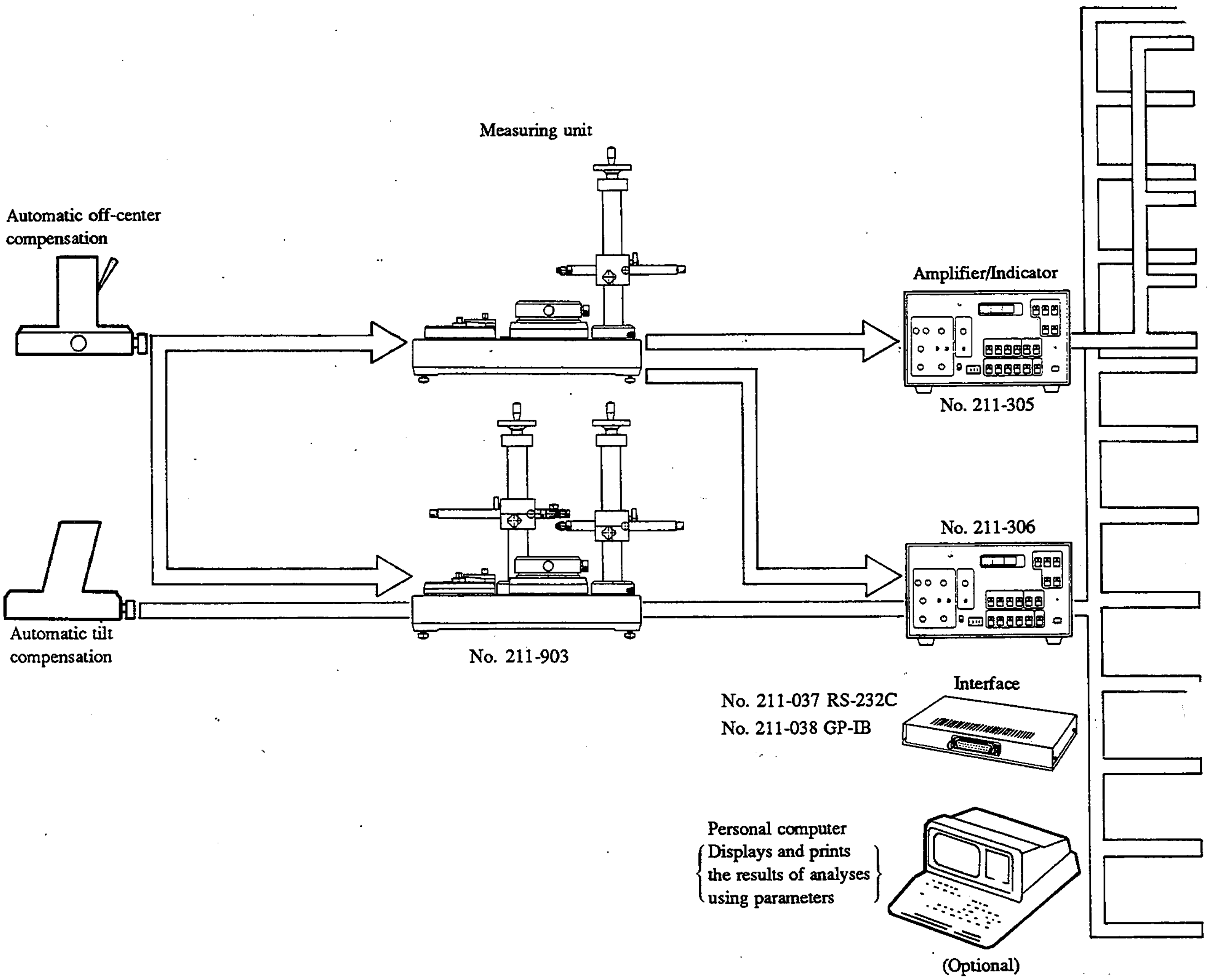
The amplifier/indicator unit processes measurement data from the detector. Measurement results are displayed on the LED display and a roundness chart is graphed by the recorder. The amplifier/indicator unit is also used to set measurement conditions, and control the turntable movement. Control switches and knobs are orderly arranged on a control panel for easy operation.

7.2.5 Air regulator unit

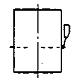
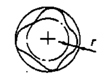
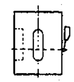
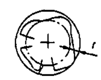
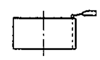
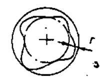
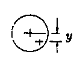
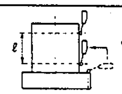
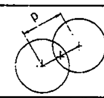
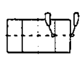
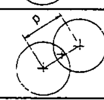
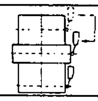
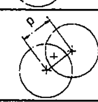
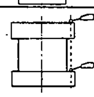
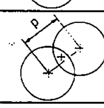
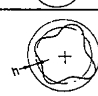
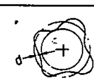
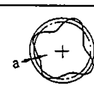
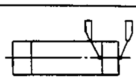
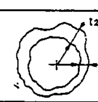
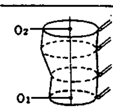
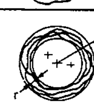
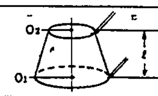
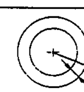
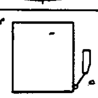
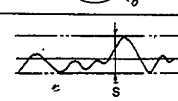
The air regulator unit supplies compressed air to the turntable air bearing. The compressed air supply is filtered, and regulated at a pressure of 390kPa (4kgf/cm^2). When the air pressure drops below this set point a pressure-activated switch turns off the main power supply to the system.

7.3 System and Functions

The turntable is supported by a static air pressure bearing. The motor rotates the turntable at 6 rpm via the electromagnetic clutch and the drive belt. The amplifier/indicator unit controls the turntable rotation and the rotary encoder. The rotary encoder, which is incorporated in the main unit, generates 720 sampling pulses per turntable revolution. The analog measurement data input signal from the detector is converted into digital data by an A/D converter and then analyzed by the microprocessor in the amplifier/indicator unit.



Measuring unit
Automatic off-center compensation
Amplifier/Indicator
No. 211-305
No. 211-306
Automatic tilt compensation
No. 211-903
Interface
No. 211-037 RS-232C
No. 211-038 GP-IB
Personal computer
Displays and prints the results of analyses using parameters
(Optional)

	Mode No.	Parameter	Measurement/Evaluation method	Recorded graph	Digital display	RA-1	RA-211 RA-212	RA-2A	RA-7 RA-711
Parameters available for digital display	0	Roundness (complete circle)			0 888 r/M M: Magnification	●	○	○	○
		Roundness (notched)			0 888 r/M M: Magnification	●	●	Note 1) ○	Note 1) ○
		Flatness			0 888 r/M M: Magnification	●	○	○	○
	1	Off-center (X-axis direction)	X-axis distance between the rotational center of the turntable and the center of the measured profile		1 888 x/M M: Magnification	—	○	○	○
	2	Off-center (Y-axis direction)	Y-axis distance between the rotational center of the turntable and the center of the measured profile		2 888 y/M M: Magnification	—	○	○	○
	3	Squareness			3 888 p/M M: Magnification	●	●	○	○
	4	Concentricity			4 888 2p/M M: Magnification	●	●	○	○
		Coaxiality			4 888 2p/M M: Magnification	—	●	Note 4) ○	Note 4) ○
		Parallelism			4 888 2p/M M: Magnification	●	●	○	○
	5	Peak height	Difference between the radii of the mean circle in LSC and the maximum circle		5 888 h/M M: Magnification	—	●	○	○
	6	Valley depth	Difference between the radii of the mean circle in LSC and the minimum circle		6 888 d/M M: Magnification	—	●	○	○
	7	Mean line average departure	Difference between the radii of the mean circle in LSC and the mean deviation		7 888 a/M M: Magnification	—	—	○	○
Parameters evaluated from recorded profile	—	Thickness deviation			Note 3) t1−t2/M M: Magnification	●	●	●	●
	—	Cylindricity		 Note 2) O1, O2	Note 3) r/M M: Magnification	—	—	—	Note 4) ●
	—	Diameter deviation		 Note 2) O1, O2	Note 3) δ/M M: Magnification	—	—	—	Note 4) ●
	—	Straightness			Note 3) S/M M: Magnification	—	—	—	●

Note 1: Maximum number of notches: 8
Minimum angular displacement between two notches: 40°
Total notched portion: 20% or less
Note 2: Centers O_1 and O_2 must coincide with the center of the recording paper.
Note 3: Determined from recorded graphs.
Note 4: Tilt compensation must be used.

○ : Digital display.
● : Determined from recorded graphs using a template.

Fig. 13 System and functions

7.3.1 Off-center compensation function

When the central axis of the workpiece is not aligned with the rotational axis of the turntable (i.e. off-centered), the axial displacement is detected and incorporated into the measured data. So, the center of the recorded workpiece profile is displaced the same distance from the center of the recording paper (see **Fig. 14**). The Roundtest RA-112/122 uses the Least Square Circle method (LSC) to compensate for off-centering, so that the chart will be drawn about the center of the recording paper.

In **Fig. 14** let the distance between O, the center of rotation of the profile recorder, and Q, a point on the least squares mean circle, be L. The least squares mean circle is determined by minimizing the value of the following formula:

$$\Sigma(r - L)^2$$

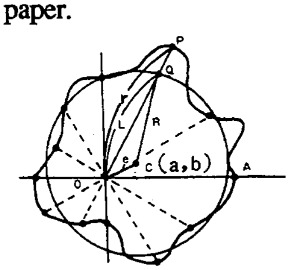
Radius R, and the center coordinates (a, b) of the mean circle are obtained by the following formulas:

$$R = \frac{\Sigma ri}{n}$$

$$a = \frac{2\Sigma xi}{n} = \frac{2\Sigma r\cos\theta i}{n}$$

$$b = \frac{2\Sigma yi}{n} = \frac{2\Sigma r\sin\theta i}{n}$$

The measured profile is drawn so that the center (a, b) of the mean circle coincides with the center of the recording paper.



OP=r
OQ=L
CQ=R
OC=e
AOQ=θ

Fig. 14 Recorded profile without off-center compensation

Note: The least squares method for off-center compensation is also applied to the other methods that evaluate the roundness of a measured profile. The center of the measured profile is then relocated according to each evaluation method.

7.3.2 Tilt compensation function (available on RA-221)

Coaxiality measurements require that the workpiece be measured across at least two different sections in order to determine two center positions. If the axis of the workpiece is tilted with respect to the rotational axis of the turntable, errors proportionate to the degree of tilt will be produced.

The tilt compensation function of the RA-221 determines a reference axis by preliminarily measuring two sections of the workpiece. The line that connects the centers of the two sections is the reference axis. The form errors of the measured sections are determined with respect to this reference axis.

The procedure for coaxiality measurement using tilt compensation is as follows:

(1) Measure reference sections a and b, in that order, and the coordinates of the centers of each section, O_1 and O_3, respectively, will be determined.

(2) Enter height difference L, between O_1 and O_3. Execute tilt compensation by pressing the TILT key, and the tilt angle of reference axis S, will be determined.

(3) Move detector B to section b' and enter the new height difference l. The coordinates of the reference center O (intersection of the reference axis and cross-sectional plane b') are now determined. Then measure section b'.

(4) After the measurement has been completed, the distance between center O_2 of measured section b' and reference center O, is calculated, and the coaxiality (two times the distance between the two centers) is displayed on the amplifier/indicator unit.

The coordinates (x, y) of the center of section b' are determined with respect to reference axis S.

If off-center compensation is not specified, the measured profile is recorded with reference axis S placed at the center of the recording paper.

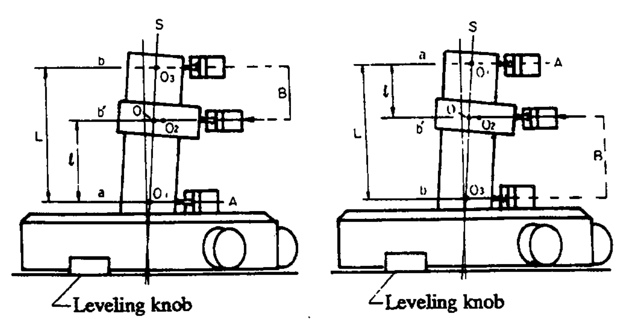


Fig. 15 Coaxiality measurement

7.4 Application Measurement

Inaddition to the roundness measurement (including notched workpieces), the Roundtest can also be used to measure coaxiality, concentricity, parallelism, and perpendicularity. These parameters can be determined, and read directly from the RA-221, with the following methods.

7.4.1 Coaxiality measurement

a) Determining coaxiality from recorded profiles
The coaxiality of the cylinder shown in **Fig. 16** is determined by measuring the workpiece profile at three different sections, A, B, and C and recording the profiles on the same recording paper. The workpiece should be mounted as close to vertical as possible so that the measured profiles do not go beyond the recording range, especially at high magnifications. Record each measurement height to determine the distance L (height difference AC) and 1 (height difference AB). Determine the centers (O_A, O_B, and O_C) of the plotted profiles using a template. Draw a line connecting O_A and O_B. Measure distance l' between the two points. Extend this line beyond O_B and plot point P at a distance of L' from O_A so that the following formula is satisfied:

$$L' = l' \times L/l$$

Measure distance a, between O_C and P, and divide it by the magnification to obtain the coaxiality between two sections AB and AC.

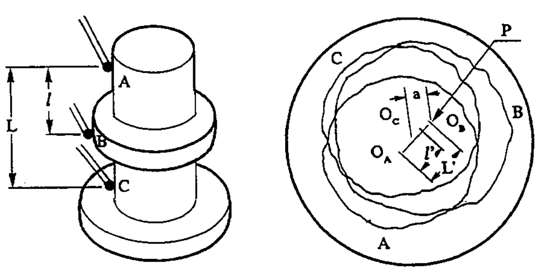


Fig. 16 Coaxiality measurement

b) Determining coaxiality by calculation
Read the center coordinates of measured profiles A, B, and C from the display (use the [CENTER] switch).

Let their coordinates and distances O_AO_C and O_AO_B be:
$O_A = (x_1, y_1)$, $O_B = (x_2, y_2)$, $O_C = (x_3, y_3)$
$O_AO_C = L$, $O_AO_B = l$

Coaxiality (a) is given by the following formula:

$$a = \sqrt{\{x_2 - (\frac{L-l}{L}x_1 + \frac{l}{L}x_2)\}^2 + \{y_2 - (\frac{L-l}{L}y_1 + \frac{l}{L}y_2)\}^2}$$

7.4.2 Concentricity measurement

a) Determining concentricity from recorded profiles
Determine the concentricity of outside circle A and inside circle B of a given section of a workpiece by measuring the two profiles and recording them on the same recording paper, with the off-center compensation function off. The concentricity of these profiles is given by 2a (two times the distance between two centers O_A and O_B) divided by the magnification.

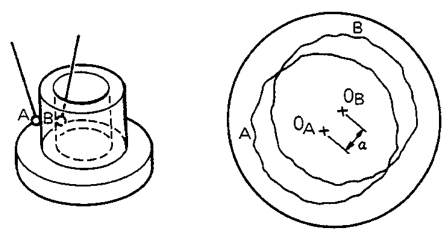


Fig. 17 Concentricity measurement

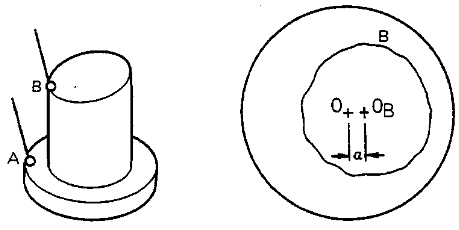
b) Determining concentricity by calculation
Read the center coordinates of measured profiles A and B from the display. Let $O_A = (x_1, y_1)$ and $O_B = (x_2, y_2)$. The concentricity (2a) is given by the following formula.

$$2a = 2\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

7.4.3 Parallelism measurement

a) Determining parallelism from recorded profiles
Level reference face A of the workpiece, then measure surface B with the off-center compensation function

off. Measure distance a, between center O, of the recording paper, and center O_B, of the recorded circle. The parallelism between the two faces is given by 2a (two times the distance between two centers O and O_B) divided by the magnification.



O: Center of recording paper
O_B: Center of plotted circle

Fig. 18 Parallelism measurement

b) Determining parallelism by calculation
Level reference face A of the workpiece. Read the center coordinates (x_1, y_1) of measured face B from the display. The parallelism (2a) between the two faces is given by the following formula:

$$2a = 2\sqrt{x_1^2 + y_1^2}$$

7.4.4 Perpendicularity measurement

a) Determining perpendicularity from recorded profiles
Level the reference face of the workpiece. Measure two sections A and B, and record them on the same recording paper, with the off-center compensation function off. Measure distance a, between centers O_A and O_B of the two circles. The perpendicularity per length l, of the measured axis with respect to the reference face is given by, a divided by the magnification.

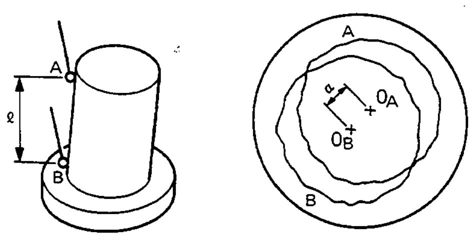


Fig. 19 Perpendicularity measurement

b) Determining perpendicularity by calculation
Read the center coordinates (x_1, y_1) and (x_2, y_2) of sections A and B, from the display as described in **7.4.1** **(b)**. The perpendicularity of the measured axis is given by the following formula:

$$a = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

7.4.5 Measurement of notched workpieces (available on RA-221)

When a notched workpiece is measured using the RA-211, the measurement data that corresponds to the notched section goes off scale. Measurement is interrupted at this point and an error message is displayed. The RA-221 avoids an off-scale error by interpolating data points, based on the measured data before and after the notched section. An unbroken profile line is plotted in this way.

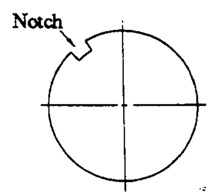


Fig. 20 Notched workpiece

Fig. 21 graphically shows how the data points for a notched section are interpolated.

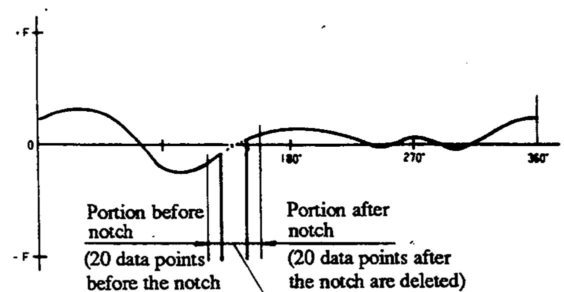


Fig. 21 Rectangular coordinate profile of the notched workpiece (Linear recording)

In the rectangular coordinate profile shown in **Fig. 21**, the notched section goes off scale in one direction (negative direction for O.D. measurements, positive direction for I.D. measurements). The portions of the profile before and after the notch, where the measured data starts to go off scale or returns to scale, are plotted differently from the actual workpiece profile, depending on the size of the stylus tip and the diameter of the workpiece. In order to eliminate a potential uncertainty, 20 measuring points before and after the off scale section are deleted. These deleted points are replaced by straight lines (i.e. linearly interpolated data).

An error will result if measurement is started at a notched section (the origin in **Fig. 21**), or if the angular displacement between two notches is so small that the deleted portions of data from the two adjacent notches overlap.

In order to measure a notched workpiece the following conditions must be observed:

(1) Maximum number of notches : 8
(2) Minimum angular displacement between two notches : 40°
(3) Total notched portion (of circumference) : 20% or less

8. ROUNDNESS TOLERANCING ON DRAWINGS

Fig. 22 shows the standard roundness tolerancing system applied to engineering drawings. The symbol O is used to specify the type of tolerance (i.e. roundness). In this case the roundness tolerance for machining is specified as 5 μm for the section with a diameter of D. This specification is contained in a feature control frame with a leader pointing to the workpiece section concerned. The workpiece's profile is measured at one or more sections, and the measured value or the mean of the measurements is taken as the representative roundness of the feature. Roundness tolerances may be applied a portion of the circle if the workpiece features holes or grooves that are not subject to a uniform tolerance.

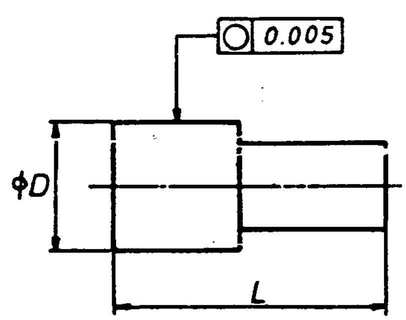


Fig. 22 Roundness tolerancing on a drawing

9. ROUNDNESS MEASUREMENT CONSIDERATIONS

9.1 Frequency Components in Roundness Measurement

The conformity of machined parts to specifications is determined by the intervals between surface irregularities. Accordingly, there are three different categories used for measuring surface features of machined parts. They are; surface roughness for microscopic irregularities, which are very small compared to the surface area in question; straightness and roundness for defining the form errors of a workpiece as a whole, with small irregularities being insignificant; and surface waviness, for irregularities that fall between the two categories above.

Low frequency irregularities are removed using Fourier analysis when the surface roughness of a profile is measured. High-pass (low-cut) filters are incorporated into circuitry to cut off low frequency irregularities. Many surface roughness testers use styli with tips that have a 5 μm or 10 μm radius.

When measuring a workpiece with a Roundtest, minute surface irregularities of a profile are ignored by removing high frequency components via low-pass (high-cut) filters, and by using styli with tips that have larger radii. The cut-off value of the filter can be changed on most Roundtests. The cut-off value should be recorded for each measurement. **Fig. 23** shows the effect of changing the cut-off value of the filter for the same workpiece profile at the same magnification. The filter level is selected depending on the function of the workpiece. Use a 150 UPR (undulations per revolution) or a 500 UPR filter for parts which are relatively free from frictional wear, and whose performances are affected by high frequency surface irregularities. A 15 UPR filter is normally used for parts which are subject to frictional wear, and whose performance is not affected by high frequency surface irregularities.

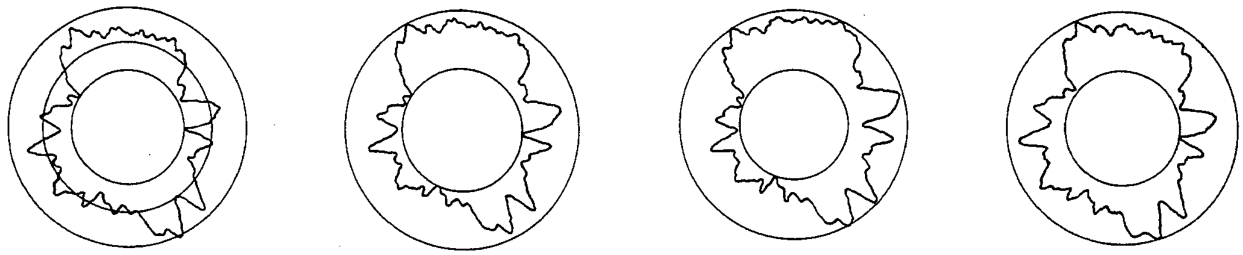


Fig. 23

9.2 Effect of Off-centering with the Axis of Rotation

If the central axis of the workpiece is not aligned with the axis of rotation of the roundness tester, the recorded profile is distorted. The relationship between the off-center and the difference in radius (between the recorded profile radius and the true workpiece radius) is as follows:

Off-center:	Radius difference:
1 mm	0.013 µm
2.5 mm	0.08 µm
5 mm	0.31 µm
7 mm	0.70 µm
10 mm	1.25 µm

If the profile is plotted at a magnification of 1000X, the actual error for each off-center is 0.013 µm, 0.08 µm, 0.31 µm, 0.7 µm, and 1.25 µm, respectively.

9.3 Effect of Magnification

When the deviations of measured profiles are magnified, the irregularities in the profile are emphasized. This can result in convex contours being recorded as concave contours. For example, an elliptical section of a workpiece may be recorded in the shape of a guitar, when concavities along the minor axis are emphasized by magnification.

The facts above must be taken into account when measuring roundness and analyzing recorded profiles.

9.4 Installation Environments

Ideally, roundness measuring machines should be installed on a solid base in a location where the machine will be subjected to minimal amounts of vibration, dirt, and dust, and small temperature changes. Mitutoyo Roundtests are designed to operate under normal shop-floor conditions. When measuring at high magnifications or using a 500 UPR filter, the Roundtest should be placed on a vibration damping stand. Under normal conditions the air regulator unit will remove moisture from the compressed air supply. However, if the humidity is high an air-dryer should be used.

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