TEXTBOOK No. 7025

Coordinate Measuring Machine

TEXTBOOK

Mitutoyo

CONTENTS

PREFACE

A few decades ago the coordinate measuring machine (CMM) was known only in limited sectors of industry. Since then, advances in electronics, computer technology, and detection devices have greatly enhanced the performance and functionality of CMMs. The rapid development and expansion of the manufacturing industries has spawned the need for improved performance, greater efficiency, and more versatility in measuring systems. Because of these technological developments and industry demands, the CMM is now used extensively in industry as a powerful and versatile measuring machine. It is an indispensable tool used in quality control sections that pursue increased efficiency and accuracy in dimensional, geometric, and contour measurements.

Demand for CMMs are diversifying in two major directions; toward the simple, convenient and economical, and toward the automated, multi-functional, specialized and ultra-high-accuracy. In particular, demand for CNC CMMs has notedly increased in recent years. The CNC CMM now accounts for a considerable portion of total CMM production. Mold manufacturers and related industries are some of the major industries that use CMMs extensively. Recently the mold industry has introduced CMMs to stay competitive by having on-time delivery and product quality. Small- to medium-size mold makers, which have long realized the advantages NC machine tools offer, are beginning to recognize the worth of CAD/CAM and CMM systems. The CNC CMM is also beginning to play an important role as an unmanned quality control tool in the FMS (flexible manufacturing system) that is being rapidly introduced to the machine and electronic equipment/appliance industries.

It would please the author if this textbook could be used in gaining an understanding of all aspects of the operation and working of the CMM.

1. OUTLINE OF THE COORDINATE MEASURING MACHINE

1.1 Overview

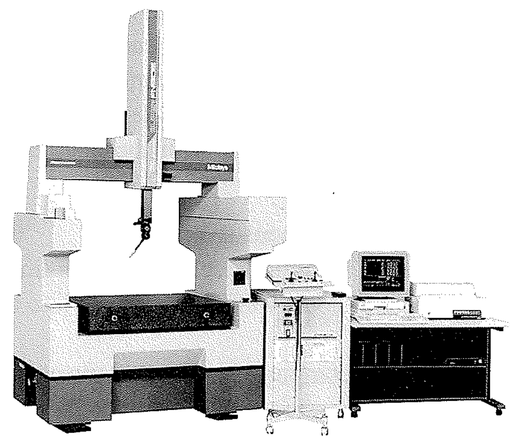


Fig. 1.1 Coordinate measuring machine

The coordinate measuring machine (CMM) may be defined as "a machine that employs three movable components that travel along mutually perpendicular guideways to measure a workpiece by determining the X, Y, and Z coordinates of points on the workpiece with a contact or non-contact probe, and displacement measuring systems (scales), which are on the three mutually perpendicular axes." Since measurements are represented in a three-dimensional coordinate system, the CMM can make many different types of measurements such as dimensional, positional, geometrical deviation, and contour measurements.

Conventional measuring methods involve various types of measuring tools for each specific type of measurement where a surface plate is used as a reference plane. For example, the measurement of form errors, such as squareness and flatness, requires straightedges, squares, and optical flats. Micrometers, calipers, and height gages are used for general length measurement; air gages, bore gages, and limit gages for hole diameter measurement; mandrels for indirect measurement of hole intervals.

Measurement/inspection work using conventional measuring tools require expertise and experience to ensure reliable measurements with high repeatability. Efficiency can be very low depending on the type of measurement. Reading errors may be involved because measurements are indicated on an analog scale.

Manufacturing techniques have made rapid advances because of the vigorous introduction of NC machine tools in industry. This has resulted in the increased complexity of part shapes being manufactured and intensified the requirements for greater accuracy for a high-quality product. A few companies started manufacturing the first practical CMMs in early 1960s. At that time only automobile manufacturers were beginning to use the CMM. In late 1960s demand for the CMM began to increase along with the number of CMM manufacturers.

The demand for CMMs increased because:

(1) Developments in digital technology for linear measurement systems were incorporated into the CMM.
(2) Integration of a computer into CMM systems has facilitated the measurement of lengths, hole diameters, angles, etc.
(3) Fast and powerful computers have become available at low prices.

Other industry and market demands also contributed the use of CMMs:

(1) Streamlining of mass production systems called for improvements in the efficiency of inspection work.
(2) Conventional methods can no longer be used to inspect complex-shaped products (curved surfaces, imaginary origin points) made by NC machine tools.
(3) A limited number of experienced inspectors are available these days.
(4) Companies require their subcontractors to implement stricter quality control.

In its infancy, the CMM was mainly introduced to large industrial corporations. In late 1970s the CMM market entered an expansion stage where leading manufacturers not only placed orders for their second or third machines for quality control, but also began to introduce CMMs in production, R&D, and incoming part inspection sections. Small- to medium-size companies have also emerged as CMM users, greatly contributing to the market expansion. Recently, the demand for special-purpose CMMs has increased to meet the users' specific requirements and applications. For example, manual type CMMs with the following configurations or features have been introduced in the market:

(1) High accuracy
(2) Economy type with medium accuracy
(3) A wide range of selections in terms of measurement range
(4) Sophisticated data processing to measure complex-shaped parts
(5) Simple and easy-to-use data processor
(6) Generation of punched tapes for NC machine tool, based on measurement data

The demand for motor-driven CMMs, which minimize human errors and operator fatigue, and CNC CMMs for automated and unattended operation, are also increasing. Applications have diversified for CNC CMMs these days. These applications include highly accurate repeated measurements, contour measurements, and high-speed in-process measurements integrated into production systems using NC machine tools.

1.2 The History and Development of the CMM

Although every workpiece is three-dimensional, the features of most workpieces were conventionally measured as single-dimensional linear values. This is because dimensional specifications and tolerances of part features were generally given as values represented in a rectangular coordinate system. There are, however, some parts such as tapered screw plug gages for high-pressure equipment, which are practically impossible to measure without an instrument capable of three-dimensional measurement. These requirements called for equipment capable of three-dimensional measurement in the 1920s. CMMs for measuring tapered screw plug gages, which were developed by a Swiss maker around 1930, were one of the original types. This machine had a standard scale and a reading microscope that permit readings to 0.001mm on each of its three axes. It used a level for locating measurement points. The machine was very expensive and only a few units were manufactured. Later, other types of CMMs, which were more economical, appeared on the market. Some of these machines were a combination of a precision machine tools, such as a boring machine and a microscope mounted on the cutter chuck, or a universal measuring machine attached with a vertical measuring device, or an attachment for Z-axis measurement. Although these machines had almost the same structure and measuring principle as today's CMMs, the measuring efficiency was far inferior and the prices were extraordinary high. In addition, neither appropriate devices for detecting measurement points nor data processing systems were available those days. From the viewpoint of performance and utility, these old machines were woefully inadequate in comparison with today's CMMs.

The first industrial-use CMM was developed by Ferranti, a British manufacturer, in 1960. It was a revolutionary machine that adopted a digital display, which was an improvement on the conventional analog system in that expertise was not needed to read measurements. For measuring length this machine employed an optical grating (Moiré encoder), which was developed by the NPL (National Physical Laboratory) and NEL (National Engineering Laboratory) in the U.K. Ferranti uses the same length measuring principle for its CMMs today. Since then, many other manufacturers have developed various types of CMMs which use different length measuring principles, including the Moiré encoder, the rack & rotary encoder, the Inductosyn encoder, the magnetic encoder, and the optical linear encoder.

In Japan, the first CMM (**Fig. 1.2**) was manufactured in 1960 by the Central Inspection Office of Metrology (now the National Research Laboratory of Metrology, Agency of Industrial Science and Technology). This CMM was developed for measuring gages for API screw threads (American Petroleum Institute Pipe Threads). Standard scales and a micrometer projector were used for coordinate detection.

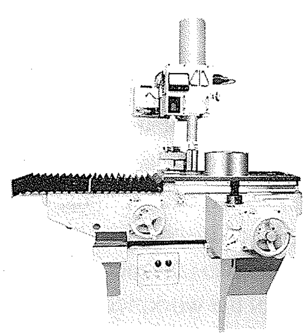


Fig. 1.2 CMM for measuring API screw threads

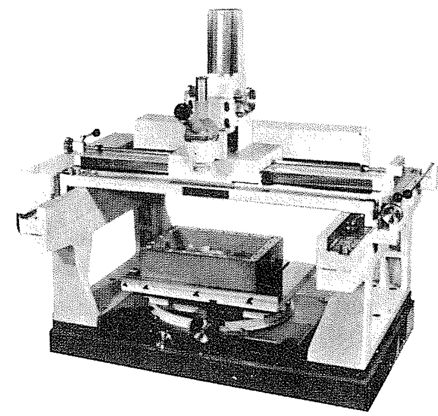


Fig. 1.3 Mitutoyo CMM Model A-1

General-purpose CMMs have been manufactured in Japan for a relatively short time. In 1968 Mitutoyo started marketing the first commercial CMM in Japan under the product name Model A1 (**Fig. 1.3**). It used vernier scales for determining point coordinates. Around that time, Sony developed Magnescale (a scale system using a magnetic encoder), which had a 0.01mm resolution, for the commercial market. This scale was adopted for use by Tokyo Seimitsu and Mitutoyo (Model A2) for their digital CMMs that were marketed in 1969 and 1970, respectively.

Mitutoyo developed a linear encoder with a 0.001mm resolution, which was capable of high speed measuring. In 1972 CMM Model A21 was manufactured with this linear encoder. The vernier reading CMM Model A1 evolved into a digital display model which incorporated rotary encoders. These encoders employ a rack and pinion mechanism. Model A21 is highly accurate and sophisticated, while Model A1 is simple to operate and economical, meeting the two major market requirements mentioned above.

• Data Processing Unit

CMMs incorporating a data processor (computer) were not formally marketed until Ferranti (U.K.) and DEA (Italy) introduced an integrated system around 1969. Data processing functions in these systems were sophisticated enough to include tolerancing, although they were relatively simple compared to today's machines.

In 1970, Mitutoyo started marketing a CMM system that incorporated a Hitachi minicomputer. In the mid seventies low-price microcomputers powerful enough for CMMs became available, which rapidly led to the computerization of data processing for CMMs. This advance established the CMM as a highly accurate and efficient measuring machine.

Initially, the data processing functions were only capable of simple two-dimensional processing, such as point and circle measurements and axis alignments by coordinate system rotation. The mid seventies, when powerful computers with large-capacity memories were developed, saw the addition of advanced functions, such as plane alignment to allow 3D measurement data processing. Geometrical tolerancing functions were also added. Sophisticated software for general purpose-measurement and data manipulation, such as statistical analyses, inspection certificate generation, and design data generation, was developed to meet the diverse needs of the users in the early eighties.

With the advances in electronic technology having increased memory and data processor capacities and decreased prices, dedicated microcomputers and general-purpose personal computers are now powerful enough to handle the sophisticated software that the modern CMM requires.

- **The probe – Measurement point detector**

The advent of the nondirectional touch-trigger probe was one of the most significant events in the development history of the CMM (the probe will be described in detail later). Rolls Royce applied for a patent for the touch-trigger probe in 1971. The probe was developed and manufactured by Renishaw (U.K.). A few years after entering the market in 1973, all the major CMM manufacturers, with the exceptions of Zeiss, Leitz, and DEA, used this type of probe on their machines.

The greatest advantage of this probe is that it is triggered from any direction. Conventional probes' styli are only capable of moving in one axial direction (back and/or forth). This new probe dramatically improved the operating efficiency of the CMM, while offering greater freedom in developing three-dimensional measurement data processing programs. The nondirectional touch-trigger probe has also played a key role in the development of the CNC CMM in recent years.

There is a different type of nondirectional probe which can detect minute stylus displacements in three axes. Zeiss developed this probe with their CNC CMM model UMM500 in 1973. In addition to measurement point detection, this probe is capable of measuring the surface contour of a workpiece by continuously tracing the workpiece surface under CNC. Leitz and DEA developed similar types of probes. The probe developed by Mitutoyo is a scanning probe for use with its CMMs.

With these new developments, CMM systems have found wide-spread acceptance as highly efficient and accurate measuring systems which are indispensable to today's manufacturing industries.

1.3 The Advantages and Economy of the CMM

1.3.1 Advantages of the CMM

The CMM has the following advantages over the conventional methods of measurement on a surface plate:

(1) Improved measuring efficiency

(a) The conventional surface-plate method requires a lot of time to set up the workpiece (leveling, axis alignment, etc.). The CMM, with the aid of its computer, can do the job almost instantaneously.

(b) All faces of a workpiece except the bottom face can be measured without changing its position or orientation.

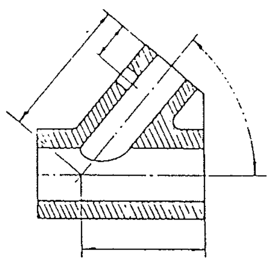
(c) The conventional method requires measurements to be taken at several points with a microscope or other device, while "fine-feeding" the table and reading its displacements. Then, calculations on the measurements had to be made to determine the coordinates of a point. The CMM can determine point coordinates by a simple probing operation.

(d) The calculations were time-consuming since they usually involved complicated trigonometric calculations. The CMM system does not need to perform such manual calculations.

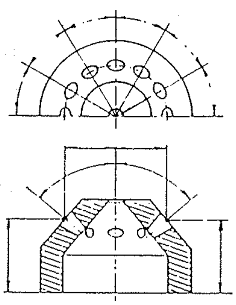
(e) For pass/reject-type inspections, the conventional method first needed to take measurements to know the dimensions of the workpiece, then these measurements had to be compared with design values and tolerances. The CMM can perform these inspections directly and quickly by using a tolerancing program.

(2) The CMM can perform measurements that were previously difficult to make.

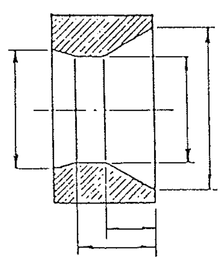
For example, it can easily determine a distance from an imaginary point, spatial distances between related points on a workpiece, and contour and dimensions inside a hollow, as shown in **Fig. 1.4.** This capability also enables accurate and efficient digitization of coordinate values of solid model (such as clay models) contours, which paves the way for linking CAD/CAM and automatic programming systems.



(a) Distances and angles based on an imaginary point



(b) Spatial distances and angles between related points



(c) Interior contour and dimensions

Fig. 1.4 Examples of complicated measurements

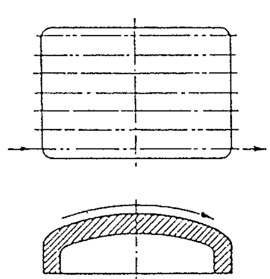


Fig. 1.5 Example of contour measurement

(3) Minimizing human errors

Reliable measurement results can be obtained without the need for the skill of experienced inspectors. Motor-driven CMMs and CNC CMMs will eliminate variation in measurements resulting from different operator skill levels and techniques.

(4) Reduced operator fatigue

CMM operator fatigue is significantly less than that caused by conventional measuring methods.

Reasons:

(a) Generally, CMM operation requires much less work from the operator than conventional methods do. (The extent of operator-performed work depends on the type of the CMM.)

(b) Measurements and calculations are displayed automatically, eliminating strain caused by having to take measurements and calculate on them manually.

(c) Leveling and axis alignment, which have to be done repeatedly when measuring by conventional surface-plate methods, do not need to be performed.

(d) Stable measurements are easily obtained without finicky probe operation.

(5) Elimination of fixtures, jigs, and reference gages

Since the CMM is a flexible measuring machine, fixtures, jigs, and reference gages do not need to be fabricated for each new inspection item. This reduces the cost and time of inspection when developing/manufacturing new products.

(6) Variation in measurements caused by using different gages (standards) is minimized, resulting in higher reliability.

For making simple measurements, such as hole/shaft diameter and width (between two faces) measurements, one measuring tool will suffice. In general, however, measuring a workpiece requires more than one measuring tool. Due to different accuracies of measuring tools, the use of more than one instrument lowers the overall accuracy of the combined measurements. The CMM presents no such problems, ensuring highly reliable measurements.

(7) Automated data management

The CMM system is capable of not only outputting the results of calculations and tolerancing, but also of statistical analyses of data, drawing graphs on an X-Y plotter, and generating inspection certificates. These capabilities dramatically simplifies data management and quality control routines and give speedy data feedback to the production line.

(8) Advantages of automatic measurement using a CNC CMM

(a) The reliability of measurements is further improved by using a CNC CMM system, as travel directions, contacting speed, and points of data entry can be controlled constant for repeated measurements.

(b) Measuring a number of workpieces with identical features can be greatly simplified by using a part program, eliminating the need to repeat the same procedures for each workpiece.

(c) Unattended operation frees the operator for other jobs.

(9) Improved reputation for quality

The CMM enables manufacturers to implement close quality control practices and increases the employees' quality-consciousness. The resulting improvement in product quality will also raise the reputation of the corporation to one that is committed to a superior product.

1.3.2 Economy of the CMM

There are many benefits to be gained by introducing a CMM to an inspection work. It is not always easy to evaluate the economy of the CMM, in terms of its capital expenditure, versus its contribution to the operation because it does not produce a product. The rate of operation is difficult to estimate. It is not so easy to quantify quality improvements and reduced production time and evaluate their effects on an investment-profit basis. For these reasons, we will look at the quality control process, focusing on the reduction of inspection time, and evaluate the economic feasibility of the CMM.

(1) Reduction of measuring time

Table 1.1 gives examples of eight types of workpieces and the time required to measure them using conventional tools, a manual CMM, and a CNC CMM.

(2) CMM cost savings

As shown in **Table 1.1**, the time required for measurement is reduced dramatically by introducing a CMM to perform inspections. Here, we calculate the pay-off period of a CMM compared with the costs involved in a conventional measuring method, based on the following assumptions.

Assumptions:

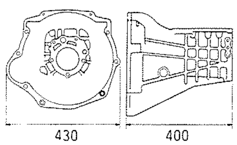
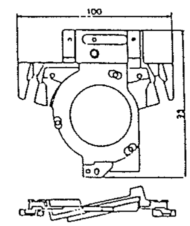
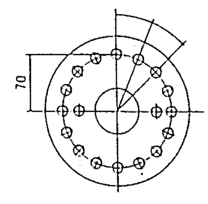
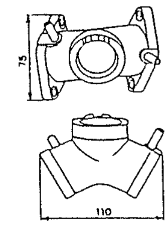
- Amount of work: 100% of operating capacity
- Ratio of measuring time: 4.0 (conventional method) : 1.0 (manual CMM) : 0.7 (CNC CMM)
- Equipment and cost: See **Table 1.2**.
- Interest rate: 6% per annum
- Cost depreciation: 8 years by straight line method
- Running cost: Costs of equipment maintenance, electric power, and material consumption are estimated as follows:
  Conventional method — 2% of the equipment value
  CMM — 5% of the equipment value
- Labor cost involved in inspection:
  Average labor cost per head: ¥100/minute (¥6000/hour)
  Working hours: 1680 hours/year (20% idle ratio)
- Cost comparison: See **Table 1.3** (yearly basis)
- Pay-off period for the invested cost in comparison with the conventional method:
  (Based on the interest payment for the first year)

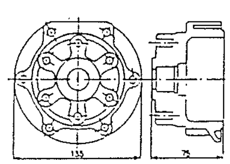
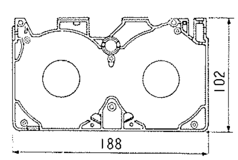
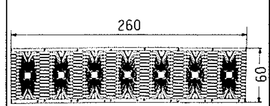
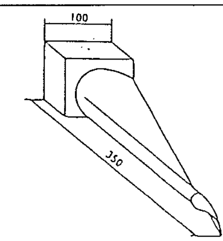
For the manual CMM:
(Increase in investment cost) ÷ (Cost saved in the first year)
= (② - ①) ÷ (④ - ⑤)
= (18,000.0 - 3,700.0) ÷ (41,078.5 - 14,310.0)
= 0.49 year (6 months)

For the CNC CMM:
(Increase in investment cost) ÷ (Cost saved in the first year)
= (③ - ①) ÷ (④ - ⑥)
= (27,500.0 - 3,700.0) ÷ (41,078.5 - 13,518.5)
= 0.86 year (10.4 months)   (Unit: ¥ 1,000)

In this example, the annual cost saving realized by introducing a CMM amounts to ¥2.7 million. The investment cost for a manual CMM and a CNC CMM can be paid off in only six months and ten months, respectively. Although the initial investment cost of a CMM is higher than the initial investment cost of conventional tools, it will be compensated for easily

Table 1.1 Examples of CMM measurements

	Example 1	Example 2	Example 3	Example 4
Workpiece type	Transmission case	Chassis for video-recorder head	Jig for boring	Joint
Production method	Die-cast aluminum	Die-cast aluminum	Molded cast iron	Molded hard rubber
Illustration				
Measured item and number of features (IT tolerance class)	Diameter: 40 features Hole position: 38 features Distance between surfaces : 3 features Other items: 6 features (IT Class 7 - 8)	Angle: 12 features Distance between surfaces: 9 features Diameter: 4 features Other: 9 features (IT Class 5)	Indexed angle: 16 features Diameter: 20 features Perpendicularity: 16 features Other: 5 features (IT Class 4 - 6)	Angle: 13 features Coordinates of intersection: 7 features Diameter: 5 features Other: 6 features (IT Class 8 - 10)
Conventional measuring tools	Holtest Linear Height Test indicator Other 180 min.	Micrometer Height gage Toolmaker's microscope Caliper 150 min.	Indexing table Shaft Sine bar Gauge block 300 min.	Height gage Test indicator Shaft Master block Other 120 min.
Manual CMM	BJ710 with MICROPAK 800 40 min.	F704 with MICROPAK 220 20 min.	FJ905 with MICROPAK 220 15 min.	B710 with MICROPAK 800 20 min.
CNC CMM (Part program creation time)	KN810 with MICROPAK 2810 35 min. (50 min.)	FN704 and MICROPAK 2810 15 min. (45 min.)	FN905 and MICROPAK 2810 10 min. (5 min.)	BN710 and MICROPAK 2810 20 min. (40 min.)

	Example 5	Example 6	Example 7	Example 8
Workpiece type	Casing	Video tape cassette	Lead frame	Turbine blade
Production method	Machined aluminum	Injection-molded plastics	Pressed metal	Machined cast iron
Illustration				
Measured item and number of features (IT tolerance class)	Coaxiality: 4 features Perpendicularity: 2 features Parallelism: 2 features Other: 23 features (IT Class 5 - 6)	Hole interval: 17 features Diameter: 10 features Distance between surfaces: 8 features Other: 10 features (IT Class 7 - 9)	Distance between surfaces: 100 features Coordinates of intersection: 400 features Angle: 400 features Other: 175 features (IT Class 5 - 6)	Surface contour (1 section) (IT class 8 - 9)
Conventional measuring tools	Height gage Test indicator Linear Height Micrometer Other 180 min.	Toolmaker's microscope Test indicator Caliper Other 260 min.	Toolmaker's microscope Other 60 hours	Form measuring instrument Toolmaker's microscope Other 60 min.
Manual CMM	F704 with MICROPAK 120 40 min.	MX504 with MICROPAK 120 30 min.		F704 with MICROPAK 800 (Manual tracing) 40 min.
CNC CMM (Part program creation time)	FN704 with MICROPAK 2810 30 min. (50 min.)	VSR201 3 min. (140 min.)	VSR203 60 min. (480 min.)	FN704 and MICROPAK 2820 (Auto tracing) 15 min. (15 min.)

Note: Measuring time does not include the time required for determining the measuring method and compiling the measured data.

by the increased measuring efficiency and reduced inspection cost. It should be pointed out that the actual efficiency of the CMM can often be higher than the one estimated here. The time required for creating part programs is included in the estimated measuring time of the CNC CMM. Since identical workpiece measuring procedures can be stored, measuring time will be reduced greatly as a library of features is compiled over time. This is one of the advantages of the CNC CMM over the manual CMM, in terms of economy and accuracy.

There are many other economic advantages which have not been mentioned in the above analysis. For example, increased measuring efficiency not only reduces inspection cost but also streamlines production. "Down time" on the production line caused by inspection delays can be minimized. Reliable and accurate measurement will improve quality which, in turn, will improve sales and customer satisfaction.

Table 1.2 Measuring equipment costs (Unit: ¥1000)

	Conventional method	CMM	CNC CMM
Equipment item	Graplate, Height gage, Height Master, Holtest, Micrometer, Caliper, etc.	FJ905 with MICROPAK 220, Touch-trigger probe, etc.	FN905 with MICROPAK2810, Touch-trigger probe, etc.
Cost of equipment	3,700 (3 - 4 sets for each item)	18,000	27,500

Table 1.3 Cost comparison (Unit: ¥1,000)

	Conventional method	CMM	CNC CMM
Ratio of measuring time	4.0	1.0	0.7
Total investment	① 3,700.0	② 18,000.0	③ 27,500.0
Cost depreciation (8 years by straight line method)	462.5	2,250.0	3,437.5
Interest payment (6% for the first year)	222.0	1,080.0	1,650.0
Running cost	74.0	900.0	1,375.0
Inspection labor cost	40,320.0	10,080.0	7,056.0
Total cost per year	④ 41,078.5	⑤ 14,310.0	⑥ 13,518.5

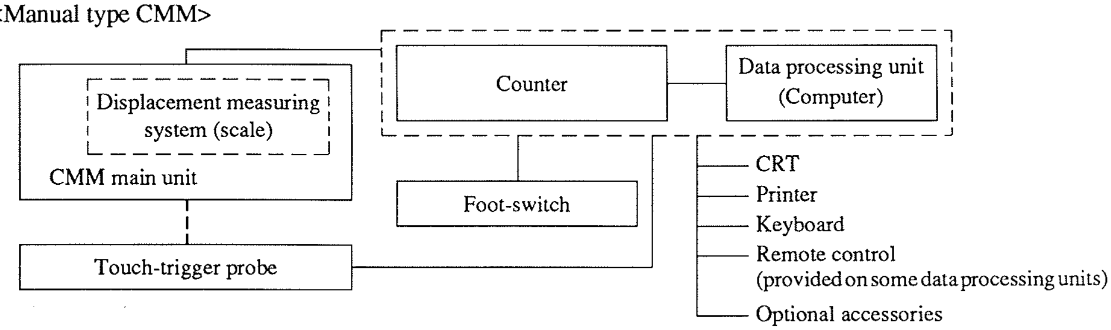
Note: Operational use (as percentage of full capacity) of the CNC CMM is taken to be 70%. The machine can cope with an additional 43% of work with no supplemental investment.

2. CMM SYSTEM CONFIGURATION

Fig. 2.1 shows the standard CMM system configuration.
CMM measuring and data processing procedures follow a series of steps which are outlined below:
The displacement measuring systems (scales) incorporated in each of the three axes of the CMM main unit detect the position of the probe that is attached to the end of the spindle. The scales send the detection signals to the counter which then converts them into X, Y, and Z coordinates, representing the probe's position. (Some CMM data processing units are provided with a counter.)

When an interrupt signal for data input is sent by the probe or the foot switch, the counter values are sent to the data processing unit which performs calculations on these values in accordance with preprogrammed formulas. The calculation results are displayed on the CRT and/or output to the printer.
In motor-driven CMMs, the joystick is used to operate the servomotors which move the probe to the desired point on the workpiece. Command entries can conveniently be made to some data processors (MICROPAK 220, MICROPAK 800, MICROPAK 2800) by remote control. For CNC CMMs, the data processor can automatically move the probe to a specified point at a specified speed and in a specified direction.

<Manual type CMM>



<CMM with a joystick and CNC CMM>

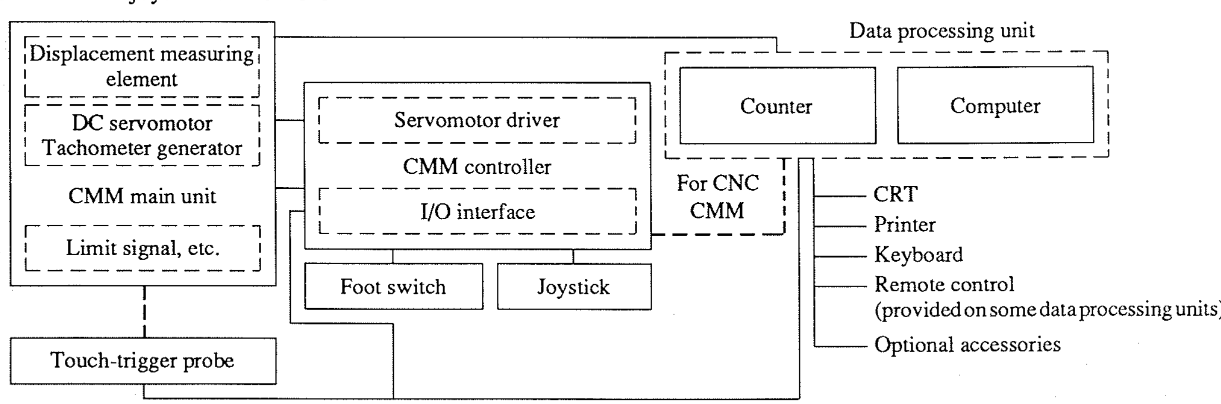


Fig. 2.1 CMM system configuration

3. FUNCTIONS AND PERFORMANCE OF THE CMM

3.1 Classification by Structure

Different CMM structures are available to meet different requirements for operability, measuring range, and accuracy. The features of each type are described below.

3.1.1 Moving bridge type

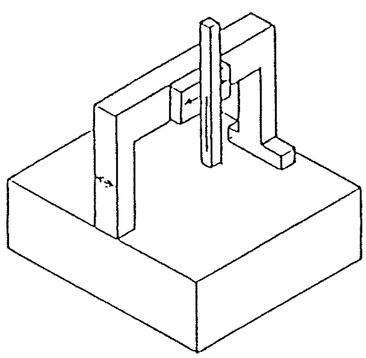


Fig. 3.1 Moving bridge type

(1) Structure (Fig. 3.1)
The Z-axis spindle moves in the vertical direction. The carriage which guides the spindle moves in the X-axis direction along the horizontal beam which is perpendicular to the Z aixs and supported at both ends by two columns. The beam and the columns form a "bridge" which moves in the Y-axis direction along two guideways which are in a horizontal plane and perpendicular to the X and Z axes. (The X and Y axes may be reversed depending on the manufacturer.)

(2) Features
The moving bridge type is the most popular CMM structure. Since the beam is supported at both ends, the beam's flexure is minimized, providing higher accuracy than the cantilever type. Moving the bridge to one end of the CMM makes a wide space available to provide easy loading/unloading of workpieces because there are no obstacles on the measuring table. It also has an advantage that a series of CMMs of different measuring ranges can be made without changing the design, just by extending the measuring table in the longitudinal (Y-axis) direction.

However, the heavy weight of the bridge has a large inertia which makes moving the the probe manually somewhat difficult. Another disadvantage is that when using a CMM with a large measuring range in the longitudinal direction, the operator must often stand at the side of the machine during measurement and the columns get in the way. To cope with these problems, large machines use a motor drive on each axis for remote-controlled movement.

3.1.2 Bridge bed type

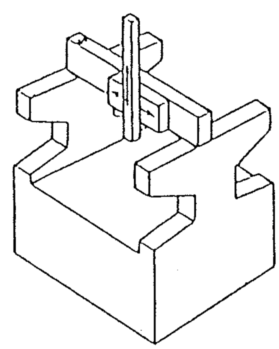


Fig. 3.2 Bridge bed type

(1) Structure (Fig. 3.2)
The Z-axis spindle moves in the vertical direction. The carriage which guides the spindle moves in the X-axis direction along the beam which is perpendicular to the Z aixs. The beam moves in the Y-axis direction along two guideways which are in a horizontal plane. The guideways are provided on the bases at the top of two columns which are fixed to the machine base.

(2) Features
In this type, as with the moving bridge type, the beam is supported at both ends, so the beam's flexure is minimized, providing higher accuracy than the cantilever type. Since only the beam is moved in the longitudinal (Y-axis) direction with a smaller inertia than the entire bridge, manual operation is easier than the moving bridge type.

3.1.3 Bridge floor type (Gantry type)

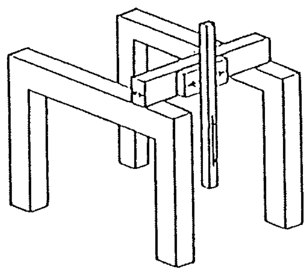


Fig. 3.3 Bridge floor type (Gantry type)

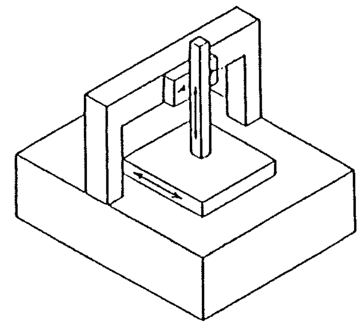


Fig. 3.4 Fixed bridge type

(1) Structure (Fig. 3.3)

The structure is the same as that of the bridge bed type except that the bridges stand directly on a floor with a firm foundation, providing higher rigidity than the bridge bed type. This structure is employed in comparatively large CMMs. (The X and Y axes may be reversed depending on the manufacturer.)

(2) Features

This type generally has a large measuring range and the operator works in the space inside the gantry structure. As the moving members are heavy, each axis is driven by a motor. In some extra wide types, a dual-drive (i.e. one drive system on each side of the beam) is used in order to prevent an uneven or jerky movement of the beam which would affect measuring accuracy. Foundations, however strong they may be, settle and change with age. The supporting columns must be checked periodically to see if they are level, and adjusted if necessary.

3.1.4 Fixed bridge type

(1) Structure (Fig. 3.4)

The Z-axis spindle moves in the vertical direction. The carriage which guides the spindle moves in the X-axis direction along the horizontal beam which is perpendicular to the Z axis and supported at both ends by two columns. The two columns that support the beam are fixed to the machine base. The measuring table moves in the Y-axis direction along a guideway which is in a horizontal plane and perpendicular to the X and Z axes.

(2) Features

Unlike the above-mentioned types, the fixed bridge type involves no movement of the bridge or the beam. This allows the beam to be designed for maximum rigidity to provide a high accuracy. For this reason, high accuracy CMMs employ the fixed bridge structure. Each axis is driven by a motor to ensure displacement accuracy and also because manual operation is difficult, as both the probe and the workpiece have to be moved for measuring.

3.1.5 L-shaped bridge type

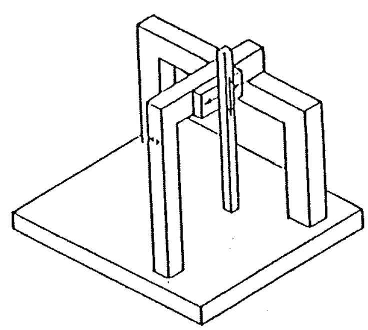


Fig. 3.5 L-shaped bridge type

(1) Structure (Fig. 3.5)

This design is a variation of the moving bridge type for minimizing the inertia when moving the bridge in the longitudinal (Y-axis) direction.

(2) Features

Compared with the moving bridge type, the inertia of the moving members is smaller, resulting in easier operation. Because each moving member is light weight, it is less rigid and less strong. Sufficient care should be taken to maintain its accuracy by periodically checking accuracy deterioration and structural deformation over time.

3.1.6 Moving Y-axis cantilever type

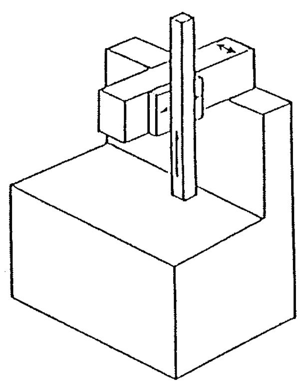


Fig. 3.6 Moving Y-axis cantilever type

(1) Structure (Fig. 3.6)

The Z-axis spindle moves in the vertical direction. The carriage which guides the spindle moves in the Y-axis direction along the horizontal cantilever beam which is perpendicular to the Z axis. The beam moves in the X-axis direction along a guideway which is in a horizontal plane and perpendicular to the Y and Z axes.

(2) Features

Since three sides of the CMM are open, it is easy to load/unload workpieces. It also offers the advantage of being able to measure a workpiece that protrudes out the ends of the measuring table. Using a crane to load or unload a workpiece, however, involves the danger of striking the protruding beam. Operation is easy from the front and sides, but very difficult from the rear. As the Y-axis beam is supported only on one side, it flexes more than the types whose beams are supported on both sides. To cope with this problem some models have a compensation mechanism to ensure straight movement of the Z-axis spindle in the Y-axis direction, but it is not suitable for large-sized machines. Accuracy maintenance is also difficult. For these reasons, the cantilever type is becoming less popular.

3.1.7 Single moving column type

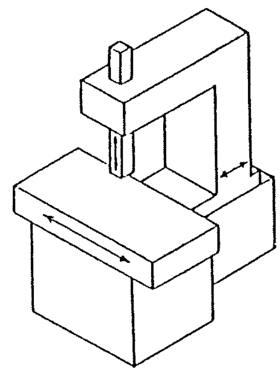


Fig. 3.7 Single moving column type

(1) Structure (Fig.3.7)

The Z-axis spindle moves in the vertical direction. The entire column which incorporates the Z-axis guide moves in the Y-axis direction along a guideway which is in a horizontal plane and perpendicular to the Z-axis. The measuring table moves in the X-axis direction along a guidway which is in a horizontal plane and perpendicular to the Y and Z axes. One variation of this type has a design where the lower part of the column is fixed to the machine base and the upper part moves in the Y-axis direction.

(2) Features

Since the measuring table, column and other parts are highly rigid with minimal deformation, this design is employed in high accuracy types. In addition, high geometric accuracy is ensured because each linear scale is positioned close to the axis to satisfy Abbe's principle. This type of CMM uses a motor-drive system because manual operation is difficult, as both the probe and the workpiece have to be moved for measuring.

3.1.8 Single column XY table type

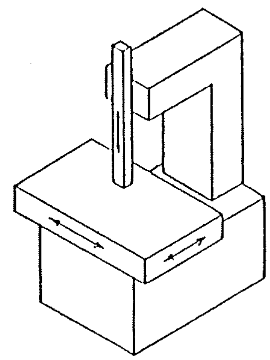


Fig. 3.8 Single column XY table type

(1) Structure (Fig. 3.8)

The Z-axis spindle moves in the vertical direction. The column which incorporates the Z-axis guide is fixed to the machine base. The measuring table moves in two orthogonal directions (X and Y) in a horizontal plane.

(2) Features

This design is mainly employed in small-sized CMMs. Manual operation is difficult as both the table and the spindle have to be moved for measuring. This type is not very popular because manufacturing and maintenance of a high precision cross-travel table is difficult.

3.1.9 Horizontal arm moving table type

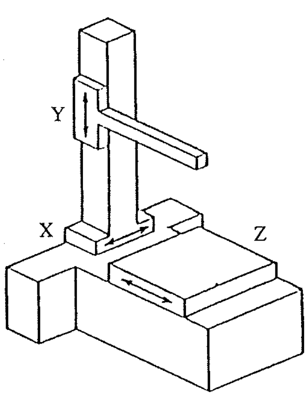


Fig. 3.9 Horizontal arm moving table type

(1) Structure (Fig. 3.9)

The carriage holding the horizontal arm moves in the vertical (Y-axis) direction along the vertical column. The probe is horizontally attached to the arm. The column moves in the X-axis direction along a guideway which is in a horizontal plane and perpendicular to the Y axis. The measuring table moves in the Z-axis direction along a guideway which is in a horizontal plane and perpendicular to the X and Y axes. This type usually has a rotary table as standard equipment.

(2) Features

This is an improved design of the horizontal arm type which undergoes flexure of its arm when it extends and retracts in the Z-axis direction. Loading and unloading of workpieces are easy due to the open-ended design. Since a table moving mechanism is used, this type is not suitable for heavy workpieces. Each axis is driven by a motor because manual operation is difficult.

3.1.10 Horizontal arm fixed table type

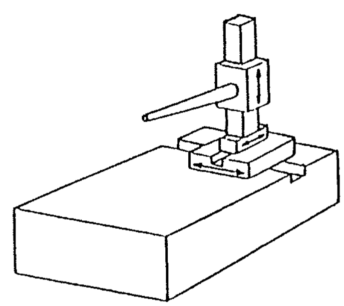


Fig. 3.10 Horizontal arm fixed table type

(1) Structure (Fig. 3.10)

The carriage holding the horizontal arm moves in the vertical (Y-axis) direction along the vertical column. The probe is horizontally attached to the arm. The column moves in the Z-axis direction along a guideway which is provided on the X-axis sliding table and perpendicular to the X and Y axes. The X-axis sliding table moves in the direction perpendicular to the Y axis.

(2) Features

Since the column is moved in the Y-axis direction without using table travel, a heavy workpiece can be measured, overcoming the disadvantage of the moving table type described above. However, manufacturing and maintenance are not easy. As with the horizontal arm moving table type, this type is usually provided with a rotary table.

3.1.11 Horizontal arm type

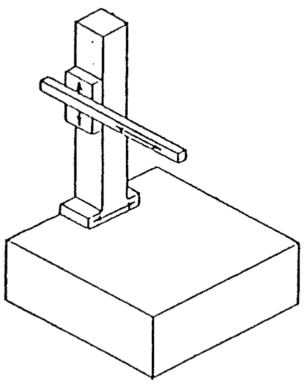


Fig. 3.11 Horizontal arm type

(1) Structure (Fig. 3.11)

The Z-axis arm moves in the horizontal direction. The carriage which guides the arm moves in the Y-axis direction along the vertical column which is perpendicular to the Z axis. The column moves in the X-axis direction along a guidway which is in a horizontal plane and perpendicular to the Y and Z axes.

(2) Features

This type of CMM is generally less expensive than the above two types because the moving members are more compact and simpler in design. One of the advantages of this type is the small size relative to the large size of the workpieces it can measure. On the other hand the horizontal arm type is not suitable for measurement that requires high accuracy because of the arm's flexure when it extends and retracts. There are some CMMs of this type that are designed to solve the problem of accuracy deterioration due to flexure of the arm.

3.1.12 Other types

All the above CMM types use an XYZ rectangular coordinate system. Other types include a multi-joint, or multi-axis CMMs and those which use a cylindrical coordinate system (R, θ, Z).

3.2 Classification by Operation Method

The CMM can be classified into the following three groups by the method of operation.

Manual type
Motor-driven type
CNC type

3.2.1 Manual CMM

In the manual type CMM, the operator moves the spindle along the X, Y and Z axes by hand. CMMs that use a motor drive only for fine feeding are also included in the manual type. It is natural that the manual type is most widely used considering its price advantage and the development history of the CMM.
Many types of probes may be used in manual CMMs, including touch-trigger probes, and ball-tipped probes, hard probes such as non-contact probes such as centering microscopes. The available data processing systems for manual type CMMs range from simple measurement programs to application programs for statistical analyses and contour measurement.
To ensure measuring accuracy, the following points should be kept in mind when using a manual CMM:

(1) When a hard probe such as a ball-tipped probe or a cylindrical probe is used, make sure that a minimal and uniform measuring force is applied.

(2) When taking measurements by holding the end of the spindle, excessive acceleration can cause the structural and axial members of the CMM to bend, resulting in measurement errors. To avoid this problem when using a touch-trigger probe, slow down the spindle speed when the probe comes near the point of contact. When the probe is close enough (about 2mm) to the point, hold the spindle with both hands and slowly bring the probe tip into contact with the workpiece so that a constant measuring force is applied.

The requirement in item (1) above can be satisfied by using a touch-trigger probe which provides a constant measuring force according to its performance. For item (2), it is necessary to practice measurement at different probe speeds in order to perfect the technique.

For measurement with a centering microscope a fine feed mechanism is used. The following types of fine feed devices are available depending on the type of CMM and the manufacturer.

(a) Full-range motor-driven fine feed device
(b) Full-range manual fine feed device
(c) Limited-stroke manual fine feed device

3.2.2 Motor-driven CMM

A motor-driven CMM has motors, which are operated by remote control, to drive each of the three axes. (See block diagram in **Fig. 2.1**.)

The following are the main advantages of the motor-driven CMM:

(1) High measuring accuracy

(a) The measuring operation is remote-controlled without an operator's intervention and with a minimal flexure of the spindle and other parts, resulting in high measuring accuracy.
(b) A uniform measuring speed is ensured which improves repeatability of measurements. It is also free from human errors.

(2) Easy operation and reduction of the operator's fatigue

Remote control of each moving member allows both easy operation and reduction of fatigue to the operator. In the following CMM types the advantages are even greater.

(a) Moving bridge type and bridge floor type CMMs; in some of these types manual operation is difficult due to wide measuring range or heavy moving members.
(b) Fixed bridge type and horizontal arm moving table type CMMs; manual operation is difficult because both the spindle and the measuring table have to be moved for measuring.
(c) Moving bridge type CMMs; the column gets in the way when the operator has to perform measurement from the side of the machine.

One of the most important considerations when using a touch-trigger probe on a motor-driven CMM is protection of the probe from collisions with the workpiece or fixtures. The Mitutoyo motor-driven CMMs have a "touch stop" function, a safety mechanism to protect the probe. The moment the touch-trigger probe's stylus touches the workpiece and sends out a signal, the touch stop function is automatically activated to stop the drive feed of each axis, regardless of the angle of the joystick. It also incorporates a function that checks the angle of the joystick at the instant of the touch stop and prohibits movement of the probe toward the area (restricted area) that corresponds to the approach direction. **Fig. 3.12** shows the area through which the probe can withdraw from the workpiece after the touch stop function is activated. The function releases when the probe's stylus returns to the neutral position.

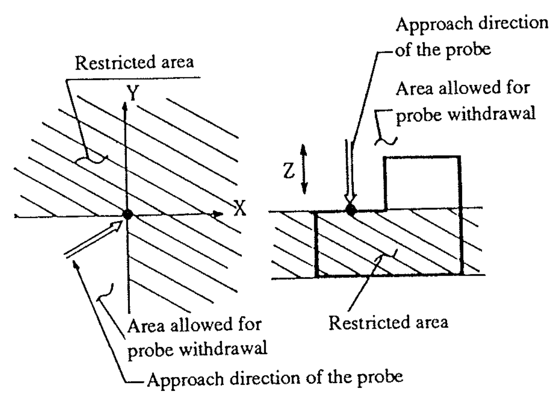


Fig. 3.12 Restricted area and area allowed for probe withdrawal

Some motor-driven CMMs can switch between manual operation and motor drive on the remote control box. There are some manual CMM types that can be upgraded to motor-driven CMMs by retrofitting in the room where it is installed.

3.2.3 CNC CMM

CNC CMMs have motor-driven X, Y and Z axes and automatically perform measurement in accordance with a preprogrammed set of computer commands. Few CNC models provide automatic workpiece loading/unloading.

Since CNC CMMs perform automatic measurements in response to computer commands, the control must know the current probe position at all times by receiving position feedback signals. There are two systems for position feedback: one is the "scale feedback system" which receives feedback signals from the scales incorporated in each axis of the CMM, and the other is the "pulse generator feedback system" which receives signals from the pulse generators attached to the drive motors. The former system is more commonly used.

Measurement by a CNC CMM is classified as follows:

CNC measurement —
- Dimensional measurement (point-to-point measurement)
- Contour measurement of curved surfaces —
  - Point-to-point measurement
  - Scanning measurement

The following are the main advantages of the CNC CMM:

(1) Automatic measurement promotes labor saving and the streamlining of the inspection process, especially for mass-produced items.

(2) Improvement of measuring accuracy
- Improvement of repeatability
- Elimination of human errors

(Refer to **3.2.2 (1)** on motor-driven CMM for detailed descriptions.)

In CNC CMMs, the travel speed and acceleration are kept constant, which completely eliminates human errors. For repeated measurements of identical workpieces, high repeatability is assured as measurements are taken at the same points on the workpieces.

(3) Difficulties in manual operation due to the CMM design are eliminated.

(4) High-speed CNC CMMs, such as Mitutoyo VS/VSR series (high-speed non-contact view measuring CMM), MIC RH606 (horizontal arm CMM for fast in-line measurement) or BRAVO series from DEA, greatly improve the inspection efficiency.

(5) CNC CMMs are capable of measuring workpiece contours that cannot be measured without CNC, as in the following cases.

(a) When measuring a contour in diagonal directions with respect to the CMM axes, as shown in **Fig. 3.13**.

(b) When measuring a curved surface contour at fine intervals between points, which takes too much time without CNC.

(c) When measuring curved surface contours with a scanning probe, which requires continuous control of the probe to trace the workpiece surface.

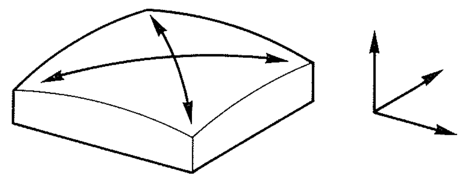


Fig. 3.13 Measurement in diagonal directions

The types of probes used for CNC CMMs include the touch-trigger probe for point-to-point measurement and the scanning probe (described later in details) for scanning measurement. CNC CMMs also allow joystick-control measurement (the same operating mode as motor-driven CMMs). Some CNC CMMs offer a manual operation mode; the advantage being that simple contour measurement can be performed without requiring design data (a part file) to define the tracing path. Some manual and motor-driven CMMs are designed to allow upgrading to CNC CMMs by retrofitting in the room where it is installed.

Generally, the following two methods are available for part programming for CNC measurement.

(a) Desktop part programming

Part programs consisting of measurement procedures, the probe path, measurement points, etc. are programmed for each different workpiece on the computer without using a CMM.

(b) Teaching method

While the first workpiece is measured using a joystick, the measurement procedures, probe path, measurement points, etc. used in this measurement are automatically stored as a part program for CNC measurement.

3.3 Components of the CMM

The CMM main unit consists of functional components and rigid structural members. This section outlines the following functional components.

- Axial guide
- Displacement measuring system (scale)
- Feed mechanism (for CNC and motor-driven CMMs)
- Table elevating mechanism
- Rotary table

3.3.1 Axial guiding mechanisms

CMM's axial guideways have precision-machined guide surfaces along which the bearings attached to the moving member slide. Typical types of guide mechanisms adopted for the CMM are as follows:

Air bearing guide
Roller bearing guide
Ball or roller guide

(1) Air bearing guide

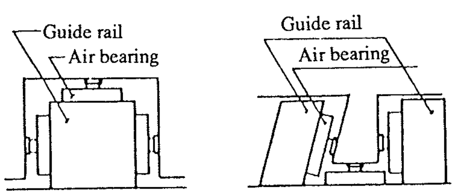


Fig. 3.14 Air bearing guide

Fig. 3.14 shows the typical structures of the air bearing. The performance of an air bearing is generally expressed by the load capacity and the rigidity (see **Fig. 3.15**).

- Load capacity: The load that a bearing can support. (Unit: kgf)
- Rigidity: The ratio of the load on a bearing to the resultant displacement (Unit: kgf/μm)

The air bearing's load capacity range where the maximum rigidity is obtained can be determined from a load-clearance graph. This graph indicates the relationship between the load on the bearing and the clearance between the bearing and the guide surface, as shown in **Fig. 3.15**. The optimum bearing to provide maximum rigidity is designed for each moving member according to the load to be supported by the bearing.

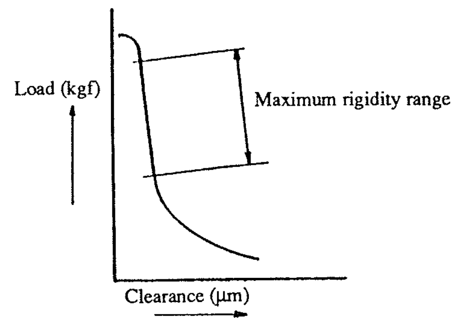
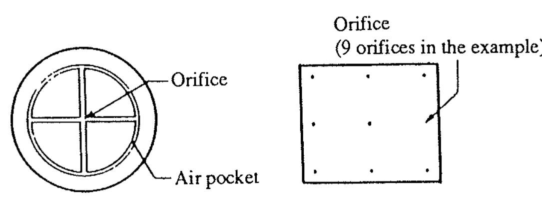


Fig. 3.15 Air bearing characteristics

Air bearings may be either a single-hole or multi-hole type (see **Fig. 3.16**). The multi-hole type provides a higher rigidity per unit area than the single-hole type.



(a) Round, single-hole type (b) Square, multi-hole type

Fig. 3.16 Air bearings (bottom view)

A uniform clearance between an air bearing and its guide surface will not be obtained if the air bearing is rigidly fixed to the moving member and not aligned with the guide surface (parallelism error). To eliminate the influence of this misalignment, air bearings are themselves supported by a ball as shown in **Fig. 3.17**.

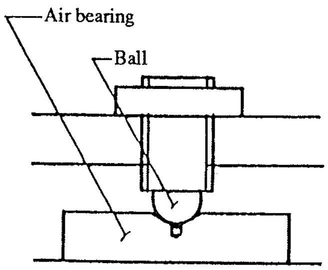


Fig. 3.17 Supporting an air bearing with a ball

The air bearing has an "averaging effect" that averages out or evens the clearance from the guide surface over the entire area of the air bearing, to minimize the influence the guide surface roughness (see **Fig. 3.18**). It also has an advantage that there is no hysteresis (lag) of the movement of the moving members because no friction is involved in sliding. For these advantages, air bearings are used in the majority of CMMs today.

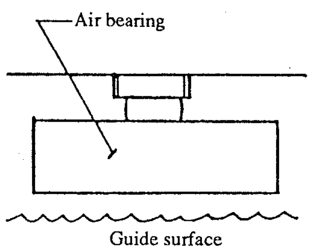


Fig. 3.18 Averaging effect

(2) Roller bearing guide

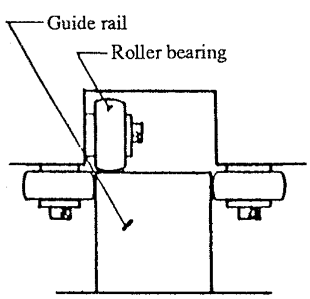


Fig. 3.19 Roller bearing guide

Fig. 3.19 shows a roller bearing guide. High-precision roller bearings are used for CMMs since the guiding accuracy is determined by the magnitude of the run-out error of the roller bearing as well as the straightness of the guide surface. Some CMMs have bearings with a thick-walled outer ring in order to minimize the deformation of the outer ring under load. The advantages of a roller bearing guide are that it does not require an air supply and is relatively rigid for its small size.

(3) Ball or roller guide

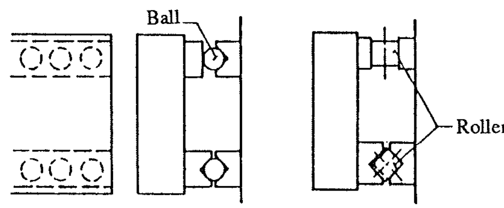


Fig. 3.20 Ball guide and roller guide

Fig. 3.20 shows a ball guide and a roller guide. The balls or rollers to be used on a CMM are carefully selected so that the differences in diameters between each ball or roller are minimal. An advantage of this guide method is that high guiding accuracy is assured without distortion of the moving member because the balls or rollers are evenly spaced underneath the moving member. For this reason, ball or roller guides are used in high-precision CMMs.

3.3.2 Displacement measuring systems (scales)

Today's CMMs have digital readouts for each of the three axes which show the displacement of each movable component. The major types of displacement measuring systems are as follows.

(1) Linear encoder
  Reflection type linear encoder
  Transmission type linear encoder

(2) Moiré fringe encoder

Note: Some older CMMs used other types of measuring elements such as a rotary encoder, magnetic encoder (Magnescale), or Inductosyn encoder. Some of the most advanced CMMs are equipped with a measuring system based on laser interferometry.

The digital readout system offers the following advantages:

(a) Human errors in data reading are eliminated.
(b) No expertise is required for reading data.
(c) Time required for reading data is far less than that required for the analog system.
(d) Zero-setting (also presetting) can be made at any position.
(e) Measured data is readily available for processing on a computer.

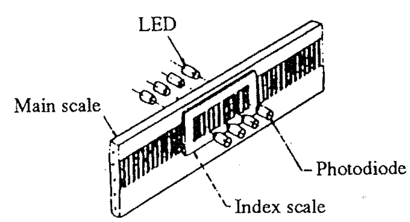
Today, most CMMs are provided with a data processing system of some kind or another. Since the coordinates of a point entered in the data processing system are automatically stored, the counter display is chiefly used to check that the counter is operating or to check the zero-setting of the counter.
Recent demands for even higher accuracy from CMM measurement have made it necessary to improve the displacement accuracy and repeatability of the CMM. This has led to the requirement for a higher resolution of the counter in order to minimize quantizing errors. Thus, the resolution of many of the CMMs released in recent years has increased from 0.001mm of the conventional models to 0.0005mm, 0.0002mm or even 0.0001mm.

The basic principles of the two major displacement measuring systems are described below.

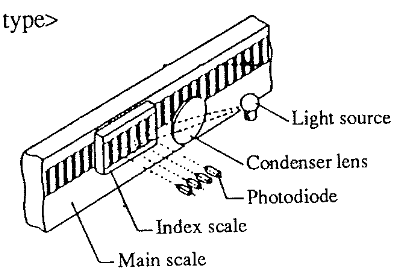
(1) Linear encoder

The linear encoder uses either a transmission or a reflection method.
In the transmission type, an optical grating with an interval of 8 - 20μm is photo-etched on the main scale surface. The index scale is set in parallel with the main scale, and has two or four optical gratings with the same interval, each shifted by a fourth of the interval. When the index scale moves along the main scale, the luminous energy of the light received by the photoelectric device changes sinusoidally, one cycle per grating interval. The light is then converted to electrical signals whose amplitude changes with the light intensity, producing a sinusoidal waveform (see **Fig. 3.21**).
The moving direction of the index scale is detected by the direction discriminator using two output signals, each different in phase by 90° (i.e. one forth the grating interval). These two signals are electrically divided by interpolation into a set of phase-shifted square pulse signals, which are then further divided digitally. The displacement of the index scale is measured by counting these pulses. This process greatly increases the scale's resolution, for example, signals for which each pulse corresponds to a displacement of 1μm can be produced from a scale grating of 20μm intervals.
The reflection type linear encoder also has an optical grating of 8 - 20μm intervals, and uses the same principle as that of the transmission type except that the reflection type determines the displacement by detecting the changes in the intensity of the light reflected from the main scale surface.
The remarkable improvement of the grating accuracy of the linear encoder in recent years has made possible more sharply defined waveforms and therefore a higher S/N ratio (even higher than that of the Moiré encoder), allowing the development of higher resolution linear encoders.

<Transmission type>



<Reflection type>



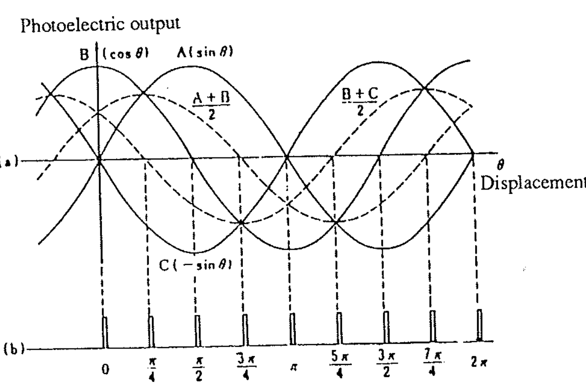


Fig. 3.21 Detection principle of linear encoder (transmission and reflecting types)

(2) Moiré encoder

When two identical gratings of intervals *a* are superimposed so that the lines cross at small angle *θ*, a pattern of dark and light bands with intervals *W* is produced, as shown in **Fig. 3.22**. This interference pattern is called a Moiré fringe. It is known that the relationship between *W*, *a*, and *θ* can be approximately expressed as $W = a/\theta$. When one of the gratings moves in the lateral direction (X direction in the diagram) by a distance of one interval, the Moiré fringe moves in the Y direction by one interval *W*. Moving the grating in the opposite direction reverses the direction of the movement of the fringe. The same photoelectric method as used in the liner encoder can determine the displacement of the grating by detecting the displacement of a band in the fringe. Since the grating's intervals are magnified and wide bands are produced, the Moiré fringe method can easily determine minute displacements of the grating. Interval *a* is usually 8 - 40 μm, but a displacement down to 0.001mm can be measured by means of electrical interpolation.

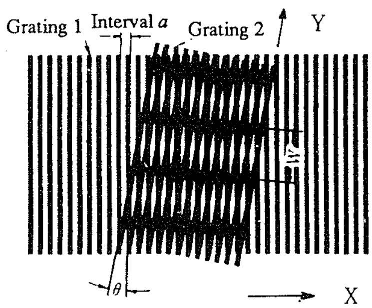


Fig. 3.22 Principle of Moiré fringe

3.3.3 Feed mechanism (for CNC and motor-driven CMMs)

The typical driving mechanisms used for CNC and motor-driven CMMs are as follows:

(1) Ball screw mechanism
(2) Rack and pinion mechanism
(3) Half nut mechanism
(4) Belt drive mechanism
(5) Shaft and roller mechanism
(6) Screw and roller mechanism

(1) Ball screw mechanism

A ball screw consists of a threaded shaft and nut with balls between the thread faces in order to reduce friction (see **Fig. 3.23**). It converts the revolving motion of a motor to the linear motion of an axial member with high transmitting efficiency. Backlash can be practically eliminated by selecting the optimum ball diameter and by using preloaded double nut. One of the major advantages of the ball screw is smooth and stable feed movement due to the rolling motion. Engagement smoothness can be improved by applying a tension to the screw shaft in the axial direction to prevent the shaft from bending under its own weight.

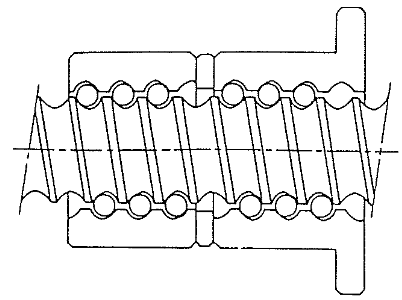


Fig. 3.23 Ball screw

(2) Rack and pinion mechanism

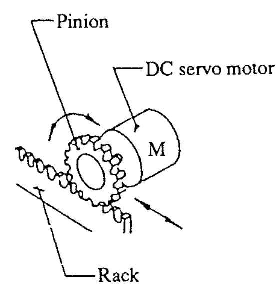


Fig. 3.24 Rack and pinion mechanism

Fig. 3.24 shows a feed mechanism using a rack and pinion. Since a fairly large displacement is produced per revolution of the pinion, the motor rotation is transmitted via a reducing gear train, so the motor power may be small relative to the size of the moving member. This mechanism can be used in CMMs with a large measuring range by joining a number of racks. Switching from motor drive to manual operation is made available by incorporating a clutch. A disadvantage of this mechanism is the backlash between the rack and pinion, requiring design and structural considerations.

(3) Half nut mechanism

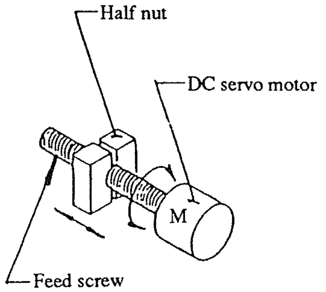


Fig. 3.25 Half nut mechanism

Fig. 3.25 shows a feed mechanism using a half nut. The half nut is used primarily for simple switching between motor drive and manual operation. Backlash is also unavoidable in this mechanism, so design and structural considerations are required. Disadvantages are low transmission efficiency due to the large amount of friction and the low feed speed due to the fine screw pitch.

(4) Belt drive mechanism

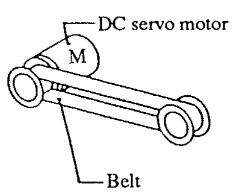


Fig. 3.26 Belt drive mechanism

Fig. 3.26 shows a feed mechanism using a belt drive. It has an advantage of smooth power transmission. Motor drive can be switched to manual operation by disengaging the belt drive from the moving member. Consideration must be given to preventing slip between the belt and the drive shaft and to maintaining the optimum belt tension.

(5) Shaft and roller mechanism

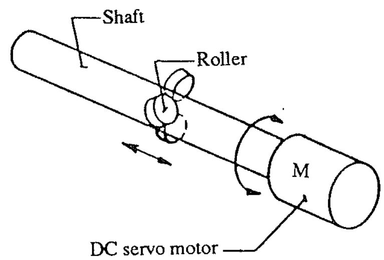


Fig. 3.27 Shaft and roller mechanism

Fig. 3.27 shows a feed mechanism using a shaft and rollers. The rotation of the shaft is converted to the linear motion of the rollers which are pressed against to the shaft at a certain lead angle. The displacement per revolution of the shaft is determined by the shaft diameter and the lead angle of the rollers. The motor drive can be switched to manual operation by disengaging the rollers from the shaft.

(6) Screw and roller mechanism

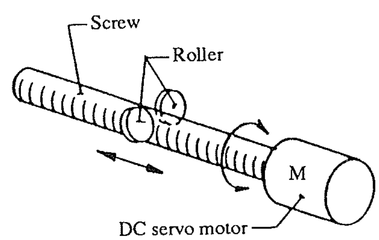


Fig. 3.28 Screw and roller mechanism

Fig. 3.28 shows a feed mechanism using a screw and rollers, which was developed by Mitutoyo. The rotation of the shaft is converted to the linear motion of the rollers which are engaged with the shaft at an inclination equal to the lead angle of the screw thread. This mechanism permits easy switching between motor drive and manual operation. One of the advantages is that because the rollers and the supporting arms can move together about the arms' pivot (follow-up mechanism, see **Fig. 3.29**), straight displacement is obtained even if the screw has run-out errors or if the screw axis is not aligned with the CMM's guideway. **Fig. 3.30** shows the relative positions of the screw and the rollers, which will not produce backlash. In addition, high transmission efficiency is achieved because each rotating section is fitted with roller bearings.

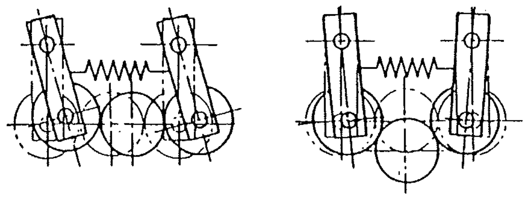


Fig. 3.29 Follow-up mechanism

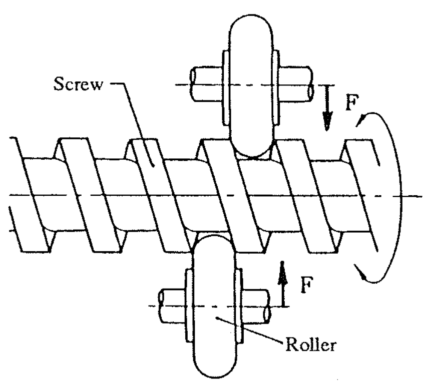


Fig. 3.30 Relative position of screw and rollers

3.3.4 Table elevating mechanism

There used to be some CMMs with a motor-drive mechanism to move the measuring table up and down in order to minimize the extension of the Z-axis spindle when measuring small workpieces and also to provide a large space when measuring large workpieces. Today's CMMs do not use this mechanism because they have a long Z-axis stroke and the rated accuracies are ensured even when the Z-axis spindle is lowered down to the end of its stroke.

3.3.5 Rotary table

A rotary table is used with a CMM when measuring efficiency and accuracy can be improved by rotating the workpiece (e.g. gears, cylindrical cams), or when measurement is not possible without rotating the workpiece (e.g. impellers). The main advantages offered by the use of a rotary table are: (1) for horizontal arm CMMs, the measuring range of the Y-axis spindle can be doubled, and (2) holes with a slanted axis and inclined surfaces can be measured without changing the probe orientation. Some CMMs (such as Mitutoyo MIC RH606) use a rotary table as the fourth axis, and others use a rotary table which is set on the measuring table as necessary.

3.4 Measuring Accuracy of the CMM

3.4.1 Standardization of the measuring accuracy

The widespread use and increasing importance of CMMs in industry prompted the formation of the Coordinate Measuring Machine Manufacturing Association (founded in 1978). Because of the inconvenient and incompatible accuracy standards of CMM manufacturers the CMMA urgently set about creating an international standard for CMM accuracy. Based on the CMMA Standard the following inspection standards were established.

- VDI/VDE 2617-1893 (Genaugkeit von Koordinatenmeßgeräten; Kenngro Ben und deren Prüfung, Grundlagen) (West Germany)
  This is a major European accuracy standard.
- ANSI/ASME B 89.1.12 M-1985 (Method for Performance Evaluation of Coordinate Measuring Machines)
  This standard was approved and published by the American Society of Mechanical Engineers in 1986.
- JIS B 7440 (1987 - 1980, 1981)
  The Japanese standard for CMM accuracy was based on the CMMA, VDI/VDE, and ISO standards.

The ISO inaugurated a working group, in February 1987, titled "Dimensional and Form Measurement with a CMM" to internationally standardize CMM accuracy. They began by discussing the terminology, performance, and methods of accuracy standardization.

3.4.2 Accuracy test items provided by JIS

The following accuracy test items are provided by JIS:

(1) Measurement accuracy

(a) Axial length measuring accuracy
(b) Volumetric length measuring accuracy

(2) Axial motion accuracy

(a) Linear displacement accuracy

(b) Straightness

(c) Perpendicularity

(d) Pitch, yaw, and roll

3.4.3 Accuracy test methods provided by JIS

(1) JIS specifies the following test methods to determine the measuring accuracy of a CMM.

(a) Axial measuring accuracy

(i) Indication of permissible values

Permissible values of measuring accuracy are given by the following formulae and are represented by "U_1" (unit: mm).

$U_{1x} = A_x + B_x \cdot L_x \leqq C_x$: Measuring accuracy of X axis

$U_{1y} = A_y + B_y \cdot L_y \leqq C_y$: Measuring accuracy of Y axis

$U_{1z} = A_z + B_z \cdot L_z \leqq C_z$: Measuring accuracy of Z axis

where,

A, B, and C: Constants presented by manufacturer

L: Measured length (mm)

Remark: The confidence level of permissible values is 95%.

(ii) Test positions

The axial measuring accuracy should be tested at the lowest position of the Z axis on the opposite side of the main axial guide (where the scale is attached) of the CMM (see **Fig. 3.31**).

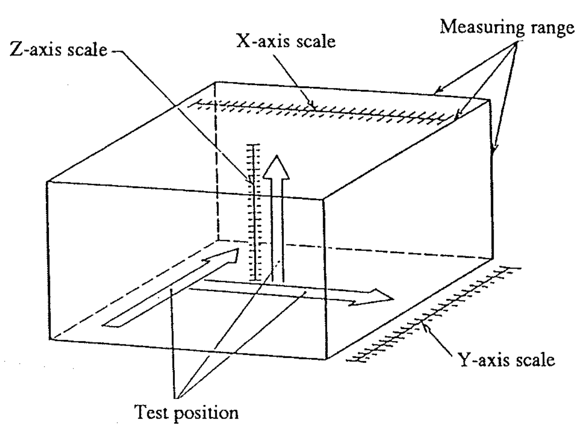


Fig. 3.31 Test positions

(iii) Test methods

The lengths to be tested should be approximately 1/10, 1/5, 2/5, 3/5, and 4/5 of the measuring range of each axis of the CMM. Repeat the test five times for each measuring length and plot the results. Evaluate the results with an overlay template that indicates the permissible range of plot values (see **Fig. 3.32**).

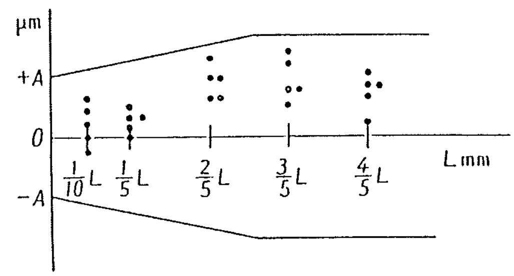


Fig. 3.32 Examples of measured value evaluation

(b) Volumetric measurement accuracy

(i) Indication of permissible value

The permissible values of volumetric measurement accuracy are given by the following formula and are represented by "U_3" (unit: mm).

$U_3 = D + E \cdot L \leqq F$

where,

D, E, and F: Constants presented by manufacturer

L: Measured length (mm)

Remark: The confidence level of permissible value is 95%.

(ii) Test positions

The volumetric measuring accuracy should be tested at two points on a spatial axis at 45° to the X or Y axis and about 35° to the XY plane (see **Fig. 3.33**).

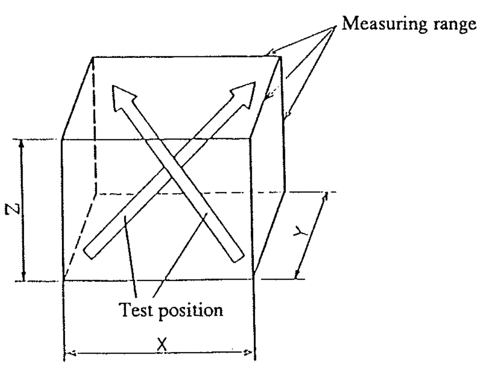


Fig. 3.33 Test positions on spatial axis

(iii) Test method

Take measurements at the positions shown in **Fig. 3.33** using a probe. The number of tests and the method for evaluating the results are the same as those used for testing the axial measuring accuracy.

(2) JIS specifies the following test methods to determine the axial motion accuracy of a CMM.

(a) Linear displacement accuracy

(i) Indication of permissible values

Permissible displacement accuracy values for each axis are given by the following formulae and are represented by "G" (unit: mm).

$G_x = H_x + J_x \cdot L_x \leqq K_x$: Linear displacement accuracy of X axis

$G_y = H_y + J_y \cdot L_y \leqq K_y$: Linear displacement accuracy of Y axis

$G_z = H_z + J_z \cdot L_z \leqq K_z$: Linear displacement accuracy of Z axis

where,

H, J, and K: Constants presented by manufacturer

L: Measured length (mm)

(ii) Test positions

Same as those used for the axial length measuring accuracy test (see to **Fig. 3.31**).

(iii) Test method and evaluation method

Take measurements at ten or more points in both directions over the entire stroke of each axis.

Evaluate the test results with the overlay template that indicates the permissible range. Check to see that the plotted measurements are within the range of the template (see **Fig. 3.34** Examples of evaluation of measured values).

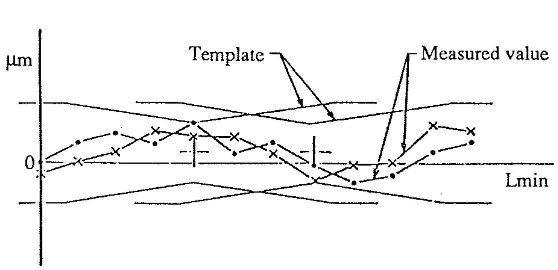


Fig. 3.34 Examples of evaluation of measured values

(b) Deviation from straightness

The deviation from straightness "M" of each axis is given below (unit: µm).

Mxy: X axis straightness in Y axis direction
Mxz: X axis straightness in Z axis direction
Myx: Y axis straightness in X axis direction
Myz: Y axis straightness in Z axis direction
Mzx: Z axis straightness in X axis direction
Mzy: Z axis straightness in Y axis direction

(c) Perpendicularity

The deviation from perpendicularity "N" of each axis is given by the following items (unit: mm).

Nxy: Perpendicularity between X and Y axis motions
Nyz: Perpendicularity between Y and Z axis motions
Nxz: Perpendicularity between X and Z axis motions

(d) Pitch, yaw, and roll

Table 3.1 shows the standard methods of determining pitch, yaw, and roll of the motion of each axis.

Axial length measuring accuracy U_1 and a volumetric length measuring accuracy U_3 are usually tested upon delivery of the CMM.

3.4.4 Relationship between resolution and measuring accuracy

Ideally, a measuring instrument should have the following relationship between the resolution, measuring accuracy and repeatability:

Resolution = Measuring accuracy
Resolution > Repeatability

However, there are few precision measuring instruments which satisfy this relationship, and the CMM is not an exception.

i.e.,

Resolution < Measuring accuracy

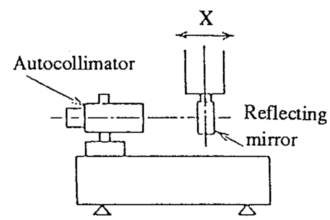
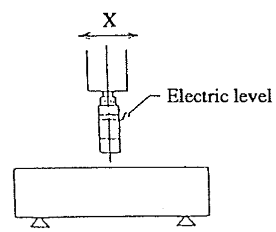
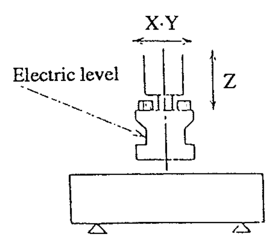
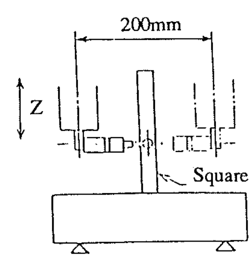
This is because;

① The resolution is too high for the large measuring range.

② Small dimensions are also measured despite a large measuring range.

Another reason why the resolution is set very small is to minimize the quantizing error of the measurement.

Table 3.1 Method of measuring pitch, yaw, and roll

Item of measurement	Measuring method	Figure
Pitch and yaw of X (Y) axis motion	Set an autocollimator on the measuring table. Attach a reflecting mirror to the lower end of the Z axis. The pitch and yaw readings are represented by the maximum difference in the readings of the autocollimator when the X (Y) axis is displaced over its entire measuring range.	
Roll of X (Y) axis motion	Attach an electric level to the lower end of the Z axis. The roll is the maximum difference in the readings of the electric level when the X (Y) axis is displaced over its entire measuring range.	
Pitch and yaw of Z axis motion	Attach an electric level to the lower end of the Z axis in the direction of the X or Y axis. The pitch and yaw readings are represented by the maximum difference in the readings of the electric level when the Z axis is displaced over its entire measuring range.	
Roll of Z axis motion	Set up a square on the measuring table so that its measuring face is parallel to the Z axis. Attach the detector (electric micrometer or equivalent) to the lower end of the Z axis so that it touches the measuring face of the square. Displace the Z axis over its entire measuring range. The roll is given by converting the maximum difference in the readings of the detector to an angle.	

3.5 Criteria for Selecting a CMM

3.5.1 Dimensional tolerance and measuring accuracy

(1) Dimensional tolerance

Parts are manufactured according to design specifications by machining, grinding, honing, pressing, casting, or die casting. Tolerance specifications are not given to dimensions of individual part features that do not have a specific functional accuracy (e.g. dimensions not relating to fit). Instead they are indicated as a general tolerance on drawings. Precision part features that require accurate size control (e.g. mating parts) are accompanied by specific tolerances. **Tables 3.2** and **3.3** show the standard tolerance values for each tolerance class (IT) specified in JIS B0401-1986 (System of Limits and Fits). According to this specification, when a 42 mm diameter shaft is to be fitted in a hole with tolerance class IT 6, for example, the tolerance limits of the hole and shaft can be read from **Table 3.2**.

Tolerance value:
  16µm (the size falls between 30 mm and 50 mm)

Lower dimensional limit of the hole diameter:
  42.000 mm

Upper dimensional limit of the hole diameter:
  42.016 mm (42.000 + 0.016)

Lower dimensional limit of the shaft diameter:
  41.992 mm (42.000 - 0.016/2)

Upper dimensional limit of the shaft diameter:
  42.008 mm (42.000 + 0.016/2)

Table 3.2 Standard tolerance values (less than 500 mm) Unit: µm

Tolerance class / Increment size (mm)		IT1	IT2	IT3	IT4	IT5	IT6	IT7	IT8	IT9	IT10	IT11	IT12	IT13	IT14	IT15	IT16	IT17	IT18
Over	Up to	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
–	3	0.8	1.2	2	3	4	6	10	14	25	40	60	100	140	260	400	600	1000	1400
3	6	1	1.5	2.5	4	5	8	12	18	30	48	75	120	180	300	480	750	1200	1800
6	10	1	1.5	2.5	4	6	9	15	22	36	58	90	150	220	360	580	900	1500	2200
10	18	1.2	2	3	5	8	11	18	27	43	70	110	180	270	430	700	1100	1800	2700
18	30	1.5	2.5	4	6	9	13	21	33	52	84	130	210	330	520	840	1300	2100	3300
30	50	1.5	2.5	4	7	11	16	25	39	62	100	160	250	390	620	1000	1600	2500	3900
50	80	2	3	5	8	13	19	30	46	74	120	190	300	460	740	1200	1900	3000	4600
80	120	2.5	4	6	10	15	22	35	54	87	140	220	350	540	870	1400	2200	3500	5400
120	180	3.5	5	8	12	18	25	40	63	100	160	250	400	630	1000	1600	2500	4000	6300
180	250	4.5	7	10	14	20	29	46	72	115	185	290	460	720	1150	1850	2900	4600	7200
250	315	6	8	12	16	23	32	52	81	130	210	320	520	810	1300	2100	3200	5200	8100
315	400	7	9	13	18	25	36	57	89	140	230	360	570	890	1400	2300	3600	5700	8900
400	500	8	10	15	20	27	40	63	97	155	250	400	630	970	1550	2500	4000	6300	9700

Table 3.3 Standard tolerance values (over 500 mm)

Tolerance class		Unit: µm											Unit: mm						
Basic size step (mm)		IT1	IT2	IT3	IT4	IT5	IT6	IT7	IT8	IT9	IT10	IT11	IT12	IT13	IT14	IT15	IT16	IT17	IT18
Over	Up to	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
500	630	9	11	16	22	30	44	70	110	175	280	440	0.7	1.1	1.75	2.8	4.4	7	11
630	800	10	13	18	25	35	50	80	125	200	320	500	0.8	1.25	2	3.2	5	8	12.5
800	1000	11	15	21	29	40	56	90	140	230	360	560	0.9	1.4	2.3	3.6	5.6	9	14
1000	1250	13	18	24	34	46	66	105	165	260	420	660	1.05	1.65	2.6	4.2	6.6	10.5	16.5
1250	1600	15	21	29	40	54	78	125	195	310	500	780	1.25	1.95	3.1	5	7.8	12.5	19.5
1600	2000	18	25	35	48	65	92	150	230	370	600	920	1.5	2.3	3.7	6	9.2	15	23
2000	2500	22	30	41	57	77	110	175	280	440	700	1100	1.75	2.8	4.4	7	11	17.5	28
2500	3150	26	36	50	69	93	135	210	330	540	860	1350	2.1	3.3	5.4	8.6	13.5	21	33

Standard tolerances from classes IT 1 to IT 4 are mainly for gages, classes IT 5 to IT 10 are for portions to be fitted, and classes IT 11 to IT 18 are for portions which are not fitted. When a transition fit* or a interference fit* in the hole-based system are specified for mechanical parts, standard tolerances classes IT 6 and IT 7 are generally applied to the hole and classes IT 5 and IT 6 to the shaft.

Transition fit: Fit which provides either a clearance or an interference in assembly.
Interference fit: Fit which always provides an interference in assembly.

(2) Dimensional tolerance and measuring accuracy

The following relationship should exist between the specified dimensional tolerance and the measuring accuracy:

Dimensional tolerance ÷ 10 = Measuring accuracy

However, when a close dimensional tolerance is specified or when a large dimension is to be measured, it is difficult for measuring instruments to satisfy such a relationship. The Measurement Law of Japan specifies that standard gages should have the following relationship between tolerance and measuring accuracy.

Tolerance of standard ÷ X = Tolerance of measurements

where X is:
5 for standard scales
3.5 - 5 for standard weights
3.5 - 6 for standard glass thermometers

A very expensive CMM would be needed if a demanding value of 10 for X was required. Considering the measuring accuracy of the scales built in the CMMs and the measurement error caused by temperature conditions, the appropriate value of X for the CMM would be around 4.

Tables 3.4, **3.5**, and **3.6** show the measuring accuracies and the applicable JIS tolerance classes (IT classes) for the Mitutoyo H503, F704 and BH504 series CMMs.

Table 3.4 H503 series CMMs (Z300)

Volumatic accuracy: U_3 1μm	Measured length: L mm	Measuring accuracy: A μm	A x 4 μm	Applicable tolerance class
(1.3 + 3L/1000 ≤ 2.4)	40	1.42	5.68	IT4
	80	1.54	6.16	IT4
	100	1.6	6.4	IT4
	160	1.78	7.12	IT3
	240	2.02	8.08	IT3
	400	2.4	9.6	IT3

Table 3.5 F704 series CMMs (Z300)

Volumatic accuracy: U_3 μm	Measured length: L mm	Measuring accuracy: A μm	A x 4 μm	Applicable tolerance class
(4.0 + 4L/1000)	50	4.2	16.8	IT7
	100	4.4	17.6	IT6
	150	4.6	18.4	IT6
	250	5	20	IT5
	500	6	24	IT5

Table 3.6 BH504 series CMMs (Z300)

Volumatic accuracy: U_3 μm	Measured length: L mm	Measuring accuracy: A μm	A x 4 μm	Applicable tolerance class
(5 + 6L/1000)	50	5.3	21.2	IT7
	100	5.6	22.4	IT7
	150	5.9	23.6	IT6
	250	6.5	26	IT6
	500	8.0	32	IT6

3.5.2 Check points in selecting a CMM

The following are the key considerations in selecting a CMM:

(a) Required measuring accuracy
(b) Measuring range (X, Y, Z) and maximum load
(c) Ease of operation and measuring efficiency
(d) Price

Other points to consider when purchasing a CMM include the availability of accessories and peripheral devices such as probes, fixtures, jigs, and data processing units. Although these items are closely related to (a), (c), and (d) above, probes, fixtures and jigs are not discussed here because they can be added to the CMM system as required. (Refer to the next chapter for the data processing unit.) In selecting a CMM, it is necessary to specifically define the requirements (e.g. the type and size of workpieces to be measured, and the type of measurement). Every CMM is not capable of every measurement task.

(1) Required measuring accuracy
As described above, use one third of the dimensional tolerance as a guideline for determining the required accuracy. The prices of CMMs increase greatly as measuring accuracy increases. One important factor that tends to be overlooked is that the full extent of measuring accuracy of a CMM cannot be realized without providing proper environmental conditions (this will be discussed further in Chapter 6).

(2) Measuring range
The following two points need to be considered when selecting the measuring range of a CMM.
(a) Universal use should not always be expected from large-size CMMs. Usually, the ease of operation is reduced with a large-size CMM.
(b) In addition to the space for the workpiece, approximately a 100 mm margin on each side of the workpiece is required to allow room for probe orientations. Space must also be provided on the measuring table for a master ball and origin point block.

(3) Ease of operation and measuring efficiency
CNC CMMs offer the highest measuring efficiency and accuracy, followed by motor-driven CMMs, and manual floating type CMMs. Qualities relating to ease of operation include the smooth and even motion of the sliding members, the ease of access to measurement points, the ease of axis clamping and fine feed. CNC offers a great advantage with respect to the ease of operation for large size CMMs.

(4) Price
Although price is one of the most decisive factors when selecting a CMM, it is important that the other three criteria above meet the measurement requirements. Also, take into account the savings that result from the investment and the cost of incidental facilities such as a dust-prevention or temperature-controlled chamber.

4. DATA PROCESSING UNITS FOR THE CMM SYSTEM

4.1 Overview

A wide variety of data processing units are used for CMM systems according to the requirements, available computers and maintenance services in different countries. The CMM data processing units are broadly classified into two categories: the simple operation type that does not require special training to use, and the heavy-duty type that are capable of statistical processing, data conversion and transmission in addition to general purpose and contour measurements. **Fig. 4.1** shows a schematic diagram of the MICROPAK 2810 system (Mitutoyo data processing system for CNC CMMs), and **Fig. 4.2** shows a diagram of the MICROPAK 220 and MICROPAK 800E systems for manual and motor-driven CMMs. The measurement and application programs that are available for each data processing unit are shown in **Table 4.1**.

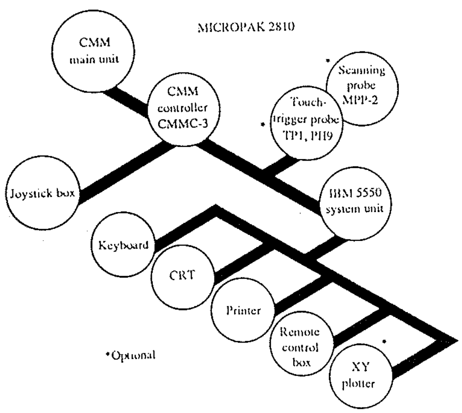


Fig. 4.1 Schematic diagram of CNC CMM system

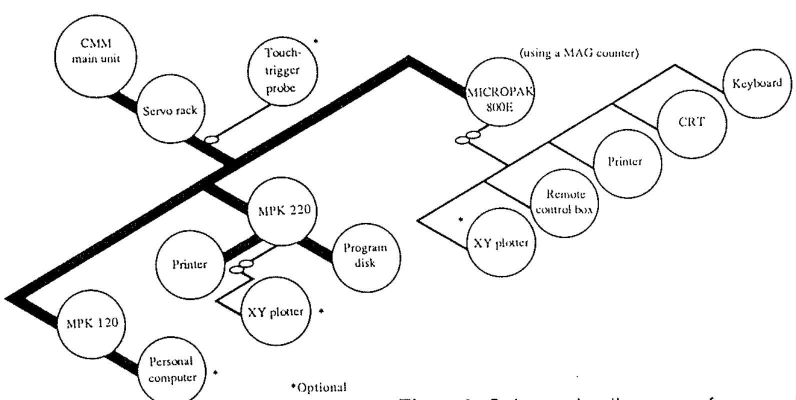


Fig. 4.2 Schematic diagram of manual and motor-driven CMM systems

Table 4.1 Data processing units and software

Data processing unit	Geopak (General-purpose measurement)	Scanpak (Contour measurement)	Statpak/S (Statistical processing)	Statpak/D (Inspection certificate generation)	Unipak-II (Universal inspection certificate generation)	G-Scan (Design data generation)	Other application programs
MICROPAK 120	O (Tolerancing is not available)				O On-line		
MICROPAK 220	O	O	O		O On-line		
MICROPAK 800E	O	O	O	O	O On-line	O	O
MICROPAK 2800E	O	O	O	O	O On-line	O	O

*1: The universal inspection table generation program uses an NEC PC9801 (with an i80286 or more advanced CPU and a hard disk drive).

4.1.1 MICROPAK 120

Fig. 4.3 MICROPAK 120

Features

(a) MICROPAK 120 is especially designed for ease of operation so that a novice can master its operation in a short period of time. For example, patterned measurement keys make part coordinate system setting easy, and both the current and next operations are indicated by LEDs on the keys.

(b) A display, printer, and keyboard are integrated in one unit to reduce the price and the size, yet the 16-bit CPU provides powerful processing functions.

4.1.2 MICROPAK 220

Fig. 4.4 MICROPAK 220

Features

(a) MICROPAK 220 is designed to be used with manual and motor-driven CMMs. It incorporates an i8086-2 CPU, 512KB of main memory, and two 3.5" floppy disk drives.

(b) Part programs and measurement results can be stored on 3.5" floppy disks (1.2MB capacity).

(c) A large 14-inch display provides easy reading and multiple display modes.

(d) A compact and ergonomic keyboard specially designed for CMM operations is supplied.

4.1.3 MICROPAK 800E

Fig. 4.5 MICROPAK 800E

Features

(a) MICROPAK 800E is designed to be used with manual and motor-driven CMMs. The main processing unit consists of an IBM5550 personal computer that incorporates a very advanced i80386/80387 CPU.

(b) A 2MB main memory, a 60MB hard disk drive and a 1.44MB floppy disk drive are provided as standard, allowing large volumes of data to be handled and supporting highly sophisticated software.

(c) The PC-DOS operating system is used, as it provides easy file handling and compatibility with other systems. The system uses interactive operations with menus and screen messages, which are the easiest to use.

(d) A large-size, high-resolution CRT displays clear and sharp graphic images.

(e) Thirty extended function keys, incorporated on a large remote control box, greatly simplify complex operations.

4.1.4 MICROPAK 2810/2820

Features

(a) MICROPAK 2810/2820 is designed for automated operation with CNC CMMs using a CMM drive control unit. The main processing unit consists of an IBM5550 personal computer that incorporates a very advanced i80386/80387 CPU.

(b) A 2MB main memory, a 60MB hard disk drive and a 1.44MB floppy disk drive are provided as standard, allowing large volumes of data to be handled and supporting highly sophisticated software.

(c) The MS-DOS operating system is used, as it provides easy file handling and compatibility with other systems. Part programs are easily created using a 'teaching function'. The system uses interactive operations with menus and screen messages, which are the easiest to use.

(d) A large-size, high-resolution CRT displays clear and sharp graphic images.

(e) Thirty extended function keys, incorporated on a large remote control box, greatly simplify complex operations.

(f) MICROPAK 2810 is a popular type designed for easy operation. MICROPAK 2820 is a multi-purpose, high-performance type which allows automated and unmanned operation by using an automatic probe changer.

4.2 The Basics of CMM Data Processing

Below is a description of the fundamentals required for CMM operation.

4.2.1 Basic terms

(1) Axis and plane alignment

Dimensions of workpieces must be determined in the direction specified on the engineering drawing. For this reason, measurements using a surface plate require the workpiece reference plane to be set parallel with the surface plate (leveling), and the workpiece reference axis must be aligned with the measuring direction (axis alignment). The CMM's computer performs all these alignments by establishing a part coordinate system (described later) with reference to workpiece features, thus eliminating the need to move the workpiece.

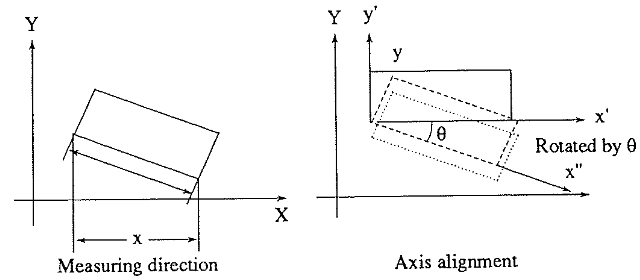


Fig. 4.6 Aligning a workpiece reference axis with a measuring direction (axis)

(2) Measured point

CMM data processing units use commands to specify different types of measurements such as dimensions, angles, hole center coordinates, etc. Each command requires that a specific number of points on the workpiece be entered. When the required number of points have been entered, one point is usually determined along with dimensions or other measurements. This point is referred to as the "measured point." Some commands do not determine a measured point (e.g. width measurement) and other commands determine two measured points (e.g. cylinder measurement).

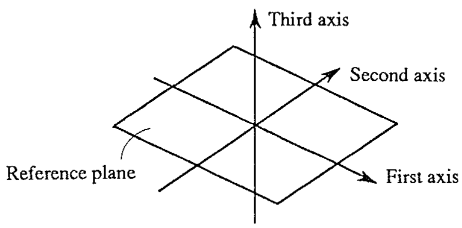
(3) Reference plane and reference axis

The reference plane of a workpiece corresponds to the projection plane in an engineering drawing. It serves as the base plane onto which the entered points are projected for specific types of data processing. For example, if a cylindrical hole is perpendicular to the reference plane, any points entered on the surface of the cylinder are projected onto the reference plane as points forming a circle on which data processing is performed.

The X, Y, and Z axes are called the reference axes for convenience. In order to express the relationship between the reference plane and the reference axes, the axes are designated the first, second, and third axes respectively. The relationship between the reference axes and the reference plane is shown below.

Table 4.2 Reference plane and reference axes

Reference plane \ Reference axis	First axis	Second axis	Third axis
XY plane	X	Y	Z
YZ plane	Y	Z	X
ZX plane	Z	X	Y



(4) Dummy point entry

When a workpiece surface is measured using a probe, the coordinates of the probe center is entered in the data processor. Therefore, these coordinates must be compensated for (offset) by the probe radius to determine the actual workpiece dimensions. A "dummy point" is entered in space to specify the direction of the probe radius compensation, which is made in the opposite direction to the dummy point (see **Fig. 4.7**). Some data processing units and software perform probe radius compensation in response to specific commands, or automatically based on the approach direction of the probe.

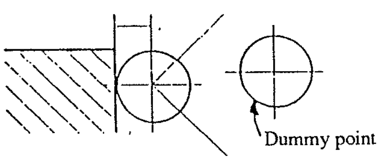


Fig. 4.7 Dummy point entry

4.2.2 Coordinate systems

(1) Machine coordinate system

The machine coordinate system consists of the X, Y, and Z axes of the CMM itself and is used as a reference for determining the displacement along each axis of the CMM, storing coordinate data in the data processing unit, and CNC operations. In general, the machine origin (the origin of the machine coordinate system) is the position of the probe the moment the CMM is powered-up. This origin can be subsequently altered by measuring a Master Ball or Origin Point Block which is fixed on the measuring table. For CNC CMMs, the machine origin is set to a predetermined point by the program.

(2) Part coordinate system

For measurements, it is necessary to establish a coordinate system, independent of the machine coordinate system, using the workpiece's reference surface. This is called the "part coordinate system," and it can be defined according to the drawing by measuring datum surfaces and features on the workpiece. The part coordinate system is established by leveling and aligning the workpiece to the measuring axis. Once a part coordinate system is established, measurement data thereafter is represented by the coordinates in the part coordinate system. Therefore, it is important to set the part coordinate system that best suits the measurement tasks required, with reference to the drawing.

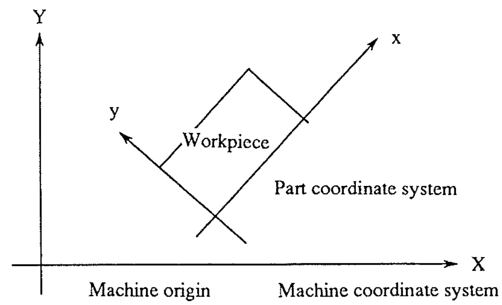


Fig. 4.8 Machine and part coordinate systems

(3) Reference origin

The machine origin is automatically set at the probe center position the moment the CMM is powered-up. If a measurement operation involves changes in probe orientations, probe replacements, or use of multiple probes, the machine origin must be re-specified or offset, in order to permit measurements that require the use of different probes or orientations to be represented in one coordinate system. The machine origin can be specified by measuring a reference origin point block, such as a Master Ball or Origin Point Block, which is fixed to the measuring table.

4.2.3 Memory function

Measured data can be stored and retrieved at any time.

4.2.4 Teaching function

The teaching function is used to store a sequence of measurement procedures. The measurement procedures can be retrieved as required. This function is especially useful when performing repeated measurement of workpieces from the same lot.

(1) Learn mode
In the learn mode, sequential operation procedures that are used to measure a workpiece are stored as a part program in a file. These operation procedures can be retrieved in the repeat mode.

(2) Repeat mode
In the repeat mode, measurement procedures which have been stored as a part program are retrieved for program execution. To execute the part program, the operator has only to specify the part program number and then enter the measured points. No keyboard commands need to be issued.

(3) Edit function
This function is used to modify a part program file previously created or to create measurement procedures through keyboard entries only, without actually performing measurements. These procedures can also be stored as a part program in a file.

4.3 Software

Software used for CMM measurement and data processing is shown below.

(1) Measurement programs
- General-purpose measurement program (standard program plus tolerancing program)
- Contour measurement program

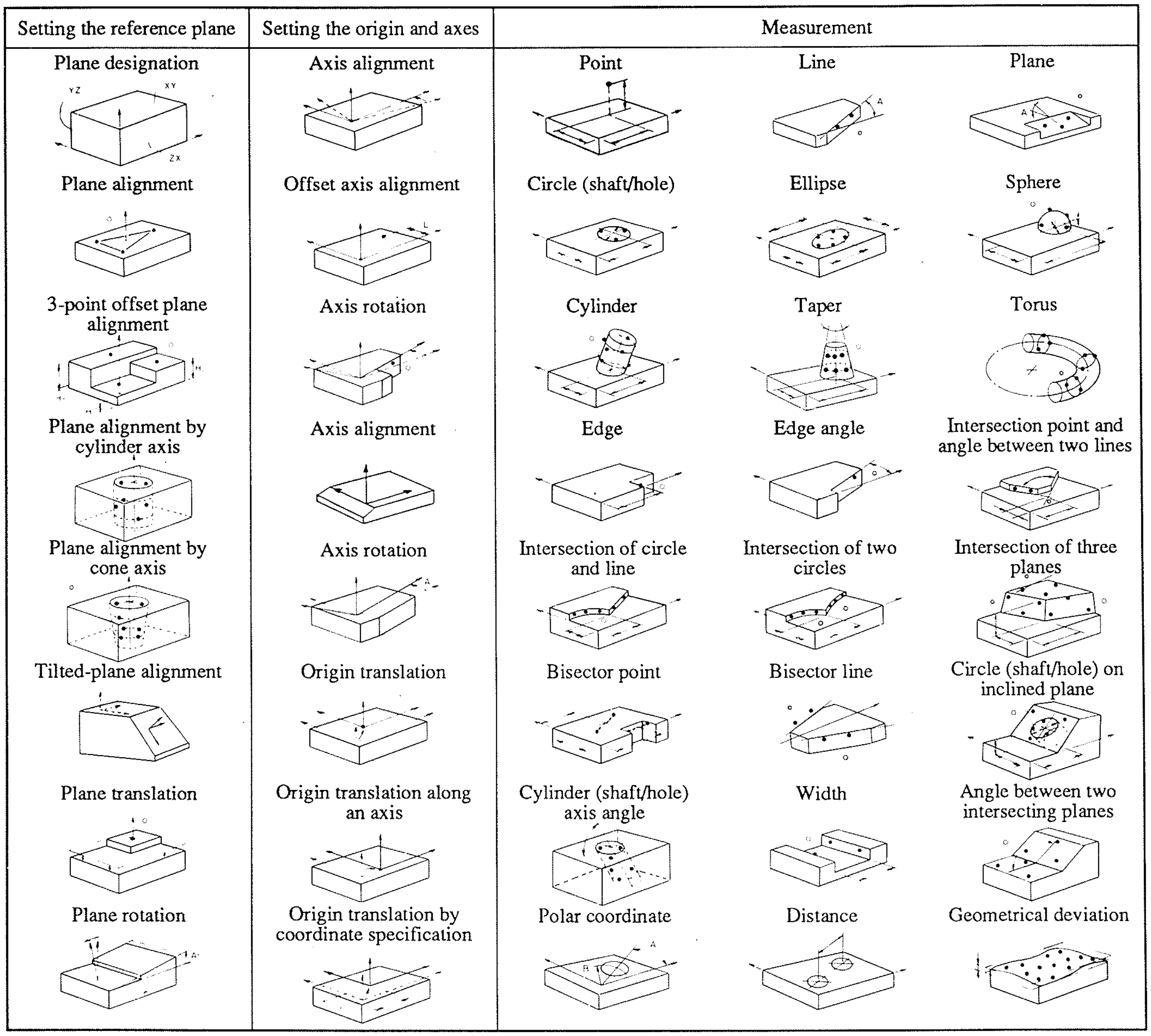
(2) Measurement data processing programs
- Statistical processing program
- Inspection certificate generation program
- Universal inspection certificate generation program

4.3.1 General-purpose measurement program – Geopak

This is a program for measuring coordinates, dimensions and geometrical deviations on workpieces such as machined parts, dies, and die-cast products.

This program has many functions that are accessed through an assortment of commands. The basic functions include: (1) Probe tip diameter specification, (2) Reference plane (projection plane) specification, (3) Plane measurement, (4) Point measurement, and (5) Circle measurement. Combinations of these basic functions accomplish various tasks such as dimensional measurement, coordinate system setting (which involves plane and axis alignments and origin setting), and part program creation.

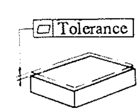
Fig. 4.9 Basic measurement functions of a general-purpose measuring program



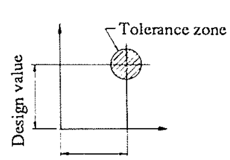
- Multi-point entry up to 30 to 150 points (varies depending on the software used) is permitted.

In addition to the above functions, the general-purpose measurement programs (except MICROPAK 120) provide tolerancing functions as shown in **Fig. 4.10**.

- Checking against geometrical tolerances
  Determines deviations from design values and makes go/nogo judgments based on specified geometrical tolerances (flatness, parallelism, etc.).



- Checking against positional tolerances = True position
  Determines deviations from design values and makes go/nogo judgments based on specified positional tolerances (circular tolerance zone).



- Checking against rectangular coordinate tolerances
  Determines deviations from design values and makes go/nogo judgments based on specified coordinate tolerances.

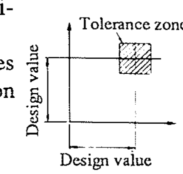


Fig. 4.10 Tolerancing functions

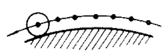
4.3.2 Contour measurement program – Scanpak

This program is used to measure curved surface contours of workpieces such as turbine blades, cams, dies, and die-cast products. Measured points are represented by a series of coordinate data to be used for contour assessment.

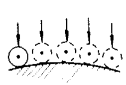
(1) Data input

The following three data input methods are used for contour measurement:

Continuous input by tracing



Input by point-to-point measurement



Input from data file

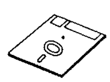
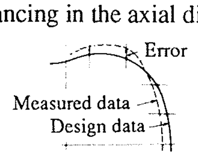


Fig. 4.11 Data input methods for contour measurement

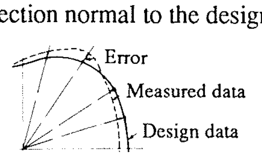
(2) Printout of tolerancing result using nominal (design) data and tolerance limits

If design data is available, the following three methods of tolerancing calculations can be used to make go/nogo judgements.

Tolerancing in the axial directions



Tolerancing in the direction normal to the design contour



Tolerancing at a constant angular pitch

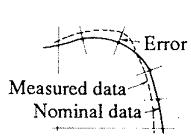


Fig. 4.12 Tolerancing with design data and tolerance limits

(3) Result output to the graphic display unit and plotter

A drawing of the measured contours, design contours, and tolerance zones can be output to the plotter with deviations being magnified a specified amount, for quick and easy analysis. If the system includes a graphic display unit and a printer, the contours and tolerance can be displayed and the numerical results of tolerancing can be printed.

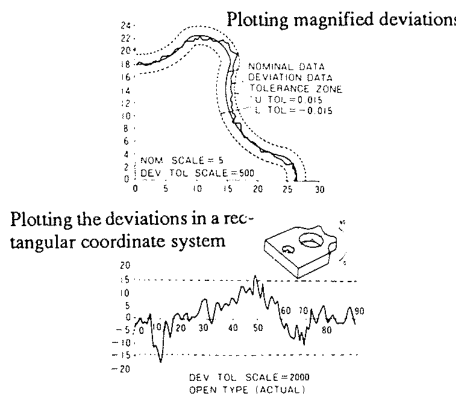
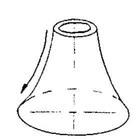
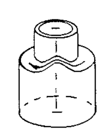


Fig. 4.13 Plot/display examples

In addition to making contour measurements, Geopak can use different coordinate systems to measure cylindrical cams, bodies of revolution, etc. (see **Fig. 4.14**).



R (radius) - Z (height) measurement



A (angle) - Z (height) measurement

Fig. 4.14 Measurement of solid forms

4.3.3 Statistical processing program – Statpak/S

Optional statistical processing programs are available for the MICROPAK 220, MICROPAK 800E, and MICROPAK 2800E systems. These programs process, according to statistical parameters, the coordinate and dimensional data obtained by general-purpose measurement programs. The results can be tabulated for output to a printer and graphically output to a plotter or a display unit.

The main statistical processing functions include:

- Tabulation and plot of a process capability chart (**Fig. 4.15**)

- Tabulation and plot of a histogram
- Tabulation and plot of an $\bar{X}$-R chart
- Tabulation and plot an $\bar{X}$-S chart
- Plot of a scatter diagram
- Calculation and tabulation of the process capability index (Cp)
- Tabulation of statistical data
  Number of measurements (N), Maximum value, Minimum value, Mean value, Range, Standard deviation, Number of defectives (Pn), Fraction defective (P), Skewness, Kurtosis, Process capability indices (Cp, Cpu, Cpl, Cpk)
- Tabulation of input data

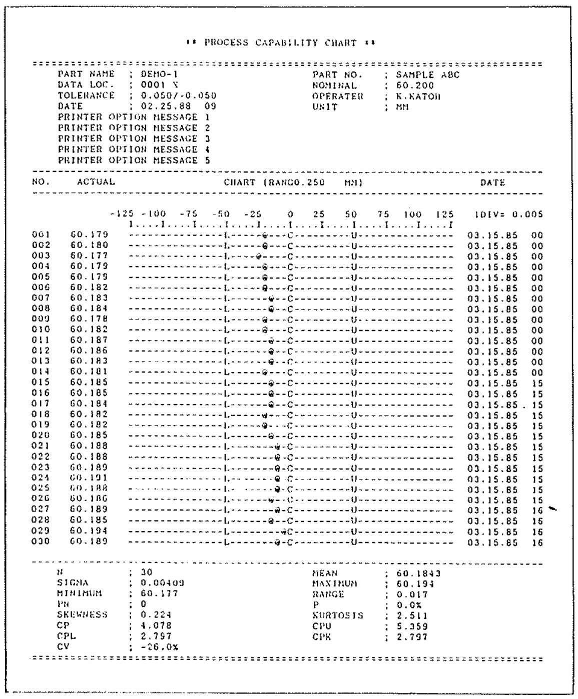


Fig. 4.15 Process capability chart

4.3.4 Inspection certificate generation program – Statpak/D

This is an application program to generate inspection certificates in a user-specified format based on the measured data obtained from general-purpose measurement programs (see **Table 4.3**).

Table 4.3 Inspection certificate

** INSPECTION CERTIFICATE **

Macrosoft Inc.

PART NAME : DEMO-2
DATE : 08.12.21.13
SAMPLE NO. ; 3
M.MACHINE : MITUTOYO CMM
PART NO. : SAMPLE XYZ
OPERATOR : K.KATOH
UNIT : MM

SKETCH

NOTE

LOC.	NOM.	TOL.	SAMPLE 1	2	3	MEAN	SIGMA
0001 X	60.200	0.050 -0.050	-0.021	-0.020	-0.023	-0.0212	0.00162
0001 Y	31.800	0.050 0.000	0.023	0.027	0.024	0.0249	0.00185
0001 D1	38.000	0.050 0.000	0.032	0.026	0.030	0.0292	0.00268
0002 X	100.100	0.050 -0.050	0.004	0.011	0.027	0.0141	0.00967
0002 Y	66.600	0.100 -0.100	0.016	0.027	0.014	0.0189	0.00576
0002 D2	14.000	0.100 0.000	0.066	0.063	0.066	0.0652	0.00133
0002 LC	53.000	0.050 -0.050	-0.042	-0.034	-0.025	-0.0335	0.00694
0003 CX	30.000	0.500 -0.500	-0.234	-0.243	-0.252	-0.2430	0.00712
0003 L	42.000	0.100 0.050	0.069	0.081	0.112*	0.0872	0.01822
0004 A1	49.500	0.167 -0.167	0.102	0.100	0.104	0.1022	0.00147
0004 L	64.800	0.050 -0.050	-0.017	-0.011	-0.014	-0.0140	0.00262
0004 D1	8.100	0.050 -0.050	0.013	0.008	0.012	0.0110	0.00232

Mitutoyo

The main functions include:

(1) Generation of an inspection certificate in various formats
(a) Tabulation of measurement data (Column: measurement items; Line: workpieces)
(b) Tabulation of measurement data (Column: workpieces; Line: measurement items)
(c) Tabulation of tolerancing results (Column: measurement items; Line: workpieces)
(d) Tabulation of tolerancing results (Column: workpieces; Line: measurement items)

(2) The size of the drawing area can be specified by the user. Headings, footnotes, and comments can be printed in the upper and lower margins.

(3) For the tolerancing results tabulation type, not only the judgment but NG symbols for the out-of-tolerance data can be printed.

(4) Deviations from design data can be printed using one of three formats: real number (e.g. 0.027), integer (e.g. 27), or symbolic ("+/–") format.

(5) Statistical results can also be appended to the table.

4.3.5 Other applications

In addition to the programs described above, other types of application programs are available to meet the diverse needs of users.

5. PROBES AND ACCESSORIES FOR THE CMM

5.1 Probes

Selecting the optimum probe according to the measurement task is a key to obtaining the best possible performance from a CMM. The measuring accuracy and efficiency that a CMM is capable of is highly dependent on the probe selected.

5.1.1 Mechanical probes

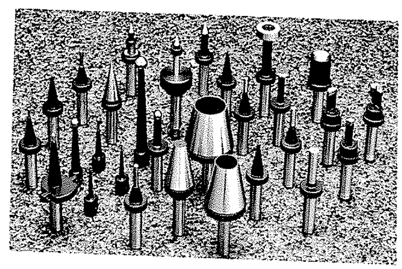


Fig. 5.1 Mechanical probes

There are various types of mechanical probes as shown in **Fig. 5.1**.

(1) Ball-point probe
This is the standard probe for the CMM and has the widest range of applications. The typical stylus tip ball is made of carbide with a diameter of 2 - 10 mm.

(2) Taper probe
This probe is used to determine hole locations. Because taper probes can determine two-dimensional coordinates only, the surface of the workpiece having holes to be measured must be leveled before taking measurements.

(3) Cylindrical probe
This probe is used for measuring thin plates. Like the taper probe, the cylindrical probe can determine two-dimensional coordinates only, so the workpiece must be leveled before taking measurements.

(4) Universal probe
This is a kind of ball-point probe in which stylus orientation can be changed to measure inclined or side faces of a workpiece.

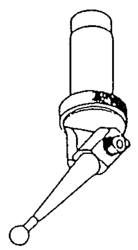


Fig. 5.2 Universal probe

(5) Special-purpose probes

There are various types of special-purpose probes, such as a hemisphere-tipped probe for measuring surface contours, a chucking probe capable of mounting an optional stylus, or a pointed probe used for scribing. To measure deep holes, probes with a long shank are often used. Special care is required when measuring with a long-shanked probe, since it is easily deflected, producing a measurement error.

<Reference>

$$\delta = \frac{WL^3}{3EI} = \frac{W \times L^3}{0.1473 \times E \times d^4}$$

where,

δ: Deflection of shank W: Measuring force

L: Shank length E: Young's modulus

d: Shank diameter

(Deflection is proportional to the length raised to the third power, and inversely proportional to the diameter raised to the fourth power.)

5.1.2 Centering microscope

Centering microscopes are used for measuring small holes and elastic or soft workpieces that mechanical probes cannot measure.

(1) Centering microscope (Fig. 5.3)

Monocular or binocular types are available.

Magnification: 10X, 20X, 30X, 50X, 100X

(2) Centering projector

This provides easier operation than centering microscopes.

Magnification: 15X

View field diameter: 6 mm

Working distance: 16 mm

Screen diameter: 100 mm

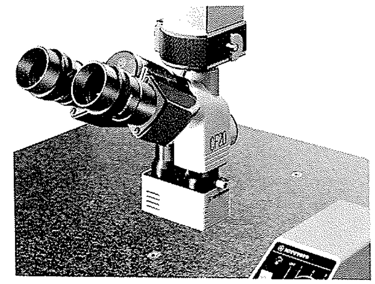


Fig. 5.3 Centering microscope (with binocular eyepiece)

(3) CCTV monitor system (Fig. 5.4)

This monitor system, which is particularly useful when it is incorporated in a remote-control CMM, displays the image from the centering microscope on the video monitor (14" color monitor) .

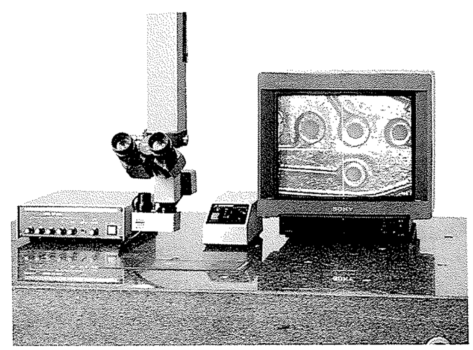


Fig. 5.4 CCTV monitor system for CMM

5.1.3 Touch-trigger probes

Touch-trigger probes can issue a point detection signal the moment the stylus is displaced from its neutral position, regardless of the displacement direction.

(1) Detecting principle

Fig. 5.5 shows the typical operating principle of a touch-trigger probe. This type of probe was developed by Renishaw, a British company, and is employed widely by the major CMM manufacturers, except Zeiss, Leitz, and DEA. **Figs. 5.6** and **5.7** show Renishaw's standard probe, TP1, and their small type of probe, TP2, respectively. The TP2 is used for measuring deep holes and casing interiors. The major specifications of these probes are shown in **Table 5.1**.

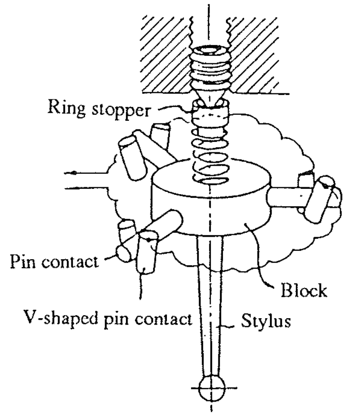


Fig. 5.5 Operating principle of touch-trigger probe

(2) MTP touch signal probes

The touch-trigger probes developed by Mitutoyo are called the "MTP series tough signal probes," and are used on the MXF203 and C series CMMs. The MTP-1 probe has a straight shank, and the MTP-2 probe has a universal holder. **Figs. 5.8** and **5.9** show the MTP-1 and MTP-2 touch signal probes, respectively. Their major specifications are shown in **Table 5.2**.

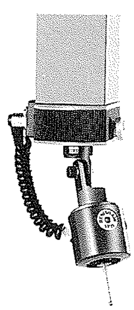


Fig. 5.6 Touch-trigger probe TP1 (standard type)

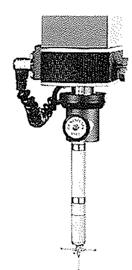


Fig. 5.7 Touch-trigger probe TP2 (small type)

Table 5.1 Major specifications of TP1 and TP2

Model		TP1 (standard)	TP2 (small type)
Measuring direction		Omnidirectional (±X, ±Y, +Z)	
Measuring force (horizontal)		0.15 – 0.25N (15 – 25gf)	
* Repeatability (standard deviation, σ)		1μm	
Stylus displacement limit	Horizontal	20mm	5mm
	Vertical	8mm	4mm
Response speed		100mm/s	

* TP1 and TP2 models with high repeatability are also available.

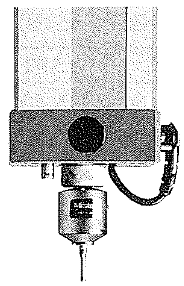


Fig. 5.8 Touch signal probe MTP-1

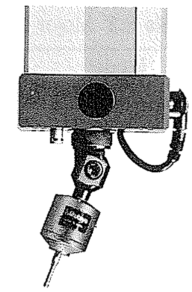


Fig. 5.9 Touch signal probe MTP-2

Table 5.2 Major specifications of MTP-1 and MTP-2

Model		MTP-1	MTP-2
Probe holding		With straight shank (8 mm dia.)	With universal holder (for 14 mm shank dia.)
Measuring direction		Omnidirectional (±X, ±Y, +Z)	
Measuring force (standard type)	Horizontal	0.15 – 0.25N (15-25gf)	0.05–0.3N (5–30gf)
	Vertical	0.5–0.6N (50–60gf)	0.15–0.8N (15–80gf)
Repeatability (standard deviation, σ)		1.2μm	
Stylus displacement limit (standard type)	Horizontal	2mm	
	Vertical	2mm	

(3) High-precision touch signal probe HTP

The HTP series high-precision touch-trigger probes were developed by Mitutoyo to meet requirements that called for higher accuracy and functionality from CMMs. These probes have a highly sensitive detection mechanism, a high S/N ratio, and a very small measuring force. The HTP series probes perform optimum probing because detection signals are issued by a constant force, regardless of the direction of contact. These probes are mainly used on CNC CMMs. **Table 5.3** shows the major specifications of the HTP probes.

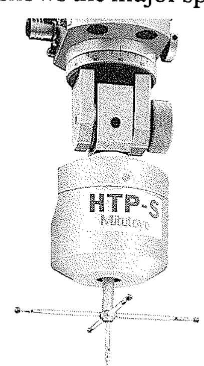


Fig. 5.10 Touch signal probe HTP-S

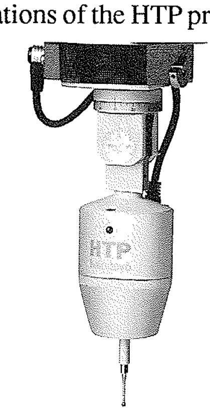


Fig. 5.11 Touch signal probe HTP

Table 5.3 Major specifications of HTP and HTP-S

Model		HTP	*HTP-S
Measuring direction		Omnidirectional (±X, ±Y, ±Z)	
Measuring force (on signal output)		0.01–0.03N	
* Repeatability (standard deviation, σ)		0.5μm or less	0.2μm or less
Stylus displacement limit	Radial	7–8mm	5–6mm
	Axial	±4mm	
Stylus		ø3 mm x 20 mm (Standard)	

* For H503 series CMMs

(4) Touch-trigger probe TTP

This is a high-precision touch-trigger probe from Zeiss. Generally, Zeiss uses this type of probe on their CMMs that are not capable of making scanning measurements.

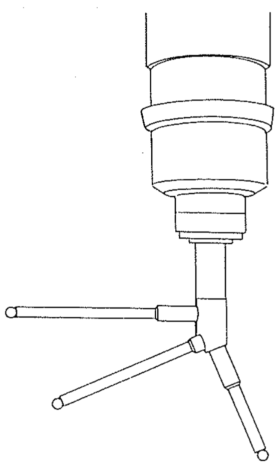


Fig. 5.12 Touch-trigger probe TTP

(5) Scanning probe MPP-2

The Mitutoyo scanning probe MPP-2 is a contact-type displacement detecting probe which has a built-in air bearing and linear scales. Stylus displacements detected by the probe's linear scales are fed back to the CMM system, allowing automatic scanning measurement of workpiece surfaces. (See **Fig. 5.13**.)

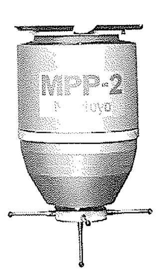


Fig. 5.13 Scanning probe MPP-2

The main features of the scanning probe MPP-2 include:

(a) Capable of tracing workpiece surfaces; this greatly increases the efficiency of contour measurement compared with the conventional point-to-point measuring method.
(b) There is no need to program the probe travel path to trace workpiece surfaces.
(c) Detection signals are triggered in all directions under a constant measuring force, permitting curved surfaces to be accurately measured.

(6) 3D touch-trigger probe

The 3D touch signal probe, developed by Zeiss in 1973, incorporates scale systems (differential transformer type) in its probe head for detecting stylus displacement in the X, Y, and Z directions. For high-accuracy measurement, a static mode is used where the coordinates are automatically locked when the origin of the built-in scales is detected. In the dynamic mode, the displacement of the stylus is added to that of the probe itself (measured by the CMM scale system) to determine the coordinates of the measured point.

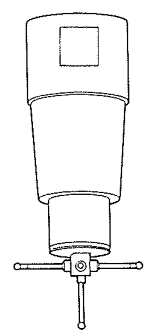


Fig. 5.14 3D touch-trigger probe

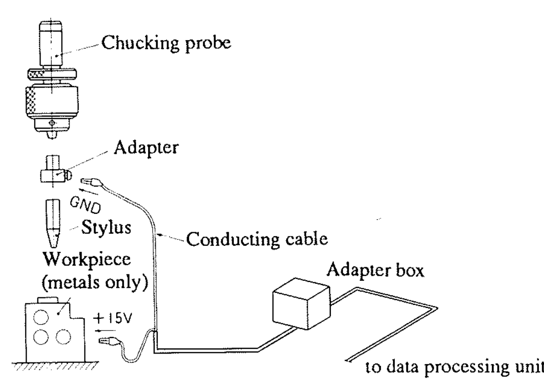


Fig. 5.15 Conductive type touch signal probe

(7) Conductive type touch signal probe

The moment this probe touches the surface of a metal workpiece it completes an electrical circuit and thereby signals that contact has been made (see **Fig. 5.15**). This type is less expensive than the standard touch-trigger probe.

(8) Low measuring force touch signal probe

This probe can take measurements by exerting a small measuring force and is used for soft or elastic workpieces which can be deformed by a normal measuring force. This type can only probe in the downward vertical direction. The measuring force is adjustable to a minimum of 0.002 N (0.2gf).

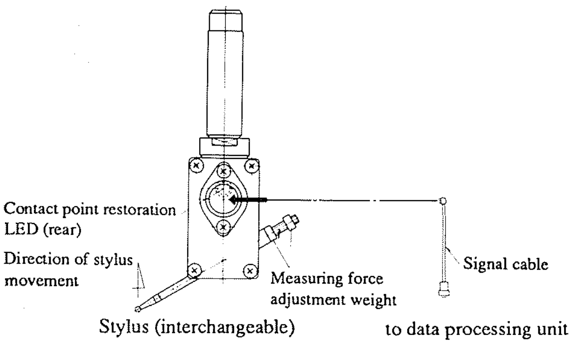


Fig. 5.16 Low measuring force touch signal probe

5.1.4 Probe head

(1) PH5/1

The Renishaw probe head PH5/1 has five probe receptacles, four in horizontal directions and one in a vertical direction, for mounting TP2 probes. Various types of probes and styli can be attached to this probe head to suit different measuring tasks. Its indexing mechanism allows the head to be manually rotated in precisely 15° increments in the horizontal plane. (See **Fig. 5.17.**)

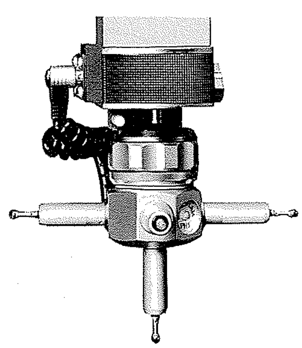


Fig. 5.17 Probe head PH5/1

(2) Probe head PH9

The Renishaw probe head PH9 (**Figs. 5.18** and **5.19**) can change the orientation of the attached touch-trigger probe TP2 when signalled by a remote controller, or automatically by computer control. It is highly precise in restoring probe orientations. By storing the reference origin coordinates for each probe orientation in memory, the reference origin does not need to be offset when the probe orientation is changed, thus improving measuring efficiency.

The main features of the probe head PH9 include:

(a) The probe is driven both in the horizontal and vertical directions by a motor that completes probe positioning in two to six seconds.

(b) If the probe head touches a workpiece, the probe head clamp release mechanism and the slipping clutch provided on the axes activate to prevent damage to both the probe head and the probe. At the same time, an error signal is sent to the data processing system.

(c) Combinations of the touch signal probe TP2, interchangeable styli, and extension bar allow complex workpieces to be measured.

Fig. 5.18 Probe head PH9

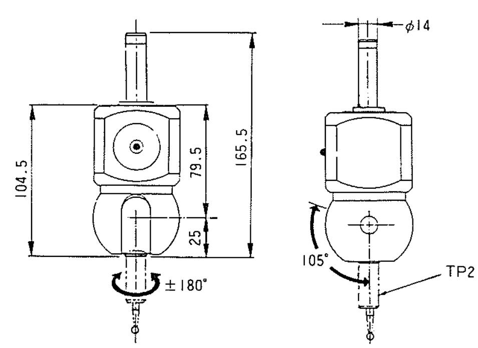


Fig. 5.19 Dimensions of PH9

5.1.5 Other detectors and probe replacement devices

Besides the probes described above, there are other types of position detectors for the CMM as well as probe replacement devices, as outlined below.

(1) CCD camera

The CCD camera is used as a position detector for non-contact measuring systems such as the Mitutoyo VS and VSR series CMMs. (For information regarding measurement efficiency, refer to examples 6 and 7 in **Table 1.1**.) To improve the measuring efficiency and accuracy, these CMM systems incorporate automatic edge detection, auto-focusing, 4-division circular illuminator, and a non-contact view measuring program, thus forming integrated position detecting systems.

(2) Laser detector

This is one of the most advanced detecting system which performs continuous non-contact measurement by means of a laser beam.

(3) Auto Probe Changer

The Auto Probe Changer from Renishaw can hold eight TP-2 probes and allow automatic probe replacement for probe head PH9A, a modified version of PH9.

(4) Universal positioning probe head

This universal positioning probe head, manufactured by Renault, can "steplessly" change the probe orientation using a miniature servomotor. (The PH9 can change the probe orientation in 7.5° increments.)

The Mitutoyo RV812 series CMMs are provided with an automatic probe replacement device for automatic measurement.

5.1.6 Probe calibration

(1) Calibrated probe ball diameter

The touch-trigger probe issues a detection signal when the stylus is displaced a very small distance (δ in **Fig. 20**) after touching the workpiece surface. This is due to the deflection of the stylus caused by the measuring force and the sensitivity that is inherent to the probe. Displacement, δ, is close to constant in any contact direction if the measuring force is adjusted properly. It will vary slightly depending on such factors as measuring force adjustment, probing direction, probe attachment position, approaching acceleration, etc. (See **Fig. 5.20**.)
In order to ensure accurate measurements, it is necessary to calibrate the probe ball diameter under the same conditions that the workpiece will be exposed to during measurement. Calibration blocks (described below) or gauge blocks are used to calibrate probe ball diameters.
When using a mechanical probe, the probe ball diameter should also be calibrated under the same conditions, and by the same operator that will measure the workpiece since the pressure applied to the workpiece by the probe varies depending on the operator.

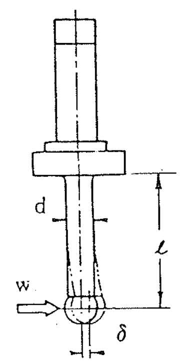


Fig. 5.20 Stylus deflection due to measuring force

(2) Calibration block

The calibration block offers an efficient way to calibrate balls of touch-trigger probes (see **Fig. 5.21**). The probe ball diameter is calibrated by measuring the inside and outside faces of the block.

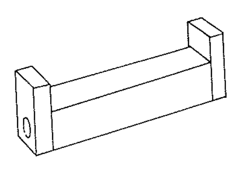


Fig. 5.21 Calibration block

(3) Master Ball and Origin Point Block

These can be fixed to the measuring table for setting and offsetting the machine origin, which is required at the start of measurement and each time the probe orientation is changed (see **Fig. 5.22**).

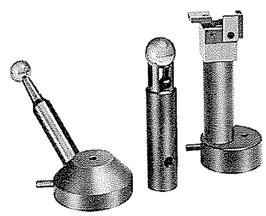


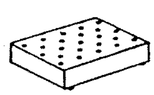
Fig. 5.22 Master Ball and Origin Point Block

5.2 Workpiece Fixtures, Setup Tools, and Tables

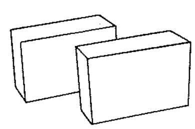
Appropriate setup tools and workpiece fixtures affect the efficiency and accuracy of CMM measurement. The general-purpose fixtures, setup tools, and tables, shown below, are designed for most of the ordinary applications. Dedicated fixtures may be fabricated to improve efficiency when measuring many identical workpieces.

① Surface plate
② Parallel block
③ Precision vice
④ Clamping kit
⑤ Adjustment jack
⑥ Vertical indexing center
⑦ Horizontal indexing table
⑧ CNC turntable

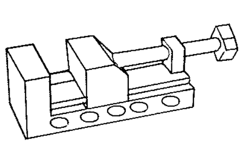
Some CMMs employ a digital-display or CNC turntable for making easy and accurate measurements in a cylindrical coordinate system.



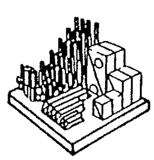
① Surface plate



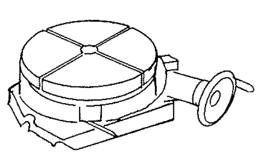
② Parallel block



③ Precision vice



④ Clamping kit



⑦ Indexing table

Fig. 5.23 Fixtures, setup tools, and tables

5.3 Accuracy Inspection Tools

Periodic inspections of the CMM is vital for maintaining the measuring accuracy for long periods of time. The following types of inspection tools are generally used.

① Check Master (length standard)
② Checking plate (for repeatability test)
③ Straightedge and reference square

Gauge blocks can be used in place of a Check Master.

6. ENVIRONMENTAL CONDITIONS

Environmental conditions affect CMM measurements in terms of accuracy, measuring efficiency, and maintenance. The following sections will discuss the important environmental conditions that affect CMM performance.

6.1 Effects of Temperature

Objects expand or contract with changes in temperature. Therefore, it is very important for manufacturers to make parts so that they measure correct dimensions at a specific temperature, 20°C, called the standard temperature, which is internationally adopted and used to determine the dimensions of a workpiece.

CMMs are generally assembled and adjusted to the rated performance in a room where the temperature is maintained constant at 20°C ± 0.5°C or ±1°C, before shipment. They are again inspected and adjusted against accuracy specifications upon delivery at the installation site.

If the temperature conditons are not satisfactorily controlled, it becomes difficult to ensure the measuring accuracy and repeatability specified for the CMM. The signifcant effect of temperature changes is exemplified in realizing the fact that a simple-shaped 100 mm gauge block expands/contracts by about 1 μm with a temperature change of 1°C. The effect of temperature changes on three dimentional structure of the CMM could diminish the measuring accuracy to much greater extent.

In an environment where the temperature cannot be controlled, the temperature changes/fluctuations are random in terms of duration and location in the room, and as a result the temperature of the entire machine is not uniform. This also applies to workpieces in such environments. Under such conditions measurment reliability is not ensured, even if the ambient temperature is 20°C at the time of measurement.

Even in an ordinary temperature-controlled room, temperature variations are often observed at different levels in the vertical section, while horizontal temperature distribution is relatively uniform. This also leads to measurement errors.

JIS B7440 (1987) "Test Code for Accuracy of Coordinate Measuring Machines" specifies the following environmental test conditions for testing a CMMs accuracy so that manufacturers and users can evaluate the performance of their CMM under these standardized conditions.

- The coordinate measuring machine and the standards, measuring instruments, etc. to be used in testing should be allowed to stand for at least 24 hours in the environment where they will be tested.
- The temperature condition where the coordinate measuring machine is located shall be clearly indicated with respect to the following three criteria:
  Ambient temperature: T ± t°C
  Temperature variation per hour: U°C/h
  Temperature distribution in the place where the measuring machine is installed: V°C/m

  where values T, t, U, and V are jointly agreed upon by the user and the manufacturer.

Users' claims that discrepancies exist between the rated accuracy and the actual measuring accuracy can in most cases be attributed to improper temperature conditions. A field survey of CMM operating environments revealed that only 10% of the installation sites satisfied the temperature requirements.

Some simple and economical ways that CMM users can achieve proper temperature conditions include the following:

- Use a simple temperature-controlled booth.
- Minimize the temperature difference between the workpiece and the CMM. (This is quite effective for steel workpieces because the rates of expansion/contraction of the workpiece and CMM are almost equal at the same temperature.)
- Place the workpiece on a heat sink with a large thermal capacity to disipate heat and thermally stabalize the workpiece to the ambient temperature.

6.2 Relative Humidity

High humidity may rust important machined surfaces, causing the measuring accuracy and performance of the CMM to deteriorate. The relative humidity should be maintained between 55% and 65%. (According to the JIS specifications for the environmental conditions for testing the CMM accuracy, relative humidity should be 50% ± 10%.) However, few users' CMM installation sites satisfy this humidity requirement. Even if the CMM is installed in a temperature-controlled room, practices such as turning off the power to the temperature/humidity control at night or on holidays causes a significant temperature variation, which leads to difficulties in maintaining the optimum humidity.

It is just as important to maintain the proper humidity of the air supplied to the air bearings of a CMM, as it is to maintain the proper humidity of an installation site. Excessive humidity in the supply air may cause rust on the sliding surfaces of the CMM, which may cause the sliding members to stick and affect the otherwise smooth movement. In many cases the air source is not capable of supplying dry air. For example; the air inlet is outdoors, which is often done to minimize vibration and noise, and is not properly protected against water (ex. rainfall, sprinklers).

If the humidity of the supply air is a problem, an air drier unit (with sufficient capacity) needs to be installed. Note that an excessively low humidity is not good for personnel.

6.3 Vibration

Since sliding members of a CMM are designed to move with a very small force, vibrations transmitted from the floor will cause measurement fluctuations. Measure the floor vibrations with a vibration meter and check the measurements against the following tolerances.

- For frequencies lower than 10 Hz: Vibration should be less than 2 μm (p-p) in amplitude.
- For frequencies between 10 Hz and 50 Hz: Vibration should be less than 0.004 gal in acceleration.

(JIS specifies the same vibration tolerances for the CMM test environment conditions and also specifies that the tolerance values must be jointly agreed upon by the user and the manufacturer.)

To prevent vibrations from being transmitting to the CMM, one of two preventative measures should be taken; either isolate the source of vibration or isolate the CMM from the vibration. Examples of the former method include: (1) construct a firm foundation for the vibration source equipment (such as a press machine or a large compressor) to minimize the floor vibration, (2) install the equipment far from the CMM, and (3) provide a vibration-damping ditch between the equipment and the CMM (fill the ditch with polyurethane — dry ditch). Examples of the latter method include: (1) construct a firm foundation for the CMM by pouring a deep foundation for machine tools (if the site is near a railroad or highway and the CMMs foundation is constructed on the same rock bed, vibrations may reach the CMM), (2) use a vibration damping stand for the CMM (the air spring type is commonly used these days), and (3) add vibration damping rubber pads that have different damping characteristics from those supplied for the CMM.

Each of the above methods has advantages and disadvantages, and the method(s) that best suit the installation site conditions must be selected.

6.4 Dust

Dust may cause damage to the CMM's high precision components, such as the axial guideways, or the computer or floppy disks used in the data processing system. Install the CMM and its peripherals in an environment which is as free from dust as possible.

The following show examples of dust-free conditions:

(1) The installation site is established as an independent measuring room which has an anteroom to prevent dirt and dust from entering.

(2) The air conditioner is equipped with a dust cleaner.

(3) The floor is tiled with linoleum which produces little dust. The floor is cleaned with an electric vacuum or a mop.

(4) Nobody is permitted to enter the measuring room with shoes. Supply slippers or special shoes that will only be used for the measuring room.

(5) The measuring room has no sources that generate dust, mist, or corrosive gas. Smoking is not permitted.

(6) Operators wear clean work clothes.

6.5 Other Environmental Considerations

(1) Corrosive gas

There may be corrosive gases in such places as chemical plants, plating sites and fiber production factories. These gases can corrode critical parts of a CMM, thus affecting measuring accuracy.

Observe the following precautions:

- The CMM must be isolated from the outside air.
- Ensure that not only the air inlet of the air conditioning system but the air inlet of the air compressor is located in an area that is free from corrosive gases.
- Keep the relative humidity in the measuring room at less than 60%, since the combination of high humidity and gasses may corrode mechanical parts.
- Do not use a kerosene stove in the measuring room.

(2) Power source

Always use a power source with the specified ratings both for voltage and amperage. Ground the CMM with a grounding resistance of 100Ω or less, and avoid sharing the power source with other machines in order to protect the CMM and its peripherals from electrical interference. Use a voltage stabilizer recommended by the CMM manufacture, if available, in order to avoid computer malfunctions.

(3) Electric and magnetic fields

Do not install the CMM peripherals close to a device that generates a strong electric or magnetic field, which may damage data or programs that are recorded on floppy disks.

(4) Direct sunlight and air outlet

Do not install the CMM where it is subjected to direct sunlight or near the air outlet of an air conditioner in order to prevent localized temperature changes on the CMM which will affect both the measuring accuracy and mechanical precision of the CMM. These may also cause condensation to form in the computer because of temperature differences between the floppy disk and the disk drive.

In addition to the above precautions, follow the instructions given with the CMM and its peripheral devices.

7. NEW AND ADVANCED CMMS

As mentioned in the preface of this textbook, the CMM will be diversified and specialized in two major directions: toward being simple and low in price, and toward being highly accurate, automatic, multi-functioned and CNC. This trend is expected to accelerate and spread in the CMM industry. Not only CMMs, but also measuring tools and instruments are moving toward a digital system. These digital systems will be incorporated in an integrated measuring system like the Mitutoyo μ-Net system.

Some noteworthy advancements being developed for CMMs include:

(1) High-accuracy
(2) Multi-function
(scanning measurement, rotary table)
(3) High speed
(4) Non-contact measurement
(5) In-line measuring system
(6) System integration
(MCAT•MSURF•CAD/CAM•Auto-programming system)
(7) Large size

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