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An investigation of diameter measurement repeatability using a coordinate measuring machine and a multi-baseline repeatability assessment methodology

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AN INVESTIGATION OF DIAMETER MEASUREMENT REPEATABILITY
USING A COORDINATE MEASURING MACHINE AND A
MULTI-BASELINE REPEATABILITY ASSESSMENT METHODOLOGY

A Dissertation
Submitted
In Partial Fulfillment
of the Requirements for the Degree
Doctor of Industrial Technology

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ABSTRACT

The need for reliable and consistent measurement has become more acute with the use of statistical process control (SPC), gage repeatability and reproducibility (Gage R&R) assessment, and high precision, computer-controlled gaging systems. Although it is often overlooked, the inspection methodology under which various features are inspected has an impact on Gage R&R results. This notion was confirmed when a 1993 thesis study substantiated inspection methodology as a source of measurement variability in direct computer-controlled, coordinate measuring machines (DCC/CMMs). Although this study explored a methodology to bring measurement variability under statistical control, the tested assessment methodology--single baseline repeatability assessment--was not validated.

This study was initiated to assess the effectiveness of multi-baseline repeatability assessment (MBRA) in (a) identifying diameter/probe hit categories with inherent stability in measurement repeatability on the XY, XZ, and YX planes and (b) generating planar inspection programs that yield improvements in diameter measurement repeatability on each of the three planes. The methodology of this study was based on a Brown & Sharpe Xcel 7•6•5 CMM, twenty-three circular test specimens of different diameters, an inspection methodology varying from 3-10 probe hits, and two repeatability determination methods--range and standard deviation.

The results of this study indicated: (a) in general, diameter measurement repeatability can be improved by increasing the number of contact probe hits; (b) MBRA is an effective methodology for quantifying

stability in measurement repeatability; and (c) MBRA is not an effective methodology for improving measurement repeatability (diameter/probe hit categories with the greatest stability did not necessarily possess the "best" repeatability). The principle implication presented by this study is that multi-baseline repeatability assessment gives CMM users an assessment tool that can be used to establish (a) inspection methodologies under which different features can be inspected with high precision, (b) part orientations (planes) under which circular features can be inspected with high precision, (c) machine signatures upon which machine wear can be monitored and tracked, and (d) machine signatures upon which repeatability comparison studies can be conducted.

CHAPTER I

INTRODUCTION

During the 1980s, numerous U.S. companies demonstrated that world-class quality was an attainable goal. At the beginning of the 1990s, several major US companies had attained world-class quality and were serving notice to their suppliers that they too must make significant quality improvements if they wanted to continue being their suppliers. This approach to quality management has not only propelled the entire supplier chain to new levels of product quality but has also instilled in businesses a new economic reality--continuous quality improvement is an essential element to ensure competitiveness in global and domestic markets.

One of the directions manufacturers have taken to contend with changing market requirements and quality-based competition has been to improve product quality by take a more aggressive stand in reducing manufacturing variability, commonly referred to as process variability. Process variability, according to Smith (1991), is a quantitative assessment of the accumulated effects of all sources of variability, including gage variability. Through the integration of electronic and computer-controlled gaging systems and the improved accuracy and repeatability these systems provide over traditional, manually-read measuring instruments such as micrometers, calipers, height and depth gages, manufacturers are provided a truer estimation of actual process variability. In other words, reductions in gage variability yield a truer estimation of process variability.

Although electronic and computer-controlled gaging system provide numerous benefits and advantages over manual gaging systems, these advantages can be further enhanced provided sources of gage variability and instability are investigated. In short, a gage capability study is a useful tool for identifying and analyzing sources of gage variability and instability so that steps can be taken to eliminate the cause of the variability or at the very least bring it under statistical control. Smith (1991) indicated the importance of gage capability studies when he identified four gage characteristics that can be assessed from these studies. These characteristics were accuracy, repeatability, reproducibility, and stability. Smith went on to state that "gauge repeatability errors are generally the largest contributors to gauge variability . . . " (p. 330).

Repeatability, as defined within ASME B89.1.12M-1990, *Methods for Performance Evaluation of Coordinate Measuring Machines*, is "a measure of the ability of an instrument to produce the same indication (or measured value) when sequentially sensing the same quantity under similar measurement conditions" (p. 10). In other words, repeatability is a quantitative assessment of the extent of measurement variability that can be expected when a given part is measured repeatedly using the same methods, apparatus, and environmental conditions. In quantitative-based measurement activities measurement precision and gage repeatability go hand in hand; precision being the standard deviation of the measurement error (σ_{ME}) and repeatability being the extent of measurement error that can be expected within a specified level of confidence (σ_{ME}) * (Z_{CL}). It should be noted that any improvement in measurement precision and gage repeatability involves a numeric reduction in both precision and repeatability values.

In 1993 Marsh conducted a repeatability study on a direct computer-controlled coordinate measuring machine (DCC/CMM). The purpose of this study was to investigate the effects of diameter and probe hit variations on the assessment and optimization of diameter measurement repeatability. The results of this study indicated: (a) gage repeatability, in most cases, improves as the number of probe hits used in diameter measurement activities is numerically increased and (b) optimizing probe hit repeatability using a single baseline repeatability assessment methodology is not a viable approach for analyzing and minimizing diameter measurement repeatability (within the context of this previous study the expression "single baseline repeatability assessment" denotes the assessment of gage repeatability using different diameter test specimens and probe hit measurement routines). The conclusions presented within the study were based on an analysis of probe hit repeatability using twenty-three circular test specimens ranging in diameter from 0.25 inches to 5.75 inches at 0.25 inch increments and eight inspection routines varying from 3 to 10 probe hits. It should be noted that the analysis of diameter measurement repeatability was also structured on two well known and widely-used repeatability assessment methodologies, the range method and the traditional standard deviation method.

Although various steps were taken in this study to minimize factors that influence measurement variability (factors such as temperature change, vibration, and dust and dirt), the results of this study indicated an inherent instability in diameter measurement repeatability within certain diameters and probe hit categories. This instability influenced the overall assessment of diameter and probe hit repeatability and prevented an effective optimization of diameter measurement repeatability. For example, it was noted in the 1993 study that repeatability data from two different optimization programs differed from their baseline counterparts in the following three ways:

1. On average, 76% of the repeatability values from the optimized inspection programs indicated, to varying degrees, worse repeatability than their baseline counterparts (i.e., measurement precision and gage repeatability values numerically increased).

2. On average, 15% of the repeatability values from the optimized inspection programs indicated, to varying degrees, better repeatability than their baseline counterparts (i.e., measurement precision and gage repeatability values numerically decreased).

3. On average, 9% of the repeatability values from the optimized inspection programs had very similar results with respect to their baseline counterparts (i.e., little or no change in measurement precision and gage repeatability values).

A more detailed analysis of the repeatability differences within the two optimization programs indicated the occurrence of similar "difference" values 66 percent of the time. It was concluded in the study that the inability to achieve significant improvements in gage repeatability using repeatability assessment and optimization was primarily attributable to noted instabilities in repeatability within specific diameter and probe hit categories.

Although the 1993 study substantiated "inspection methodology" as a source of measurement variability in CMMs and even explored a methodology to bring it under statistical control, it failed to yield the results needed to validate the single baseline assessment methodology.

One positive aspect of the study was that the findings indicated a potential methodology that could be used to assess stability in measurement repeatability. This approach would involve the analysis of repeatability values between repeated baseline inspections (multi-baseline repeatability assessment). In other words, the repeatability results of repeated baseline inspections would be compared to identify all diameter/probe hit categories that yield similar repeatability results. Once identified, the diameter/probe hit categories with inherent stability in repeatability would be used to conduct repeatability optimization tests.

Problem Statement

The problem of this study was to determine the effects of multi-baseline repeatability assessment on the optimization of planar diameter measurement repeatability using a direct computer-controlled coordinate measuring machine (DCC/CMM), specific diameter test specimens, and different probe hit inspection routines.

Purpose of the Study

The purpose of this study was to determine (a) the effectiveness of multi-baseline repeatability assessment in identifying particular diameter/probe hit categories with inherent stability in repeatability; (b) the effectiveness of multi-baseline repeatability optimization in generating planar inspection routines that yield improvements in diameter measurement repeatability beyond that of the "best" single category baseline inspection; and (c) the effectiveness of multi-baseline repeatability analysis as a potential test method for identifying, assessing, and monitoring machine-specific characteristics and/or software differences.

The significance associated with repeatability studies on CMMs has been indicated by various authors and researchers. For example, Ray (1992) proposed that SPC is composed of four legs: (a) evaluating the capability of a process, (b) predicting when a process is going to get out of control, (c) timely corrections to keep the process in control, and (d) gage repeatability and reproducibility (Gage R&R) studies. Ray justified his fourth leg of SPC by stating:

> It stands to reason that if the gages aren't under control, neither is the process, since process monitoring depends on getting reliable information from the gage. Gage R&R today is the missing link in many industrial SPC programs. Neglecting it can negate many of the benefits of SPC. (p. 22)

Ray's investigations of measurement variability attributable to differences in part fixturing has led to new and innovated fixturing methods incorporating vacuum-based part clamping.

Shay (1988) also indicated support for gage repeatability assessment when he stated that a need exists for "inspection and metrology laboratories to perform repeatability studies on each gaging system to determine the system's ability to gage critical characteristics before doing any capability analysis on a manufacturing process" (p. 91). In my opinion, Lavole (1989) identified the true significance of gage repeatability assessment when he stated: "you can have good repeatability without good accuracy, but you cannot have good accuracy unless you also have good repeatability" (p. 68).

Statement of Need

The value and necessity for a comprehensive study of diameter measurement repeatability is based on (a) the widespread use of

DCC/CMMs in industry, (b) a need to improve CMM performance, (c) a need to determine the minimum amount of data needed to accurately gage geometric shapes, and (d) a need to investigate various inconsistencies noted in the results of the 1993 diameter measurement repeatability study, as well as limitations imposed on the study itself (Marsh, 1993). The following is an explanation of each of these needs as reported in the literature.

Widespread Use of CMMs in Industry

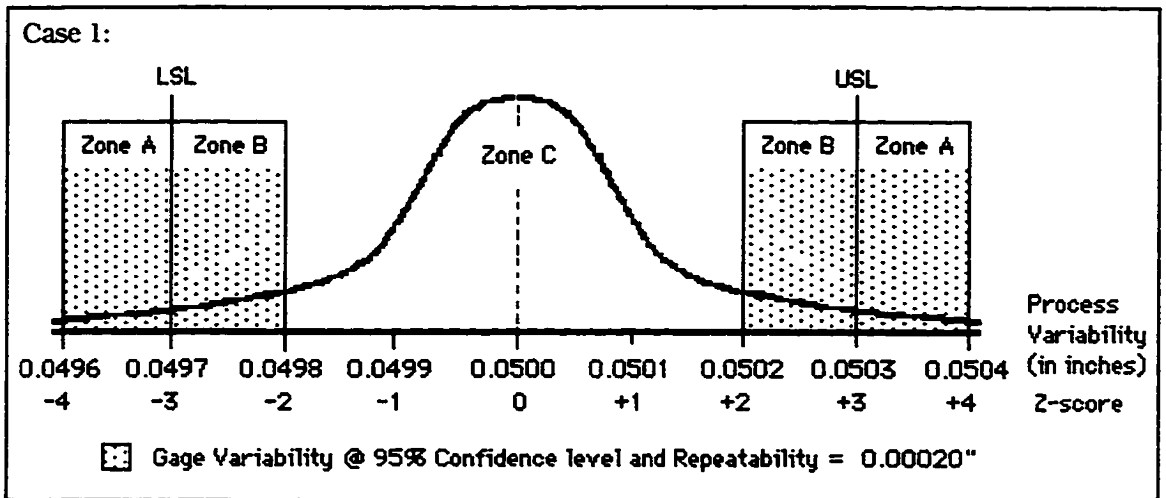
Direct computer-controlled coordinate measuring machines (DCC/CMMs) are extremely powerful metrological instruments. The information collected by these measuring instruments is analyzed and used in a variety of quality control and assurance activities. Of all the descriptions used to describe a DCC/CMM, Bergstrom (1990) offered one of the most concise when he described it as " an automated, programmable, highly productive, high technology three dimensional height gage with the flexibility to verify the various dimensions of almost any object" (p. 67).

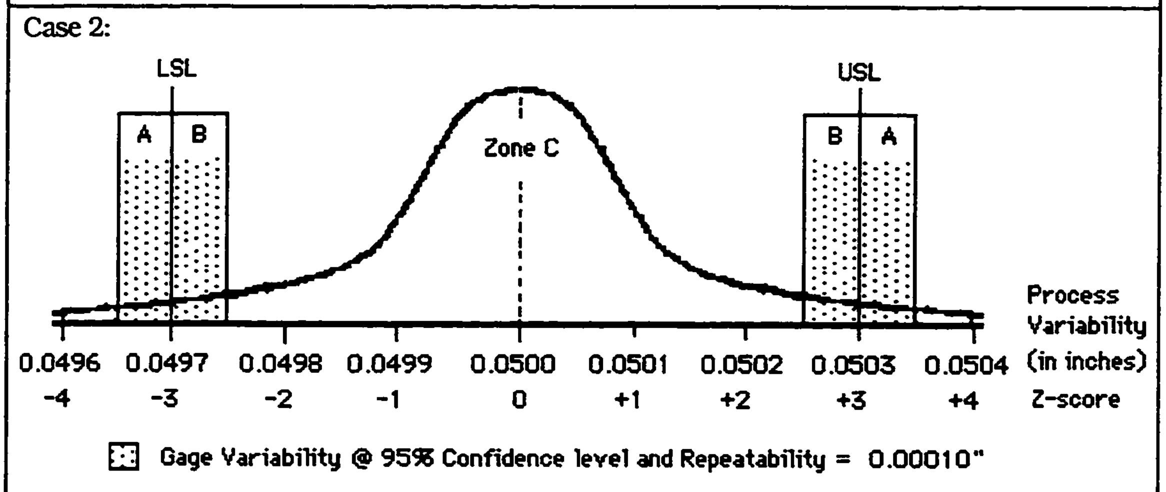
One of the main reasons for the steady growth and technological advancement in coordinate measurement technology over the last fifteen years has been the integration of CMMs into process and quality control applications on the factory floor. Manufacturing companies, both large and small, have increased their CMM purchases especially in smaller, less expensive units such as the Brown and Sharpe *MicroVal*; the Digital Electronic Automation *Swift*; the Mitutoyo *MXF*; and the Numerex *BT 1518-10*, to name a few. The use of larger, more traditional CMMs, normally found in strictly controlled environments, has not disappeared. These CMMs are still being used to verify dimensional stability in other gaging instruments as well as first piece and specialized inspections. The widespread use of CMMs can also be seen in the growing prevalence of this measuring instrument in manufacturing environments. According to Owen (1990), "there is one CMM for every three machining centers in the U.S. The number of CMMs installed in shops with fewer than 100 people has doubled in the last five years" (p. 162). One of the reasons for the increased use of CMMs was supplied by Quinlan (1995) when he indicated that "new structures, drives, controls, sensors--above all, new programming and operation software--are turning the CMM into one of the most valuable and versatile instruments a manufacturer can own" (p. 37). Regardless of the type of CMM used or its location within a manufacturing environment, one critical factor essential for all CMMs is conformance with manufacturer's specifications. These specifications are based on the procedures identified in ASME Report # B89.1.12M, 1990, *Methods for Performance Evaluation of Coordinate Measuring Machines*, or some other statistically-derived methodology. Breyer and Ohnheiser (1994) confirmed this assertion when they stated that ". . . the basic aim [metrological and economical targets of gaging systems] is to perform all necessary measuring jobs with minimum standard deviation and at the lowest possible cost" (p. 38).

Improving CMM Performance

According to Farago (1982), the basic purpose of dimensional measurements in manufacturing is to assure product conformance with design specifications. Recent advances in measurement technology have given added credibility to Farago's statement: "as long as you can measure it, you can make it" (p. 1). Consequently, knowing what can be measured and what degree of accuracy and repeatability can be achieved have proven to be valuable assets in manufacturing and engineering. A useful illustration that demonstrates the potential impact of gage repeatability on part inspection can be seen in Figure 1. In this example, the manufacturing specification for a particular part is indicated as 0.0500" ± 0.0003" (upper and lower specification limits of 0.0503" and 0.0497" respectively). The process under which the part is manufactured is also assumed to be under statistical control. Given this information, it can be determined that a 3.32% reduction (improvement) in the number of parts with dimensional uncertainty (4.30% - 0.98%) can be achieved through a 50% reduction in gage repeatability (0.00020" to 0.00010"). The values within the *% of parts affected* column were determined by calculating and summing the area under the curve within both B zones. For example, the *% of parts affected* value of 4.30 was calculated by subtracting the area under the curve between the mean and the measured value of 0.0502, an area of 0.4972, from the area under the curve between the mean and the measured value of 0.0503, an area of 0.4987. This difference, 0.0215 or 2.15% was then multiplied by two to compensate for two Zone B areas.

Although the fundamentals of dimensional metrology are fairly simple and straightforward, the range of their applications and the techniques and instruments used in its implementation are becoming more complex. Once one relied on traditional, manually-read gaging instruments such as micrometers, calipers, and height and depth gages. These instruments are now being replaced with digital read-out micrometers, calipers, and height gages with SPC output capabilities; direct computer-controlled coordinate measuring machines (DCC/CMMs); vision systems; laser scanning systems; and computer-based metrology networks. This





Zones	Implications	P_{max}
A	Probability of rejecting a part when it is actually within specification	50%
B	Probability of accepting a part when it is actually out of specifications	50%
C	No direct gage impact on part acceptance/rejection	0

Gage Repeatability (in)	Zone Uncertainty (in)	% of Parts Affected	Conditions
0.00020"	0.00010"	4.30	Process is under statistical control
0.00010"	0.00005"	0.98	

Figure 1. Impact of repeatability on part inspection.

increased dependence on technology, specifically computer-controlled gaging systems, as the means to solve quality problems was summed up best by Inglesby (1989) when he reported that the Yankee Group, a survey company in Boston, stated ". . . ' just as money can't buy you love, money can't buy you quality. It can buy you technology but technology alone won't get you quality - it can, however, provide you with the tools to help '. . . " (p. 19). As a result, the need for gaging instruments and systems with inherent accuracy and repeatability, adaptability to diverse part configuration, and greater flexibility and versatility in inspection processes has placed increasing demands for continued advancements in gaging instrument design, performance, and operating methods.

Accurately Defining Geometric Shapes

According to Traylor (1993), tough customer standards, ISO 9000 approvals, 100% inspection requirements, and quality-based competition are putting intense pressure on manufacturers to perform precise, detailed part measurements. One example used by Traylor as an indicator of this pressure is a four-point check on a bore. He indicated that this inspection methodology may be satisfactory for low level inspections, however, there are instances when more detailed information is needed to support more precise decision making. When this situation arises, manufacturers are faced with a dilemma--a need to collect more data points in the same amount of time. Stout (1993) also noted in an interview with Warren Baxter of Baxter Associates the significance associated with data frequency in measurement acquisition. In this interview, Baxter indicated that when a four inch square block is measured with a tactile probe only the contact points are known data; all other points are calculated by software algorithms. He communicated his concern about data frequency with a realistic question: "What is the minimum amount of data needed to accurately define a part or geometric shape" (p. 34)?

The need for consistent and reliable measurement techniques along with the control or elimination of measurement variability has become critical with the emergence of SPC, Gage R&R, and computer-controlled gaging systems. Although it is often overlooked, the right inspection methodology or part orientation for the measurement of various features can have an important impact on achieving acceptable Gage R&R results and repeatability improvements. If CMM manufacturers, owners, and operators continue to disregard potential sources of measurement variability in their measurement activities or fail to evaluate machine specific characteristics, gage variability will continue to influence measurement operations.

Inconsistencies and Limitations of the 1993 Study

Various inconsistencies noted in the results of a 1993 repeatability study as well as limitations imposed on the study itself, dictate a need for a more comprehensive investigation of diameter measurement repeatability. The various inconsistencies noted in the 1993 study were introduced and discussed in the introduction section of this chapter. Limitations imposed on the study itself are a different subject entirely. Through various limitations that were imposed on the 1993 study, the scope of the study as well as the usefulness of the results were greatly reduced. To understand more fully the impact of limitations placed on the 1993 study, the following explanations are provided:

1. The 1993 study failed to evaluate diameter measurement repeatability on all three measurements planes (XY, XZ, and YZ); only

the XY plane was investigated. Since measurement activities in industrial settings encompass all three planes, any further repeatability study of diameter measurement should be structured to evaluate all three measurement planes.

2. The 1993 study made an assumption that gage repeatability was the same, regardless of the test specimen's location within the working envelope of the CMM. Although this can be a justifiable assumption, the potential effect of location on diameter and probe hit repeatability has not been adequately assessed nor has any research been presented to document the effect, if any. Consequently, any further study of diameter measurement repeatability should avoid this assumption or place smaller limits on the size of the measuring envelope.

3. The 1993 study based repeatability optimization on the results of a single baseline inspection. Since the purpose of this study was to determine the effects of diameter and probe hit variation on diameter measurement repeatability, the use of a single baseline inspection was consistent with the intent of the study. However, with the identification of instability in repeatability within certain diameters and probe hit categories, a single baseline repeatability study should be avoided.

4. Although improvements were made in average repeatability using repeatability optimization, the study failed to evaluate time differences between baseline inspections and the optimization programs. This is an important consideration since any improvement in diameter measurement repeatability using an alternate inspection methodology should be structured to assess various benefits that can be received from its use.

Research Hypotheses

Four research hypotheses were formulated to study the effects of multi-baseline repeatability on diameter measurement repeatability optimization. These hypotheses have been constructed to determine (a) the effectiveness of multi-baseline repeatability data in identifying specific probe hit inspection patterns with inherent stability in repeatability and (b) the effectiveness of multi-baseline repeatability optimization in generating inspection routines that yield improvements in diameter measurement repeatability without significant increases in inspection time and related costs.

Identification of Research Hypotheses

Although various research hypotheses were developed to investigate diameter measurement repeatability, the data collected from this study will also yield information on the effectiveness of multi-baseline repeatability analysis as a potential test method/procedure that can be used to identify, assess, and monitor machine-specific characteristics and/or software differences.

Hypothesis #1

Similarities will be noted in the direction and magnitude of the relationship between average probe hit repeatability and probe hit variations between repeated baseline programs and baseline programs of different planes. Correlational similarities will be deemed significant if:

1a. little or no difference is noted in the direction and magnitude of the relationship between average probe hit repeatability and probe hit variations between repeated baseline programs.

1b. little or no difference is noted in the direction and magnitude of the relationship between average probe hit repeatability and probe hit variations between baseline programs of different planes.

Hypothesis #2

Within each planar baseline program (XY, XZ, and YZ), at least one probe hit category from each circular test specimen will indicate measurement stability. Measurement stability will be deemed significant if:

2a. little or no difference is noted in the standard deviation values of counterpart test specimens and probe hit categories from repeated baseline programs.

2b. little or no difference is noted in the kurtosis and skewness values of counterpart test specimens and probe hit categories from repeated baseline programs.

2c. little or no difference is noted in the distribution means of counterpart test specimens and probe hit categories from repeated baseline programs.

Hypothesis #3

Within each planar measurement test (XY, XZ, and YZ), improvement in diameter measurement repeatability will be achieved through the assessment and optimization of multi-baseline repeatability data within each planar measurement test (XY, XZ, and YZ). Repeatability improvement will be deemed significant if:

3a. the average repeatability values of the multi-baseline optimization programs, MB(3-10) and MB(3-6), are less than the average repeatability values of all baseline probe hit categories within the stated probe hit ranges and plane.

3b. the time required to complete one measurement pass of each test specimen plate using the MB(3-10) optimization program is less than the time required to complete one measurement pass using the baseline probe hit category with the "best" average probe hit repeatability. The term "best" implies the smallest numeric value. An identical condition will also be noted with the MB(3-6) optimization programs and a given baseline probe hit category using the same probe hit range.

3c. t statistic analysis of probe hit repeatability values from the optimization programs and the "best" probe hit categories from counterpart baseline programs will indicate that a reduction in diameter measurement repeatability can be expected from the assessment and optimization of multi-baseline repeatability data with a 95% confidence level.

Hypothesis #4

Differences will be noted in the general structure of each planar optimization program but will not be noted in the calculated average repeatability and mean probe hit values. Structural differences and average repeatability and mean number of probe hit similarities will be deemed significant if:

4a. the time required to complete one measurement pass of all test specimens is distinctly different between planar optimization programs.

4b. the mean number of probe hits between planar optimization programs with identical probe hit ranges are the same.

Null Hypotheses

1. No similarities will be noted in the direction and magnitude of the relationship between average probe hit repeatability and probe hit variations between repeated baseline programs nor between baseline programs of different planes.

2. Within each planar baseline program (XY, XZ, and YZ), no probe hit category from any circular test specimen will indicate measurement stability.

3. Within each planar measurement test (XY, XZ, and YZ), no significant improvement in gage repeatability will be achieved through the use of multi-baseline repeatability assessment and optimization.

4. No significant difference will be noted in the general structure of planar optimization programs but will be noted in the calculated average repeatability and mean probe hit values.

Assumptions

Since the variables surrounding the testing and determination of diameter measurement repeatability are broad in many respects, the following assumptions were made with respect to this study:

1. Since this study was an analysis of diameter measurement repeatability and not an evaluation of a particular CMM to stated repeatability specifications, minor variations in the factors that influence measurement variability were not considered critical as long as the effects of such variability are equally distributed among all test specimens, probe hit categories, inspection programs. Consequently, one diameter measurement was collected from each test specimen on a particular plate prior to the collection of the second diameter measurement. In addition, the assessment and optimization of diameter measurement repeatability was completed on an individual plate basis. In other words, a test specimen plate, once fixtured in the measuring envelope, was not disturbed until all baseline and/or optimization tests had been completed.

2. Since all of the test specimens were manufactured using a similar machining process, minor variations in surface metrology in each of the test specimens as well as their influence on repeatability was assumed to be equal.

3. It is assumed that outliers in the data sets of any one test specimen could occur due to random chance. The occurrence of such outliers would necessitate the retesting of the test specimen or test specimens in question. If it was determined that the occurrence was a random event, the second data set(s) replaced the first data set(s).

Limitations

Due to various constraints associated with a CMM study, the following limitations were made with respect to this study:

1. Since the CMM used in this study may have possessed inherent operational characteristics that produce specific diameter measurement repeatability values with respect to diameter and probe hit variations, no attempt was made to generalize the results of this study to all CMMs or software measurement packages.

2. Since this CMM possessed existing wear and machine breakdown during the course of the study could not be anticipated, no attempt was made to generalize the results of this study to this model of CMM or software measurement package.

Delimitations

Due to various constraints associated with the CMM, its availability, and operating environment, the following delimitations were made with respect to this study:

1. Although the CMM involved in this study possessed the capability for programmed diameter measurement using a various part orientations,

only XY, XZ, and YZ part orientations were used. In other words, the alignment of specific test specimen planes with respect to XY, XZ, and YZ axes of the CMM was maintained throughout the entire data collection process.

2. Although the CMM involved in this study possessed the capability for programmed circular measurement using 96 different probe hit patterns, only eight probe hit patterns were selected for repeatability assessment and optimization (probe hit range of 3 to 10) . This delimitation was imposed because it had been determined through a review of the literature that the use of larger numbers of probe hits has limited applications in manufacturing environments.

3. Although it is possible to measure circular test specimens as large as the working envelope of the CMM, the study was limited to circular test specimens with diameter ranges between 0.25 inches and 5.75 inches at increments of 0.25 inches.

4. Since the potential effect of test specimen location on diameter and probe hit repeatability cannot be adequately assessed, a limit was placed on the size of the measuring envelope. The size of the measuring envelope was restricted to 1,728 cubic inches (12 x 12 x 12 inches) and located in the lower center of the CMM's measuring envelope.

Research Methodology

This study was initiated to (a) analyze the effects of diameter and probe hit variations on diameter measurement repeatability and (b) determine if an alternate inspection methodology would yield significant improvements in gage repeatability. To accomplish these two objectives, the research methodology was structured around three areas: (a) research design, (b) control of extraneous variability, and (c) data collection and analysis. The inclusion of these components as part of the research methodology was based on prior repeatability studies and documented repeatability testing procedures.

Research Design

Based on research and information provided by CMM manufacturers, the research design was divided into four components: (a) equipment selection, test specimens, (c) inspection program development, and (d) control of extraneous variability.

Equipment Selection

The CMM selected for use in this study was a Brown and Sharpe Xcel 7•6•5 CMM belonging the Center for Quality, Measurement, and Automation (CQMA) at Bowling Green State University. This DCC/CMM has a moving bridge configuration and a rigid unitary base structure made out of granite. In addition, a Renishaw multi-positional touch trigger head assembly and a 2 mm ruby-tipped stylus equipped with a one inch extension will be incorporated as part of the measurement setup. Various specifications associated with this CMM and of interest for inspection program development are shown in Table 1.

This CMM was selected for two reasons. First, it is the same CMM that was used in the 1993 study. This permits some cross-comparisons and correlations of data to assess machine stability over time. Second, the location of this CMM in a university setting permits regular use of the machine for the duration of the study. This is an important aspect since most CMMs located in manufacturing environments are under constant use or restricted to authorized company personnel. In short, this study would be extremely difficult to conduct if access to a CMM in a manufacturing setting was required.

Test Specimens

Twenty-three circular test specimens were used in this study. These test specimens, which range in diameter from 0.25 to 5.75 inches at 0.25 inch increments, are the same test specimens that were used in the 1993 study. The decision to incorporate these test specimens into this study is based on two rationales. First, the results of the 1993 study indicated that the use of 23 test specimens was of sufficient size to yield useful data on diameter measurement repeatability. Second, the results of the study also indicated that test specimen sizing (0.25 to 5.75 inches at 0.25 inch increments) was a useful sampling pattern for establishing correlational trends and other types of statistical analysis.

Table 1

Xcel 7•6•5 CMM Specifications

Description	Parameter	Inches	Millimeters
Measuring Range	X-axis	25.6	650.0
	Y-axis	23.6	600.0
	Z-axis	19.7	500.0
Performance	Repeatability	0.00014	0.0035
	Resolution	0.00002	0.0005
	Accuracy	0.0004/15.75	0.011/400

Inspection Program Development

Although this CMM possesses the capability for programmed circular measurement using 3 to 99 probe hits, only the 3 to 10 range was selected for study. The selection of this probe hit range is based on the contention that time and cost constraints imposed on manufacturers during production restricts the use of long inspection times (i.e. increased numbers of probe hits). This range selection was also based on information provided by Digital Equipment Automation (DEA) in which it was suggested that circular repeatability testing should be structured on two criteria: (a) the automatic circle program option and (b) a probe hit inspection pattern of 16 or less. This range selection also takes into account the 3 to 10 probe hit range used in the 1993 study. In addition to this probe hit range, fifteen inspection programs were used in this study. Three of the programs measured the diameters of each test specimen on each measurement plane, XY, XZ, and YX, using all eight probe hit categories. The other twelve programs also measured the diameters of each test specimens on the same three planes with one exception; the programs were based on optimized repeatability values and two probe hit ranges, a 3 to 6 probe hit range and a 3 to 10 probe hit range. It should be noted that the tested probe hit pattern may or may not be similar between the two probe hit ranges.

Control of Extraneous Variability

In addition to the three previous components, various steps were taken to minimize the potential influence of factors that are known to cause measurement variability, factors such as temperature variations, vibrations, and cosine error. The first factor, temperature variation, has been shown to have a dramatic but somewhat predictable effect upon dimensional measurements. The second factor, vibration, has been shown to have a dramatic and unpredictable effect upon gage repeatability. The final factor, cosine error, occurs when a lack of squareness exists between the surface being measured and the contact surface of the probe tip of the CMM. The specific steps that were taken to minimize the influence of these three factors are:

1. The construction of an environmental enclosure around the CMM. The purpose of this enclosure, supported by Brown (1991), was to assist in temperature stabilization by eliminating drafts blowing on the measurement setup.

2. The placement of the test specimens within the enclosed area and on top of the granite surface of the CMM 24 hours before data collection. The purpose of this step was to ensure temperature consistency between the test specimens and the CMM.

3. The monitoring of the air temperature within the enclosure during data collection. The purpose of this activity was to ensure that dramatic variations air temperature do not occur during data collection.

4. The sequencing of data collection. In other words, the CMM was be programmed to take one measurement of each test specimen prior to collection of the next set of measurements. The purpose of the procedure was to ensure that the effects of accepted temperature variations within the stated range are equally distributed among all probe hit categories.

5. The scheduling of data collection during time frames when other machines within the lab were not in operation. The purpose of this procedure was to minimize the effects of vibration on gage repeatability.

6. The setting of the multi-positional touch-trigger probe head in the vertical position (0 degrees) for the XY plane, the horizontal position (90 degrees) for the XZ, and the horizontal position (90 degrees) for the YZ plane. The purpose of this procedure was to minimize cosine error and its potential effects on measurement data.

7. The use of the automatic circle (AUTO/CIR) measurement option. The purpose of this program option was to ensure that probe movement toward the surface, once the probe approach distance had been reached, was aligned with the center of the circular feature and the designated contact point. This program option also divides the angular vectors between probe hit contacts into equal parts.

Data Collection and Analysis

In this study, diameter data were collected from three repeated baseline inspections and twelve optimization programs. In each of the baseline inspections (two on the XY plane, two on the XZ plane, and two on the YZ plane), 10 diameter measurements were collected from each test specimen in each of the eight probe hit categories. In all, 1,840 diameter measurements were collected in each baseline inspection for a total of 11,040 diameter measurements from all six baseline inspections. Once the baseline data was collected, it was entered into a statistical software package where descriptive and inferential analyses was performed to determine the structure of the planar optimization programs.

With respect to the twelve optimization programs, six of the programs assessed gage repeatability using a single baseline approach to repeatability assessment and optimization. The single baseline assessment was used to replicate and/or validate the results of the 1993 study. The remaining six optimization programs also assessed gage repeatability using repeatability assessment and optimization with one noted exception; the optimization programs were structured on a multi-baseline repeatability assessment. The multi-baseline assessment were used to assess the stability in repeatability associated with diameter and probe hit variations. The multi-baseline assessment was also used to determine if gage repeatability improvements can be achieved using this approach. To analysis the diameter data collected from the baseline and optimization programs, the following procedures were used: (a) repeatability determination, (b) correlation analysis, (c) repeatability optimization, (d) inferential statistical analysis, and (e) benefit analysis.

Repeatability Determination

Two methods of repeatability determination were used in this study, the ASME B89 Range Method and the Standard Deviation Method. Both of these methods utilized the single operator approach to Gage R&R analysis. In other words, the variability a single operator brings into a gaging system was considered part of equipment variability and reported along with other gage variability factors as one value, repeatability. The decision to incorporate both methods into this study was based on current literature in which a lack of standardization in the use of a particular repeatability testing method was indicated. In short, the use of a particular repeatability assessment method is based solely on manufacturer preference. Once base repeatability values for each test specimen were determined in each probe hit category and baseline program, average probe hit repeatability values for each probe hit category and average baseline repeatability values were determined.

Correlation Analysis

Once repeatability values were calculated, correlational analyses using Pearson's product moment correlation coefficient were performed to determine the direction and magnitude of the relationship between average probe hit repeatability and probe hit variation within each baseline inspection. In addition, comparisons were made to determine the extent of similarity or difference between the correlations of all baseline programs.

Repeatability Optimization

In this assessment, the repeatability values of each test specimen, taking into account all probe hit categories within a given planar baseline program, were compared to identify the particular probe hit categories with the "best" repeatability. The term "best" implies the smallest numeric value. Once these values were identified for each test specimen on a given plane, the probe hit measurement routines associated with the selected values were incorporated into planar optimization programs. Repeatability information from these programs were assessed in a similar manner as the baseline inspections. The purpose of the optimization programs was (a) validate or invalidate the results of the 1993 study and (b) test the hypothesis that multi-baseline repeatability assessment and optimization, regardless of planar orientation, would maximize stability in gage repeatability and yield significant improvements in diameter measurement repeatability.

Inferential Statistical Analysis

Inferential analyses were conducted to determine if significant improvements can be achieved in diameter measurement repeatability using multi-baseline repeatability assessment and optimization. In the first inferential analysis, single sample t statistic tests were conducted to make inferences about the degree of confidence that can be placed in the results of the multi-baseline (3-10) and multi-baseline (3-6) optimization programs in comparison with counterpart baseline results. Simply stated, the null hypothesis indicates that no significant improvement in average gage repeatability can be achieved using multi-baseline repeatability assessment and optimization. The alternate hypothesis, on the other hand, indicates that a statistically significant improvement in average gage repeatability can be achieved using multi-baseline repeatability assessment and optimization (i.e., the repeatability mean of each multi-baseline optimization program would be less than the repeatability mean of the "best" baseline probe hit category within their stated probe hit range and plane). It should be noted that the term "best" implies the probe hit category with the smallest numeric repeatability value. To provide additional support for the multi-baseline approach, an identical t statistic test was also performed on the results of the single baseline (3-10) and single baseline (3-6) optimization programs. All null and alternate hypotheses associated with this inferential analysis were also tested using a significant level of 0.05. The specific null and alternate hypotheses associated with this inferential statistical analysis are detailed in Chapter III.

Benefit Analysis

In this analysis, the potential benefits derived from the optimization of diameter measurement repeatability were assessed. In the first benefit analysis, a determination of the mean number of probe hits for each optimization programs was made. Once determined, the time required to make one inspection pass of all test specimens in each of the optimization programs were compared to the inspection time of the respective baseline inspection indicated by the mean values. The purpose of this assessment was to enable percent difference comparisons of average repeatability and inspection time relative to each plane.

Timeline of the Study

A Gantt chart was developed to show the time frames of the activities involved in this study.

			1995					1996		
	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Develop Proposal	•	•	•	•						
Review of Literature		•	•	•	•					
Submit Proposal						•				
Collect Data							•			
Prepare Findings								•		
Formulate Conclusions									•	
Submit Dissertation										•

Terminology

Various sources were used in the formulation of this section. To permit ease of identification between specific terms and their related sources, references have been placed at the end of each definition.

1. Accuracy. Several definitions for this term exist all of which have equal value in the description of accuracy. These definitions are:

a) a quantitative measure of the degree of conformance to recognized national or international standards (Busch, 1989, p. 19).

b) a qualitative term used to relate the output to the true value of the input with declared probability limits. It is normally specified as an inaccuracy (uncertainty) and is the sum of errors contributed by a number of factors such as non-linearity, hysteresis, temperature, vibration, and drift (Wrightman, 1972, p. 10).

2. ASME. American Society of Mechanical Engineers

3. Average repeatability. The repeatability value calculated by averaging the probe hit repeatability values within a specific baseline or optimization program.

4. Average probe hit repeatability. The repeatability value calculated by averaging the probe hit repeatability values within a specific probe hit category.

5. Baseline. A group of diameter/probe hit repeatability values considered together because of planar or inspection run similarities.

6. Diameter measurement repeatability optimization. A method or technique that compares the repeatability values of various diameters and probe hit categories to identify the particular probe hit category with the "best" repeatability.

7. Cosine error. The error that is induced by a lack of squareness between the feature of the part and the measurement instrument (Busch, 1989, p. 708).

8. Discrimination. The fineness of the scale divisions of an instrument. In other words, the smallest division of the scale that can be read reliably (Salvendy, 1982, p. 8.2.4).

9. Error. The difference between the measured value and the true value. Error always exist and in many cases be measurable (Busch, 1989, p. 709). The measure of error may be expressed in specific units of measurement, as a percentage of the true value, or as a percentage of some specified value, usually full scale (Wrightman, 1972, p. 10). The most common types of errors, according to Busch, are:

a) observational error - the error that is formed during the reading of an instrument.

b) parallax error - the error that is caused by apparent shifting of objects when the viewing position is changed.

c) manipulative error - the error that is caused by the handling of the instrument and the part.

d) bias error - the error that forms through the conscious or unconscious influencing of measurement.

10. Gage. A mechanical artifact used either for checking a part or for checking the accuracy of a machine, or a measuring device with a proportional range and some form of indicator, either analog or digital (ASME B89.1.12M-1990, p. 9).

11. Multi-baseline repeatability assessment. An assessment method that compares the measurement repeatability values from two or more baseline inspections.

12. Outliers. Observations with residuals that are extremely large in comparison to the majority of the collected data. In more specific terms, outliers are collected data with residuals that are greater than 3 standard deviations from zero or values that are larger than the limits of a six sigma (6σ) spread (Mendenhall & Sincich, 1989, p. 289).

13. Precision. Three definitions for this term exist, all of which have equal value in the description of precision. These definitions include:

a) a measure of the fineness of readings or the dispersion of results (Busch, 1989, p. 19).

b) a measure of how closely identical values are obtained when repeating the same measurement at various intervals, or duplicating them by means of different instruments. In other words, precision expresses the degree of repeatability within a measuring process (Farago, 1982, p. 4).

c) the degree of agreement among the individual measurements of the sample ordinarily summarized by the standard deviation of the measurement process (Salvendy, 1982, p. 8.2.3).

14. Probe. With regards to a CMM, the probe is a device which is used to establish the location of the movable component relative to a measurement point. In the ASME B89.1.12M-1990 standard, four types of probes were defined:

a) nulling probe - a probe which, when referenced to a workpiece, gives a signal which causes the machine to be driven to a position that will null the probe reading.

b) passive (solid or hard) probe - a probe which mechanically fixes the movable component relative to the workpiece. Within this category, there are two types of probes, seating probes and nonseating probes. Seating probes are hard probes that retain their location with respect to a measurement point without operator contact. Nonseating probes, on the other hand, are hard probes that require force applied by a machine operator to maintain their position with respect to a measurement point.

c) proportional probe - a probe which gives a signal proportional to the displacement of the probe from its free position.

d) switching probe - a probe which gives a binary signal as a result of contact with or in proximity to the workpiece.

15. Probe hit category. A term used to differentiate between the data collected from specific probe hit measurement routines.

16. Random error. The error that results from erratic malfunction of the gaging system. This type of error is often found through discrepancies within repeated measurement activities (Busch, 1989, p. 712).

17. Repeatability. Several definitions for this term exist all of which have equal value in the description of repeatability. These definitions are:

a) a measure of the ability of an instrument to produce the same measured value when sequentially sensing the same quantity under similar measurement conditions (ASME B89.1.12M-1990, p. 9).

b) measurement variation resulting from limitations of CMM accuracy, the gaging environment, the probing system, the fixturing method, and CMM programs (Ray, 1992, p. 22).

c) the closeness of agreement of a group of measurements of the same measured quantity made by the same observer, using the same conditions, methods and apparatus (Wrightman, 1972, p. 10).

d) the variation among several measurements taken with one instrument on one part feature. It is a test of precision, not of accuracy (Busch, 1989, p. 423).

18. Reproducibility. Measurement variation resulting from different gage operators who sometimes work with different models of a similar measuring instrument in monitoring the same characteristic from a common process (Ray, 1992, p. 23).

19. Single baseline repeatability assessment. An assessment method that compares the measurement repeatability values from one baseline inspections.

20. Special cause. A source of variation that is intermittent, unpredictable, or unstable and affects only some of the individual values of the process output being studied. Sometimes called assignable cause. A quality problem manifested by a non-random source of variation in a process (Process Control Chart Tool Kit: Reference Manual for the Macintosh, 1990, p. 175).

21. Stability. The absence of special or assignable causes of variation; the property of being in statistical control. The characteristic of remaining within the limits of expected variation over time (Process

Control Chart Tool Kit: Reference Manual for the Macintosh, 1990, p. 175).

22. Systematic error. The error that occurs in all readings uniformly and can be caused by any element in the measurement system, including the observer. Systematic errors are not revealed by repetition as are most other errors (Busch, 1989, p. 714).

CHAPTER II

REVIEW OF LITERATURE

The purpose of this chapter is to examine the literature relevant to the growth coordinate measuring machines (CMM), their integration into manufacturing, various methods that are used to evaluate their performance, and past performance evaluation studies. Consequently, this chapter is organized around four distinct sections: (a) Growth and Development of CMMs, (b) Operation and Design Considerations, (c) Performance Testing and Evaluation, and (d) Overview: 1993 CMM Repeatability Study. The first section gives an historic overview of CMMs and describes their roles in quality and productivity improvements. The second section focuses on CMM design and operational considerations and their linkage with flexible inspection systems (FIS). The third section identifies various performance testing methods that are commonly used to evaluate CMMs and the significance associated with past repeatability studies. The final section gives an overview of a related CMM repeatability study that was conducted in 1993. It not only highlights relevant findings of this study and its relationship to this study but other studies as well.

Growth and Development of CMMs

Success in manufacturing today requires a commitment to a philosophy of manufacturing excellence. This philosophy, commonly termed World-Class Manufacturing (WCM), is characterized by several strategies, three of which are continual and rapid improvement, improved flexibility, and variability reduction. Changes in manufacturing practices due to the implementation of these strategies have been among the driving forces behind the evolution of CMMs. According to Bosch (1991), manufacturers see in CMMs the means to improve production efficiency by moving the inspection process closer to the machines that produce the parts. The net effect of this transfer is a shift in inspection emphasis from post-process detection to on-line prevention and process correction. The evolution of coordinate measurement technology can best be understood through an historic overview of CMMs and the roles they have played in manufacturing, quality control and assurance, and productivity improvements.

Historic Overview of CMMs

Although various terms have been used to describe CMMs, Bergstrom (1990) summed it up best by stating that the CMM is "an automated, programmable, highly productive, high technology three dimensional height gage with the flexibility to verify the various dimensions of almost any object" (p. 67). Stevens (1991) augmented Bergstrom's description of CMMs by describing them from an historical perspective. According to Stevens, CMMs are about to embark on their third major incarnation. When first introduced in the 1950s, CMMs were awkward to use and required operators to manually position the probe during measuring operations. Even though these early machines were primitive when compared to present day technology, their use helped to stimulate quality and productivity increases and continued advancements in coordinate measurement technology. During the 1960s and 70s, second-generation CMMs utilizing motorized probes and computer numerical control (CNC) systems ensured the design specifications of manufactured parts and components through first pieces inspections and hand gage calibrations. The use of these second generation machines also led to further improvements in quality and productivity. With the move toward world-class manufacturing during the 1980s, these second-generation CMMs proved to be inadequate for automated process control since most were located away from manufacturing processes. What was clearly needed was a measuring system that could accurately monitor manufacturing processes during production and determine how production variability was affecting the end-product or final component.

During the 1980s and the rise of third-generation CMMs, many areas surrounding coordinate measurement experienced rapid advancement. Many of these advances, according to Stevens (1991), were hardware-based in areas such as high-speed linear motors and faster computer speeds while others, according to Inglesby (1989), were software-based in areas such as temperature compensating algorithms and CAD/CAM communication programs. In addition to evolutionary changes in hardware and computer software, the 1980s witnessed full-scale development of alternative dimensional measuring devices. These new devices incorporated noncontact sensing technologies and proved their worth in applications where large amounts of three-dimensional data were needed quickly.

Even with the development of alternative means of dimensional measurement gathering, Stevens (1991) envisioned that tactile or contact-based CMM will remain the most widely used method for post-process dimensional measurement. With further advancements in computer technology, artificial intelligence, and sensor technologies, the decade of the 90s promises to be an exciting period for continued advancements in coordinate measurement technology and CMMs specifically.

The Roles of CMMs in Manufacturing

The importance attributed to the integration of CMMs into manufacturing can also be seen through an examination of two important roles they play in helping the manufacturers achieve quality and productivity improvements: (a) greater manufacturing flexibility and (b) product variability reductions.

Greater Manufacturing Flexibility

Due to increasing global competition and decreasing product life cycles, manufacturers are being pressured to incorporate greater flexibility into their manufacturing operations. One approach most accepted by manufacturers to achieve greater manufacturing flexibility has been automation. The word "automation" when applied to manufacturing conjures up a multitude of images and definitions. Regardless of whether it is called flexible manufacturing systems (FMS), computer-integrated manufacturing (CIM) or something else, the goal of automation, according to Placek (1990), is to improve product quality and production flexibility while reducing manufacturing costs and product throughput time.

Huge (1988), on the other hand, considered FMS a viable way to execute WCM philosophy since it is a subset of CIM and represents the automated approach to the implementation of the just-in-time (JIT) concepts that surround cellular manufacturing/group technology production. Huge also indicated that flexibility increases in manufacturing operations necessitate the use of inspection systems that possess the same degree of flexibility as the machine tools that make the parts and the material handling systems that transport the parts.

Hugh's support for increased manufacturing flexibility through CMM-based inspection systems was confirmed when he stated:

> The most widely used definition of FMS is a cell of computer numerically controlled (CNC) machines, with automated material handling between machines. The FMS cell frequently includes a coordinate measuring machine (CMM) to provide automatic inspections on both in-process and finished work. All machine operations, inspection, and movement of material between machines is controlled by a host or central computer. (p. 33)

Schonberger (1986) stated that this approach to production has important applications in plants that have high-variety, low-volume production and where parts have been divided into production families based on similar setup times, cycles times, tool and fixture requirements, and inspection needs. Placek (1990) supplied additional support for CMM-based inspection systems when he stated that an important element needed to increase manufacturing flexibility and support CIM and FMS concepts is real-time process control. Placek also suggested that one of the vital ingredients in achieving process control is process-specific data obtained through CMMs that employ either contact or noncontact measuring techniques during dimensional inspection. Additional support for the incorporation of CMMs into inspection and real-time process control applications was given by Gerald Franck, Product Manager for Flexible Inspection Systems at Sheffield Measurement, when he stated that:

> Today's CMMs can generate data at rates approaching one per second. High-speed CMM software automatically records data, verifies part features against engineering tolerances and reports results. This makes the CMM an ideal data collection/processing instrument for automated statistical process control. (p. 32)

Product Variability Reductions

Product variability is detrimental to improvements in quality and productivity. One technique used to reduce variability and its related costs is statistical process control (SPC). The primary goal of SPC is to determine whether or not a process is operating within defined limits. If it is determined that a process is not operating within defined limits, an "out-of-control" situation exists and the cause or causes of the variability need to be investigated. Once the cause is identified and steps are taken for its control or elimination, the process will returned to an "in-control" status. Schonberger (1986) disclosed that Ford Motor Co. and other manufacturers have been aggressively combating quality concerns through variability reduction. Their manuals on this subject have been widely distributed and have helped other companies in other industries achieve similar results. It should be noted, however, that even though SPC is an important technique for eliminating product variability, the operator is still considered an important link in the prevention of defects.

To combat product variability, increasing numbers of manufacturers are employing a three-way approach that includes more sophisticated gaging and inspection systems, SPC, and operator training/control. The diverse nature of these three areas has helped manufacturers to identify and separate random causes of variation from what Schmenner (1990) termed as nonrandom, assignable causes of variation such as operator error, gage error, faulty setup, or poor materials. Once the assignable causes of variation are identified and the process is brought under statistical control, what remains is random or normal variation, sometimes referred to as natural tolerance. Shingo (1989) provided additional support for the use of automated inspections in quality improvement and variability reduction when he stated that "quality can be assured reasonably only when it is built in at the process and when inspection provides immediate, accurate feedback at the source of defects" (p. 18).

Because of the importance attributed to inspection in variability reduction, the planning for this function, according to Bosch, Taylor, and Zipin (1985), must be given the same amount of attention that has been given to other elements in flexible manufacturing systems (FMS) such as process planning, material handling, and controlling functions. Consequently, an important consideration in the selection of an effective quality control method is the identification and implementation of a flexible inspection system (FIS) that best satisfies the requirements for a particular process. The importance of a CMM-based inspection system in FMS was supported by Hicks (1990) when he stated:

> CMMs traditionally have been used for post-process quality control. But the evolution of quality control, plus advances in computer-based technology, has led CMM builders to reformulate how their products operates within the factory system. Now armed with the right software, the CMM is no longer limited to a passive role. Instead, it can provide information that helps reduce lead times, helps determine the best and most efficient way of producing a product, and aids management in making decisions about capital equipment needs and product or process development before problems arise. (p. 32)

A micro example of what is taking place on at the macro level across the manufacturing sector can be seen by using Caterpillar Tractor Co. as an example. Caterpillar's acceptance of the CMM as a means of achieving quality improvements through on-line automated inspection as well as operator involvement in the quality process was indicated by Stovicek (1990) when he stated:

> Restructuring for swifter demand-driven turnaround times makes zero-defect process control (rather than post-process inspection) a high priority. To achieve a high level of process control in metalworking operations, Caterpillar is putting coordinate measuring machines (CMMs) on the line with machine tools, and under the control of the operators. (p. 24)

Design and Operational Considerations

Since quality and productivity improvements have close links to the implementation of flexible inspection systems (FIS), a closer look at the characteristics and functions of FIS is warranted. In developing this understanding, the first step is to identify what actually constitutes an FIS. In this regard, Inglesby (1989) reported that John Bosch, president of Giddings & Lewis (formerly Sheffield Measurement), defined FIS as 'a system that measures the dimensional characteristics of randomly presented parts of virtually any configuration or complexity and provide real-time feedback to the manufacturing process' (p. 22). Inglesby also noted that the central element in building a flexible inspection system is a CMM. This contention was supported by Bosch when he stated that 'for the same reasons CNC is synonymous with production, CMM means inspection - increased throughput, minimized operator error and repeatable quality' (p. 22). Bosch further emphasized that a CMM-based inspection system must be able to perform several essential functions, such as:

1. It must measure parts of virtually any configuration or complexity with little or no special fixturing.

2. It must operate unattended or with relatively unskilled operators, communicate with remote host computers and accommodate automated material handling.

3. It must tolerate harsh environmental factors such as temperature, humidity, vibration, oil, dirt, coolants, etc.

4. It must incorporate advanced devices for probes--articulators, changers, noncontact component--along with part marking and/or pallet or part recognition systems.

5. It must have fast, comprehensive data base management with statistical process control as manufacturing moves from a parts acceptance function to a process auditing function.

It was also reported by Placek (1990) that Bosch stated that it is easy to justify the cost of a CMM when the real costs of off-line or post process inspection are considered, such as:

1. Scrap loss
2. Rework of salvageable parts
3. Machining center downtime
4. Increased staffing costs
5. Additional material handling
6. Less in-process inventory
7. Final assembly problems
8. Warranty and liability claims

A case was also made for bringing in a CMM ahead of other machine tools during the initial stages of FMS setup. In conversations with Westinghouse Electric Corp., Placek (1990) noted that the early installation of CMMs at Westinghouse's Winston-Salem facility in North Carolina was difficult for them to justify at first, but eventually proved to be a worthwhile strategy. The information received by Placek indicated that the decision to incorporate the CMM ahead of other machine tools helped mold the inspection process and enhance plant-wide acceptance of the strategy.

Since the integration of the CMM into flexible inspection systems (FIS) and flexible manufacturing systems (FMS) are viewed as viable and realistic options, further enhancements in CMM capabilities would not only ease the transition to FMS but would also speed up the transition process. As a result, further enhancements in CMM capabilities are being directed toward two areas: (a) flexibility improvements through design and (b) operational variability reductions.

Flexibility Improvements Through Design

Flexibility improves in manufacturing processes necessitate the use of inspection systems that possess the same degree of flexibility as the machine tools that make the parts and the material handling systems that transport the parts. To meet FIS and quality assurance requirements, the CMM inspection system needs to possess flexibility in the following areas:

Shop Floor Applications

As manufacturing systems have moved in the direction of real-time operations, process trend analyses, and quicker process corrections, one important flexibility requirement that has emerged is the application of CMMs on the shop floor. When the CMM is moved closer to manufacturing processes, reliability and stability become important concerns. Three approaches are being taken to ensure that these concerns are not compromised when the CMMs is used in shop floor applications. According to Genest (1988), these approaches include: environmental enclosures, shop-hardened CMMs, and error compensating software. Although these approaches afford CMMs a greater degree of reliability and stability, further improvements are needed within each approach to overcome inherent disadvantages.

In the first approach, environmental enclosure, the major disadvantages are the expense associated with the construction of the enclosure, the time needed to bring the part to the desired measurement temperature, and the labor needed to monitor the process. In the second approach, shop-hardened CMMs, the major disadvantage is the need for periodic recalibration of the CMM due to temperature variations in the shop environment. In the third approach, the major disadvantage, according to Stevens (1991), is that current error compensating methods do not work well especially when the temperature change is too rapid or falls outside established limits.

In addition to the three concerns identified above, two other flexibility issues relating to the use of CMMs on the shop floor have also surfaced. These additional flexibility issues have concerns in the areas of micro and portable CMMs.

Micro CMMs. This aspect of shop floor flexibility involves the use of smaller CMMs. Many of these smaller, PC-based CMMs possess similar capabilities found on higher-end machines at a fraction of the cost. According to Bosch (1991), the availability of these entry-level CMMs have made coordinate measurement practical and affordable for a wide range of manufacturers seeking to increase productive and quality.

Portable CMMs. With regards to portable CMMs, Simon (1991) stated that there are two types, the ones that are moved from one fixed base to another and the ones that have the ability to be moved through the shop as a complete unit. Unfortunately, the use of portable CMMs has been slow to gain widespread acceptance due to the long setup and alignment times involved with relocation.

Accessibility

The flexibility a CMM needs to possess with regards to accessibility centers on the selection of a design configuration that best satisfies inspection requirements. It also has a direct bearing on the type of production line the CMM can be integrated into and the part size/measuring volume it can handle. As with machine tools, CMMs are available in a variety of configurations; each designed for specific needs and each possessing its own inherent limitations. Three key design parameters for a CMM in an FMS environment, as reported by Fix (1988), are high accuracy, high throughput, and larger part size/measuring volume capability. In most applications, the optimization of performance in one area necessitates compromises or tradeoffs in other areas. The various types of CMMs (see Figure 2) and their respective tradeoffs can be described in the following ways:

Moving table cantilever type. This design is popular for small manual CMMs since it provides openness and accessibility on three sides. Although the Y-axis places a size limitation on this configuration, the small Y-Z assembly is lightweight and can achieve fast measuring speeds in direct computer control (DCC) applications.

Moving bridge type. This design overcomes the size limitations of the cantilever design by incorporating a second leg and an extended Y-axis.

The limitations of this configuration usually center around walking problems associated with one legged drive units. For example, higher operating speeds have a tendency to increase dynamic forces, reduce machine settling time, and accentuate the walking problem. A variation of the moving bridge is the fixed bridge CMM. This particular configuration provides a very rigid structure and allows for a relatively light-weight and fast moving X-Z structure.

Column type. The column design provides higher accuracy and a very rigid Z-axis. As with the fixed bridge configuration, part mass and table considerations can restrict measuring volume and speed.

Moving ram horizontal arm type. With regards to horizontal arm designs, there are a variety of different configurations. Horizontal arms for large machines have a lower profile than their vertical arm counterparts. In some applications horizontal access is desirable; for others, it is too restrictive and requires the use of a rotary table.

Gantry CMM. This type of configuration provides relatively unrestricted part access unless utilized in very small machines. If the foundation or machine base in larger designs of this type are properly designed, larger axis travels can be obtained and heavy parts can be measured. Although this design is widely used in large machine applications, it has been shown to be a disadvantage for smaller CMMs.

Probing Systems

Probe system technology, both contact and noncontact, has an important impact on inspection flexibility. Consequently, this area has received a considerable amount of attention. The three general classes of probes identified by Busch (1989) are hard, soft, and noncontact. Hard tip probes, normally found on manually operated CMMs, are particularly

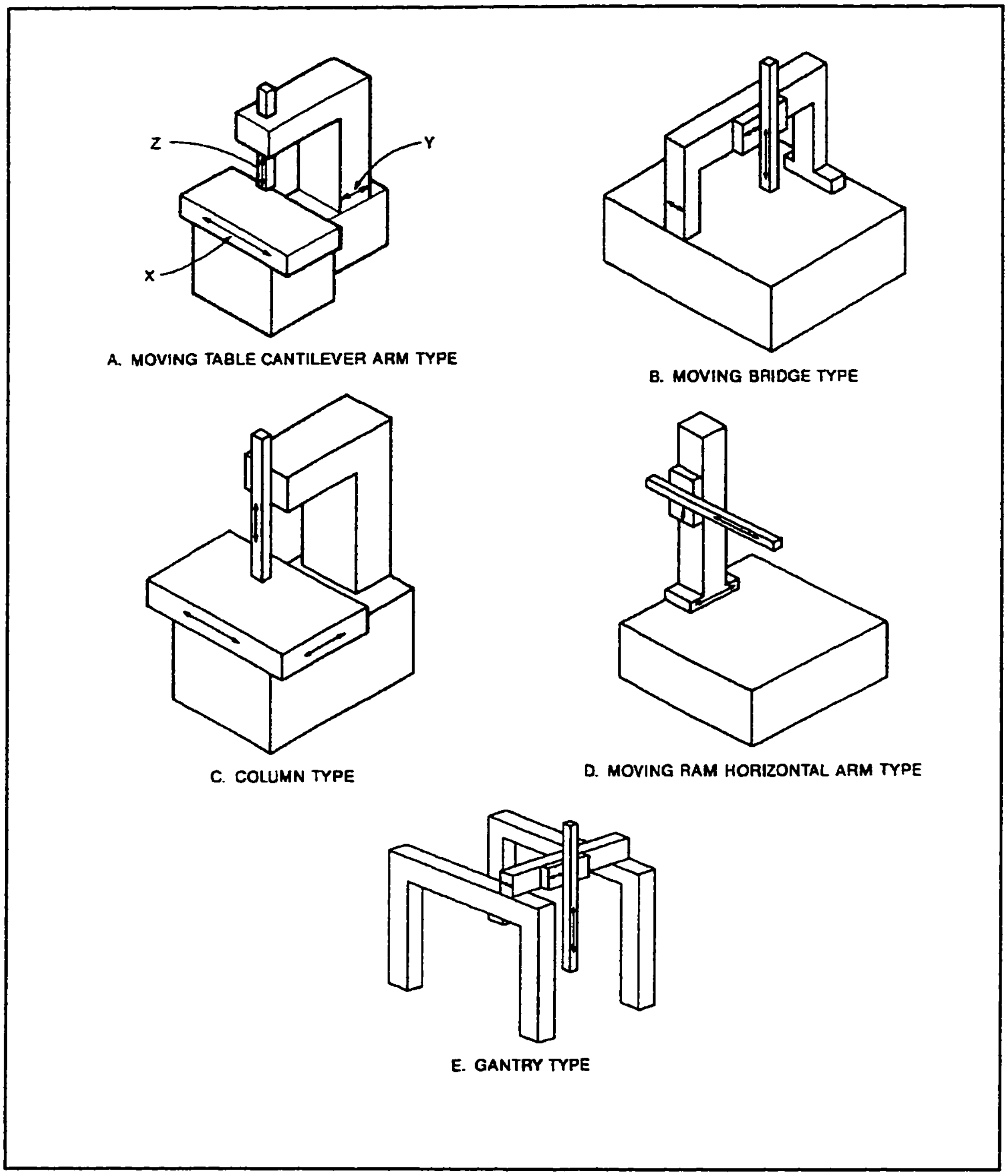


Figure 2. Common Configurations of CMMs. Note. From Fundamentals of Dimensional Metrology (p. 528), by Ted Busch, 1989, Albany, New York: Delmar Publishing Inc. Copyright 1989 by Delmar Publishing Inc. Reprinted with permission.

well suited for applications involving moderate accuracy requirements, shapes that require the feel of the operator, and repetitive or specialized measurements. Soft probes, commonly referred to as touch trigger probes, provide faster, more accurate results by eliminating much of the operator feel required with hard probes. According to McMurtry (1991), most CMMs are equipped with touch trigger probes because they are simplistic, robust, and easy to understand. He also identifed and described three types of touch trigger probes.

Standard. This probe is a simple device with a single stylus that can be changed to permit the use of different size ball or disk tips. This probe senses part contact by a change in resistance at the kinematic location contacts.

Piezoelectric. This analog-based probe generates a specific voltage based on the amount of displacement. This probe can yield greater accuracy, but is limited by slower speed and higher sensitivity to grease and dirt on a part.

Strain gage. This type of probe measures the microdeflection of the probe tip on a continuous basis and is not speed sensitive as with the other two touch trigger probes. This high performance probe is commonly used in applications that require high-accuracy deflection measurement.

Stevens (1991) disclosed that CMM manufacturers may have already reached, or will soon reach, the limits of speed that can be achieved using contact-based, touch-probe technology. As a result, developmental work has been underway to integrate noncontact sensing technologies onto CMMs. The three areas of noncontact sensing that seem to be the most promising are optical, laser, and vision systems.

To provide flexibility for the full range of contact and noncontact probing systems, automatic probe changing systems have also been developed. The development of these systems was deemed necessary because each probing system possesses inherent advantages and disadvantages and one system alone could not be expected to provide the CMM with the flexibility it needs for FMS environments. With system flexibility and accuracy as the primary goals in coordinate measurement, contact probing, according to McMurtry (1991), will probably remain the dominant probing system. However, it is expected that noncontact sensing will eventually play a vital role in CMM-based inspection systems. McMurtry also believes that CMMs will eventually include other sensing capabilities such as "component temperature measurement, surface hardness, eddy current probes for crack detection together with part marking, and more, all autochangable on the CMM" (p. 22). This contention was also supported by Placek (1990) when he stated that:

> As automatic probe changers become more common and sophisticated, Hicks [Jack Hicks, president of DEA] thinks other forms of inspection will be added to CMMs, such as hardness testing, ultrasonics probes for measuring thickness; eddy current probes for thickness, coating and flaw detection; and surface finish measurements. And the CMM soon may be able to build its own part-holding fixture from a set of modules -- not only to assemble the fixture but calibrate it at the same time. (p. 38)

Operational Modes

The operational mode used in a CMM has important implications for system flexibility. Busch (1989) reported that the operational modes available with CMMs can be divided into four general classes: manual, manual computer-assisted, motorized computer-assisted, and direct computer-controlled (DCC). It should be noted that the only major distinction between the manual computer-assisted and motorized computer-assisted categories is the method used for the movement of the axes. Consequently, these two operational modes will be treated as one option, the computer-assisted mode. The major modes of operation, therefore, are manual operation, computer-assisted operation, and direct computer-controlled (DCC) operation.

Manual operation. The manually-operated CMM has a free-floating probe that the operator moves along the machine's three axes to contact various features. The use of this operational mode has several inherent disadvantages for manufacturing applications such as lack of measuring flexibility, inability to be integrated into automated activities, and the need for an operator to be present at all times. Another disadvantage, according to Ray (1992), is the inability to achieve stated accuracy specifications or pass gage R&R studies unless XYZ lockouts and micrometers heads are used during measuring activities.

Computer-assisted operation. CMMs in this category can be either manually-operated or motor-driven. In either case, the main advantage associated with the use of CMMs in this category, according to Busch (1989), is the time savings the computer provides in minimizing calculations, obtaining printouts, and converting dimensional units.

Direct computer-controlled (DCC) operation. With respect to this option, Busch (1989) reported that whenever computer assistance is integrated into measuring activities versatility, convenience, and reliability is increased. When the DCC operational mode is used, the advantages related with computer assistance are enhanced even further. The main advantage for the use of DCC CMMs, as reported by Placek

(1992), was given by Michael Mariani, Brown and Sharpe's marketing manager for core products in which he stated that 'gaging flexibility' was the key concern. Mariani went on to stated that 'right now, the most common application for these small CNC/DCC models [larger models as well as smaller models have diverse manufacturing applications] appears to be gaging support for manufacturing cells' (p. 47). Ray (1992) stated that another advantage for the use of DCC CMMs is that gage R&R and process capability studies will be easier to perform and more repeatable.

Ease of use

When CMMs are moved onto the shop floor and have to be operated by production workers, ease-of-use becomes an important flexibility factor. Stevens (1991) supported this assessment when he stated that as the computer sophistication of the average operator decreases between the Quality Control (QC) lab and the shop floor, the friendliness of the software will have to increase. Genest (1993) also supported the necessity for ease-of-use when he suggested that as steps are taken to move the CMM closer to the manufacturing environment, analogous step will also have to be taken to move it psychologically closer to manufacturing. This transition can be smoother by creating operator interfaces and measurement and programming software that are not only more powerful but easier to use and understand.

An additional user flexibility need suggested by Genest (1993) was a more extensive use of off-line programming. This flexibility aspect, according to Genest, would ensure maximum utilization of the CMM by giving the operator the ability to perform part programming while the machine is involved in inspection activities. Another user flexibility need offered by Denomme (1988) was the ability of CMMs to be used in reverse engineering applications. He stated that the role of CMMs is quickly expanding beyond simple data documentation. As a result, the use of CMMs in reverse engineering applications will open up new areas of application in many various fields of science and engineering. The benefits associated with CMM-based reverse engineering, according to Denomme, include, "dramatic reductions in inspection time and cost for accumulating part profile data, higher accuracy in the data accumulated, and the ability to easily manipulate that data or apply them to differing material design principles" (p. Q-22).

Another factor making CMMs easier to use is the increase of application-specific software packages. These programs, according to Stevens (1991), reduce the need for programming each shape as is required in many general-purpose measurement packages. As a result, new CMM software has been developed that uses symbols keys, icons, and menus in place of complicated computer syntax. Stevens expects that future CMM interfacing will eventually incorporate the use of touch screens, natural language, and voice recognition systems.

Networking Capabilities

The ability to communicate with other computer software programs is an important concern for flexible inspection systems, regardless if they are CMM-based or not. If FMS is ever going to become a reality, real-time information exchange is needed between all levels of the organization including gaging instruments and machine processes. One area of FIS development that has been given increased importance is metrology networking. Campbell (1988) emphasized that the several goals exist within the area of metrology networking. These goals include aspects such as providing measurement feedback to maintain part quality, increasing throughput, making measurement easier, improving gage performance, and maintaining a record for process improvement. Networking systems, in general, and specifically metrology networks provide interfacing capabilities between measuring gages, desktop computers, and the central computer. The main role of the central computer in networked systems is that of network server. Data that are stored in the server are accessible from any station on the network.

With regards to the integration of CMMs into metrology networks and network supported FIS, a study of CMM specifications and cost issues by Lavole (1989), provided the following conclusions:

> In sum, there are no nice, pat formulas for determining which CMM to buy. Nor is there a simple way to prioritize machine characteristics, since these too depend on the individual's application. Buying a CMM machine is a very personal, company-specific decision, the ramifications of which can go far beyond the initial purchase price. However, taking the time to evaluate company needs can dramatically reduce the risk of making a wrong buying decision. (p. 70)

Operational Variability Reductions

The changes that are occurring in the manufacturing environment due to FMS and FIS requirements are driving the CMMs out of the QC labs and onto the shop floor. A major implication associated with this movement is that CMMs will be expected to operate in inspection schemes that require increased speed. They may also be expected to operate under conditions that can inject variability into the measurement process. Due to these concerns, CMM manufacturers are actively pursuing several different methods which can be used to ensure that CMMs employed in the shop floor applications possess similar degrees of stability and reliability that are found with CMMs located in QC labs.

The areas that are currently receiving attention by those concerned with shop floor stability and reliability are environmental factors, the CMM, methods and procedures, materials, and the CMM operator.

Environmental Factors

The environment surrounding the CMM is an important concern in the effort to reduce measurement variability. This variable is composed of several different factors such as temperature variations, dirt and dust, and vibrations. While it is possible to minimize the effects of these factors through careful environmental design and software enhancements, they remain, according to Lavole (1989), the ultimate limit to accuracy and the most expensive elements to control. As a result, purchasers of CMMs must realistically assess their needs in terms of the parts the machine will be inspecting and the environmental conditions the machine will be required to operate under. To overcome the influences presented by temperature changes and dirt and dust-filled environments, Gazdag (1988) suggested three basic approaches: enclosures, error compensating software, and CMM constructed with materials that have thermal stability.

Enclosures. According to Koelsch (1992), temperature change is the biggest enemy of accuracy since it possesses the ability to distort machine components and the measured part. To overcome the variability caused by temperature changes, some users have decided to sheltered their CMMs from temperature changes by surrounding them with environmental enclosures. Most of these enclosures incorporate internal air pressure controls to maintain a constant air flow from the enclosure, thus prevent preventing dirt, dust, and oil from collecting on the machine.

Error compensating software. Gazdag (1988), on the other hand, suggested that a less expensive approach in neutralizing the effects of temperature change is to "tune out" the environment by using temperature sensors and temperature compensating software. One drawback of current temperature compensating software noted by Stevens (1991) is its inability to effectively deal with temperature changes are too rapid or fall outside of established limits (normally 60 to 90 degrees).

Thermally stable materials. Deller (1988) stated that the most effective approach in neutralizing the effects of temperature change is to construct CMMs with materials that are harder, more thermally stable, and impervious to deterioration and water absorption. The materials presently being used on thermally sensitive areas of CMMs include granite, aluminum, and ceramics.

Vibration is another environmental factor that needs to be addressed when variability reductions are being considered. According to the ASME B89.1.12M-1990, *Methods for Performance Evaluation of Coordinate Measuring Machines*, it is the user's responsibility to provide not only an acceptable environment for on-site performance testing of the CMM but also to conduct all environmental tests at the site of installation. Since the nature of floor vibrations are constantly changing and a vibration analysis is only valid for the "window of time" in which the measurements are recorded, Hegarty (1991) recommends the selection of the worst case scenario for vibration analysis and evaluation. Hegarty went on to state that a properly designed vibration isolation system can be critical in ensuring expected CMM performance. Knowing what natural frequency and damping rates are needed to bring vibration levels to acceptable limits is only half the battle. The other half of the battle is designing a vibration damping system that is compatible with the CMM design. In addition to the previously mentioned factors, other environmental factors need to be monitored and closely controlled to reduce measurement variability. These additional factors, according to Hobson and Majlak (1987), include barometric pressure, humidity, gaseous and particulates, lighting, and seismic activity.

The CMM

An essential requirement for on-line operation is high throughput. In this regard, CMMs need to possess the capability to keep pace with high production rates. Driving conventional CMMs at higher speeds to meet throughput requirements adversely affects measuring accuracy. To achieve high accuracy at faster operating speeds, it is necessary to construct CMMs with exceptional stiffness and damping characteristics. Fix (1988) stated that greater stiffness and damping capabilities will not only help the CMM to withstand the forces of acceleration and deceleration but also provide it with quicker stabilization. The design characteristics that have an influence on speed of operation and measurement variability are:

1. High stiffness-to-weight structure
2. Material symmetry
3. Workpiece mass/table design
4. Bridge design
5. Machine drive
6. System architecture
7. Accuracy

Since these factors are established during the design and construction of the CMM, any measurement variability due to these factors need to be addressed by the manufacturer of the CMM.

Methods and Procedures

Variations in the methods and procedures used during setup and operation have an influence on measurement variability. Although there are a number of concerns that should be addressed, two areas that should receive initial consideration for procedural standardization are calibration and fixturing.

Calibration. Ford (1992) stated that calibration can be defined as "the comparison of a piece of a equipment with an unknown accuracy to a measurement standard of known accuracy" (p. 73). Ford stated further that calibration serves two vital functions. One, it is used to determine the difference, or amount of error, between unknown and known readings. Two, it is used to adjust the output of the measured equipment to bring it to a desired value. Proper calibration not only helps to keep materials and products within specification but also helps to reduce the cost associated with errors, scrap, and rework. Consequently, the procedures used to perform machine and probe calibrations as well as the time frames between calibrations are important aspects in variability reduction.

Fixturing. Cole (1989), on the other hand, suggested that the right fixturing method is an essential element for the control of measurement variability. For example, the force applied during clamp fixturing can cause distortions in the part being inspected. These distortions can influence gage repeatability. An addition problem associated with clamp fixtures is lengthy setup and increased inspection times. To eliminate the problems associated with clamp-based fixturing, universal fixturing systems have been developed to hold parts firmly in position without part distortion. An added advantage associated with these vacuum-based systems is unrestricted probe path movement. Additional support for universal fixturing was provided by Ray (1992) in which he stated that "a better solution would be a universal fixture that uses controlled force to avoid clamping distortion, enables faster and more flexible setups, and puts the CNC CMM's capabilities to better use" (p. 23).

Materials

Another area that has been given consideration for variability reduction pertains to the characteristics of the workpiece being measured. Lavole (1989) depicted this variable as one of the largest sources of CMM error because it involves variations in the measured workpiece that have an influence on the repeatability of measurements. Workpiece characteristics that should be given consideration in this area include: surface finish, roughness, straightness, roundness, and parallelism.

CMM Operator

According to Ray (1992), CMM programmers can contribute, next to fixturing, the most to measurement variability. In his opinion, CMM programmers (operators) need to possess measurement and computer background as well as familiarity with the fit and function requirements of the parts being measured. An additional area of concern for variability reduction is operator training. In this regard, companies that employ CMM programmers (operators) must be willing to supply the necessary training. Lavole (1989) suggested that CMM training should be concentrated in four areas: part programming, machine operations, blueprint interpretations, and preventive maintenance procedures.

One operator/software area that needs to be given greater emphasis during training is the potential influence operators can have on gage repeatability due to the programming methodology he or she uses to measure various features; one such example is circular measurement. In the case of circular measurement, the majority of DCC/CMMs possess the capability to measure circular features with a multitude of probe hit options, usually somewhere between 3 to 50 and 3 to 100. Consequently, time and cost constraints placed on the inspection process by the manufacturing environment influence not only the selection of a particular probe hit measurement pattern but also gage repeatability as well.

Performance Testing and Evaluation

In a recent study of first-time CMM buyers, Lavoie (1989) reported that:

> Many were disappointed with their purchases. Reasons varied and were not focused on any particular manufacturer but on overall performance. Some buyers felt they had not gotten the level of accuracy they required, others that they had paid for accuracy they didn't need. Some felt their machines were too slow, that they required too much time to program and set up, that they were too complicated to operate, or that their software was too limited for their application. In none of these cases, however, did the machine fail to meet advertised specification. Instead, they failed to meet their new owner's expectations. And the bottom line, the study showed, was that, despite all the investigations, analysis, and discussion that went into the purchase of such high-ticket items as CMMs, many buyers simply did not understand what they were buying. (p. 67)

Lavole further reported that one of the biggest problem people have in purchasing CMMs is a lack of understand of the terminologies used to define CMM specifications. Although most buyers of CMMs are engineers and possess a basic understanding of technical terminology, few are well versed in the subtle differences in metrological terms surrounding CMM terminology. According to Lavole, three terms were particularly troublesome. One was resolution--the finest incremental reading of an instrument; the second was repeatability--the ability of the machine to duplicate identical measurements; and the third was accuracy--the expected error from known standards. While resolution and repeatability are important components of accuracy, they are not indicators of it.

According to Busch (1989), a good analogy of the relationship between these three terms can be seen in rifle shots at a bull's eye target. If a person fires six shots and gets a tight cluster of hits in the upper right, the shooter has good precision, but does not have accuracy. On the other hand, if the entire cluster is tightly packed and located in the bull's eye, the shooter has both precision and accuracy. Increasing the number of rings around the target increases the resolution of the target, but has no effect on the shooter's basic marksmanship. A useful illustration that demonstrates the relationship between precision and accuracy and reinforces the previous statements can be seen in Figure 3.

Performance Testing Methods

Coordinate measuring machines are becoming a mainstay in many manufacturing environments. Companies both large and small have used them for inspection to the point of unquestioned reliance. This unquestioned reliance, according to Watts and Prout (1991), is often expressed by users through the following statement: "It must be right, I checked it on the CMM" (p. 25).

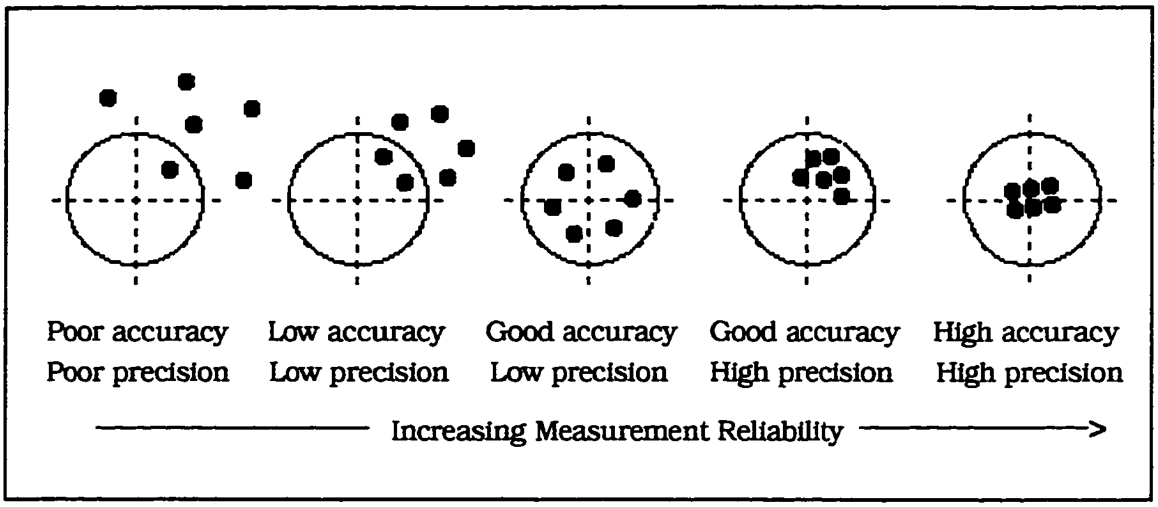


Figure 3. The relationship between precision and accuracy. Note. From Fundamentals of Dimensional Metrology (p. 18), by Ted Busch, 1989, Albany, New York: Delmar Publishing Inc. Copyright 1989 by Delmar Publishing Inc. Adapted with permission.

Even though CMM data is relied on for the acceptance and rejection of various products, many users have no formal method of checking the validity of their CMM data other than annual or semi-annual evaluations by the CMM manufacturer. The failure to establish formal in-house monitoring practices could be attributed to a lack of understanding of the performance testing methods currently used to evaluate CMMs. Although the authors of ASME B89.1.12M-1990 list several methods for CMM performance testing, Lavole (1989), simplified the process by stating it in terms of three basic components: linear displacement accuracy, volumetric accuracy, and repeatability.

Linear Displacement Accuracy

The measurement of linear displacement accuracy is conducted on all three axes, using either either a step gage or a laser interferometer. The purpose of this test is to assess the conformance of the machine scales to the international standards of length. When the test is performed using a step gage, the measurement line must be along three orthogonal lines through the center of the working envelope parallel to the three axis directions. When the test is performed using a laser interferometer, attention needs to be given to alignment such that cosine error is less than 10% of the working tolerance of the axis under test. According to the authors of ASME B89.1.12M-1990,

> Linear displacement accuracy for a given axis at a step position shall be the difference between step gage calibration and the mean corrected machine reading for that position. Displacement accuracy is determined by taking the difference between the step gage calibration and the mean corrected machine reading at each step, and then determining the maximum displacement error from any point to any other point in the full travel. This is equivalent to determining the maximum range of the mean differences. (p. 27)

When the laser interferometer is used instead of the step gage, the displacement accuracy is calculated by determining the maximum spread of the mean difference of the individual points. Of the three performance tests, Lavole (1989), considered linearity one of the weakest measure of performance since only 3 of the 21 machine motion variables are linear. Variables such as straightness and perpendicularity (squareness), which are considered critical to overall accuracy, do not normally show up in linear performance tests.

Volumetric Accuracy

According to Lavole (1989), volumetric accuracy is probably the best all around test of CMM accuracy. In this test, commonly called a ball bar test, the length of a metal rod equipped with precision balls at either end is measured by the CMM at various positions within the working envelope. The manner in which the ball bar test is conducted is dependent on the design characteristics of the CMM. When the working area of the CMM is cubic in shape (1:1:1), the ball bar is measured in 20 different positions. When the CMM possesses a single long axis and two smaller axes (2:1:1), the ball bar is measured in 30 different positions. When the CMM has two long axes and one short axis (2:2:1), the ball bar is measured in 35 different positions.

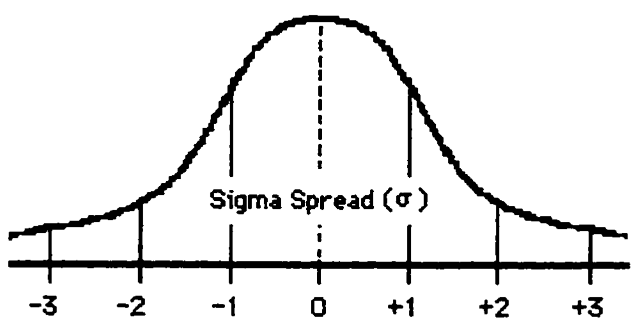
After the position number is determined and the measurements have been taken, the data from the ball bar measurements are analyzed by preparing a simple plot or table of the deviation in the ball bar length without regard to measurement location. From this plot or table, the working tolerance of the CMM is determined by the range of data in the plot or the total range in the values in the table.

Gage Repeatability and Reproducibility

Gage Repeatability and Reproducibility (Gage R&R) is a widely used method for assessing gage stability and operator differences. In a Gage R&R analysis several different methods can be employed. According to the authors of Measurement Systems Analysis (1985), the appropriateness of a particular method is initially based on whether one or more operators are involved in the study. When one operator is involved in the study, the variability the operator brings into the system is considered part of the equipment variability. This variability is reported along with the other gage variability factors as one value, repeatability. Consequently, total measurement error (T.M.E.) in single operator gage studies is equal to repeatability. When two or more operators are involved in the gage study, the measurement error is broken down into two separate components: repeatability, or equipment variability (E.V.) and reproducibility, or appraiser variability (A.V.). Once calculated, these two components are combined using the *least square method* and reported as total measurement error [T.M.E. = $\sqrt{(E.V.^2 + A.V.^2)}$]. With the advent of electronic and computer-controlled gaging systems, Gage R&R is gradually being reduced to Gage R (Gage Repeatability).

Repeatability (E.V.) is a widely used measure of machine and gage performance. Its primary purpose is to indicate inherent variability within the equipment. In short, it is an indicator of the amount of random error inherent within the gaging system. ASME Report No. B89.1.12M-1990, *Methods for Performance Evaluation of Coordinate Measuring Machines*, described repeatability as "a measure of the ability of an instrument to produce the same indication (or measured value) when sequentially sensing the same quantity under similar measurement conditions" (p. 10). According to the authors of the B89.1.12M-1990 report, repeatability tests should be structured to evaluate the complete system including the effects caused by machine characteristics, operators, and computer algorithms. They also suggested that repeatability performance tests should be performed in a manner that closely represents the way in which the gage is normally used. In contrast to the B89 standard, Ray (1992) described repeatability as measurement variation resulting from limitations in accuracy, gaging environments, data collection methods, fixturing methods, and software measurement programs. His use of repeatability analysis has led to a new and innovative approach to part fixturing for CMMs. The significance of repeatability analysis was indicated by Lavole (1989) when he stated that: "you can have good repeatability without good accuracy, but you cannot have good accuracy unless you also have good repeatability" (p. 68).

In quantitative-based measurement processes precision and repeatability go hand in hand, precision being the standard deviation of the measurement error ($\sigma_{E.V.}$) and repeatability being the extent or spread of measurement variability (error) that can be expected within a specified level of confidence. Some of the most widely recognized sigma spreads (σ) and respective levels of confidence are shown in Figure 4.



Confidence Levels	Sigma Spreads	SD (σ)
90.00%	3.29	± 1.644
95.00%	3.92	± 1.960
99.00%	5.15	± 2.575
99.73%	6.00	± 3.000

Figure 4. Confidence levels and sigma spreads.

In short, the methods used to determine gage repeatability are dependent on three factors:

1. The number of sample measurements to be collected and analyzed during each measurement routine.

2. A single operator study versus a multiple operator study.

3. The use of an automated, computer-controlled gaging instrument versus a manually operated instrument (e.g., a coordinate measuring machine versus a vernier caliper).

Reproducibility (A.V.) is the measurement variability due to the effect of different operators using the same equipment. It, along with accuracy, are the principal generators of systematic error. In the past, manually-operated gaging instruments were extensively used to gage parts. Gaging processes that utilized these instruments were subjected to measurement variability resulting from differences in the "feel" of each individual operator. As more electronic and computer-controlled gaging systems find their way into manufacturing environments, the measurement variability individual operators bring into gaging activities will gradually be eliminated.

Single Operator Repeatability Assessment

Within the single operator category four methods for repeatability testing were identified: the ASME B89 Range Method, the Standard Deviation Method, the British BS6808 Method, and the CMMA Standard. The first two methods, the ASME B89 Range Method and the Standard Deviation Method, are the most commonly used methods in the U.S. while the British BS6808 Method and the CMMA Standard are primarily used in England and other European countries.

ASME B89 Range Method

Throughout ASME B89.1.12M-1990, the concept of range is used extensively as the measure of machine performance. In this method 10 measurement samples are taken and the range or spread between the largest and smallest value is calculated. Once calculated, the range value is reported as repeatability. This method of repeatability testing was chosen by ASME because they concluded that "the dominant errors in coordinate measuring machines are not random but rather systematic. In such cases, no generally accepted statistical procedures currently exist" (p. 2).

In reporting repeatability, the authors of ASME B89.1.12M-1990 stated that either the largest range in coordinate values measured or the range in coordinate values on a per axis basis should be used. They also indicated that in the event an outlier is obtained, the point cannot be discarded; rather the test and subsequent range evaluation must be repeated. Algebraically, the procedures involved in the analysis of total measurement error (TME) are:

1. Range (R) = $\underline{X}_{largest}$ - $\underline{X}_{smallest}$.
2. Repeatability = Range.
3. Total Measurement Error (TME) = Repeatability.

Standard Deviation Method

The determination of standard deviation, according to Gravetter & Wallnau (1991), is the most widely used and most important measure of variability. As a measure of variability, the general purpose of the standard deviation value is to describe the extent to which a set of scores is spread out or clustered together. Gravetter and Wallnau stated further that:

> If a sample comes from a population with low variability, you can be reasonably confident that the sample provides a good representation of the general population. But when the standard deviation is large, extreme samples are possible, and any single sample may not accurately reflect the population. (p. 95)

In the standard deviation method five or more measurements are collected from the gaging instrument. Once calculated, the standard deviation value is multiplied by a selected sigma spread and reported as repeatability. The use of this formula in repeatability analysis was supported by Griffith (1989), Groover (1987), and Shay (1988). Algebraically, the procedures involved in the analysis of TME are:

1. SD of Measurement Error (M.E.) = $\sqrt{[\Sigma(\underline{X}_i - \underline{M}_{sample})^2 / \underline{n} - 1]}$.
2. Repeatability = (Sigma Spread) x (SD of M.E.).
3. Total Measurement Error (TME) = Repeatability.

The sigma range or confidence level associated with the determination of repeatability can vary depending on the manufacturer's reporting methods. The confidence levels associated with the most common sigma spreads can be seen in Table 2.

One approach recommended by the authors of the British BS6808 standard with respect to the assessment of unidirectional repeatability is to calculate the standard deviation values from ten repeated measurements on each CMM axis. The repeatability of each axis is calculated by multiplying the respective standard deviation value by 0.72. The largest recorded standard deviation value is CMM unidirectional repeatability.

Table 2

Widely-Used Confidence Level and Sigma Spreads

Confidence Interval	Sigma Spreads	Standard Deviation
68.26%	2.00	± 1.00
90.00%	3.29	± 1.64
95.00%	3.92	± 1.96
95.44%	4.00	± 2.00
99.00%	5.15	± 2.58
99.73%	6.00	± 3.00

Multi-Operator Repeatability Assessment

Within the multi-operator category, three methods for the determination of total measurement error (TME) were identified. These methods, as identified by Electronic Data System (EDS) in their manual *Measurement Systems Analysis* (1985), are range, the average and range, and analysis of variance (ANOVA). In the first two methods the range value is used as the primary means for calculating TME. According to Griffith (1989), the use of range as an estimator of population standard deviation is biased unless multiplied by the factor $(1/d_2)$ appropriate to the sample size. Griffith also reported that ". . . because the range tends to be inefficient, it is not recommended that ranges be used for large sample sizes. A rule of thumb suggests a maximum sample size of 10" (p. 154). The suggestion to limit the sample size to 10 when using the range as an estimator of population standard deviation was also supported by the authors of *Measurement Systems Analysis*

(1985). The following is an analysis of the three methods that are currently used to perform multi-operator repeatability assessment.

Range Method

According to the authors of *Measurement Systems Analysis* (1985), this method is a modified variable gage study that provides a quick, approximation of the total measurement variability. It does not, however, decompose the total variability into the separate repeatability and reproducibility components. Both the authors of *Measurement Systems Analysis* (1985) and Griffith (1989) reported that the range method uses two operators and a minimum of five parts (test specimens) for the study. In this method both operators measure each part once. The difference between the individual readings of the two operators is recorded. Once the range values for each part category have been determined, the sum of the ranges is determined and an average range (R-bar) is calculated. The total measurement error (TME) in the gaging system is determined by multiplying the average range (R-bar) by 5.15 $\underline{z}$ score. This $\underline{z}$ score value is equal to 99% of the area under the normal curve. Algebraically, the procedures involved in this analysis of total measurement error are:

1. Average Range = $\Sigma \underline{R}_i / \underline{n}$ where Range (R) = $\underline{X}_{largest} - \underline{X}_{smallest}$.
2. Appraiser/Equipment Variability = 5.15 (Average Range).
3. Total Measurement Error = Appraiser/Equipment Variability.

This method for the reporting of TME can also be used in the assessment of process capability. Once the TME has been determined, an assessment of the percent of tolerance consumed by the total measurement error can be calculated. This assessment, commonly termed Potential MPC Study

(Measuring Process Capability), is performed by dividing the total measurement error (TME) by the total part tolerance and multiplying the value by 100. Algebraically, the additional step for the calculation of process capability is: %MPC = 100 (TME / Total Tolerance).

In evaluating the %MPC, the authors of *Measurement Systems Analysis* (1985) and Griffith (1989) had different criterion. In the *Measurement Systems Analysis*, the general guideline to follow is, if the percentage of total measurement error is less than or equal to 20% of the specified tolerance, the measurement system is considered acceptable; if it is greater than 20% than improvement is needed in the gaging system. Griffith, on the other hand, stated that if the MPC is 10% or less the capability is acceptable, if 10% to 25% the capability is marginal, and if greater than 25% the capability is unacceptable.

Average and Range Method

This method, unlike the range method, allows the total measurement error to be decomposed into two separate components, repeatability and reproducibility. According to the authors of *Measurement Systems Analysis* (1985), if reproducibility is larger in comparison to repeatability, operator training in using and reading the gage is needed or calibrations of the gage should be more clearly defined. If, on the other hand, repeatability is large in comparison to reproducibility, the following symptoms are indicated: (a) the need for gage maintenance, (b) the gage may be inherently unstable and needs redesigned, (c) the fixturing methods need to be improved, or (d) part variations may be usually large. According to the authors of *Measurement Systems Analysis* (1985) and Griffith (1989), the test parameters used in this method, operators (x), parts (g), and trials (m), may vary, but usually involve 3 operators, 10 parts, and 3 trials. In this method the operators measure each part once. Once the first trial is taken, the measuring cycle is repeated until the desired number of trials are completed.

Once the data are collected, range values for each part category for each operator are calculated. These ranges values are summed for each operator and an average range is calculated. The next step in the process is to sum the various average range values and calculate the grand range value, commonly referred to as R-double bar. In addition to the calculation of the grand range, the measurements for each operator are summed and the mean for each operator is calculated. After the grand range and mean values have been determined, the standard deviation of repeatability is calculated by dividing the grand range by the $\underline{d}_2$ constant, a constant determined from Table M of *Quality Control and Industrial Statistics* (1965). The value used as the $\underline{d}_2$ constant varies depending on the sample size selected (see Table 3). References to the $\underline{d}_2$ constants as well as other commonly used constants can be found in various statistical and process control reference books.

After the standard deviation of repeatability has been calculated, the standard deviation of reproducibility is calculated by subtracting the largest mean from the smallest mean and dividing the difference by the $\underline{d}_2$ constant. The total measurement error in the gaging system is then determined by multiplying the square root of the sum of the squares of the standard deviations of the repeatability and reproducibility by the desired sigma spread. Algebraically, the procedures involved in the calculation of total measurement error or Gage R&R are:

1. Range (each operator, each part) = $\underline{X}_{largest} - \underline{X}_{smallest}$.
2. Average Range for each operator = Σ Range / $\underline{n}$.

3. Average Range for all ranges (R-double bar) = Σ Average Range / $\underline{n}$.
4. Average measurement (each operator) = $\Sigma \underline{X}_i$ / $\underline{n}$.
5. $\underline{SD}$ of Repeatability (E.V.) = R-double bar / $\underline{d}_2$.
6. $\underline{SD}$ of Reproducibility (A.V.) = ($\underline{M}_{max}$ - $\underline{M}_{min}$) / $\underline{d}_2$.
7. TME = $\sqrt{[\,(\underline{SD} \text{ of E.V.})^2 + (\underline{SD} \text{ of A.V.})^2\,]}$ x (Sigma Spread).

Table 3

Sample Size Constants for Range-Based SD Estimation

Sample Size	d_2	Sample Size	d_2
2	1.128	14	3.407
3	1.693	15	3.472
4	2.059	16	3.532
5	2.236	17	3.588
6	2.534	18	3.640
7	2.704	19	3.689
8	2.847	20	3.735
9	2.970	21	3.778
10	3.078	22	3.819
11	3.173	23	3.858
12	3.258	24	3.895
13	3.336	25	3.931

As with the Range Method, the total measurement error that is calculated using this method can also be used to assess process capability (%MPC). The procedures and evaluation criterion used in this calculation are identical to the ones described in Range Method.

Analysis of Variance

In this method, the measurement variation is decomposed into four components: parts, operator, operator X part interaction, and gage error. According to the authors of *Measurement Systems Analysis* (1985), the major difference between this method and the average and range method is (a) the manner in which the individual standard deviations are calculated, (b) the addition of the standard deviations for the part to part and operator X part interactions, and (c) the data collection method. The authors of *Measurement Systems Analysis* also stated that the data must be collected in a random manner to prevent the absorption of bias error into the data. One way to assure a balanced design is to randomize the measuring order of the parts (n), the operators (k), and the number of trials (r) that are used in the gage study. After the data are collected in a randomized fashion, the analysis of the data takes place by calculating the values for the following categories:

Source	SS		df		MS	f
Operator	SSO	÷	k-1	=	MSO	MSO/MSE
Parts	SSP	÷	n-1	=	MSP	MSP/MSE
Oper X Part	SSOP	÷	(n-1)(k-1)	=	MSOP	MSOP/MSE
Gage (Error)	SSE	÷	nk(r-1)	=	MSE	
Total	TSS		nkr - 1			

Where:

k = number of operators involved in study

n = number of part measurements per operator

r = total number of trials

SSO = sum of the squares operator

SSP = sum of the squares part

SSOP = sum of the squares operator and part

SSE = sum of the squares error

MSO = mean square operator

MSP = mean square part

MSOP = mean square operator and part

MSE = mean square error

The analysis of the interaction between the operator x part and gage (error) results in an F ratio value. If the operator x part variability is greater than the gage (error) variability within the different groups, a large F ratio will result. If the reverse is true, a small F ratio will result.

The next step in the analysis is the determination of the alpha level or confidence level that will be used and the established operator x part and gage (error) degrees of freedom. Once this is accomplished, the critical value is determined. According to the authors of *Measurement Systems Analysis* (1985), ". . . a significance level of $\alpha = .25$, has been decided on because of the decreased risk of concluding the interaction term is not significant" (p. 37). With an alpha level of 0.25 and the degrees of freedom associated with the operator x part variability and the gage error, the location of the critical value within the F distribution is determined.

Once the critical value location has been established, the location of the calculated F ratio (MSOP/MSE) with respect to the critical value is used to determine the significance of the operator x part interaction. The determination as to whether the interaction is or is not significant has a direct bearing on the procedures that are used to determine repeatability, reproducibility, and total measurement error. A pictorial representation of the F distribution of the referenced values can be seen in Figure 5.

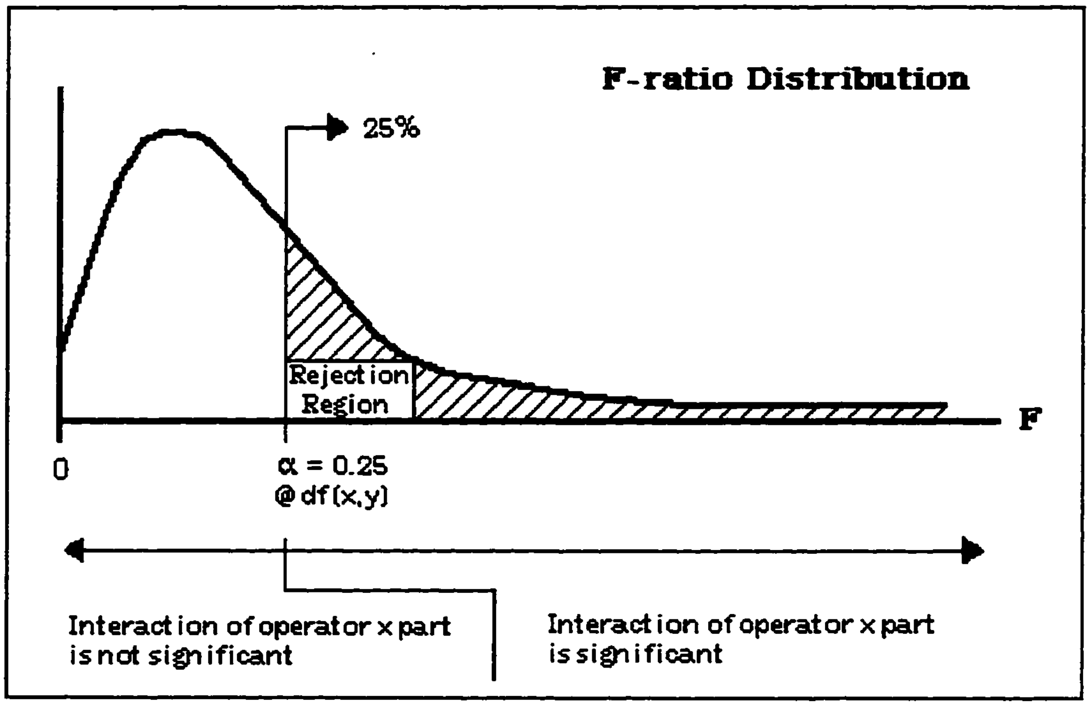


Figure 5. Operator x part interaction analysis.

If the F ratio is larger than the critical value, the interaction of operator x part is deemed significant. In such cases, the following procedures are used to determine repeatability, reproducibility, and total measurement error:

SOURCES		VARIANCE ESTIMATE
Gage	=	MSE
Interaction	=	(MSOP - MSE) / r
Operator	=	(MSO - MSOP) / nr

COMPONENTS		5.15 SIGMA SPREAD
Repeatability (E.V.)	=	$5.15\sqrt{MSE}$
Reproducibility (A.V.)	=	$5.15\sqrt{((MSOP - MSE) / r) + ((MSO - MSOP) / nr)}$
TME or Gage R&R	=	$5.15\sqrt{MSE + ((MSOP - MSE) / nr)}$

If the reverse is true and the F ratio is smaller than the critical value, the interaction of operator x part is deemed not significant. In such cases, the following procedures are used to determine repeatability, reproducibility, and total measurement error:

SOURCES		VARIANCE ESTIMATE
Gage	=	MSpool = (SSPO + SSE) / (nkr) - (n + k) + 1
Operator	=	(MSO - MSpool) / nr

COMPONENTS		5.15 SIGMA SPREAD
Repeatability (E.V.)	=	$5.15\sqrt{MSpool}$
Reproducibility (A.V.)	=	$5.15\sqrt{(MSO - MSpool) / nr}$
TME or Gage R&R	=	$5.15\sqrt{MSpool + ((MSO - MSpool) / nr)}$

As with the range method and average and range method, the total measurement error that is calculated using this method can also be used to assess the process capability (%MPC). The procedures and evaluation criterion used in this assessment are identical to the ones described under the Range section.

Overview of the 1993 CMM Repeatability Study

The 1993 study was initiated to determine: (a) the effects of diameter and probe hit variations on gage repeatability and (b) if an alternate inspection methodology based on single baseline repeatability assessment and optimization could yield significant improvements in gage repeatability. To analyze the effects of diameter and probe hit variations on diameter measurement repeatability, the following methodological components were used:

1. A Brown and Sharpe Xcel 7•6•5 CMM equipped with a multi-positional touch trigger probe head and a 2 mm ruby-tipped stylus.

2. Twenty-three circular test specimens ranging in diameter from 0.25 inches to 5.75 inches at 0.25 inch increments. These test specimens were machined on four 12 x 12 x 1 inch aluminum plates.

3. Eight inspection routines utilizing 3 to 10 probe hits. Within the context of this text, these eight inspection routines are referenced as *probe hit categories* in a plural tense and *<number> pt. category* in a singular tense (example: 3 pt. category).

4. Twenty-five diameter measurements collected from each test specimen within each of the stated probe hit categories.

5. The assessment of diameter and probe hit repeatability using two well known and widely used repeatability assessment methods, the range method identified within the ASME B89 report and the traditional standard deviation method.

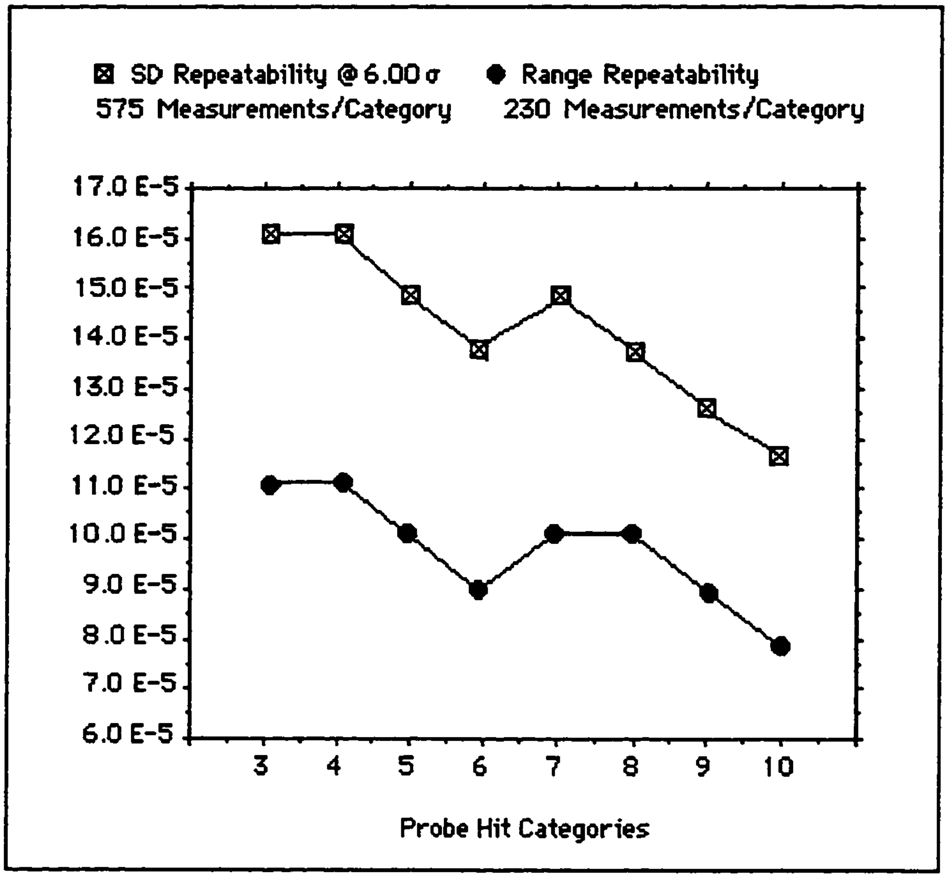
6. The assessment of diameter and probe hit repeatability on the XY plane using the entire XY measuring envelope of the CMM (2 ft x 2 ft).

Research Findings

The 1993 study yielded several results with respect to diameter measurement repeatability. These results along with their respective research questions were:

1. What are the effects of diameter and probe hit variations on gage repeatability? Although it is possible to list all of the individual

repeatability values for each test specimen within each probe hit category, a list of this type is not considered important to the presentation of the research findings. What is important, however, is the identification of the average repeatability values within each probe hit category. A graphic representation of these values can be seen in Figure 6.



<u>Figure 6.</u> 1993 average repeatability results on the XY Plane. From "Performance enhancement of CMMs through feature-based repeatability assessment and optimization," by B. Marsh. In <u>Proceedings for the Annual Quality & Metrology Symposium</u>, 1995, (p. 48). Center for Quality, Measurement, and Automation, Bowling Green State University.

One of the distinct features of this graph is a strong negative correlation between average probe hit repeatability and probe hit variation in both range and standard deviation-based repeatability. This finding was substantiated with an r value of -.8 in range-based repeatability and an r value of -.9 in standard deviation-based repeatability. In short, the correlation analyses indicated that as the number of probe hits in circular measurement is increased gage repeatability numerically decreases (improves). The coefficients of determination (r^2) of these correlations indicate that, depending on the repeatability method used, 64 to 81 percent of the variability in diameter measurement repeatability within the tested probe hit categories is attributable to probe hit differences.

2. Can an alternate inspection methodology based on repeatability optimization yield significant improvements in gage repeatability? The average repeatability values furnished by the two optimization programs indicated that significant improvements in repeatability beyond that of the probe hit category with the "best" average repeatability, the 10 pt. category, could not be obtained using repeatability optimization (see Table 4). A graphic representation of the results of the two optimization programs in comparison with their respective probe hit ranges can be seen in Figures 7 and 8. Further analysis of these results indicated that repeatability values from the two optimization programs differed from their baseline counterparts in the following three ways: (a) on average, 76% of the repeatability values from the optimization programs indicated, to varying degrees, worse repeatability than their baseline counterparts; (b) on average, 15% of the repeatability values from the optimization programs indicated, to varying degrees, better repeatability

than their baseline counterparts; and (c) on average, 9% of the repeatability values from the optimization programs had very similar results with respect to their baseline counterparts.

Table 4

1993 Average Repeatability Values (x 10^{-5})

Source data	Average range-based repeatability	Average SD-based repeatability
	Baseline categories	
3-pt.	11.0	16.0
4-pt.	11.0	16.0
5-pt.	10.0	15.0
6-pt.	9.0	14.0
7-pt.	10.0	15.0
8-pt.	10.0	14.0
9.pt.	9.0	13.0
10-pt.	8.0	12.0
	Optimization results	
Multi-category (3-10)	8.0	13.0
Multi-category (3-10)	10.0	15.0

Note. All standard deviation-based repeatability values were based on a six sigma spread (6σ) and are expressed in inches (x 10^{-5}).. The mean number of probe hits for M/C (3-10) and (3-6) were nine and five, respectively. From "Performance enhancement of CMMs through feature-based repeatability assessment and optimization," by B. Marsh. In Proceedings for the Annual Quality & Metrology Symposium, 1995, (p. 52). Center for Quality, Measurement, and Automation, Bowling Green State University.

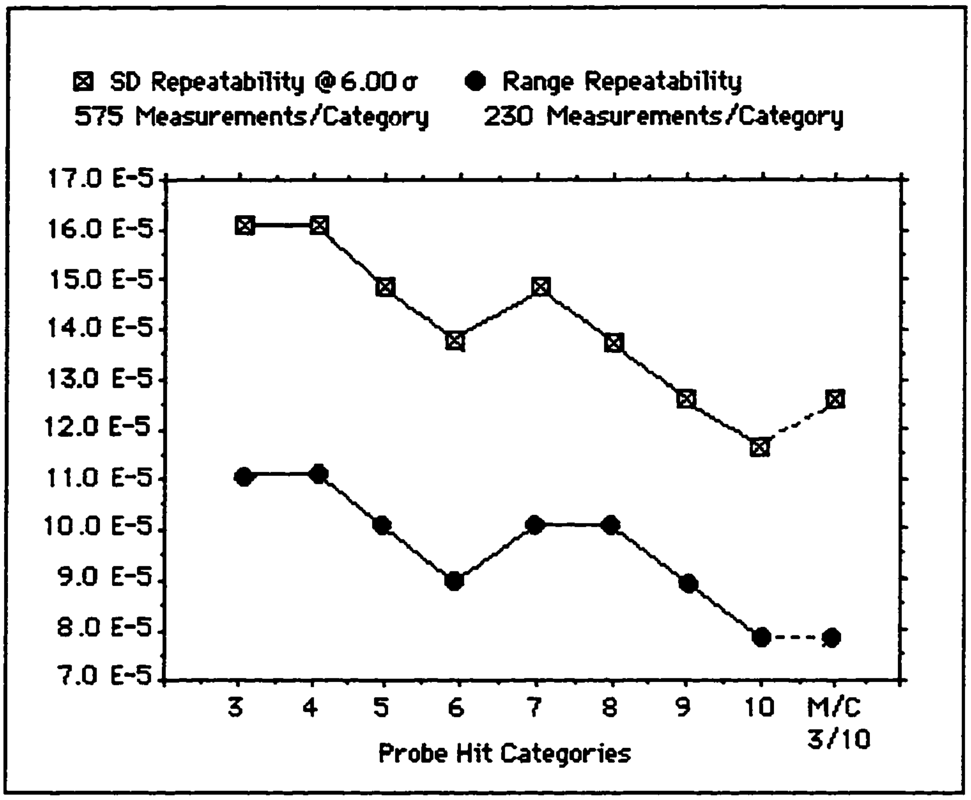


Figure 7. 1993 M/C(3-10) repeatability optimization results. From "Performance enhancement of CMMs through feature-based repeatability assessment and optimization," by B. Marsh. In Proceedings for the Annual Quality & Metrology Symposium, 1995, (p. 50). Center for Quality, Measurement, and Automation, Bowling Green State University.

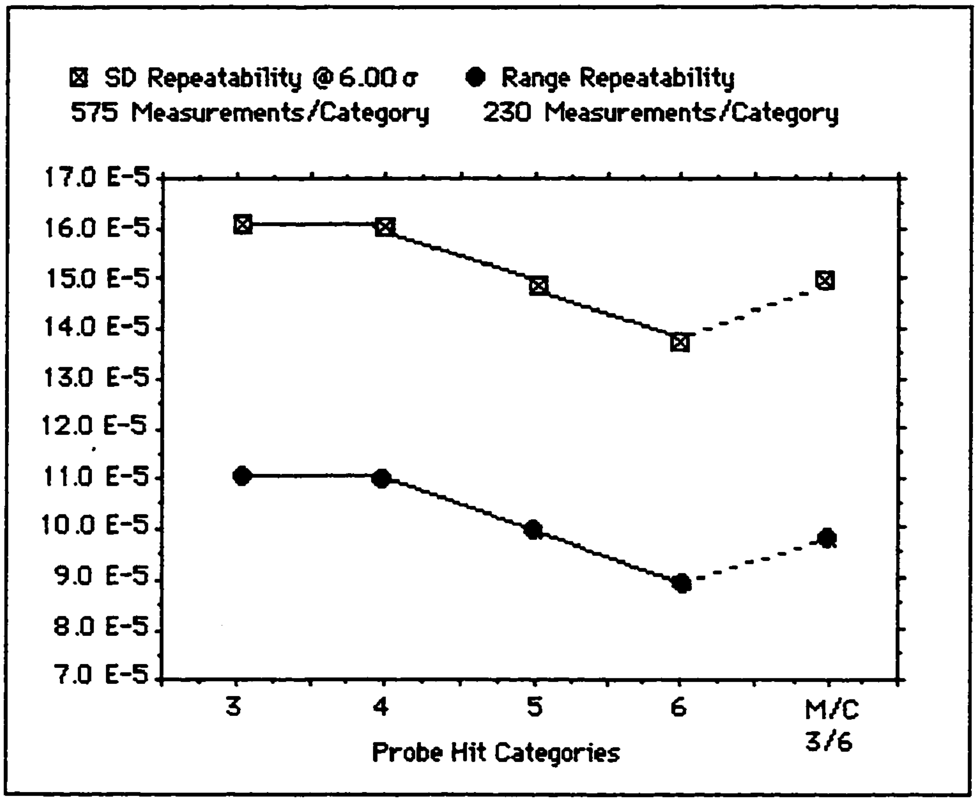


Figure 8. 1993 M/C(3-6) repeatability optimization results. From "Performance enhancement of CMMs through feature-based repeatability assessment and optimization," by B. Marsh. In Proceedings for the Annual Quality & Metrology Symposium, 1995, (p. 51). Center for Quality, Measurement, and Automation, Bowling Green State University.

A more detailed analysis of the repeatability differences between the two optimization programs indicated the occurrence of similar difference values 66 percent of the time. Given this information, it can be concluded that the inability to achieve significant improvement in gage repeatability (improvements beyond that of the "best" probe hit category) using repeatability optimization can be attributed to an inherent instability in the repeatability of certain diameter and probe hit categories.

In addition to a comparison of average repeatability values, mean probe hit values were also determined for both optimization programs. The results of this analysis indicated that the multi-category (3-10) program had a mean probe hit value of nine while the multi-category (3-6) program had a mean probe hit value of five. As shown in Table 4., the average repeatability values of both range- and standard deviation-based repeatability within the 9- and 5-pt. probe hit categories indicated similar results when compared with the results of the multi-category (3-10) and (3-6) programs, respectively.

Conclusions and Recommendations

Based on the findings of this study, several conclusions were formulated. The first conclusion was that diameter measurement repeatability can be significantly improved by increasing the number of data points collected. Unfortunately, manufacturers may be hesitant to employ inspection routines that incorporate greater numbers of probe hits due to time and cost constraints imposed on gaging and inspection activities. However, manufacturers can be confident that increasing the number of probe hits when measuring circular features will yield better gage repeatability. The second conclusion is that improvements in average repeatability may or may not be achieved through the optimization of repeatability. Although various measures were taken to minimize factors that influence measurement variability, the results of this study indicated an inherent instability in repeatability within certain diameter and probe hit categories. It should be noted that this instability may only indicate a machine or software-specific characteristic and not a generalizable characteristic of all similar CMMs.

Using the results of this study, two recommendations were made. First, additional studies are needed on a variety of CMMs and software measurement packages to further investigate the nature of diameter measurement repeatability with respect to probe hit differences. Although this study substantiated *inspection methodology* as a source of measurement variability in CMMs and even explored an alternate inspection methodology to bring it under control, it failed to yield the results needed to validate single baseline repeatability assessment as the appropriate methodology for optimizing diameter measurement repeatability. One positive aspect of this study was that the results of the single baseline repeatability assessment and subsequent optimization programs indicated a direction for further optimization research. In short, further research into diameter measurement repeatability and its optimization should be structured on multi-baseline repeatability assessments. Repeatability optimization based on this approach would compare probe hit repeatability values from two or more single baseline assessments and construct the optimization programs on the probe hit categories that yield the greatest stability in repeatability.

Second, further studies into diameter measurement repeatability and its optimization should be structured to evaluate and compare all three measurement planes (XY, XZ, and YZ). Although this study made significant headway in developing an appropriate methodology for assessing the nature of diameter measurement repeatability, the XY plane upon which the assessments and optimizations were made do not mirror actual measurement activities in industrial settings.

One possible outcome that can be derived from the optimization of diameter measurement repeatability on all three measurement planes is a functional methodology that can be used to assess and monitor the stability of CMMs over time. Another possible outcome is that diameter measurement repeatability, may eventually prove to be a software or machine-specific characteristic much like fingerprints are to people. If this proves to be the case, CMM operators may realize the importance of evaluating their particular machines and software to determine which inspection methodology or measurement software package yields the least measurement variability.

Significance of Other Repeatability Studies

According to Ray (1992), the integration of CMMs into the manufacturing environments can be one of the most economical decisions that could made toward continuous improvement and reduced cost. Ray further stated that "measurement theories and fixturing methods need to be tested by conducting Gage R&R studies to eliminate the elements that cause CMM measurement variations. Neglecting to do so can only result in SPC programs that fail and CMMs being relegated to nothing more than high-tech boat anchors" (p. 24). Ray's investigation of CMMs and Gage R&R techniques also yielded several approaches that can be taken to reduce variability in CMM gaging activities. These approaches or methods include:

1. The selection of a CMM with a higher stated accuracy.
2. The use of a direct computer-controlled (DCC) CMMs over manually-operated CMMs.
3. The use of fixturing devices that eliminate workpiece distortions.

4. The selection of a CMM that possesses flexibility for both contact and noncontact probing systems, as well as the use of an automatic probe changing system.

5. The application of a system that controls or eliminates the environmental effects caused by temperature changes, dirt and dust, and vibrations.

One aspect of variability which Ray did not fully address in his analysis of Gage R&R was the impact an operator can have on repeatability due to his or her programming methodology. The only reference Ray made toward this area of concern was a general suggestion to focus on the methods and features that yielded the least cost but do not compromise quality improvements and customer satisfaction.

One area of investigation where little research has been noted but has direct implications into the operator/programming question is a study into the effects of diameter and probe hit variations on diameter measurement repeatability. One possible reason for the lack of interest or concern in this area could be the general assumption held by many individuals that increasing the number of probe hits automatically increases measurement precision or gage repeatability. This assumption can be carried into the manufacturing arena where time and cost constraints imposed on manufacturers during production limits the use of larger probe hit measurements options, thus leading manufacturers to believe that they are sacrificing greater precision for time and costs reductions. Consequently, investigations into gage repeatability using different programming methodologies would yield important information for CMM users on the degree of gage repeatability lost or gained due to the number of probe hit used during measurement collection.

In addition to finding out the extent of gage repeatability lost or gained by probe hits variations, another important reason for an investigation of diameter measurement repeatability is that diameter measurement is a basic measurement process from which other shapes such as cones and cylinders are derived. Another way of perceiving the importance attached the circle is that the circle is the simplest of all closed curves and its use in art, architecture, construction, and manufacturing is almost unlimited. Consequently, any knowledge gained through an investigation of diameter measurement repeatability can have important implications on the number of probe hits that should be used to determine other circular-based features.

Chapter Summary

The chapter examined the literature relevant to coordinate measuring machines (CMM), their integration into manufacturing, and the performance testing methods that are used to evaluate them. The first section provided an historic overview of CMMs and described their roles in quality and productivity improvements. The second section focused on CMM design and operational considerations and their linkage with flexible inspection systems (FIS). The third section identified the various performance testing methods that can be used to evaluate CMMs. The fourth and final section gave an overview of the procedures, findings, conclusions, and recommendations of the 1993 study into diameter measurement repeatability. It also highlighted the significance that has been attributed to other repeatability studies and areas where further research is needed and/or ongoing.

CHAPTER III

METHODOLOGY

This chapter presents an explanation of the methods and procedures that were used to address the problem of the study and related research hypotheses. This chapter is organized with a restatement of the problem followed by the research hypotheses, research design, data collection and analysis, and concluded with the chapter summary.

Restatement of the Problem

The problem of this study was to determine the effects of multi-baseline repeatability assessment on the optimization of planar diameter measurement repeatability using a direct computer-controlled coordinate measuring machine (DCC/CMM), specific diameter test specimens, and different probe hit inspection routines.

Research Hypotheses

Four research hypotheses were formulated to investigate multi-baseline repeatability assessment and its effects on the optimization of diameter measurement repeatability. More specifically, these hypotheses were developed to determine (a) the effectiveness of multi-baseline repeatability data in identifying specific probe hit inspection patterns with inherent stability in repeatability and (b) the effectiveness of multi-baseline repeatability optimization in generating inspection routines that yield improvements in diameter measurement repeatability without significant increases in inspection time and related costs. An additional research aspect that was conducted but not integrated as a research hypothesis was a replication of the single baseline methodology used in the 1993 study. This assessment methodology was included to validate the results of the earlier study as well as clarify differences between the two assessment approaches.

Identification of Research Hypotheses

Although various research hypotheses were developed to investigate diameter measurement repeatability, the data collected from this study yields information on the effectiveness of multi-baseline repeatability analysis as a potential test method/procedure that can be used to identify, assess, and monitor machine-specific characteristics and software differences.

Hypothesis #1

Similarities will be noted in the direction and magnitude of the relationship between average probe hit repeatability and probe hit variations between repeated baseline programs and baseline programs of different planes. Correlational similarities will be deemed significant if:

1a. little or no difference is noted in the direction and magnitude of the relationship between average probe hit repeatability and probe hit variations between repeated baseline programs.

1b. little or no difference is noted in the direction and magnitude of the relationship between average probe hit repeatability and probe hit variations between baseline programs of different planes.

Hypothesis #2

Within each baseline program (XY, XZ, and YZ), at least one probe hit category from each circular test specimen will indicate measurement stability. Measurement stability will be deemed significant if:

2a. little or no difference is noted in the standard deviation values of counterpart test specimens and probe hit categories from repeated baseline programs.

2b. little or no difference is noted in the kurtosis and skewness values of counterpart test specimens and probe hit categories from repeated baseline programs.

2c. little or no difference is noted in the distribution means of counterpart test specimens and probe hit categories from repeated baseline programs.

Hypothesis #3

Within each planar measurement test (XY, XZ, and YZ), improvement in diameter measurement repeatability will be achieved through the assessment and optimization of multi-baseline repeatability data within each planar measurement test (XY, XZ, and YZ). Repeatability improvement will be deemed significant if:

3a. the average repeatability values of the multi-baseline optimization programs, MB(3-10) and MB(3-6), are less than the average repeatability values of all baseline probe hit categories within the stated probe hit ranges and plane.

3b. the time required to complete one measurement pass of each test specimen plate using the MB(3-10) optimization program is less than the time required to complete one measurement pass using the baseline probe hit category with the "best" average probe hit repeatability. The term "best" implies the smallest numeric value. An identical condition will also be noted with the MB(3-6) optimization programs and a given baseline probe hit category using the same probe hit range.

3c. $\underline{t}$ statistic analysis of probe hit repeatability values from the optimization programs and the "best" probe hit categories from counterpart baseline programs will indicate that a reduction in diameter measurement repeatability can be expected from the assessment and optimization of multi-baseline repeatability data with a 95% confidence level.

Hypothesis #4

Differences will be noted in the general structure of each planar optimization program but will not be noted in the calculated average repeatability and mean probe hit values. Structural differences and average repeatability and mean number of probe hit similarities will be deemed significant if:

4a. the time required to complete one measurement pass of all test specimens is distinctly different between planar optimization programs.

4b. the mean number of probe hits between planar optimization programs with identical probe hit ranges are the same.

Null Hypotheses

In conjunction with the four research hypotheses, four null hypotheses were developed to investigate diameter measurement repeatability. All of the following null hypotheses follow the identical numeric listing of their counterpart research hypotheses.

1. No similarities will be noted in the direction and magnitude of the relationship between average probe hit repeatability and probe hit variations between repeated baseline programs nor between baseline programs of different planes.

2. Within each planar baseline program (XY, XZ, and YZ), no probe hit category from any circular test specimen will indicate measurement stability.

3. Within each planar measurement test (XY, XZ, and YZ), no significant improvement in gage repeatability will be achieved through the use of multi-baseline repeatability assessment and optimization.

4. No significant difference will be noted in the general structure of planar optimization programs but will be noted in the calculated average repeatability and mean probe hit values.

Research Design

The site selected for this study was the laboratory facility in the College of Technology at Bowling Green State University, Bowling Green, Ohio. This site was selected for two reasons: (a) the availability of a DCC/CMM belonging to the College of Technology and the Center for Quality, Measurement, and Automation (CQMA) and (b) personal knowledge in the operation of this CMM. Other issues involved in the research design centered on (a) equipment selection, (b) test specimen selection, (c) inspection program development.

Equipment Selection

The CMM selected used in this study was a Brown and Sharpe Xcel 7•6•5 CMM belonging the Center for Quality, Measurement, and Automation (CQMA) at Bowling Green State University. This CMM has a moving bridge configuration and a rigid unitary base structure made out of granite. In addition, a Renshaw multi-positional touch trigger head assembly and a 2 mm ruby-tipped stylus equipped with a one inch extension will be incorporated as part of the measurement setup. This CMM was selected for two reasons. First, it is the same CMM that was used in the 1993 study. This aspect permits some cross-comparisons and correlations of data to assess machine stability over time. Second, the location of this CMM in a university setting permits regular use of the machine for the duration of the study. This is an important aspect since most CMMs located in manufacturing environments are under constant use or restricted to authorized company personnel only. In short, this study would be extremely difficult to conduct if access to a CMM in a manufacturing setting were required.

Other equipment utilized in this study included the Brown and Sharpe AVAIL measurement software package and related user's manual; a Macintosh computer, StatView, and Process Control Charting Tool Kit (PCCTK) software packages. Additional information and dimensional specifications on the Brown and Sharpe Xcel 7•6•5 CMM can be found in Appendix B.

Test Specimen Selection

Twenty-three circular test specimens were used in this study. These test specimens, which range in diameter from 0.25 to 5.75 inches at 0.25 inch increments, were the same test specimens that were used in the 1993 study. All of these test specimens were machined onto four 12 x 12 x 1 inch 6061 aluminum plates using a Bridgeport milling machine and an adjustable boring bar. The decision to incorporate these test specimens into this study was based on two rationales. First, the results of the 1993 study indicated that this number of test specimens (23) was of sufficient size to yield useful data on diameter measurement repeatability. Second, the results of the study also indicated that test specimen sizing (0.25 to 5.75 inches at 0.25 inch increments) was a useful sampling pattern for establishing correlational trends. The layout of the test specimens on their individual plates and the respective locations of the plates within the working envelope of the CMM can be seen in Appendix B.

Inspection Program Development

Although this CMM possesses the capability for programmed circular measurement using 3 to 99 probe hits, only the 3 to 10 range were selected for study. The selection of this probe hit range was based on the contention that time and cost constraints imposed on manufacturers during production restricts the use of long inspection times (i.e. increased numbers of probe hits). This range selection was also based on information provided by Digital Equipment Automation (DEA) in which it was suggested that circular repeatability testing should be structured on two criteria: (a) the automatic circle program option and (b) a probe hit inspection pattern of 16 or less. This range selection also takes into account the 3 to 10 probe hit range used in the 1993 study.

In addition to this probe hit range, fifteen inspection programs were written for this study. Three of the programs measured the diameters of each test specimen on each measurement plane, XY, XZ, and YX, using all probe hit categories. Repeated measurements collected from these three baseline programs were referenced as XY-1, XY-2, XZ-1, XZ-2, YZ-1, and YZ-2 , respectively. The other twelve programs also performed repeated diameter measurements of each test specimens on the same three planes with one exception; the diameter of each test specimen was measured on each of the three planes using a pre-determined probe hit category from two different probe hit range assessments, a 3 to 6 range and a 3 to 10 range. It should be noted that the probe hit pattern selected for a particular test specimen may or may not be the same between the two probe hit ranges. With respect to the twelve optimization programs, six of the programs assessed gage repeatability using a multi-baseline repeatability assessment and optimization. The results from these six programs were labelled as multi-baseline optimization programs and referenced as XY Plane MB(3-10), XY Plane MB(3-6), XZ Plane MB(3-10), XZ Plane MB(3-6), YZ Plane MB(3-10), YZ Plane MB(3-6). The remaining six optimization programs also assessed gage repeatability using repeatability assessment and optimization with one noted exception; the optimization programs were structured on a single baseline repeatability assessment. The results from these six programs were labelled as single baseline optimization programs and referenced as XY Plane SB(3-10), XY Plane SB(3-6), XZ Plane SB(3-10), XZ Plane SB(3-6), YZ Plane SB(3-10), YZ Plane SB(3-6).

It should be noted that all of the baseline and optimization programs were structured using the automatic circle program option (AUTO/CIR). This program option in the AVAIL measurement software package can be used to measure the diameter of full or partial circles with varying numbers of probe hits at specific angular increments. In this measurement option, the operator simply enters the number of probe hits desired. The selection as to whether a full or partial circle is to be measured is based on starting and ending angle input by the operator. For example, the angular increments associated with a full circle measurement operation are determined by dividing 360 degrees by the number of probe hits desired. Once the angular increment for a particular probe hit category has been established, the starting and ending angles can be entered by selecting "0" as the starting angle and "X" as the ending angle where "X" is equal to 360/(# of probe hits - 1).

Since this study involved the measurement of full-circle features as well as the use of the AUTO/CIR option, the angular increments of the eight probe hit categories that were used in this study along with their respective starting and ending angles have been provided in Table 5. Pictorial representations of the selected probe hit categories can also be seen in Appendix C. According to the AVAIL User's Manual (1990), the format for the AUTO/CIR measurement option is based on the following set of arguments:

Feature Name = AUTO/CIR: ref plane, probing dir., points, X, Y, Z, D, start angle, end angle

where:

- feature name: Circular feature identifier
- ref plane: Any feature with direction
- probing dir: IS (inside straight--measures the inside diameter with a straight line motion between hit points)
- points: 3 to 100 (number of probe hits used for measurement acquisition)
- X, Y, Z Center coordinates of the circle
- D: Circle diameter
- start/end angle: 0 to 360 degrees

Table 5

AUTO/CIR Input Values

Probe Hit Category	Angular Increment	Starting Angle	Ending Angle
3-pt.	120.0	0	240
4-pt.	90.0	0	270
5-pt.	72.0	0	288
6-pt.	60.0	0	300
7-pt.	51.4	0	308
8-pt.	45.0	0	315
9-pt.	40.0	0	320
10-pt.	36.0	0	324

In addition to the use of the AUTO/CIR option, other specific commands and subroutines were incorporated into the inspection programs. These program additions permitted program simplication and measurement repetition without operator involvement. In summary, the ability to program the inspection routine, common to most DCC/CMMs, helps ensure the adherence to the stated procedures.

Control of Extraneous Variability

In addition to the three previous components, various steps were taken to minimize the potential influence of factors that are known to cause measurement variability, factors such as temperature variations, vibrations, and cosine error.

Temperature Stability

As identified by various sources in the review of literature section, variations in temperature can have a dramatic but somewhat predictable effect upon dimensional measurements. Consequently, several steps were taken during the course of data collection to minimize any potential temperature variations. The steps that were taken to minimize the effects of temperature variations on probe hit repeatability include:

1. The construction of an environmental enclosure around the CMM. The purpose of this enclosure, supported by Brown (1991), was to assist in temperature stabilization by eliminating drafts blowing on the measurement setup.

2. The placement of the test specimens within the enclosed area and on top of the granite surface of the CMM 24 hours before data collection. The purpose of this step was to ensure temperature consistency between the test specimens and the CMM.

3. The monitoring of the air temperature within the enclosure during data collection. The purpose of this activity was to ensure that

significant variations air temperature do not occur during data collection. If temperature significant temperature variations were encountered during measurement operations, the data collection process would have been stopped and repeated at a later time when temperature stability can be assured.

4. The sequencing of data collection. In other words, the CMM was programmed to take one measurement of each test specimen prior to collection of the next set of measurements. The purpose of the procedure was to ensure that the effects of accepted temperature variations within the stated range were equally distributed among all probe hit categories.

Control of External Vibrations

Vibrations have been shown to have a dramatic and unpredictable effect upon instrument accuracy and repeatability. According to Hegarty (1991), the nature of floor vibrations are constantly changing. Consequently, a floor vibration analysis is an important element in characterizing CMM environments. Since the environment surrounding the CMM was assessed when it was originally installed, a second vibration analysis was not deemed necessary. However, one step that was taken to minimize the influence of vibration on measurement data was to schedule data collection during time frames when other machines within the laboratory were not in operation.

Cosine Error Control

The final factor, cosine error, occurs when a lack of squareness exists between the surface being measured and the contact surface of the probe tip of the CMM. The pictorial shown in Figure 9 details the relationship between cosine angle and error error.

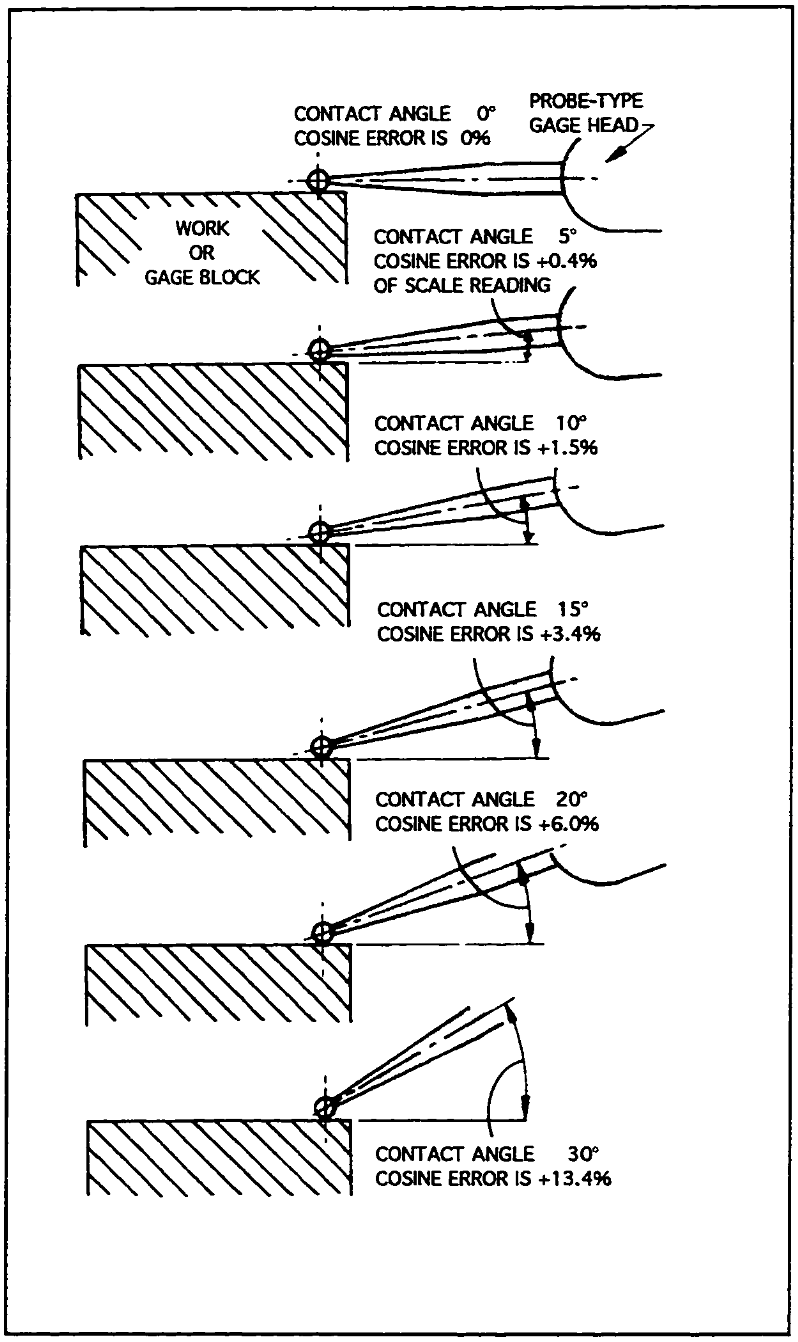


Figure 9. Contact Angle / Cosine Error Relationship. Note. From Fundamentals of Dimensional Metrology (p. 285), by Ted Busch, 1989, Albany, New York: Delmar Publishing Inc. Copyright 1989 by Delmar Publishing Inc. Reprinted with permission.

According to Busch (1989), as the contact angle is increased a plus error develops in the instrument and reading while a minus error occurs in the actual part size. The reverse is true when the contact angle is decreased. Busch also stated that the general rule for minimizing cosine error is to set the probe angle as close to zero as possible and never greater than fifteen degrees, either direction. In this study, the potential for cosine error was minimized through two separate steps:

1. Setting the angle of the multi-positional touch-trigger probe head in the vertical position (0,0 degrees) for the XY plane, the horizontal position (0,90) for the XZ, and the horizontal position (90,0) for the YZ plane.

2. The use of the automatic circle (AUTO/CIR) measurement option. This program option ensured that the probe movement toward the surface, once the probe approach distance had been reached, was aligned with the center of the circular feature and the designated contact point. This program option also divided the angular vectors between probe hit contacts into equal parts.

Data Collection and Analysis

In this study, diameter data were collected from three repeated baseline inspections (two on the XY plane, two on the XZ plane, and two on the YZ plane). In each of the baseline inspections, ten diameter measurements were collected from each of the 23 test specimens within each of the eight probe hit categories. In all, 1,840 diameter measurements were collected in each baseline inspection for a total of 11,040 diameter measurements from all six baseline inspections. Once the baseline data were collected, they were entered into a statistical software package where descriptive and inferential analyses were performed. These analyses included

1.. A determination of individual and average probe hit repeatability.

2. The identification of the probe hit category with the best overall stability in gage repeatability for each test specimen.

3. The determination of the single and multi-baseline planar optimization program structures.

Once the structure of the planar optimization programs were determined, and the programs were run, the resultant data were analyzed to determine the extent of improvement in average repeatability, if any. If it was determined that average repeatability had been improved, further analyses would be performed to determine the extent to which generalizations could be made with respect to the results. To understand more fully the data analysis process, the procedures that were used can be divided into four sequential steps: (a) repeatability determination, (b) correlation analysis, (c) repeatability optimization, and (d) inferential statistical analyses.

Repeatability Determination

Two methods of repeatability determination were used in this study, the Range Method and the Standard Deviation Method. Both of these methods utilize the single operator approach to Gage R&R analysis. In other words, the variability a single operator brings into a gaging system is considered part of equipment variability and reported along with other gage variability factors as one value, repeatability. The decision to incorporate both methods into this study was based on current literature in which a lack of standardization in the use of a particular repeatability testing method was noted. In short, the use of a particular repeatability assessment method is based solely on manufacturer preference.

In the assessment of range-based repeatability, the authors of ASME B89.1.12M-1990 recommend the collection and analysis of ten measurement samples. Once collected, the range or spread between the largest and smallest values is calculated and reported as repeatability. Algebraically, the steps used in the analysis of probe hit repeatability using the Range Method and a sample size of ten were:

1. Range = $\underline{X}_{Largest} - \underline{X}_{Smallest}$.
2. Repeatability = Range.

In the assessment of standard deviation-based repeatability, the authors of the British standard (BS6808, 1987) recommend the collection and analysis of ten measurement samples. In this method, repeatability, sometimes referred to as equipment variability (E.V.), is determined by calculating the standard deviation ($\underline{SD}_{E.V}$) of the sample measurements and multiplying this value by a pre-determined confidence interval or sigma spread. The most widely used sigma spread for the assessment of repeatability is a 3.92 sigma spread. This sigma spread is equivalent to a 95% confidence level. According to Griffith (1989), the steps used to determine repeatability in a single operator Gage R&R study using the standard deviation method and a confidence level of 95% were:

1. $\underline{SD}_{Repeatability} = \underline{SD}_{E.V.} = \sqrt{[\Sigma(\underline{X}_i - \underline{M}_{sample})^2 / (\underline{n} - 1)]}$.
2. Repeatability = 3.92 ($\underline{SD}_{E.V.}$).

Once repeatability values for each test specimen were determined in each probe hit category, average repeatability values for each probe hit category and baseline program were calculated.

Correlation Analysis

Once individual and average repeatability values were calculated, correlational analyses using Pearson's product moment correlation coefficient were performed to determine the direction and magnitude of the relationship between average probe hit repeatability and probe hit variation within each planar baseline inspection. In addition, comparisons were made to determine the extent of similarity or difference between the correlational values of planar baseline inspections. These correlational comparisons were used to assess the similarity of impact with respect to probe hit variations.

Repeatability Optimization

In this assessment, the repeatability values of each test specimen, taking into account all probe hit categories within a given planar baseline inspection, were analyzed to identify the particular probe hit categories with the "best" stability. The term "best" implies little or no difference in repeatability values, range values, kurtosis and skewness values, and mean values. Once the particular probe hit categories with the "best" stability were identified for each test specimen on a given plane, the probe hit measurement routines associated with the particular probe hit category were incorporated into planar optimization programs. Repeatability values from these programs were determined in an identical manner as the baseline inspections. The purpose of the optimization programs was to test the hypothesis that multi-baseline repeatability optimization, regardless of planar orientation, is a viable method for maximizing stability in repeatability and yielding significant improvements in diameter measurement repeatability.

Inferential Statistical Analyses

Inferential analyses would be conducted if it is determined that improvements in diameter measurement repeatability could be achieved using multi-baseline repeatability assessment and optimization. In the event of repeatability improvement, single sample $\underline{t}$ statistic tests would be conducted to make inferences about the degree of confidence that could be placed in the results of the multi-baseline (3-10) and multi-baseline (3-6) optimization programs. In other words, the alternate hypothesis indicates that a significant improvement in average repeatability can be achieved using multi-baseline repeatability assessment and optimization (i.e., the repeatability mean of each multi-baseline optimization program will be less than the repeatability mean of the "best" baseline probe hit category within their stated probe hit range and plane). It should be noted that the term "best" implies the probe hit category with the smallest numeric repeatability value. The null hypothesis associated with this analysis is that no significant improvement in average measurement repeatability would be achieved using multi-baseline repeatability assessment and optimization. The null and alternate hypotheses that would be tested on the results of the multi-baseline (3-10) and (3-6) optimization programs using a significant level of 0.05 are:

1a. Null Hypothesis: $\mu_{\text{OPT-XY/MB(3-10)}} = \mu_{\text{best XY/MB(3-10)}}$
1b. Alternate Hypothesis: $\mu_{\text{OPT-XY/MB(3-10)}} < \mu_{\text{best XY/MB(3-10)}}$

2a. Null Hypothesis: $\mu_{\text{OPT-XZ/MB(3-10)}} = \mu_{\text{best XZ/MB(3-10)}}$
2b. Alternate Hypothesis: $\mu_{\text{OPT-XZ/MB(3-10)}} < \mu_{\text{best XZ/MB(3-10)}}$

3a. Null Hypothesis: $\mu_{\text{OPT-YZ/MB(3-10)}} = \mu_{\text{best YZ/MB(3-10)}}$
3b. Alternate Hypothesis: $\mu_{\text{OPT-YZ/MB(3-10)}} < \mu_{\text{best YZ/MB(3-10)}}$

4a. Null Hypothesis: $\mu_{\text{OPT-XY/MB(3-6)}} = \mu_{\text{best XY/MB(3-6)}}$
4b. Alternate Hypothesis: $\mu_{\text{OPT-XY/MB(3-6)}} < \mu_{\text{best XY/MB(3-6)}}$

5a. Null Hypothesis: $\mu_{\text{OPT-XZ/MB(3-6)}} = \mu_{\text{best XZ/MB(3-6)}}$
5b. Alternate Hypothesis: $\mu_{\text{OPT-XZ/MB(3-6)}} < \mu_{\text{best XZ/MB(3-6)}}$

6a. Null Hypothesis: $\mu_{\text{OPT-YZ/MB(3-6)}} = \mu_{\text{best YZ/MB(3-6)}}$
6b. Alternate Hypothesis: $\mu_{\text{OPT-YZ/MB(3-6)}} < \mu_{\text{best YZ/MB(3-6)}}$

If improvements in measurement repeatability were found using multi-baseline repeatability assessment and optimization methodology, additional support for this methodology would be investigated using an identical t statistic test on the results of the single baseline (3-10) and (3-6) optimization programs. The null and alternate hypotheses that would be tested using a significant level of 0.05 are:

1a. Null Hypothesis: $\mu_{\text{OPT-XY/SB(3-10)}} = \mu_{\text{best XY/SB(3-10)}}$
1b. Alternate Hypothesis: $\mu_{\text{OPT-XY/SB(3-10)}} < \mu_{\text{best XY/SB(3-10)}}$

2a. Null Hypothesis: $\mu_{\text{OPT-XZ/SB(3-10)}} = \mu_{\text{best XZ/SB(3-10)}}$
2b. Alternate Hypothesis: $\mu_{\text{OPT-XZ/SB(3-10)}} < \mu_{\text{best XZ/SB(3-10)}}$

3a. Null Hypothesis: $\mu_{\text{OPT-YZ/SB(3-10)}} = \mu_{\text{best YZ/SB(3-10)}}$
3b. Alternate Hypothesis: $\mu_{\text{OPT-YZ/SB(3-10)}} < \mu_{\text{best YZ/SB(3-10)}}$

4a. Null Hypothesis: $\mu_{\text{OPT-XY/SB(3-6)}} = \mu_{\text{best XY/SB(3-6)}}$
4b. Alternate Hypothesis: $\mu_{\text{OPT-XY/SB(3-6)}} < \mu_{\text{best XY/SB(3-6)}}$

5a. Null Hypothesis: $\mu_{\text{OPT-XZ/SB(3-6)}} = \mu_{\text{best XZ/SB(3-6)}}$
5b. Alternate Hypothesis: $\mu_{\text{OPT-XZ/SB(3-6)}} < \mu_{\text{best XZ/SB(3-6)}}$

6a. Null Hypothesis: $\mu_{\text{OPT-YZ/SB(3-6)}} = \mu_{\text{best YZ/SB(3-6)}}$
6b. Alternate Hypothesis: $\mu_{\text{OPT-YZ/SB(3-6)}} < \mu_{\text{best YZ/SB(3-6)}}$

5. Benefit Analysis. In this analysis, the potential benefit derived from the optimization of diameter measurement repeatability was assessed. This analysis involved a determination of the mean number of probe hits for each optimization programs. Once determined, the time required to make one inspection pass of each test specimen plate in each of the optimization programs was compared to the inspection times of respective baseline inspections. The purpose of this assessment was to assess the change in optimization inspection time relative to baseline inspection times and mean probe hit values.

Chapter Summary

This chapter provided insight into the methods and procedures that were used to assess and optimize diameter measurement repeatability. It discussed the procedures that were used to determine if relationships existed between average probe hit repeatability and probe hit variation within each planar baseline inspection as well as comparisons to determine the extent of similarity or difference between the correlations of all planar baseline inspections. It also introduced the methods and procedures that were used to optimize diameter measurement repeatability on all three measurements planes (XY, XZ, and YX), and determine if significant improvements in average repeatability can be achieved using multi-baseline repeatability assessment and optimization.

CHAPTER IV

FINDINGS AND ANALYSES

Four research hypotheses were formulated to investigate multi-baseline repeatability assessment and its effects on the optimization of diameter measurement repeatability. More specifically, these hypotheses were developed to determine (a) the effectiveness of multi-baseline repeatability data in identifying specific probe hit inspection patterns with inherent stability in repeatability and (b) the effectiveness of multi-baseline repeatability assessment in generating optimized inspection routines that yield improvements in diameter measurement repeatability without a significant increase in inspection time and related costs. The findings for the research hypothesis are organized around a restatement of each research hypothesis followed by its respective findings. This chapter is concluded with a summary of the findings and analyses.

An additional research aspect that was investigated but not integrated as a specific research hypothesis was the replication of the single baseline methodology used in the 1993 study. This assessment methodology was included to (a) clarify differences between the two assessment approaches and (b) validate and expand on the results of the 1993 study.

Restatement of Hypothesis 1

The first research hypothesis states that similarities would be noted in the direction and magnitude of the relationship between average probe hit repeatability and probe hit variations between repeated baseline programs and baseline programs of different planes. Correlational similarities would be deemed significant if:

1a. Little or no difference was noted in the direction and magnitude of the relationship between average probe hit repeatability and probe hit variations between repeated baseline programs.

2b. Little or no difference was noted in the direction and magnitude of the relationship between average probe hit repeatability and probe hit variations between baseline programs of different planes.

The null hypothesis associated with this research hypothesis states that no similarities would be noted in the direction and magnitude of the relationship between average probe hit repeatability and probe hit variations between repeated baseline programs nor between baseline programs of different planes.

Results of Hypothesis 1

In this study, diameter data were collected from six baseline inspections (two on the XY plane, two on the XZ plane, and two on the YZ plane). In each baseline inspections, ten diameter measurements were collected from each of the 23 test specimens within the assigned probe hit range (3 to 10 probe hits). In all, 1,840 diameter measurements were collected in each baseline inspection for a total of 11,040 diameter measurements from all six baseline inspections.

Once the baseline diameter data were collected, each baseline data set was entered into the Excel application program where descriptive analyses were performed to determine SD- and Range-based repeatability for each diameter/probe hit category ***(individual probe hit repeatability)***. These two descriptive analyses provided the repeatability data that were needed to determine SD- and Range-based average probe hit repeatability values. Once calculated, the average repeatability values were used to calculate correlational values for the magnitude and direction of the relationships between average probe hit repeatability and probe hit variations. The various steps used in the analysis of baseline data were:

1. The determination of individual probe hit repeatability for each test specimen within each probe hit category using the SD method and a 95% confidence interval. Individual probe hit repeatability (IPHR) was determined using the equation:

$IPHR_{SD} = 3.92\ (SD_{Sample})$.

2. The determination of SD-based average probe hit repeatability for each probe hit category in each baseline inspection. Average probe hit repeatability (APHR) was determined using the equation:

$APHR_{SD} = \sum IPHR_{SD} / 23$.

3. The determination of individual probe hit repeatability (IPHR) for each test specimen within each probe hit category using the range method. Individual probe hit repeatability was determined using the equation: $IPHR_{Range} = \underline{X}_{largest} - \underline{X}_{smallest}$.

4. The determination of range-based average probe hit repeatability for each probe hit category in each baseline inspection. Average probe hit repeatability (APHR) was determined using the equation:

$APHR_{Range} = \sum IPHR_{Range} / 23$.

The results of the individual and average probe hit repeatability assessments can be seen in the following sets of tables and figures:

1. XY Plane: XY-1, SD-Based Repeatability, Table 6.
XY-2, SD-Based Repeatability, Table 7.
XY-1, Range-Based Repeatability, Table 8.
XY-2, Range-Based Repeatability, Table 9.
XY Baseline Repeatability Probe Hit, Figure 10.

2. XZ Plane: XZ-1, SD-Based Repeatability, Table 10.
XZ-2, SD-Based Repeatability, Table 11.
XZ-1, Range-Based Repeatability, Table 12.
XZ-2, Range-Based Repeatability, Table 13.
XZ Baseline Probe Hit Repeatability, Figure 11.

3. YZ Plane: YZ-1, SD-Based Repeatability, Table 14.
YZ-2, SD-Based Repeatability, Table 15.
YZ-1, Range-Based Repeatability, Table 16.
YZ-2, Range-Based Repeatability, Table 17.
YZ Baseline Repeatability Probe Hit, Figure 12.

In addition to an analysis of SD- and Range-based repeatability within each baseline inspection, an additional analysis was performed to determine mean probe hit repeatability values for each baseline program (XY, XZ, and YZ). The steps used in this analysis were:

1. The determination of mean individual probe hit repeatability (Mean IPHR) for each test specimen within each probe hit category. Mean individual probe hit repeatability for each measurement plane was determined using the following two equations:

$\text{Mean IPHR}_{SD} = (\text{IPHR}_{SD\text{-}1} + \text{IPHR}_{SD\text{-}2}) / 2$ and

$\text{Mean IPHR}_{Range} = (\text{IPHR}_{Range\text{-}1} + \text{IPHR}_{Range\text{-}2}) / 2.$

2. The determination of average probe hit repeatability (APHR) for each probe hit category in each baseline program. Average probe hit repeatability for each measurement plane was determined using the equations:

$\text{APHR}_{SD} = \sum \text{Mean IPHR}_{SD} / 23$ and

$\text{APHR}_{Range} = \sum \text{Mean IPHR}_{Range} / 23.$

Table 6

XY Plane: XY-1 SD-Based Repeatability

	Probe Hit Category							
Diameter	3-pt.	4-pt.	5-pt.	6-pt.	7-pt.	8-pt.	9-pt.	10-pt.
0.25	9.9	17.1	7.5	8.8	8.6	4.9	6.9	13.4
0.50	9.7	12.3	6.8	8.6	12.5	6.2	8.5	9.2
0.75	14.6	10.4	10.8	7.9	5.1	7.6	8.8	12.1
1.00	8.4	6.0	10.4	8.6	6.0	7.8	4.1	6.0
1.25	11.6	13.9	8.4	5.5	6.8	4.3	6.5	7.0
1.50	9.5	6.3	10.1	9.8	8.8	12.2	4.4	6.1
1.75	8.2	11.7	6.3	10.1	7.8	3.8	6.5	6.3
2.00	11.5	12.2	4.6	5.2	10.0	5.0	7.0	5.9
2.25	9.6	9.2	7.0	3.9	8.2	4.1	6.1	5.3
2.50	7.7	10.7	14.4	11.3	7.7	6.3	9.2	4.7
2.75	11.7	12.4	12.5	5.2	4.5	4.5	9.0	5.3
3.00	12.4	7.0	3.8	7.9	7.9	4.6	6.5	5.9
3.25	9.2	6.8	8.3	5.6	19.4	12.1	5.5	5.0
3.50	13.3	8.2	10.4	6.1	10.6	8.0	13.7	8.0
3.75	15.6	10.6	7.3	8.8	6.4	6.8	8.6	4.7
4.00	14.0	2.5	4.4	5.4	10.5	7.2	8.6	6.0
4.25	14.8	11.1	8.5	9.2	11.5	4.4	9.9	4.7
4.50	10.5	6.6	11.9	7.3	7.3	6.2	7.4	6.3
4.75	14.1	10.1	14.5	6.5	9.6	3.8	7.2	3.8
5.00	4.6	7.7	7.9	7.9	8.0	5.7	4.6	6.5
5.25	10.4	9.4	8.7	4.7	7.2	6.7	5.8	5.7
5.50	8.0	8.0	7.1	8.8	9.3	3.9	6.0	6.0
5.75	16.0	4.4	8.2	5.7	8.2	13.3	5.9	7.2
Avg Rep	11.1	9.3	8.7	7.3	8.8	6.5	7.2	6.6

Note. All repeatability values are expressed in inches (x 10^{-5}).

Table 7

XY Plane: XY-2 SD-Based Repeatability

	Probe Hit Category							
Diameter	3-pt.	4-pt.	5-pt.	6-pt.	7-pt.	8-pt.	9-pt.	10-pt.
0.25	11.5	17.2	15.7	6.5	5.4	5.6	7.2	6.5
0.50	14.4	6.1	7.2	13.7	8.9	6.9	6.0	5.7
0.75	7.2	7.5	8.6	5.2	9.3	5.5	6.8	9.7
1.00	6.3	4.9	10.5	6.6	7.5	6.2	4.9	4.6
1.25	14.4	6.7	9.0	7.1	4.5	6.5	6.2	5.2
1.50	10.7	7.8	12.7	8.0	10.9	4.4	5.0	6.5
1.75	8.2	11.2	8.4	11.2	4.7	10.4	9.6	7.4
2.00	5.3	11.7	6.8	8.6	8.4	5.8	10.1	6.0
2.25	12.7	5.0	11.4	6.0	7.7	5.4	7.7	6.5
2.50	7.7	9.6	11.8	9.7	7.7	8.8	6.7	5.0
2.75	10.3	7.5	12.4	6.8	5.4	4.6	6.8	8.4
3.00	7.8	7.8	4.4	5.4	5.5	4.6	5.9	5.0
3.25	7.7	6.3	6.8	2.7	7.3	3.8	7.5	2.9
3.50	14.7	5.9	7.8	2.9	6.9	3.8	7.9	6.2
3.75	9.2	7.2	10.1	6.4	9.5	3.3	7.4	3.8
4.00	11.7	9.2	7.5	4.6	8.2	4.6	6.0	7.4
4.25	5.9	10.1	6.9	10.1	12.0	6.1	9.8	5.5
4.50	8.7	7.2	7.1	7.1	5.4	5.4	5.7	4.1
4.75	14.3	9.1	7.5	7.7	5.7	6.0	5.0	7.7
5.00	11.6	9.8	8.6	8.6	5.3	9.8	6.0	7.7
5.25	12.7	7.3	13.0	7.2	10.2	6.6	5.2	4.4
5.50	6.0	8.4	6.8	7.3	6.8	6.7	7.5	5.7
5.75	10.7	8.2	8.4	6.4	6.2	9.3	7.0	7.5
Avg Rep	10.0	8.3	9.1	7.2	7.4	6.1	6.9	6.1

Note. All repeatability values are expressed in inches (x 10^{-5}).

Table 8

XY Plane: XY-1 Range-Based Repeatability

	Probe Hit Category							
Diameter	3-pt.	4-pt.	5-pt.	6-pt.	7-pt.	8-pt.	9-pt.	10-pt.
0.25	7.0	15.0	6.0	7.0	7.0	4.0	6.0	11.0
0.50	7.0	9.0	5.0	7.0	11.0	4.0	7.0	8.0
0.75	11.0	9.0	10.0	6.0	5.0	7.0	6.0	11.0
1.00	7.0	4.0	7.0	6.0	5.0	6.0	3.0	5.0
1.25	11.0	11.0	7.0	4.0	5.0	4.0	5.0	5.0
1.50	8.0	5.0	9.0	9.0	6.0	11.0	3.0	6.0
1.75	6.0	10.0	5.0	8.0	5.0	3.0	5.0	5.0
2.00	8.0	10.0	4.0	5.0	8.0	4.0	7.0	5.0
2.25	8.0	8.0	6.0	3.0	6.0	3.0	5.0	4.0
2.50	6.0	9.0	8.0	9.0	7.0	5.0	7.0	3.0
2.75	10.0	9.0	10.0	4.0	4.0	3.0	7.0	4.0
3.00	8.0	6.0	3.0	6.0	7.0	4.0	5.0	5.0
3.25	7.0	6.0	7.0	5.0	14.0	9.0	4.0	5.0
3.50	11.0	5.0	9.0	5.0	8.0	6.0	9.0	6.0
3.75	12.0	9.0	5.0	6.0	5.0	5.0	8.0	4.0
4.00	11.0	2.0	3.0	4.0	8.0	5.0	6.0	5.0
4.25	10.0	9.0	7.0	7.0	8.0	4.0	9.0	4.0
4.50	9.0	5.0	9.0	6.0	5.0	4.0	5.0	5.0
4.75	12.0	8.0	11.0	5.0	7.0	3.0	6.0	3.0
5.00	4.0	6.0	6.0	6.0	7.0	4.0	4.0	5.0
5.25	9.0	7.0	7.0	4.0	6.0	5.0	5.0	4.0
5.50	6.0	6.0	6.0	7.0	8.0	3.0	5.0	5.0
5.75	13.0	3.0	6.0	5.0	6.0	9.0	5.0	6.0
Avg Rep	8.7	7.4	6.8	5.8	6.9	5.0	5.7	5.4

Note. All repeatability values are expressed in inches (x 10^{-5}).

Table 9

XY Plane: XY-2 Range-Based Repeatability

	Probe Hit Category							
Diameter	3-pt.	4-pt.	5-pt.	6-pt.	7-pt.	8-pt.	9-pt.	10-pt.
0.25	10.0	13.0	12.0	4.0	4.0	5.0	6.0	5.0
0.50	12.0	5.0	6.0	9.0	7.0	6.0	5.0	4.0
0.75	6.0	6.0	7.0	3.0	8.0	4.0	5.0	8.0
1.00	5.0	4.0	8.0	5.0	6.0	4.0	4.0	4.0
1.25	13.0	6.0	8.0	5.0	4.0	5.0	5.0	4.0
1.50	7.0	7.0	11.0	6.0	10.0	4.0	4.0	5.0
1.75	6.0	10.0	7.0	7.0	4.0	8.0	7.0	6.0
2.00	4.0	10.0	6.0	7.0	6.0	4.0	7.0	5.0
2.25	9.0	3.0	8.0	5.0	5.0	4.0	7.0	6.0
2.50	8.0	7.0	10.0	7.0	7.0	7.0	6.0	4.0
2.75	9.0	6.0	11.0	5.0	5.0	3.0	5.0	7.0
3.00	6.0	7.0	3.0	4.0	5.0	4.0	4.0	4.0
3.25	5.0	5.0	6.0	2.0	5.0	3.0	6.0	2.0
3.50	11.0	5.0	6.0	2.0	6.0	2.0	6.0	5.0
3.75	7.0	6.0	8.0	5.0	8.0	3.0	5.0	3.0
4.00	9.0	7.0	5.0	3.0	7.0	3.0	5.0	5.0
4.25	4.0	8.0	6.0	8.0	7.0	5.0	8.0	5.0
4.50	6.0	6.0	7.0	6.0	4.0	4.0	4.0	3.0
4.75	13.0	8.0	7.0	6.0	5.0	5.0	4.0	7.0
5.00	9.0	8.0	6.0	6.0	5.0	8.0	5.0	6.0
5.25	12.0	5.0	9.0	5.0	8.0	5.0	5.0	3.0
5.50	4.0	7.0	5.0	7.0	5.0	6.0	6.0	4.0
5.75	9.0	6.0	7.0	5.0	6.0	6.0	6.0	6.0
Avg Rep	8.0	6.7	7.3	5.3	6.0	4.7	5.4	4.8

Note. All repeatability values are expressed in inches (x 10^{-5}).

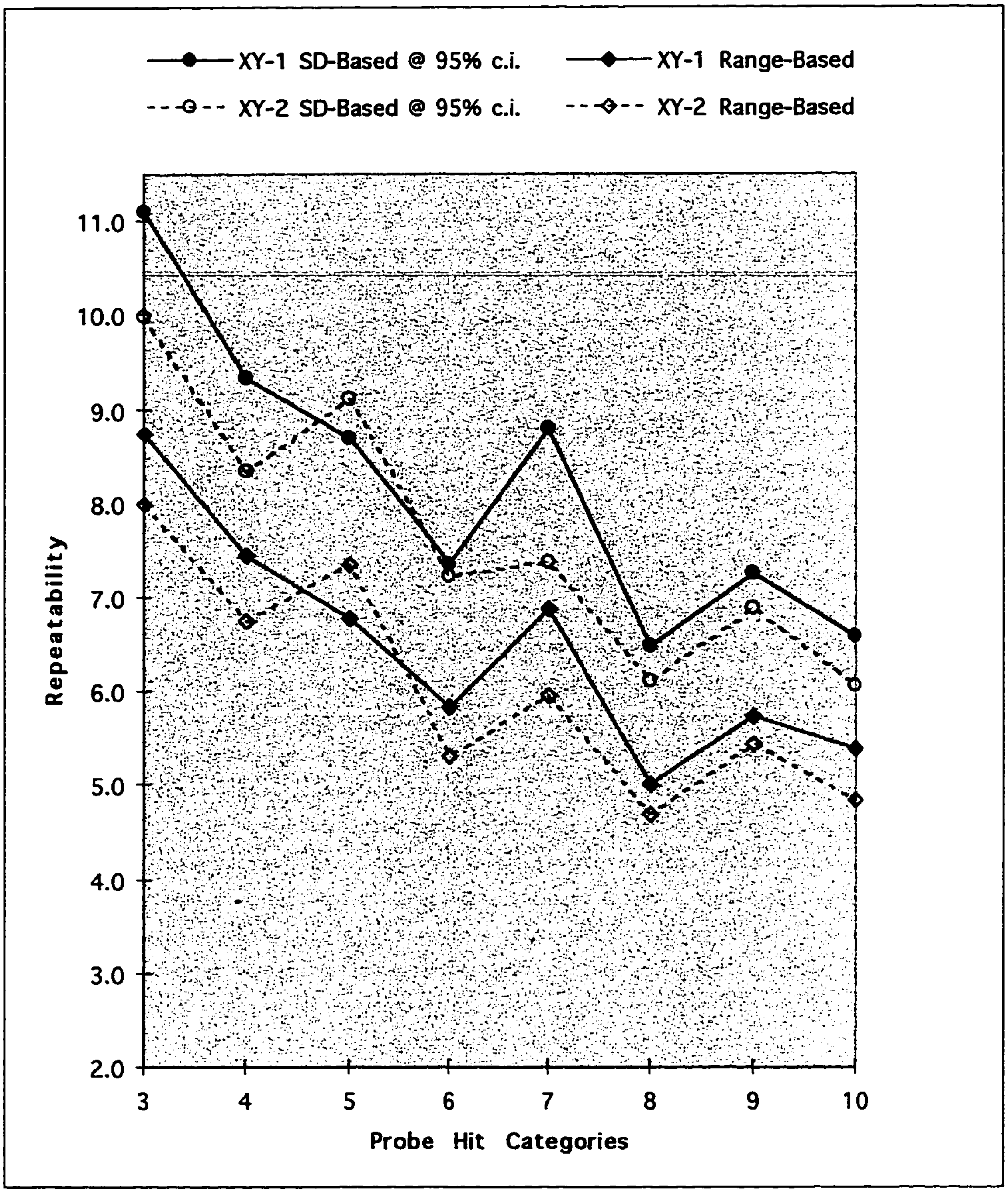


Figure 10. YZ Plane: Baseline probe hit repeatability. Note. All repeatability values are expressed in inches (x 10^{-5}).

Table 10

XZ Plane: XZ-1 SD-Based Repeatability

	Probe Hit Category							
Diameter	3-pt.	4-pt.	5-pt.	6-pt.	7-pt.	8-pt.	9-pt.	10-pt.
0.25	4.4	6.5	14.8	4.3	7.0	8.4	14.4	10.6
0.50	11.4	4.7	7.0	6.9	6.9	6.2	5.5	4.1
0.75	5.7	6.5	6.0	6.1	9.9	5.6	6.2	7.0
1.00	7.9	8.1	6.8	5.7	6.5	8.4	5.3	8.1
1.25	7.6	5.3	8.9	6.5	7.1	5.5	4.7	7.4
1.50	7.3	6.1	7.9	10.3	5.4	7.5	5.6	7.8
1.75	9.0	6.8	17.7	9.6	7.5	3.8	12.1	7.0
2.00	7.5	6.0	9.1	7.0	4.3	3.8	6.0	7.1
2.25	3.8	5.7	10.1	5.0	13.4	6.7	3.9	3.5
2.50	5.7	4.9	7.7	8.6	9.2	5.7	7.7	7.1
2.75	15.8	6.3	14.3	6.2	7.1	6.1	7.3	5.7
3.00	8.4	7.1	2.0	6.6	6.6	6.0	3.8	5.0
3.25	6.7	9.7	7.2	6.0	4.1	5.0	6.1	4.3
3.50	7.7	7.7	7.3	3.3	7.2	7.5	6.2	4.6
3.75	8.1	5.7	8.8	6.3	5.9	3.8	3.5	4.4
4.00	5.7	5.4	8.8	11.7	5.5	4.9	5.0	3.8
4.25	4.4	6.7	9.4	6.3	6.7	3.6	5.5	6.3
4.50	9.2	7.3	7.5	6.5	10.9	8.8	3.6	7.7
4.75	6.7	5.7	7.7	4.1	6.2	6.9	5.5	5.7
5.00	7.2	9.3	16.5	8.0	6.9	6.8	10.1	8.1
5.25	10.3	5.7	8.2	2.5	11.9	6.0	5.8	4.4
5.50	6.1	5.9	5.7	5.0	3.7	6.8	3.3	3.6
5.75	7.1	4.9	9.0	6.5	6.0	3.8	6.4	6.3
Avg Rep	7.6	6.4	9.1	6.5	7.2	6.0	6.3	6.1

Note. All repeatability values are expressed in inches (x 10^{-5}).

Table 11

XZ Plane: XZ-2 SD-Based Repeatability

	Probe Hit Category							
Diameter	3-pt.	4-pt.	5-pt.	6-pt.	7-pt.	8-pt.	9-pt.	10-pt.
0.25	12.7	13.6	10.9	7.8	7.7	6.3	4.9	6.0
0.50	7.7	5.1	7.2	8.4	4.4	3.6	8.2	5.0
0.75	6.3	9.2	7.0	3.3	4.6	8.0	3.8	2.6
1.00	11.5	8.6	9.8	5.2	6.7	4.9	5.1	7.9
1.25	12.0	5.0	6.8	10.3	14.1	7.4	8.1	4.5
1.50	12.0	7.7	6.2	6.7	6.8	5.8	3.4	6.0
1.75	10.1	7.4	6.3	9.2	7.9	7.0	9.1	6.0
2.00	13.0	7.2	7.1	10.3	5.6	8.3	9.0	4.6
2.25	6.9	5.1	5.6	6.0	10.4	3.5	3.4	3.3
2.50	13.1	5.5	10.6	4.9	6.4	5.7	5.0	5.1
2.75	9.7	10.9	8.4	6.5	4.6	4.7	5.3	4.2
3.00	9.9	4.9	5.4	5.7	4.4	5.3	4.2	3.3
3.25	7.7	7.6	5.0	9.7	10.4	3.8	3.8	4.6
3.50	11.7	5.3	8.7	7.8	6.2	3.8	5.3	6.0
3.75	8.4	4.9	7.9	5.8	6.3	4.7	3.8	3.1
4.00	7.0	6.3	10.0	4.3	2.9	3.3	5.3	3.9
4.25	8.9	5.2	11.4	6.7	5.6	5.9	5.0	5.0
4.50	10.0	11.2	6.7	8.1	7.8	4.9	5.9	4.6
4.75	7.8	7.9	6.5	5.7	4.5	3.6	3.9	5.3
5.00	9.4	11.5	8.0	8.4	3.6	7.1	7.5	6.4
5.25	9.2	11.0	13.3	5.9	6.4	4.6	6.8	12.6
5.50	6.6	7.7	6.0	3.2	3.8	6.0	3.9	5.1
5.75	7.6	5.7	9.6	5.4	5.3	6.0	3.8	4.7
Avg Rep	9.5	7.6	8.0	6.7	6.4	5.4	5.4	5.2

Note. All repeatability values are expressed in inches (x 10^{-5}).

Table 12

XZ Plane: XZ-1 Range-Based Repeatability

	Probe Hit Category							
Diameter	3-pt.	4-pt.	5-pt.	6-pt.	7-pt.	8-pt.	9-pt.	10-pt.
0.25	3.0	5.0	11.0	3.0	5.0	7.0	13.0	9.0
0.50	9.0	4.0	5.0	6.0	5.0	5.0	4.0	3.0
0.75	4.0	5.0	5.0	5.0	6.0	5.0	5.0	6.0
1.00	7.0	7.0	6.0	5.0	5.0	6.0	4.0	6.0
1.25	7.0	4.0	7.0	5.0	6.0	5.0	4.0	5.0
1.50	5.0	5.0	7.0	8.0	4.0	6.0	4.0	6.0
1.75	7.0	5.0	14.0	6.0	7.0	3.0	11.0	6.0
2.00	5.0	4.0	7.0	6.0	3.0	3.0	5.0	6.0
2.25	3.0	4.0	8.0	4.0	10.0	5.0	3.0	3.0
2.50	4.0	3.0	6.0	8.0	8.0	5.0	6.0	6.0
2.75	14.0	5.0	11.0	5.0	6.0	4.0	6.0	4.0
3.00	7.0	6.0	1.0	5.0	4.0	5.0	3.0	4.0
3.25	5.0	7.0	6.0	5.0	3.0	4.0	5.0	4.0
3.50	7.0	6.0	6.0	3.0	7.0	6.0	4.0	3.0
3.75	5.0	4.0	6.0	5.0	5.0	3.0	2.0	3.0
4.00	4.0	5.0	8.0	9.0	4.0	4.0	4.0	3.0
4.25	3.0	5.0	8.0	5.0	5.0	3.0	5.0	5.0
4.50	7.0	6.0	5.0	5.0	8.0	7.0	2.0	7.0
4.75	6.0	4.0	6.0	3.0	5.0	5.0	4.0	4.0
5.00	5.0	7.0	16.0	7.0	5.0	5.0	9.0	7.0
5.25	8.0	5.0	7.0	2.0	10.0	5.0	5.0	3.0
5.50	4.0	5.0	4.0	4.0	3.0	5.0	3.0	3.0
5.75	6.0	4.0	7.0	6.0	4.0	3.0	4.0	5.0
Avg Rep	5.9	5.0	7.3	5.2	5.6	4.7	5.0	4.8

Note. All repeatability values are expressed in inches (x 10^{-5}).

Table 13

XZ Plane: XZ-2 Range-Based Repeatability

	Probe Hit Category							
Diameter	3-pt.	4-pt.	5-pt.	6-pt.	7-pt.	8-pt.	9-pt.	10-pt.
0.25	9.0	11.0	10.0	5.0	6.0	4.0	4.0	5.0
0.50	5.0	4.0	5.0	6.0	3.0	3.0	6.0	4.0
0.75	5.0	7.0	5.0	3.0	4.0	6.0	3.0	2.0
1.00	8.0	7.0	8.0	4.0	5.0	4.0	4.0	6.0
1.25	11.0	4.0	5.0	9.0	10.0	6.0	7.0	4.0
1.50	10.0	5.0	5.0	5.0	6.0	5.0	3.0	5.0
1.75	7.0	6.0	5.0	7.0	7.0	6.0	7.0	5.0
2.00	10.0	5.0	6.0	7.0	4.0	7.0	7.0	3.0
2.25	5.0	3.0	4.0	4.0	8.0	3.0	3.0	3.0
2.50	9.0	4.0	8.0	3.0	5.0	5.0	4.0	4.0
2.75	8.0	8.0	8.0	6.0	3.0	3.0	4.0	3.0
3.00	9.0	3.0	5.0	4.0	4.0	4.0	3.0	3.0
3.25	7.0	6.0	4.0	8.0	9.0	3.0	3.0	3.0
3.50	8.0	4.0	6.0	7.0	5.0	3.0	3.0	5.0
3.75	6.0	4.0	7.0	4.0	5.0	4.0	3.0	2.0
4.00	5.0	5.0	8.0	3.0	2.0	2.0	5.0	3.0
4.25	7.0	4.0	8.0	6.0	5.0	5.0	4.0	3.0
4.50	7.0	10.0	6.0	7.0	6.0	4.0	5.0	4.0
4.75	6.0	6.0	5.0	4.0	3.0	2.0	3.0	4.0
5.00	7.0	9.0	6.0	7.0	3.0	6.0	6.0	4.0
5.25	8.0	7.0	10.0	4.0	5.0	3.0	5.0	11.0
5.50	5.0	6.0	4.0	2.0	3.0	4.0	3.0	4.0
5.75	6.0	5.0	7.0	3.0	5.0	5.0	3.0	4.0
Avg Rep	7.3	5.8	6.3	5.1	5.0	4.2	4.3	4.1

Note. All repeatability values are expressed in inches (x 10^{-5}).

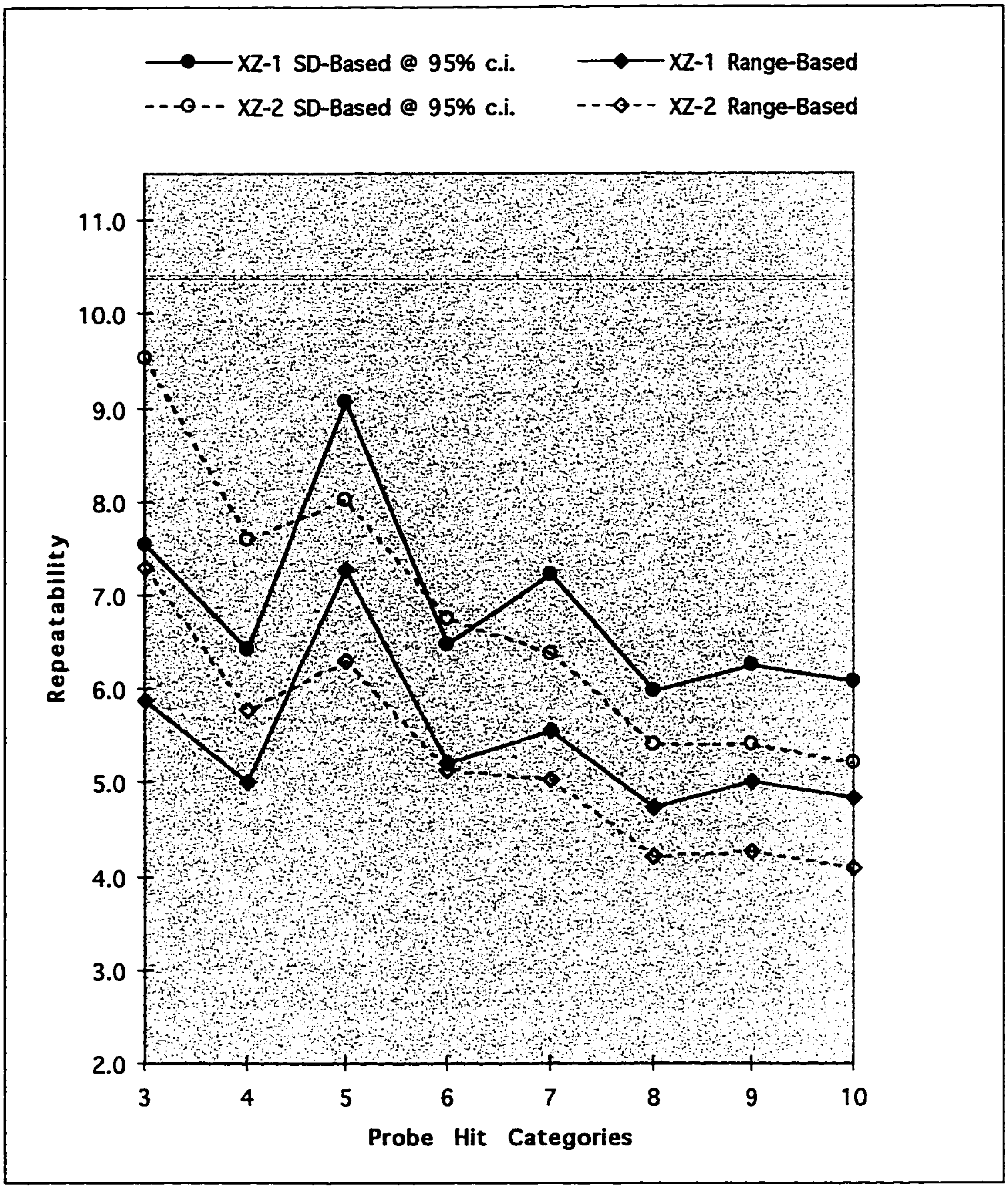


Figure 11. XZ Plane: Baseline probe hit repeatability. Note. All repeatability values are expressed in inches (x 10^{-5}).

Table 14

YZ Plane: YZ-1 SD-Based Repeatability

	Probe Hit Category							
Diameter	3-pt.	4-pt.	5-pt.	6-pt.	7-pt.	8-pt.	9-pt.	10-pt.
0.25	14.9	7.9	10.9	8.0	8.0	6.9	3.7	5.1
0.50	9.7	12.3	4.2	3.1	9.0	20.6	8.4	5.9
0.75	10.8	12.0	9.7	11.2	10.4	6.8	8.2	5.9
1.00	5.7	9.3	8.2	6.9	3.8	5.3	6.4	5.3
1.25	4.4	9.4	6.5	7.9	5.0	5.4	6.0	5.3
1.50	10.1	6.8	7.0	5.4	1.9	6.2	2.7	5.0
1.75	4.6	6.9	7.7	10.3	5.1	5.0	6.7	5.3
2.00	11.4	13.6	7.6	5.6	11.5	6.0	10.0	4.1
2.25	5.4	7.5	6.2	4.9	8.1	4.7	6.7	12.3
2.50	13.2	7.2	3.4	6.4	7.2	6.5	5.4	3.9
2.75	7.5	10.0	5.3	14.6	5.1	4.2	6.2	4.6
3.00	10.6	9.9	7.9	7.3	8.4	2.2	6.2	5.3
3.25	6.7	7.0	7.7	5.2	4.4	4.9	8.8	4.6
3.50	10.4	7.3	14.1	6.8	5.9	14.5	11.1	6.8
3.75	6.5	5.2	3.8	5.3	5.0	4.3	6.4	2.6
4.00	9.3	9.6	8.4	7.0	6.8	20.1	5.9	5.0
4.25	8.1	6.5	7.8	5.7	4.6	7.3	12.5	4.7
4.50	5.7	6.5	7.5	10.8	7.3	8.8	14.4	9.2
4.75	4.9	3.8	7.1	5.2	7.7	7.0	8.9	4.2
5.00	9.0	4.1	6.0	10.6	4.3	9.2	6.9	4.9
5.25	10.6	8.6	5.2	11.5	13.5	6.8	7.5	7.2
5.50	6.6	6.2	5.0	5.3	3.9	6.5	7.0	9.0
5.75	9.3	4.4	6.8	6.7	9.0	5.3	5.0	7.0
Avg Rep	8.5	7.9	7.1	7.5	6.8	7.6	7.4	5.8

Note. All repeatability values are expressed in inches (x 10^{-5}).

Table 15

YZ Plane: YZ-2 SD-Based Repeatability

	Probe Hit Category							
Diameter	3-pt.	4-pt.	5-pt.	6-pt.	7-pt.	8-pt.	9-pt.	10-pt.
0.25	13.4	10.9	9.7	8.0	9.9	6.7	7.9	3.8
0.50	11.8	5.6	9.0	8.4	3.8	10.0	6.0	8.1
0.75	8.6	7.7	8.6	10.1	6.2	8.8	6.8	3.8
1.00	7.7	4.2	5.2	6.2	4.9	4.3	4.3	4.3
1.25	5.3	7.7	6.5	4.2	7.0	5.4	8.4	8.2
1.50	6.8	6.8	9.0	7.0	6.0	4.5	4.6	5.0
1.75	4.6	6.4	6.1	7.2	6.6	3.3	14.6	4.7
2.00	5.3	6.0	5.7	6.9	5.0	3.9	4.2	5.0
2.25	8.8	7.9	6.5	3.1	5.7	6.2	5.3	6.3
2.50	7.4	5.9	6.8	6.6	3.4	3.4	5.7	6.0
2.75	9.0	6.7	11.2	3.8	5.5	4.6	5.4	6.3
3.00	10.9	5.4	5.3	7.5	4.7	3.5	4.2	6.8
3.25	7.4	5.3	8,8	6.2	5.6	8.4	5.1	4.6
3.50	7.8	4.4	6.0	7.2	7.2	6.7	6.5	4.9
3.75	5.0	4.3	6.7	9.3	5.9	5.3	4.9	2.9
4.00	6.7	5.7	6.5	9.9	4.6	6.5	5.0	5.0
4.25	10.3	18.8	4.5	9.1	6.5	8.8	6.0	5.5
4.50	6.2	7.3	6.5	9.7	7.4	5.0	4.1	5.3
4.75	6.0	13.5	5.9	5.4	6.5	8.3	4.1	5.1
5.00	8.1	7.2	4.2	7.1	5.7	5.5	6.0	5.3
5.25	6.0	10.6	11.5	5.4	6.2	7.0	6.3	10.9
5.50	7.0	6.2	6.5	5.3	7.5	5.6	3.8	3.8
5.75	6.8	8.0	5.9	5.3	7.4	3.8	8.4	6.0
Avg Rep	7.7	7.5	7.1	6.9	6.1	5.9	6.0	5.6

Note. All repeatability values are expressed in inches (x 10^{-5}).

Table 16

YZ Plane: YZ-1 Range-Based Repeatability

	Probe Hit Category							
Diameter	3-pt.	4-pt.	5-pt.	6-pt.	7-pt.	8-pt.	9-pt.	10-pt.
0.25	11.0	6.0	8.0	7.0	6.0	6.0	3.0	4.0
0.50	8.0	9.0	3.0	2.0	7.0	13.0	7.0	4.0
0.75	9.0	10.0	7.0	8.0	8.0	5.0	7.0	4.0
1.00	4.0	8.0	7.0	5.0	3.0	4.0	4.0	5.0
1.25	4.0	8.0	5.0	7.0	5.0	5.0	5.0	4.0
1.50	9.0	5.0	6.0	5.0	2.0	5.0	2.0	4.0
1.75	4.0	5.0	6.0	9.0	3.0	3.0	6.0	4.0
2.00	9.0	13.0	6.0	5.0	9.0	5.0	8.0	3.0
2.25	4.0	6.0	6.0	4.0	8.0	4.0	5.0	11.0
2.50	9.0	5.0	3.0	6.0	6.0	5.0	4.0	3.0
2.75	6.0	7.0	4.0	14.0	4.0	3.0	5.0	4.0
3.00	7.0	9.0	6.0	6.0	7.0	2.0	5.0	4.0
3.25	6.0	6.0	7.0	4.0	3.0	4.0	7.0	3.0
3.50	9.0	6.0	13.0	5.0	4.0	13.0	10.0	5.0
3.75	5.0	4.0	3.0	3.0	4.0	3.0	6.0	2.0
4.00	8.0	9.0	7.0	4.0	6.0	16.0	5.0	4.0
4.25	7.0	5.0	6.0	5.0	3.0	5.0	9.0	4.0
4.50	5.0	5.0	5.0	7.0	5.0	6.0	11.0	7.0
4.75	3.0	3.0	5.0	4.0	5.0	7.0	6.0	3.0
5.00	6.0	3.0	5.0	10.0	4.0	7.0	5.0	4.0
5.25	9.0	7.0	5.0	8.0	12.0	5.0	6.0	5.0
5.50	6.0	5.0	4.0	4.0	3.0	5.0	5.0	8.0
5.75	8.0	3.0	7.0	5.0	6.0	5.0	4.0	5.0
Avg Rep	6.8	6.4	5.8	6.0	5.3	5.9	5.9	4.5

Note. All repeatability values are expressed in inches (x 10^{-5}).

Table 17

YZ Plane: YZ-2 Range-Based Repeatability

	Probe Hit Category							
Diameter	3-pt.	4-pt.	5-pt.	6-pt.	7-pt.	8-pt.	9-pt.	10-pt.
0.25	12.0	8.0	8.0	7.0	8.0	6.0	5.0	3.0
0.50	9.0	4.0	6.0	6.0	3.0	8.0	5.0	6.0
0.75	6.0	6.0	7.0	9.0	4.0	6.0	4.0	2.0
1.00	5.0	3.0	4.0	5.0	3.0	3.0	4.0	3.0
1.25	5.0	6.0	5.0	3.0	5.0	5.0	7.0	7.0
1.50	6.0	5.0	8.0	5.0	6.0	4.0	3.0	4.0
1.75	3.0	5.0	5.0	7.0	5.0	3.0	13.0	3.0
2.00	4.0	5.0	5.0	6.0	4.0	3.0	3.0	4.0
2.25	6.0	7.0	5.0	2.0	5.0	5.0	4.0	5.0
2.50	6.0	5.0	5.0	5.0	3.0	2.0	4.0	4.0
2.75	7.0	5.0	9.0	3.0	4.0	4.0	4.0	5.0
3.00	9.0	4.0	4.0	6.0	4.0	2.0	3.0	6.0
3.25	6.0	4.0	7.0	4.0	4.0	7.0	5.0	4.0
3.50	6.0	3.0	4.0	6.0	6.0	5.0	4.0	4.0
3.75	4.0	4.0	5.0	8.0	4.0	4.0	3.0	2.0
4.00	6.0	4.0	5.0	7.0	4.0	5.0	4.0	4.0
4.25	9.0	16.0	4.0	7.0	6.0	7.0	5.0	5.0
4.50	4.0	6.0	5.0	7.0	6.0	4.0	3.0	5.0
4.75	5.0	12.0	5.0	4.0	6.0	6.0	3.0	4.0
5.00	6.0	5.0	3.0	5.0	3.0	4.0	5.0	4.0
5.25	5.0	9.0	8.0	4.0	5.0	5.0	5.0	9.0
5.50	5.0	5.0	5.0	4.0	6.0	4.0	3.0	3.0
5.75	6.0	7.0	5.0	4.0	6.0	3.0	6.0	5.0
Avg Rep	6.1	6.0	5.5	5.4	4.8	4.6	4.6	4.4

Note. All repeatability values are expressed in inches (x 10^{-5}).

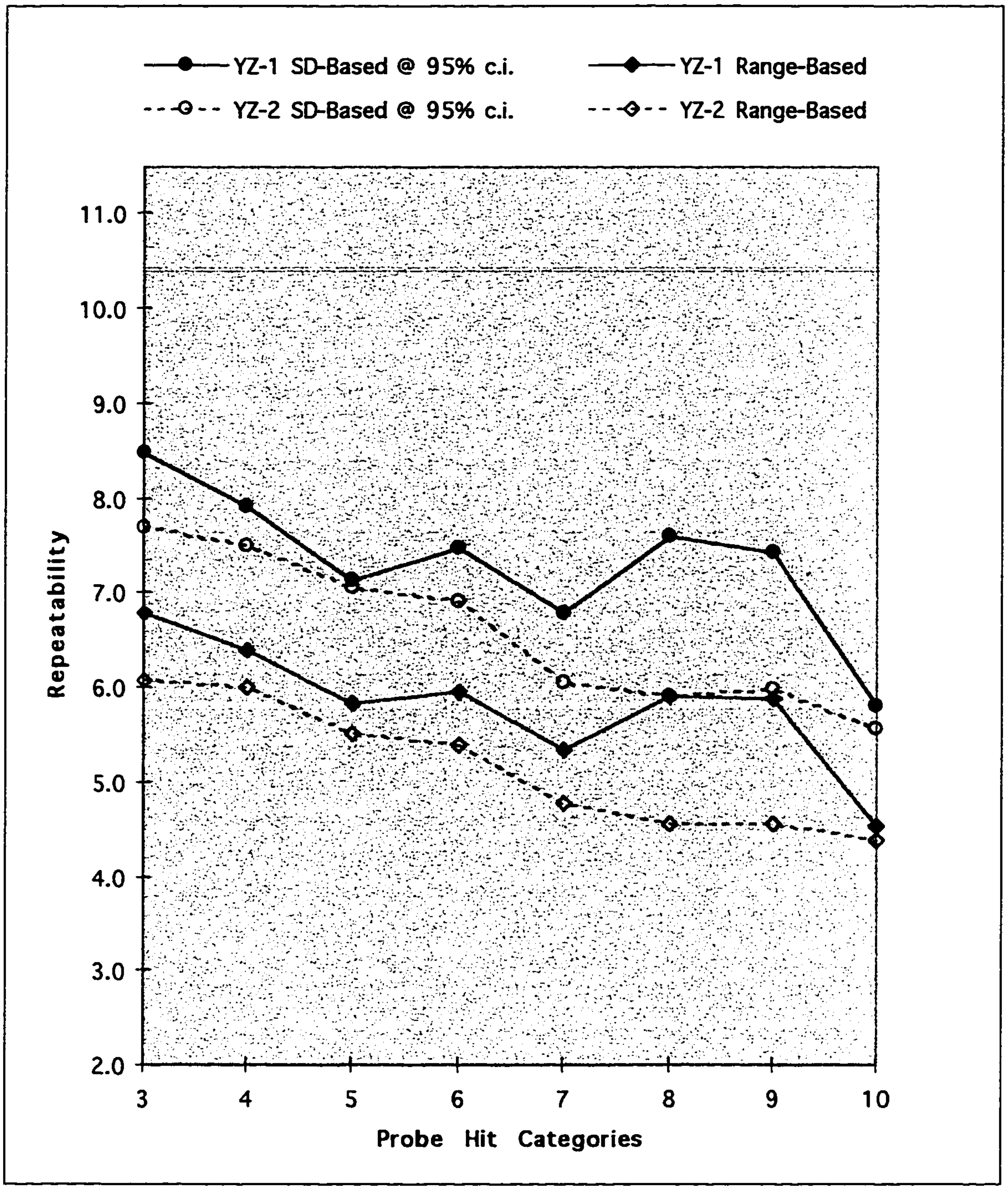


Figure 12. YZ Plane: Baseline probe hit repeatability. Note. All repeatability values are expressed in inches (x 10^{-5}).

The results of the mean repeatability analyses can be seen in the following sets of tables:

1. XY Plane: Mean SD-Based Repeatability, Table 18.
   Mean Range-Based Repeatability, Table 19.
2. XZ Plane: Mean SD-Based Repeatability, Table 20.
   Mean Range-Based Repeatability, Table 21.
3. YZ Plane: Mean SD-Based Repeatability, Table 22.
   Mean Range-Based Repeatability, Table 23.

To provide a greater understanding of the similarities and differences in baseline repeatability on the three measurement planes, pictorial representations of both SD- and range-based mean repeatability values have been provided (see Figures 13 and 14.). Once the baseline repeatability analysis was completed for each measurement plane, correlational values for the magnitude and degree of the relationship between probe hit repeatability and probe hit variations were calculated (see Table 24 for a summary listing of baseline correlation values).

With respect to the first research hypothesis, similarities were noted in the direction and magnitude of the relationship between average probe hit repeatability and probe hit variations between repeated baseline programs and baseline programs of different planes. This finding was further substantiated through the correlational values associated with mean probe hit repeatability of each planar baseline program (XY-M, XZ-M, and YZ-M). It should be noted that recorded variations in the correlational values between repeated baseline inspections in this table could be viewed as an indicator of instability in repeatability within selective diameter/probe hit categories. As a result, the correlational values associated with the mean repeatability analyses tend to reflect

Table 18

XY Plane: SD-Based Mean Repeatability

	Probe Hit Category							
Diameter	3-pt.	4-pt.	5-pt.	6-pt.	7-pt.	8-pt.	9-pt.	10-pt.
0.25	10.7	17.2	11.6	7.7	7.0	5.2	7.1	9.9
0.50	12.1	9.2	7.0	11.2	10.7	6.6	7.3	7.4
0.75	10.9	8.9	9.7	6.5	7.2	6.6	7.8	10.9
1.00	7.3	5.5	10.5	7.6	6.8	7.0	4.5	5.3
1.25	13.0	10.3	8.7	6.3	5.7	5.4	6.4	6.1
1.50	10.1	7.1	11.4	8.9	9.8	8.3	4.7	6.3
1.75	8.2	11.5	7.4	10.6	6.3	7.1	8.1	6.8
2.00	8.4	12.0	5.7	6.9	9.2	5.4	8.5	5.9
2.25	11.1	7.1	9.2	5.0	7.9	4.7	6.9	5.9
2.50	7.7	10.1	13.1	10.5	7.7	7.6	7.9	4.8
2.75	11.0	9.9	12.5	6.0	5.0	4.6	7.9	6.9
3.00	10.1	7.4	4.1	6.7	6.7	4.6	6.2	5.5
3.25	8.4	6.6	7.6	4.1	13.4	7.9	6.5	3.9
3.50	14.0	7.0	9.1	4.5	8.8	5.9	10.8	7.1
3.75	12.4	8.9	8.7	7.6	8.0	5.0	8.0	4.2
4.00	12.9	5.8	5.9	5.0	9.3	5.9	7.3	6.7
4.25	10.3	10.6	7.7	9.6	11.7	5.2	9.9	5.1
4.50	9.6	6.9	9.5	7.2	6.3	5.8	6.5	5.2
4.75	14.2	9.6	11.0	7.1	7.6	4.9	6.1	5.8
5.00	8.1	8.7	8.3	8.3	6.7	7.7	5.3	7.1
5.25	11.5	8.3	10.9	6.0	8.7	6.6	5.5	5.0
5.50	7.0	8.2	6.9	8.0	8.1	5.3	6.7	5.8
5.75	13.3	6.3	8.3	6.1	7.2	11.3	6.5	7.4
Avg Rep	10.5	8.8	8.9	7.3	8.1	6.3	7.1	6.3

Note. All repeatability values are expressed in inches (x 10^{-5}).

Table 19

XY Plane: Range-Based Mean Repeatability

	Probe Hit Category							
Diameter	3-pt.	4-pt.	5-pt.	6-pt.	7-pt.	8-pt.	9-pt.	10-pt.
0.25	8.5	14.0	9.0	5.5	5.5	4.5	6.0	8.0
0.50	9.5	7.0	5.5	8.0	9.0	5.0	6.0	6.0
0.75	8.5	7.5	8.5	4.5	6.5	5.5	5.5	9.5
1.00	6.0	4.0	7.5	5.5	5.5	5.0	3.5	4.5
1.25	12.0	8.5	7.5	4.5	4.5	4.5	5.0	4.5
1.50	7.5	6.0	10.0	7.5	8.0	7.5	3.5	5.5
1.75	6.0	10.0	6.0	7.5	4.5	5.5	6.0	5.5
2.00	6.0	10.0	5.0	6.0	7.0	4.0	7.0	5.0
2.25	8.5	5.5	7.0	4.0	5.5	3.5	6.0	5.0
2.50	7.0	8.0	9.0	8.0	7.0	6.0	6.5	3.5
2.75	9.5	7.5	10.5	4.5	4.5	3.0	6.0	5.5
3.00	7.0	6.5	3.0	5.0	6.0	4.0	4.5	4.5
3.25	6.0	5.5	6.5	3.5	9.5	6.0	5.0	3.5
3.50	11.0	5.0	7.5	3.5	7.0	4.0	7.5	5.5
3.75	9.5	7.5	6.5	5.5	6.5	4.0	6.5	3.5
4.00	10.0	4.5	4.0	3.5	7.5	4.0	5.5	5.0
4.25	7.0	8.5	6.5	7.5	7.5	4.5	8.5	4.5
4.50	7.5	5.5	8.0	6.0	4.5	4.0	4.5	4.0
4.75	12.5	8.0	9.0	5.5	6.0	4.0	5.0	5.0
5.00	6.5	7.0	6.0	6.0	6.0	6.0	4.5	5.5
5.25	10.5	6.0	8.0	4.5	7.0	5.0	5.0	3.5
5.50	5.0	6.5	5.5	7.0	6.5	4.5	5.5	4.5
5.75	11.0	4.5	6.5	5.0	6.0	7.5	5.5	6.0
Avg Rep	8.4	7.1	7.1	5.6	6.4	4.8	5.6	5.1

Note. All repeatability values are expressed in inches (x 10^{-5}).

Table 20

XZ Plane: SD-Based Mean Repeatability

	Probe Hit Category							
Diameter	3-pt.	4-pt.	5-pt.	6-pt.	7-pt.	8-pt.	9-pt.	10-pt.
0.25	8.5	10.1	12.8	6.0	7.3	7.3	9.7	8.3
0.50	9.6	4.9	7.1	7.7	5.6	4.9	6.9	4.5
0.75	6.0	7.9	6.5	4.7	7.3	6.8	5.0	4.8
1.00	9.7	8.4	8.3	5.5	6.6	6.6	5.2	8.0
1.25	9.8	5.1	7.8	8.4	10.6	6.5	6.4	6.0
1.50	9.7	6.9	7.1	8.5	6.1	6.7	4.5	6.9
1.75	9.5	7.1	12.0	9.4	7.7	5.4	10.6	6.5
2.00	10.3	6.6	8.1	8.7	4.9	6.1	7.5	5.8
2.25	5.3	5.4	7.8	5.5	11.9	5.1	3.7	3.4
2.50	9.4	5.2	9.1	6.8	7.8	5.7	6.4	6.1
2.75	12.8	8.6	11.3	6.3	5.8	5.4	6.3	4.9
3.00	9.2	6.0	3.7	6.1	5.5	5.7	4.0	4.2
3.25	7.2	8.6	6.1	7.8	7.3	4.4	5.0	4.4
3.50	9.7	6.5	8.0	5.5	6.7	5.7	5.8	5.3
3.75	8.3	5.3	8.3	6.1	6.1	4.2	3.6	3.7
4.00	6.4	5.8	9.4	8.0	4.2	4.1	5.2	3.9
4.25	6.6	5.9	10.4	6.5	6.2	4.8	5.3	5.6
4.50	9.6	9.2	7.1	7.3	9.3	6.8	4.8	6.1
4.75	7.3	6.8	7.1	4.9	5.4	5.3	4.7	5.5
5.00	8.3	10.4	12.3	8.2	5.3	7.0	8.8	7.3
5.25	9.7	8.3	10.8	4.2	9.1	5.3	6.3	8.5
5.50	6.4	6.8	5.8	4.1	3.8	6.4	3.6	4.4
5.75	7.3	5.3	9.3	5.9	5.7	4.9	5.1	5.5
Avg Rep	8.5	7.0	8.5	6.6	6.8	5.7	5.8	5.6

Note. All repeatability values are expressed in inches (x 10^{-5}).

Table 21

XZ Plane: Range-Based Mean Repeatability

	Probe Hit Category							
Diameter	3-pt.	4-pt.	5-pt.	6-pt.	7-pt.	8-pt.	9-pt.	10-pt.
0.25	6.0	8.0	10.5	4.0	5.5	5.5	8.5	7.0
0.50	7.0	4.0	5.0	6.0	4.0	4.0	5.0	3.5
0.75	4.5	6.0	5.0	4.0	5.0	5.5	4.0	4.0
1.00	7.5	7.0	7.0	4.5	5.0	5.0	4.0	6.0
1.25	9.0	4.0	6.0	7.0	8.0	5.5	5.5	4.5
1.50	7.5	5.0	6.0	6.5	5.0	5.5	3.5	5.5
1.75	7.0	5.5	9.5	6.5	7.0	4.5	9.0	5.5
2.00	7.5	4.5	6.5	6.5	3.5	5.0	6.0	4.5
2.25	4.0	3.5	6.0	4.0	9.0	4.0	3.0	3.0
2.50	6.5	3.5	7.0	5.5	6.5	5.0	5.0	5.0
2.75	11.0	6.5	9.5	5.5	4.5	3.5	5.0	3.5
3.00	8.0	4.5	3.0	4.5	4.0	4.5	3.0	3.5
3.25	6.0	6.5	5.0	6.5	6.0	3.5	4.0	3.5
3.50	7.5	5.0	6.0	5.0	6.0	4.5	3.5	4.0
3.75	5.5	4.0	6.5	4.5	5.0	3.5	2.5	2.5
4.00	4.5	5.0	8.0	6.0	3.0	3.0	4.5	3.0
4.25	5.0	4.5	8.0	5.5	5.0	4.0	4.5	4.0
4.50	7.0	8.0	5.5	6.0	7.0	5.5	3.5	5.5
4.75	6.0	5.0	5.5	3.5	4.0	3.5	3.5	4.0
5.00	6.0	8.0	11.0	7.0	4.0	5.5	7.5	5.5
5.25	8.0	6.0	8.5	3.0	7.5	4.0	5.0	7.0
5.50	4.5	5.5	4.0	3.0	3.0	4.5	3.0	3.5
5.75	6.0	4.5	7.0	4.5	4.5	4.0	3.5	4.5
Avg Rep	6.6	5.4	6.8	5.2	5.3	4.5	4.6	4.5

Note. All repeatability values are expressed in inches (x 10^{-5}).

Table 22

YZ Plane: SD-Based Mean Repeatability

	Probe Hit Category							
Diameter	3-pt.	4-pt.	5-pt.	6-pt.	7-pt.	8-pt.	9-pt.	10-pt.
0.25	14.1	9.4	10.3	8.0	8.9	6.8	5.8	4.4
0.50	10.8	8.9	6.6	5.8	6.4	15.3	7.2	7.0
0.75	9.7	9.8	9.2	10.6	8.3	7.8	7.5	4.9
1.00	6.7	6.8	6.7	6.6	4.3	4.8	5.3	4.8
1.25	4.9	8.6	6.5	6.0	6.0	5.4	7.2	6.8
1.50	8.4	6.8	8.0	6.2	4.0	5.3	3.6	5.0
1.75	4.6	6.7	6.9	8.7	5.8	4.2	10.6	5.0
2.00	8.4	9.8	6.7	6.3	8.3	4.9	7.1	4.5
2.25	7.1	7.7	6.3	4.0	6.9	5.4	6.0	9.3
2.50	10.3	6.6	5.1	6.5	5.3	4.9	5.6	4.9
2.75	8.3	8.3	8.2	9.2	5.3	4.4	5.8	5.4
3.00	10.7	7.7	6.6	7.4	6.6	2.9	5.2	6.1
3.25	7.0	6.2	8.3	5.7	5.0	6.6	6.9	4.6
3.50	9.1	5.8	10.0	7.0	6.6	10.6	8.8	5.8
3.75	5.7	4.7	5.2	7.3	5.4	4.8	5.7	2.8
4.00	8.0	7.7	7.4	8.5	5.7	13.3	5.5	5.0
4.25	9.2	12.6	6.1	7.4	5.6	8.0	9.2	5.1
4.50	5.9	6.9	7.0	10.2	7.3	6.9	9.3	7.3
4.75	5.5	8.6	6.5	5.3	7.1	7.7	6.5	4.6
5.00	8.5	5.6	5.1	8.8	5.0	7.3	6.5	5.1
5.25	8.3	9.6	8.4	8.4	9.9	6.9	6.9	9.1
5.50	6.8	6.2	5.8	5.3	5.7	6.0	5.4	6.4
5.75	8.1	6.2	6.4	6.0	8.2	4.6	6.7	6.5
Avg Rep	8.1	7.7	7.1	7.2	6.4	6.7	6.7	5.7

Note. All repeatability values are expressed in inches (x 10^{-5}).

Table 23

YZ Plane: Range-Based Mean Repeatability

	Probe Hit Category							
Diameter	3-pt.	4-pt.	5-pt.	6-pt.	7-pt.	8-pt.	9-pt.	10-pt.
0.25	11.5	7.0	8.0	7.0	7.0	6.0	4.0	3.5
0.50	8.5	6.5	4.5	4.0	5.0	10.5	6.0	5.0
0.75	7.5	8.0	7.0	8.5	6.0	5.5	5.5	3.0
1.00	4.5	5.5	5.5	5.0	3.0	3.5	4.0	4.0
1.25	4.5	7.0	5.0	5.0	5.0	5.0	6.0	5.5
1.50	7.5	5.0	7.0	5.0	4.0	4.5	2.5	4.0
1.75	3.5	5.0	5.5	8.0	4.0	3.0	9.5	3.5
2.00	6.5	9.0	5.5	5.5	6.5	4.0	5.5	3.5
2.25	5.0	6.5	5.5	3.0	6.5	4.5	4.5	8.0
2.50	7.5	5.0	4.0	5.5	4.5	3.5	4.0	3.5
2.75	6.5	6.0	6.5	8.5	4.0	3.5	4.5	4.5
3.00	8.0	6.5	5.0	6.0	5.5	2.0	4.0	5.0
3.25	6.0	5.0	7.0	4.0	3.5	5.5	6.0	3.5
3.50	7.5	4.5	8.5	5.5	5.0	9.0	7.0	4.5
3.75	4.5	4.0	4.0	5.5	4.0	3.5	4.5	2.0
4.00	7.0	6.5	6.0	5.5	5.0	10.5	4.5	4.0
4.25	8.0	10.5	5.0	6.0	4.5	6.0	7.0	4.5
4.50	4.5	5.5	5.0	7.0	5.5	5.0	7.0	6.0
4.75	4.0	7.5	5.0	4.0	5.5	6.5	4.5	3.5
5.00	6.0	4.0	4.0	7.5	3.5	5.5	5.0	4.0
5.25	7.0	8.0	6.5	6.0	8.5	5.0	5.5	7.0
5.50	5.5	5.0	4.5	4.0	4.5	4.5	4.0	5.5
5.75	7.0	5.0	6.0	4.5	6.0	4.0	5.0	5.0
Avg Rep	6.4	6.2	5.7	5.7	5.1	5.2	5.2	4.5

Note. All repeatability values are expressed in inches (x 10^{-5}).

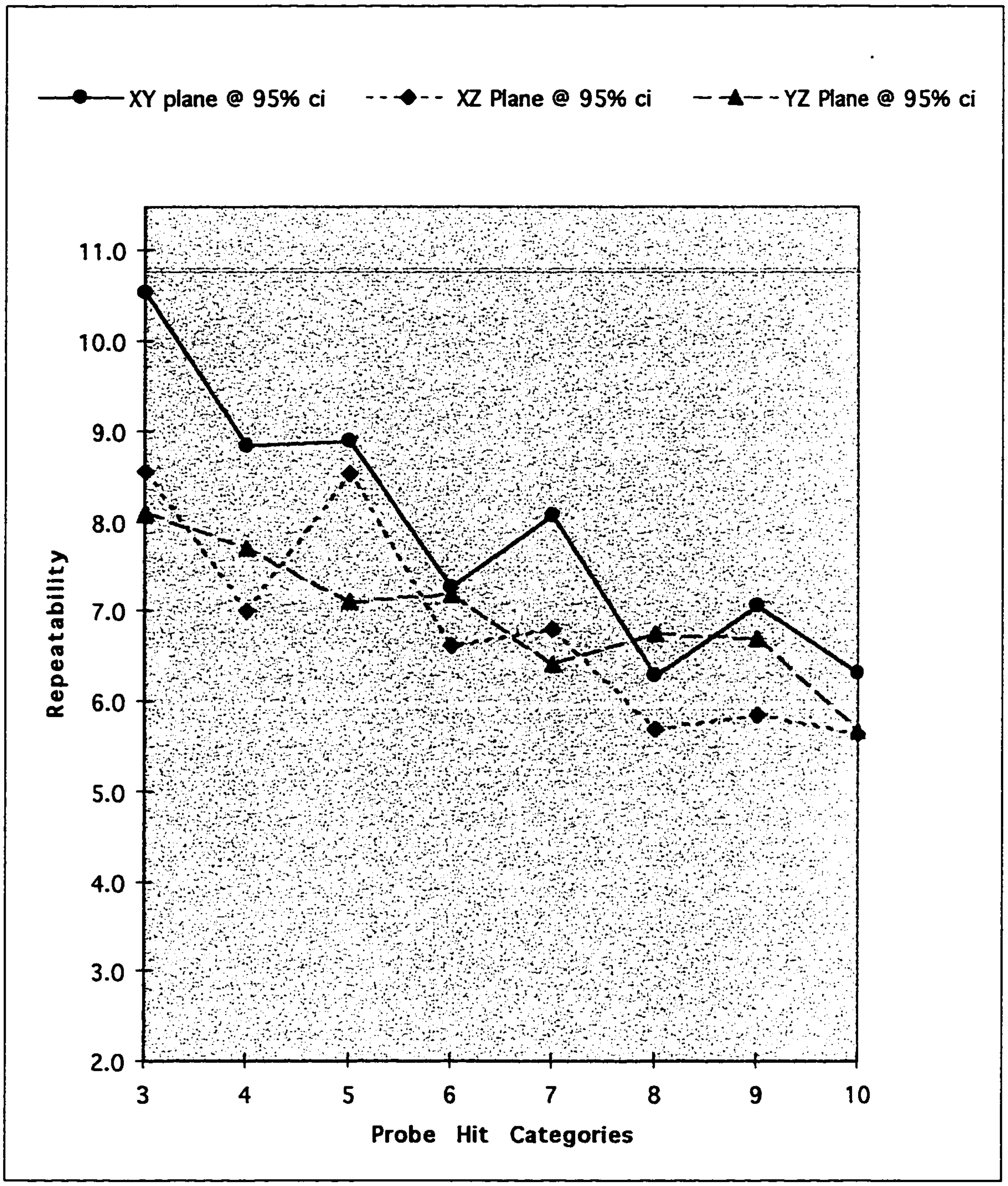


Figure 13. SD-based mean probe hit repeatability. Note. All repeatability values are expressed in inches (x 10^{-5}).

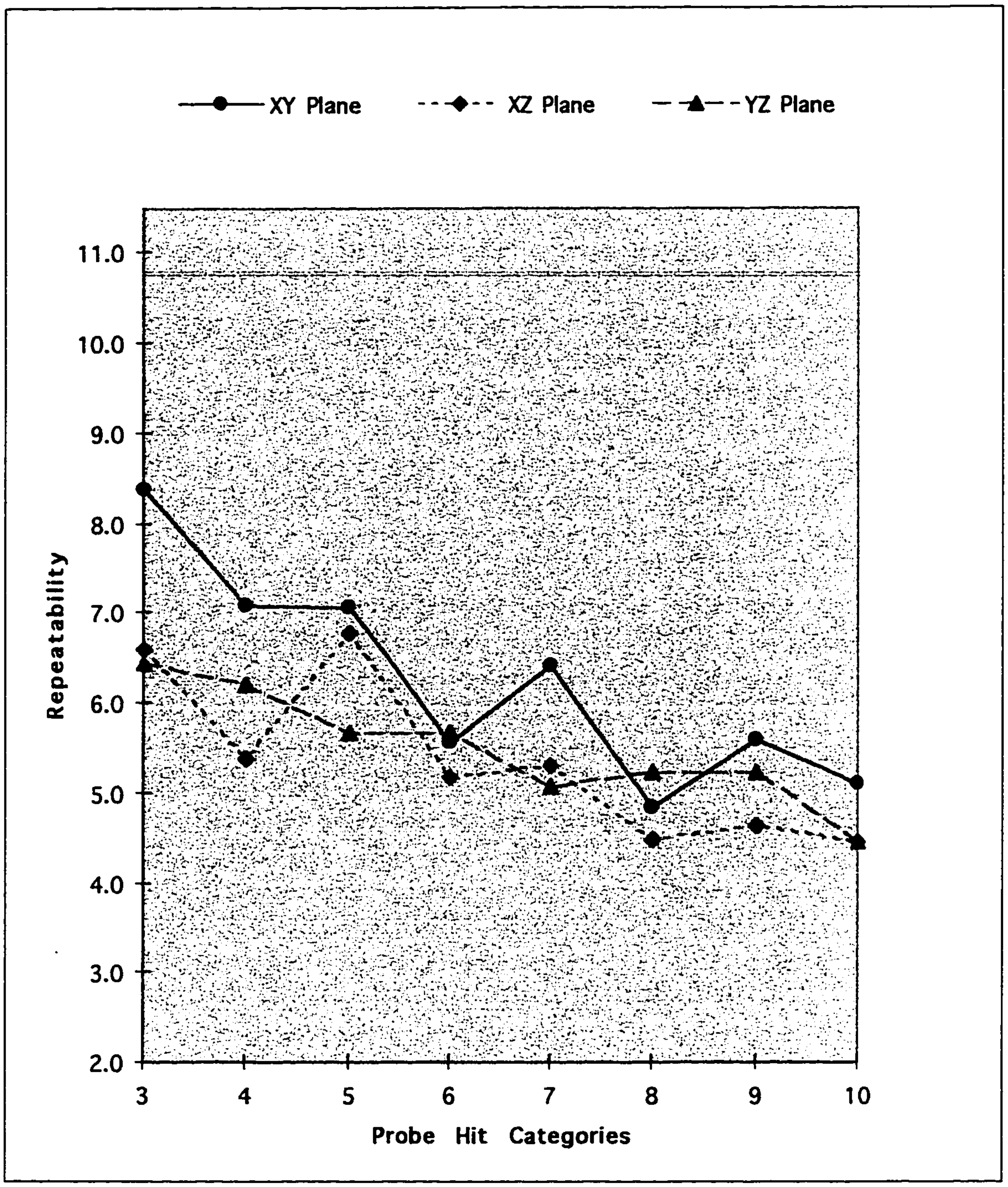


Figure 14. Range-based mean probe hit repeatability. Note. All repeatability values are expressed in inches (x 10^{-5}).

more accurately the true nature of the relationship between average probe hit repeatability and probe hit variations in diameter measurement.

Table 24

Correlations Between Average Probe Hit Repeatability and Probe Hit Variations

Baseline Data Sets	SD-Based Repeatability	Range-Based Repeatability
	XY Plane	
XY-1	-.87	-.86
XY-2	-.90	-.87
	XZ Plane	
XZ-1	-.55	-.51
XZ-2	-.95	-.93
	YZ Plane	
YZ-1	-.75	-.81
YZ-2	-.97	-.97
	Plane Means	
XY-M	-.90	-.88
XZ-M	-.86	-.82
YZ-M	-.92	-.94

Restatement of Hypothesis 2

The second research hypothesis states that at least one probe hit category from each circular test specimen within each baseline program (XY, XZ, and YZ) would indicate measurement stability. Measurement stability would be deemed significant if:

2a. Little or no difference was noted in the standard deviation values of counterpart test specimens and probe hit categories from repeated baseline programs.

2b. Little or no difference was noted in the kurtosis and skewness values of counterpart test specimens and probe hit categories from repeated baseline programs.

2c. Little or no difference was noted in the distribution means of counterpart test specimens and probe hit categories from repeated baseline programs.

The null hypothesis associated with this research hypothesis states that, within each planar baseline program (XY, XZ, and YZ), no probe hit category from any circular test specimen would indicate measurement stability.

Results of Hypothesis 2

In this study, diameter repeatability data was calculated using the diameter values collected from repeated baseline inspections (two on the XY plane, two on the XZ plane, and two on the YZ plane). This repeatability data was analyzed using two repeatability assessment methodologies, a multi-baseline assessment methodology and a single baseline assessment methodology.

The multi-baseline repeatability assessment was designed with the intent of identifying all diameter/probe hit categories with measurement stability. In other words, this methodology involved the identification of all diameter/probe hit categories that delivered identical or near identical repeatability values between repeated baseline inspections. To identify measurement stability within a given diameter/probe hit category, the repeatability values from the first baseline inspection were subtracted from their counterpart values in the second baseline inspection. An additional step incorporated as part of the difference calculations was the determination of the absolute value of the difference value. This step was added into the spreadsheet-based analysis process so that manual rearrangement of the subtraction orders would not be needed to ensure a positive difference. The use of the absolute value function in the multi-baseline assessment process was also deemed necessary since it permitted: (a) a normalized assessment of repeatability differences between counterpart baseline inspections, (b) a normalized assessment of mean probe hit repeatability difference values and (c) a realistic assessment of the theoretical differences that could be expected from optimization programs. Algebraically, the formulas used to calculate the difference between individual probe hit repeatability (IPHR) within all measurement planes were:

1. Repeatability Diff = Absolute Value ($IPHR_{SD/AB-1}$ - $IPHR_{SD/AB-2}$)
2. Repeatability Diff = Absolute Value ($IPHR_{R/AB-1}$ - $IPHR_{R/AB-2}$)

It should be noted that the assessment of repeatability difference using calculated repeatability values yielded the same results that would have been obtained if measurement precision values (SD) would have been used in the difference analysis. The results of the repeatability difference assessment of counterpart baseline inspections, both MB(3-10) and MB(3-6), can be seen in the following sets of tables:

1. XY Plane: MB(3-10) SD Repeatability Difference, Table 25.
   MB(3-10) Range Repeatability Difference, Table 26.
   MB(3-6) SD & Range Repeatability Difference, Table 27.
2. XZ Plane: SD-Based Repeatability Difference, Table 28.
   Range-Based Repeatability Difference, Table 29.
   MB(3-6) SD & Range Repeatability Difference, Table 30.
3. YZ Plane: SD-Based Repeatability Difference, Table 31.
   Range-Based Repeatability Difference, Table 32.
   MB(3-6) SD & Range Repeatability Difference, Table 33.

Once the probe hit categories for each plane and probe hit range were identified through the repeatability assessments and difference, kurtosis, and skewness analyses, the structure of the multi-baseline (3-10) and (3-6) optimization programs were established. The single-baseline repeatability assessment, on the other hand, was designed to identify one specific probe hit category from each test specimen using the repeatability results of a single baseline inspection from each of the three planes. This assessment methodology involved the identification of the probe hit category that yielded the "best" measurement repeatability for a given test specimen. It should be noted that the term "best" infers the particular probe hit category of a given test specimen with the smallest repeatability value (the least amount of measurement variability). Once the probe hit categories were identified for each plane and probe hit range, the structure of the single-baseline (3-10) and (3-6) optimization programs were established. The diameter/probe hit categories selected for use in the multi-baseline and single baseline optimization programs with respect to the three measurement planes (XY, XZ, and YZ) can be seen in Tables 34, 35, and 36, respectively.

Table 25

XY Plane: SD-Based Repeatability Difference Values Used to Assess MB(3-10) Repeatability

	Probe Hit Category							
Diameter	3-pt.	4-pt.	5-pt.	6-pt.	7-pt.	8-pt.	9-pt.	10-pt.
0.25	1.6	0.1	8.2	2.3	3.2	0.7	<u>0.2</u>	6.9
0.50	4.7	6.2	<u>0.4</u>	5.2	3.6	0.7	2.5	3.6
0.75	7.5	2.9	2.2	2.7	4.2	2.0	<u>1.9</u>	2.4
1.00	2.1	1.1	0.1	2.0	1.5	1.5	<u>0.8</u>	1.4
1.25	2.8	7.2	0.6	1.6	2.4	2.2	<u>0.2</u>	1.8
1.50	1.2	1.5	2.7	1.8	2.0	7.8	0.7	<u>0.3</u>
1.75	<u>0.1</u>	0.5	2.2	1.1	3.1	6.6	3.1	1.2
2.00	6.3	0.6	2.2	3.4	1.7	0.8	3.1	<u>0.1</u>
2.25	3.1	4.1	4.3	2.0	<u>0.6</u>	1.3	1.6	1.2
2.50	0.0	1.2	2.6	1.6	<u>0.0</u>	2.6	2.5	0.3
2.75	1.4	4.8	0.1	1.6	0.9	<u>0.2</u>	2.2	3.0
3.00	4.6	0.8	0.5	2.5	2.4	<u>0.0</u>	0.6	0.9
3.25	1.5	<u>0.5</u>	1.5	2.9	12.1	8.4	1.9	2.0
3.50	1.4	2.3	2.6	3.2	3.7	4.3	5.8	<u>1.8</u>
3.75	6.4	3.3	2.8	2.4	3.1	3.5	1.2	<u>0.8</u>
4.00	2.3	6.7	3.2	<u>0.8</u>	2.3	2.6	2.5	1.4
4.25	8.9	1.1	1.6	0.9	0.5	1.8	<u>0.1</u>	0.9
4.50	1.8	0.6	4.8	<u>0.2</u>	2.0	0.8	1.8	2.2
4.75	0.2	<u>1.0</u>	7.0	1.2	3.9	2.2	2.3	3.9
5.00	7.0	2.1	<u>0.7</u>	0.8	2.6	4.1	1.5	1.2
5.25	2.4	2.1	4.3	2.6	3.1	<u>0.1</u>	0.6	1.4
5.50	2.0	0.4	0.3	1.5	2.6	2.7	1.6	<u>0.3</u>
5.75	5.2	3.9	0.2	0.7	1.9	4.0	1.1	<u>0.3</u>
Avg. Diff.	3.2	2.4	2.4	2.0	2.7	2.6	1.7	1.7

Note. Underlined values indicate the diameter/probe hit categories selected for MB(3-10) repeatability optimization. All repeatability difference values are expressed in inches (x 10^{-5}).

Table 26

XY Plane: Range-Based Repeatability Difference Values Used to Assess MB(3-10) Repeatability

	Probe Hit Category							
Diameter	3-pt.	4-pt.	5-pt.	6-pt.	7-pt.	8-pt.	9-pt.	10-pt.
0.25	3.0	2.0	6.0	3.0	3.0	1.0	0.0	6.0
0.50	5.0	4.0	1.0	2.0	4.0	2.0	2.0	4.0
0.75	5.0	3.0	3.0	3.0	3.0	3.0	1.0	3.0
1.00	2.0	0.0	1.0	1.0	1.0	2.0	1.0	1.0
1.25	2.0	5.0	1.0	1.0	1.0	1.0	0.0	1.0
1.50	1.0	2.0	2.0	3.0	4.0	7.0	1.0	1.0
1.75	0.0	0.0	2.0	1.0	1.0	5.0	2.0	1.0
2.00	4.0	0.0	2.0	2.0	2.0	0.0	0.0	0.0
2.25	1.0	5.0	2.0	2.0	1.0	1.0	2.0	2.0
2.50	2.0	2.0	2.0	2.0	0.0	2.0	1.0	1.0
2.75	1.0	3.0	1.0	1.0	1.0	0.0	2.0	3.0
3.00	2.0	1.0	0.0	2.0	2.0	0.0	1.0	1.0
3.25	2.0	1.0	1.0	3.0	9.0	6.0	2.0	3.0
3.50	0.0	0.0	3.0	3.0	2.0	4.0	3.0	1.0
3.75	5.0	3.0	3.0	1.0	3.0	2.0	3.0	1.0
4.00	2.0	5.0	2.0	1.0	1.0	2.0	1.0	0.0
4.25	6.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
4.50	3.0	1.0	2.0	0.0	1.0	0.0	1.0	2.0
4.75	1.0	0.0	4.0	1.0	2.0	2.0	2.0	4.0
5.00	5.0	2.0	0.0	0.0	2.0	4.0	1.0	1.0
5.25	3.0	2.0	2.0	1.0	2.0	0.0	0.0	1.0
5.50	2.0	1.0	1.0	0.0	3.0	3.0	1.0	1.0
5.75	4.0	3.0	1.0	0.0	0.0	3.0	1.0	0.0
Avg. Diff.	2.7	2.0	1.9	1.5	2.1	2.2	1.3	1.7

Note. Underlined values indicate the diameter/probe hit categories selected for MB(3-10) repeatability optimization. All repeatability difference values are expressed in inches (x 10^{-5}).

Table 27

XY Plane: Repeatability Difference Values Used to Assess MB(3-6) Repeatability

	SD-Based				Range-Based			
Diameter	3-pt.	4-pt.	5-pt.	6-pt.	3-pt.	4-pt.	5-pt.	6-pt.
0.25	1.6	0.1	8.2	2.3	3.0	2.0	6.0	3.0
0.50	4.7	6.2	0.4	5.2	5.0	4.0	1.0	2.0
0.75	7.5	2.9	2.2	2.7	5.0	3.0	3.0	3.0
1.00	2.1	1.1	0.1	2.0	2.0	0.0	1.0	1.0
1.25	2.8	7.2	0.6	1.6	2.0	5.0	1.0	1.0
1.50	1.2	1.5	2.7	1.8	1.0	2.0	2.0	3.0
1.75	0.1	0.5	2.2	1.1	0.0	0.0	2.0	1.0
2.00	6.3	0.6	2.2	3.4	4.0	0.0	2.0	2.0
2.25	3.1	4.1	4.3	2.0	1.0	5.0	2.0	2.0
2.50	0.0	1.2	2.6	1.6	2.0	2.0	2.0	2.0
2.75	1.4	4.8	0.1	1.6	1.0	3.0	1.0	1.0
3.00	4.6	0.8	0.5	2.5	2.0	1.0	0.0	2.0
3.25	1.5	0.5	1.5	2.9	2.0	1.0	1.0	3.0
3.50	1.4	2.3	2.6	3.2	0.0	0.0	3.0	3.0
3.75	6.4	3.3	2.8	2.4	5.0	3.0	3.0	1.0
4.00	2.3	6.7	3.2	0.8	2.0	5.0	2.0	1.0
4.25	8.9	1.1	1.6	0.9	6.0	1.0	1.0	1.0
4.50	1.8	0.6	4.8	0.2	3.0	1.0	2.0	0.0
4.75	0.2	1.0	7.0	1.2	1.0	0.0	4.0	1.0
5.00	7.0	2.1	0.7	0.8	5.0	2.0	0.0	0.0
5.25	2.4	2.1	4.3	2.6	3.0	2.0	2.0	1.0
5.50	2.0	0.4	0.3	1.5	2.0	1.0	1.0	0.0
5.75	5.2	3.9	0.2	0.7	4.0	3.0	1.0	0.0
Avg. Diff.	3.2	2.4	2.4	2.0	2.7	2.0	1.9	1.5

Note. Underlined values indicate the diameter/probe hit categories selected for MB(3-6) repeatability optimization. All repeatability difference values are expressed in inches (x 10^{-5}).

Table 28

XZ Plane: SD-Based Repeatability Difference Values Used to Assess MB(3-10) Repeatability

	Probe Hit Category							
Diameter	3-pt.	4-pt.	5-pt.	6-pt.	7-pt.	8-pt.	9-pt.	10-pt.
0.25	8.3	7.2	3.9	3.5	0.7	2.1	9.4	4.6
0.50	3.6	0.4	0.2	1.5	2.6	2.6	2.7	0.9
0.75	0.6	2.8	1.0	2.8	5.2	2.3	2.4	4.4
1.00	3.6	0.5	3.0	0.5	0.2	3.5	0.2	0.3
1.25	4.4	0.3	2.1	3.7	7.0	1.9	3.4	2.9
1.50	4.7	1.6	1.7	3.6	1.4	1.6	2.3	1.8
1.75	1.1	0.6	11.3	0.4	0.4	3.2	3.0	1.1
2.00	5.6	1.3	2.0	3.2	1.3	4.5	3.0	2.5
2.25	3.2	0.6	4.5	1.0	3.0	3.2	0.6	0.1
2.50	7.4	0.7	2.9	3.7	2.8	0.0	2.7	2.0
2.75	6.0	4.6	5.9	0.3	2.5	1.5	2.1	1.5
3.00	1.5	2.2	3.4	0.9	2.2	0.7	0.4	1.7
3.25	1.0	2.1	2.2	3.7	6.3	1.1	2.3	0.3
3.50	4.0	2.3	1.4	4.5	1.1	3.7	1.0	1.3
3.75	0.3	0.8	0.8	0.5	0.4	1.0	0.3	1.2
4.00	1.3	1.0	1.2	7.4	2.6	1.5	0.3	0.1
4.25	4.6	1.5	2.0	0.4	1.1	2.3	0.5	1.2
4.50	0.8	3.9	0.8	1.7	3.1	3.9	2.3	3.1
4.75	1.1	2.2	1.2	1.6	1.7	3.3	1.6	0.4
5.00	2.2	2.1	8.5	0.4	3.3	0.2	2.7	1.7
5.25	1.0	5.3	5.1	3.4	5.5	1.4	0.9	8.2
5.50	0.5	1.7	0.3	1.8	0.1	0.9	0.7	1.5
5.75	0.5	0.9	0.6	1.2	0.7	2.2	2.7	1.6
Avg. Diff.	2.9	2.0	2.9	2.2	2.4	2.1	2.0	1.9

Note. Underlined values indicate the diameter/probe hit categories selected for MB(3-10) repeatability optimization. All repeatability difference values are expressed in inches (x 10^{-5}).

Table 29

XZ Plane: Range-Based Repeatability Difference Values Used to Assess MB(3-10) Repeatability

	Probe Hit Category							
Diameter	3-pt.	4-pt.	5-pt.	6-pt.	7-pt.	8-pt.	9-pt.	10-pt.
0.25	6.0	6.0	1.0	2.0	1.0	3.0	9.0	4.0
0.50	4.0	0.0	0.0	0.0	2.0	2.0	2.0	1.0
0.75	1.0	2.0	0.0	2.0	2.0	1.0	2.0	4.0
1.00	1.0	0.0	2.0	1.0	0.0	2.0	0.0	0.0
1.25	4.0	0.0	2.0	4.0	4.0	1.0	3.0	1.0
1.50	5.0	0.0	2.0	3.0	2.0	1.0	1.0	1.0
1.75	0.0	1.0	9.0	1.0	0.0	3.0	4.0	1.0
2.00	5.0	1.0	1.0	1.0	1.0	4.0	2.0	3.0
2.25	2.0	1.0	4.0	0.0	2.0	2.0	0.0	0.0
2.50	5.0	1.0	2.0	5.0	3.0	0.0	2.0	2.0
2.75	6.0	3.0	3.0	1.0	3.0	1.0	2.0	1.0
3.00	2.0	3.0	4.0	1.0	0.0	1.0	0.0	1.0
3.25	2.0	1.0	2.0	3.0	6.0	1.0	2.0	1.0
3.50	1.0	2.0	0.0	4.0	2.0	3.0	1.0	2.0
3.75	1.0	0.0	1.0	1.0	0.0	1.0	1.0	1.0
4.00	1.0	0.0	0.0	6.0	2.0	2.0	1.0	0.0
4.25	4.0	1.0	0.0	1.0	0.0	2.0	1.0	2.0
4.50	0.0	4.0	1.0	2.0	2.0	3.0	3.0	3.0
4.75	0.0	2.0	1.0	1.0	2.0	3.0	1.0	0.0
5.00	2.0	2.0	10.0	0.0	2.0	1.0	3.0	3.0
5.25	0.0	2.0	3.0	2.0	5.0	2.0	0.0	8.0
5.50	1.0	1.0	0.0	2.0	0.0	1.0	0.0	1.0
5.75	0.0	1.0	0.0	3.0	1.0	2.0	1.0	1.0
Avg. Diff.	2.3	1.5	2.1	2.0	1.8	1.8	1.8	1.8

Note. Underlined values indicate the diameter/probe hit categories selected for MB(3-10) repeatability optimization. All repeatability difference values are expressed in inches (x 10^{-5}).

Table 30

XZ Plane: Repeatability Difference Values Used to Assess MB(3-6) Repeatability

	SD-Based				Range-Based			
Diameter	3-pt.	4-pt.	5-pt.	6-pt.	3-pt.	4-pt.	5-pt.	6-pt.
0.25	8.3	7.2	3.9	<u>3.5</u>	6.0	6.0	1.0	<u>2.0</u>
0.50	3.6	<u>0.4</u>	0.2	1.5	4.0	<u>0.0</u>	0.0	0.0
0.75	<u>0.6</u>	2.8	1.0	2.8	<u>1.0</u>	2.0	0.0	2.0
1.00	3.6	0.5	3.0	<u>0.5</u>	1.0	0.0	2.0	<u>1.0</u>
1.25	4.4	<u>0.3</u>	2.1	3.7	4.0	<u>0.0</u>	2.0	4.0
1.50	4.7	<u>1.6</u>	1.7	3.6	5.0	<u>0.0</u>	2.0	3.0
1.75	1.1	<u>0.6</u>	11.3	0.4	0.0	<u>1.0</u>	9.0	1.0
2.00	5.6	<u>1.3</u>	2.0	3.2	5.0	<u>1.0</u>	1.0	1.0
2.25	3.2	<u>0.6</u>	4.5	1.0	2.0	<u>1.0</u>	4.0	0.0
2.50	7.4	<u>0.7</u>	2.9	3.7	5.0	<u>1.0</u>	2.0	5.0
2.75	6.0	4.6	5.9	<u>0.3</u>	6.0	3.0	3.0	<u>1.0</u>
3.00	1.5	2.2	3.4	<u>0.9</u>	2.0	3.0	4.0	<u>1.0</u>
3.25	<u>1.0</u>	2.1	2.2	3.7	<u>2.0</u>	1.0	2.0	3.0
3.50	4.0	2.3	<u>1.4</u>	4.5	1.0	2.0	<u>0.0</u>	4.0
3.75	0.3	0.8	0.8	<u>0.5</u>	1.0	0.0	1.0	<u>1.0</u>
4.00	1.3	<u>1.0</u>	1.2	7.4	1.0	<u>0.0</u>	0.0	6.0
4.25	4.6	1.5	2.0	<u>0.4</u>	4.0	1.0	0.0	<u>1.0</u>
4.50	0.8	3.9	<u>0.8</u>	1.7	0.0	4.0	<u>1.0</u>	2.0
4.75	1.1	2.2	<u>1.2</u>	1.6	0.0	2.0	<u>1.0</u>	1.0
5.00	2.2	2.1	8.5	<u>0.4</u>	2.0	2.0	10.0	<u>0.0</u>
5.25	<u>1.0</u>	5.3	5.1	3.4	<u>0.0</u>	2.0	3.0	2.0
5.50	0.5	1.7	<u>0.3</u>	1.8	1.0	1.0	<u>0.0</u>	2.0
5.75	<u>0.5</u>	0.9	0.6	1.2	<u>0.0</u>	1.0	0.0	3.0
Avg. Diff.	2.9	2.0	2.9	2.2	2.3	1.5	2.1	2.0

Note. Underlined values indicate the diameter/probe hit categories selected for MB(3-6) repeatability optimization. All repeatability values are expressed in inches (x 10^{-5}).

Table 31

YZ Plane: SD-Based Repeatability Difference Values Used to Assess MB(3-10) Repeatability

	Probe Hit Category							
Diameter	3-pt.	4-pt.	5-pt.	6-pt.	7-pt.	8-pt.	9-pt.	10-pt.
0.25	1.5	2.9	1.2	0.0	1.9	0.2	4.2	1.3
0.50	2.0	6.7	4.8	5.3	5.2	10.6	2.3	2.2
0.75	2.2	4.3	1.1	1.1	4.2	2.0	1.5	2.1
1.00	2.0	5.1	3.0	0.7	1.1	1.1	2.2	1.1
1.25	1.0	1.6	0.1	3.7	2.0	0.0	2.4	2.9
1.50	3.3	0.1	2.0	1.6	4.2	1.7	1.9	0.0
1.75	0.1	0.5	1.6	3.1	1.5	1.7	7.9	0.6
2.00	6.1	7.7	1.8	1.3	6.6	2.0	5.8	0.9
2.25	3.4	0.4	0.3	1.8	2.4	1.5	1.4	6.0
2.50	5.8	1.3	3.4	0.2	3.9	3.2	0.3	2.0
2.75	1.5	3.3	5.9	10.8	0.4	0.5	0.8	1.7
3.00	0.2	4.5	2.6	0.2	3.7	1.2	2.0	1.5
3.25	0.7	1.7	1.1	1.0	1.3	3.5	3.7	0.1
3.50	2.6	3.0	8.1	0.4	1.3	7.8	4.6	1.9
3.75	1.5	1.0	2.9	4.0	0.9	1.0	1.5	0.3
4.00	2.6	3.9	1.9	2.8	2.2	13.6	0.9	0.0
4.25	2.2	12.3	3.3	3.4	1.8	1.5	6.5	0.8
4.50	0.5	0.8	1.0	1.1	0.1	3.8	10.3	3.9
4.75	1.2	9.8	1.2	0.2	1.2	1.3	4.8	0.9
5.00	0.9	3.1	1.9	3.5	1.4	3.6	0.9	0.4
5.25	4.6	2.1	6.3	6.2	7.3	0.2	1.2	3.7
5.50	0.4	0.0	1.5	0.0	3.5	0.9	3.1	5.1
5.75	2.5	3.7	0.9	1.3	1.5	1.6	3.4	1.1
Avg. Diff.	2.1	3.5	2.5	2.3	2.6	2.8	3.2	1.8

Note. Underlined values indicate the diameter/probe hit categories selected for MB(3-10) repeatability optimization. All repeatability difference values are expressed in inches (x 10^{-5}).

Table 32

YZ Plane: Range-Based Repeatability Difference Values Used to Assess MB(3-10) Repeatability

	Probe Hit Category							
Diameter	3-pt.	4-pt.	5-pt.	6-pt.	7-pt.	8-pt.	9-pt.	10-pt.
0.25	1.0	2.0	0.0	0.0	2.0	0.0	2.0	1.0
0.50	1.0	5.0	3.0	4.0	4.0	5.0	2.0	2.0
0.75	3.0	4.0	0.0	1.0	4.0	1.0	3.0	2.0
1.00	1.0	5.0	3.0	0.0	0.0	1.0	0.0	2.0
1.25	1.0	2.0	0.0	4.0	0.0	0.0	2.0	3.0
1.50	3.0	0.0	2.0	0.0	4.0	1.0	1.0	0.0
1.75	1.0	0.0	1.0	2.0	2.0	0.0	7.0	1.0
2.00	5.0	8.0	1.0	1.0	5.0	2.0	5.0	1.0
2.25	2.0	1.0	1.0	2.0	3.0	1.0	1.0	6.0
2.50	3.0	0.0	2.0	1.0	3.0	3.0	0.0	1.0
2.75	1.0	2.0	5.0	11.0	0.0	1.0	1.0	1.0
3.00	2.0	5.0	2.0	0.0	3.0	0.0	2.0	2.0
3.25	0.0	2.0	0.0	0.0	1.0	3.0	2.0	1.0
3.50	3.0	3.0	9.0	1.0	2.0	8.0	6.0	1.0
3.75	1.0	0.0	2.0	5.0	0.0	1.0	3.0	0.0
4.00	2.0	5.0	2.0	3.0	2.0	11.0	1.0	0.0
4.25	2.0	11.0	2.0	2.0	3.0	2.0	4.0	1.0
4.50	1.0	1.0	0.0	0.0	1.0	2.0	8.0	2.0
4.75	2.0	9.0	0.0	0.0	1.0	1.0	3.0	1.0
5.00	0.0	2.0	2.0	5.0	1.0	3.0	0.0	0.0
5.25	4.0	2.0	3.0	4.0	7.0	0.0	1.0	4.0
5.50	1.0	0.0	1.0	0.0	3.0	1.0	2.0	5.0
5.75	2.0	4.0	2.0	1.0	0.0	2.0	2.0	0.0
Avg. Diff.	0.8	0.4	0.1	0.6	0.7	1.7	1.5	0.3

Note. Underlined values indicate the diameter/probe hit categories selected for MB(3-10) repeatability optimization. All repeatability difference values are expressed in inches (x 10^{-5}).

Table 33

YZ Plane: Repeatability Difference Values Used to Assess MB(3-6) Repeatability

	SD-Based				Range-Based			
Diameter	3-pt.	4-pt.	5-pt.	6-pt.	3-pt.	4-pt.	5-pt.	6-pt.
0.25	1.5	2.9	1.2	0.0	1.0	2.0	0.0	0.0
0.50	2.0	6.7	4.8	5.3	1.0	5.0	3.0	4.0
0.75	2.2	4.3	1.1	1.1	3.0	4.0	0.0	1.0
1.00	2.0	5.1	3.0	0.7	1.0	5.0	3.0	0.0
1.25	1.0	1.6	0.1	3.7	1.0	2.0	0.0	4.0
1.50	3.3	0.1	2.0	1.6	3.0	0.0	2.0	0.0
1.75	0.1	0.5	1.6	3.1	1.0	0.0	1.0	2.0
2.00	6.1	7.7	1.8	1.3	5.0	8.0	1.0	1.0
2.25	3.4	0.4	0.3	1.8	2.0	1.0	1.0	2.0
2.50	5.8	1.3	3.4	0.2	3.0	0.0	2.0	1.0
2.75	1.5	3.3	5.9	10.8	1.0	2.0	5.0	11.0
3.00	0.2	4.5	2.6	0.2	2.0	5.0	2.0	0.0
3.25	0.7	1.7	1.1	1.0	0.0	2.0	0.0	0.0
3.50	2.6	3.0	8.1	0.4	3.0	3.0	9.0	1.0
3.75	1.5	1.0	2.9	4.0	1.0	0.0	2.0	5.0
4.00	2.6	3.9	1.9	2.8	2.0	5.0	2.0	3.0
4.25	2.2	12.3	3.3	3.4	2.0	11.0	2.0	2.0
4.50	0.5	0.8	1.0	1.1	1.0	1.0	0.0	0.0
4.75	1.2	9.8	1.2	0.2	2.0	9.0	0.0	0.0
5.00	0.9	3.1	1.9	3.5	0.0	2.0	2.0	5.0
5.25	4.6	2.1	6.3	6.2	4.0	2.0	3.0	4.0
5.50	0.4	0.0	1.5	0.0	1.0	0.0	1.0	0.0
5.75	2.5	3.7	0.9	1.3	2.0	4.0	2.0	1.0
Avg. Diff.	2.1	3.5	2.5	2.3	0.8	0.4	0.1	0.6

Note. Underlined values indicate the diameter/probe hit categories selected for MB(3-6) repeatability optimization. All repeatability difference values are expressed in inches (x 10^{-5}).

Table 34

XY Plane: Optimization Program Structure Constructed from SD-Based Repeatability Values (## probe hits)

Diameter	MB(3-10)	MB(3-6)	SB(3-10)	SB(3-6)
0.25	9	3	7	6
0.50	5	5	10	4
0.75	9	6	6	6
1.00	9	4	10	4
1.25	9	5	7	4
1.50	10	4	8	4
1.75	3	3	7	3
2.00	10	4	3	3
2.25	7	6	4	4
2.50	7	3	10	3
2.75	8	5	8	6
3.00	8	5	5	5
3.25	4	4	6	6
3.50	10	4	6	6
3.75	10	6	8	6
4.00	6	6	6	6
4.25	9	6	10	3
4.50	6	6	10	5
4.75	4	6	9	5
5.00	5	5	7	5
5.25	8	6	10	6
5.50	10	5	10	3
5.75	10	6	7	6

Table 35

XZ Plane: Optimization Program Structure Constructed from SD-Based Repeatability Values (## probe hits)

Diameter	MB(3-10)	MB(3-6)	SB(3-10)	SB(3-6)
0.25	7	6	9	6
0.50	5	4	8	4
0.75	3	3	10	6
1.00	9	6	8	6
1.25	4	4	10	4
1.50	7	4	9	5
1.75	7	4	10	5
2.00	7	4	10	5
2.25	10	4	10	4
2.50	8	4	9	6
2.75	6	6	10	6
3.00	9	6	10	4
3.25	10	3	8	5
3.50	9	5	8	4
3.75	9	6	10	4
4.00	10	4	8	6
4.25	9	6	9	4
4.50	5	5	10	5
4.75	10	5	8	6
5.00	8	6	7	5
5.25	9	3	8	6
5.50	7	5	6	6
5.75	7	3	9	6

Table 36

YZ Plane: Optimization Program Structure Constructed from SD-Based Repeatability Values (## probe hits)

Diameter	MB(3-10)	MB(3-6)	SB(3-10)	SB(3-6)
0.25	8	6	10	6
0.50	10	3	7	4
0.75	5	5	10	4
1.00	6	6	4	4
1.25	8	5	6	6
1.50	10	4	8	3
1.75	3	3	8	3
2.00	10	6	8	3
2.25	5	5	6	6
2.50	9	6	7	4
2.75	8	3	8	6
3.00	6	6	8	5
3.25	10	3	10	4
3.50	6	6	4	4
3.75	10	4	10	4
4.00	10	5	7	4
4.25	10	5	5	5
4.50	7	3	9	3
4.75	6	6	9	6
5.00	10	3	5	5
5.25	8	4	6	6
5.50	6	6	10	6
5.75	5	5	8	6

With respect to the second research hypothesis, the repeatability difference assessments between repeated baseline programs indicated that measurement stability was not significant within all test specimens and planes. In other words, instances occurred in which similar repeatability values were not achieved in any probe hit category of a given test specimen between repeated baseline inspections. In short, the null hypothesis was shown to have merit in that measurement stability in at least one probe hit category could not be assured within all test specimens and planes. When this situation was encountered the diameter/probe hit category with the least instability (smallest difference) relative to the least repeatability and skewness and kurtosis difference was selected for use in the multi-baseline (3-10) and (3-6) optimization programs. It should be noted the single baseline repeatability assessment did not involve a difference assessment, thus repeatability difference was not a factor in probe hit category selection.

Restatement of Hypothesis 3

The third research hypothesis states that an improvement in diameter measurement repeatability would be achieved through the assessment and optimization of multi-baseline repeatability data within each planar measurement test (XY, XZ, and YZ). Repeatability improvement would be deemed significant if:

3a. The average repeatability values of the multi-baseline optimization programs, MB(3-10) and MB(3-6), were less than the average repeatability values of all baseline probe hit categories within the stated probe hit ranges and plane.

3b. The time required to complete one measurement pass of each test specimen plate using the MB(3-10) optimization program was less than the time required to complete one measurement pass using the baseline probe hit category with the "best" average probe hit repeatability. The term "best" implies the smallest numeric repeatability value. This condition would also be noted with the MB(3-6) optimization programs and a given baseline probe hit category using the same probe hit range.

3c. The t-statistic analysis of probe hit repeatability values from the optimization programs and the "best" probe hit categories from counterpart baseline programs would indicate that a reduction in diameter measurement repeatability can be expected from the assessment and optimization of multi-baseline repeatability data using a 0.05 level of significance (95% confidence level).

The null hypothesis associated with this research hypothesis states that, within each planar baseline program (XY, XZ, and YZ), no significant improvement in diameter measurement repeatability would be achieved through the assessment and optimization of multi-baseline repeatability data.

Results of Hypothesis 3

In this study, diameter data was collected from twelve optimization programs (four on the XY plane, four on the XZ plane, and four on the YZ plane). Each optimization program was unique within and between each measurement plane. In other words, the particular diameter/probe hit categories used in developing each optimization program varied depending on three assessment parameters. These parameters included: (a) the measurement plane upon which repeatability assessment was performed (i.e., XY, XZ, or YZ), (b) the manner in which repeatability assessment was performed (i.e., single- or multi- baseline), and (c) the probe hit range from which the repeatability assessments were conducted (i.e., a probe hit range of 3-10 or 3-6). It should be noted that these two probe hit ranges were selected because it was determined that (a) certain inspection processes necessitate a quicker inspection times thus a lower number of probe contact hits and (b) confirmation was needed to verify that the optimization of multi-baseline repeatability could be assured regardless of the probe hit range selected. It should also be noted that the diameter data collected from each optimization program was analyzed using the same repeatability assessment procedures that were used in the analysis of multi-baseline data (SD-based @ 95% c.i. and range-based and two inspection runs per optimization program). The results of the mean repeatability assessments for each optimization program can be seen in the following set of tables:

1. Mean Values for Multi-Baseline, SD-Based Repeatability Optimization, Table 37.
2. Mean Values for Multi-Baseline, Range-Based Repeatability Optimization, Table 38.
3. Mean Values for Single Baseline, SD-Based Repeatability Optimization, Table 39.
4. Mean Values for Single Baseline, Range-Based Repeatability Optimization, Table 40.

To provide a greater understanding of the relationship between optimized repeatability data and baseline data as well as the basis from which mean repeatability was determined, graphs of each optimization program and measurement plane were constructed:

1. XY Plane: MB(3-10) Optimization, Figure 15.
   MB(3-6) Optimization, Figure 16.
   SB(3-10) Optimization, Figure 17.
   SB(3-6) Optimization, Figure 18.
2. XZ Plane: MB(3-10) Optimization, Figure 19.
   MB(3-6) Optimization, Figure 20.
   SB(3-10) Optimization, Figure 21.
   SB(3-6) Optimization, Figure 22.
3. YZ Plane: MB(3-10) Optimization, Figure 23.
   MB(3-6) Optimization, Figure 24.
   SB(3-10) Optimization, Figure 25.
   SB(3-6) Optimization, Figure 26.

The research hypothesis stated that an improvement in measurement repeatability would be achieved through the assessment and optimization of multi-baseline repeatability data. The results of the multi-baseline optimization programs, both MB(3-10) and MB(3-6) did not indicate an improvement in measurement repeatability using this methodology (see summary repeatability results Tables 41 to 42 and Figures 27 to 30). This finding was substantiated on all measurement planes and most SD- and range-based repeatability assessments. The repeatability analysis of the single baseline optimization programs, both SB(3-10) and SB(3-6), validated the findings of the 1993 diameter repeatability study of the XY plane and can be seen in Tables 43 to 44 and Figures 31 to 34. In other words, no significant improvement in measurement repeatability was achieved through the use of the single baseline repeatability assessment and optimization methodology. In addition to a lack of improvement in repeatability using the single baseline methodology, the repeatability

Table 37

Mean Values for Multi-Baseline, SD-Based Repeatability Optimization

	Multi-Baseline (3-10)			Multi-Baseline (3-6)		
Diameter	XY	XZ	YZ	XY	XZ	YZ
0.25	7.6	7.9	6.3	6.5	6.7	10.7
0.50	6.1	7.5	6.9	10.4	8.0	8.1
0.75	7.0	5.5	6.3	9.4	7.7	7.4
1.00	6.0	4.9	6.2	10.2	8.7	5.7
1.25	6.5	7.2	7.8	9.1	11.4	7.5
1.50	7.5	7.5	4.3	6.1	6.9	9.1
1.75	9.4	5.5	8.3	13.5	10.1	8.2
2.00	5.9	4.8	5.8	9.6	7.3	4.1
2.25	4.9	6.4	7.4	6.3	11.0	4.5
2.50	4.3	6.4	6.0	7.8	20.3	6.0
2.75	6.7	7.5	6.1	7.4	5.6	7.1
3.00	5.6	4.9	5.6	9.9	10.2	5.1
3.25	8.1	6.4	4.8	11.0	10.9	7.4
3.50	6.4	5.5	5.3	13.3	6.1	7.1
3.75	5.1	7.5	4.5	8.6	6.2	6.0
4.00	6.8	6.2	5.9	13.1	9.3	7.5
4.25	6.7	5.7	3.8	7.4	8.9	5.9
4.50	6.9	5.4	4.7	7.0	7.6	8.4
4.75	11.0	6.9	8.6	7.1	8.6	7.7
5.00	8.4	5.9	5.8	12.8	6.0	8.3
5.25	4.6	8.2	8.5	8.0	8.4	9.7
5.50	4.3	7.8	6.9	6.4	6.9	5.6
5.75	5.9	6.2	4.7	11.5	5.7	6.2
Avg. Rep.	6.6	6.4	6.1	9.2	8.6	7.1

Note. All repeatability values are expressed in inches (x 10^{-5}).

Table 38

Mean Values for Multi-Baseline, Range-Based Repeatability Optimization

	Multi-Baseline (3-10)			Multi-Baseline (3-6)		
Diameter	XY	XZ	YZ	XY	XZ	YZ
0.25	6.0	6.5	5.0	5.0	5.0	9.0
0.50	4.5	6.0	6.0	8.0	6.0	7.0
0.75	5.5	4.5	5.0	7.5	6.0	6.0
1.00	4.5	4.0	5.0	8.5	8.0	4.0
1.25	5.5	6.0	6.0	8.0	8.5	5.0
1.50	6.0	5.5	3.0	5.0	6.0	7.0
1.75	7.0	4.5	6.5	11.5	7.5	6.5
2.00	4.0	4.0	4.5	7.0	5.5	2.5
2.25	4.0	5.0	6.5	4.5	8.0	3.0
2.50	3.0	5.0	5.5	6.0	14.0	4.5
2.75	4.5	6.0	4.5	6.0	4.5	6.0
3.00	4.0	4.0	4.5	7.5	8.5	3.5
3.25	6.0	5.0	3.5	9.5	8.5	6.5
3.50	5.5	4.5	4.5	10.0	5.0	6.0
3.75	3.5	6.0	3.5	7.0	5.0	4.5
4.00	5.0	4.5	5.0	11.0	7.5	6.0
4.25	6.0	4.0	2.5	6.5	7.5	5.0
4.50	5.5	4.0	4.0	5.5	6.5	6.0
4.75	8.0	5.5	6.0	5.0	7.5	6.5
5.00	6.0	5.0	4.5	10.0	4.5	6.0
5.25	3.5	6.5	6.5	6.0	6.0	7.0
5.50	3.0	6.0	5.0	5.5	5.0	4.5
5.75	5.0	5.0	3.5	8.5	5.0	5.5
Avg Rep	5.0	5.1	4.8	7.3	6.8	5.5

Note. All repeatability values are expressed in inches (x 10^{-5}).

Table 39

Mean Values for Single Baseline, SD-Based Repeatability Optimization

	Single Baseline (3-10)			Single Baseline (3-6)		
Diameter	XY	XZ	YZ	XY	XZ	YZ
0.25	10.9	4.8	8.1	4.9	8.6	10.4
0.50	7.6	6.2	5.8	11.5	5.2	5.3
0.75	9.5	9.7	7.4	6.6	10.9	14.7
1.00	7.2	7.1	10.2	8.5	9.1	7.8
1.25	9.9	5.9	6.6	12.2	9.3	5.6
1.50	6.3	5.3	5.9	6.4	8.2	10.8
1.75	11.7	5.3	8.7	14.6	7.9	9.3
2.00	14.6	6.3	6.6	14.6	9.1	9.3
2.25	7.6	4.2	5.3	7.3	6.5	4.1
2.50	11.1	4.7	5.9	12.4	9.3	6.6
2.75	9.8	6.0	7.2	4.9	4.9	5.6
3.00	10.0	5.9	5.5	6.9	7.7	5.0
3.25	8.6	6.2	4.5	12.7	5.0	6.8
3.50	10.2	6.3	12.5	10.2	7.3	8.1
3.75	10.8	4.1	5.8	4.2	10.9	8.1
4.00	13.1	6.2	4.8	8.0	8.4	5.5
4.25	9.6	5.3	9.0	16.1	7.5	7.5
4.50	11.0	5.9	5.0	8.7	6.8	7.8
4.75	10.0	9.5	4.8	9.6	6.6	5.9
5.00	10.8	6.8	10.1	9.1	6.0	10.3
5.25	7.7	4.7	7.5	8.0	4.7	6.4
5.50	4.5	7.2	4.4	11.8	8.3	4.6
5.75	13.5	4.7	6.7	11.0	5.6	5.9
Avg Rep	9.8	6.0	6.9	9.6	7.5	7.5

Note. All repeatability values are expressed in inches (x 10^{-5}).

Table 40

Mean Values for Single Baseline, Range-Based Repeatability Optimization

	Single Baseline (3-10)			Single Baseline (3-6)		
Diameter	XY	XZ	YZ	XY	XZ	YZ
0.25	7.0	3.0	7.0	4.5	6.5	8.5
0.50	6.5	4.5	4.5	10.5	4.5	4.0
0.75	7.0	8.5	6.0	5.0	8.5	12.3
1.00	5.5	6.0	8.5	7.0	7.5	7.0
1.25	8.5	4.5	6.5	11.0	7.0	4.0
1.50	5.0	4.5	4.0	5.0	7.5	8.5
1.75	9.0	4.5	7.0	11.5	6.0	7.0
2.00	11.5	5.5	5.5	12.0	7.0	6.5
2.25	6.5	3.0	4.0	5.5	5.0	3.5
2.50	9.0	4.0	4.5	9.5	7.5	5.5
2.75	7.5	4.5	5.5	4.0	3.5	4.0
3.00	8.0	4.0	4.5	5.5	6.0	4.0
3.25	6.5	4.5	3.5	10.5	4.0	5.5
3.50	9.0	5.5	10.5	8.0	6.0	7.0
3.75	7.5	2.5	5.0	3.0	9.5	6.0
4.00	11.0	5.5	4.0	6.0	7.5	4.5
4.25	7.5	4.0	7.5	11.5	6.5	6.0
4.50	9.0	4.0	4.0	7.0	5.5	6.5
4.75	8.5	8.0	3.5	8.5	5.0	4.0
5.00	8.5	5.5	8.0	6.0	5.0	8.5
5.25	6.0	3.5	6.0	7.0	3.5	5.0
5.50	3.5	5.5	3.0	10.0	6.5	3.5
5.75	11.0	3.5	5.0	9.5	4.5	5.0
Avg Rep	7.8	4.7	5.5	7.7	6.1	5.9

Note. All repeatability values are expressed in inches (x 10^{-5}).

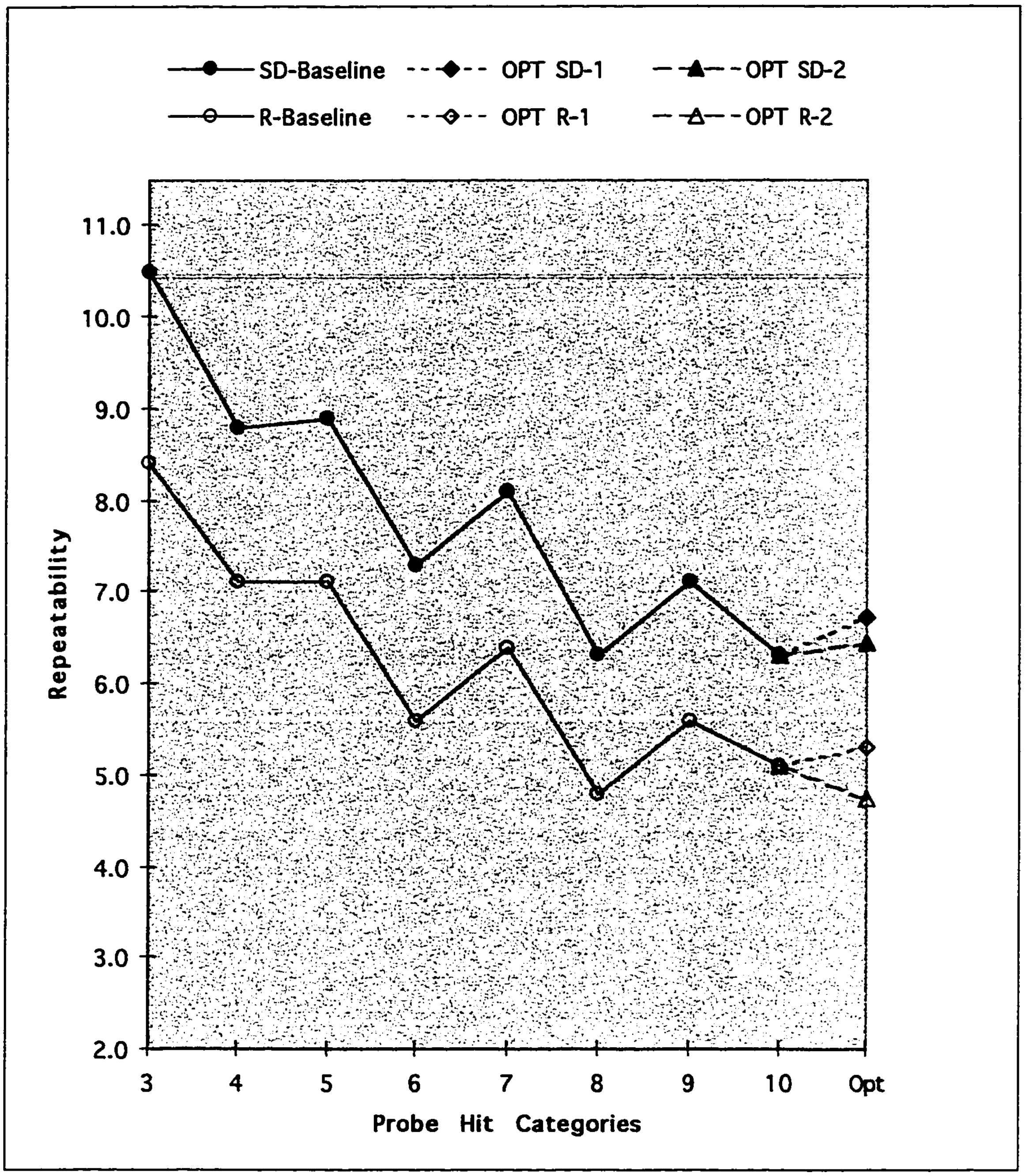


Figure 15. XY Plane: MB(3-10) Optimization. Note. All repeatability values are expressed in inches (x 10^{-5}).

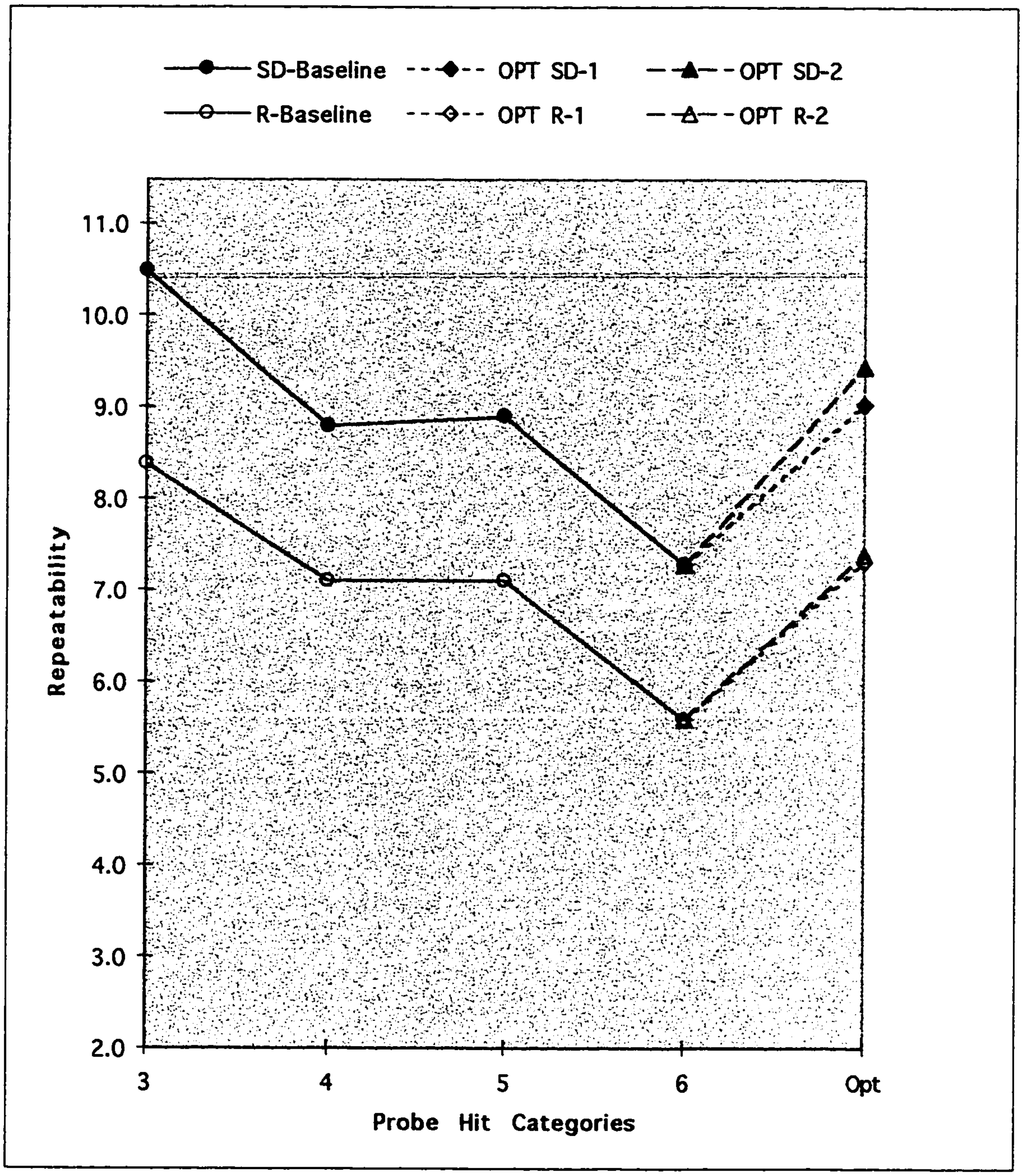


Figure 16. XY Plane: MB(3-6) Optimization. Note. All repeatability values are expressed in inches (x 10^{-5}).

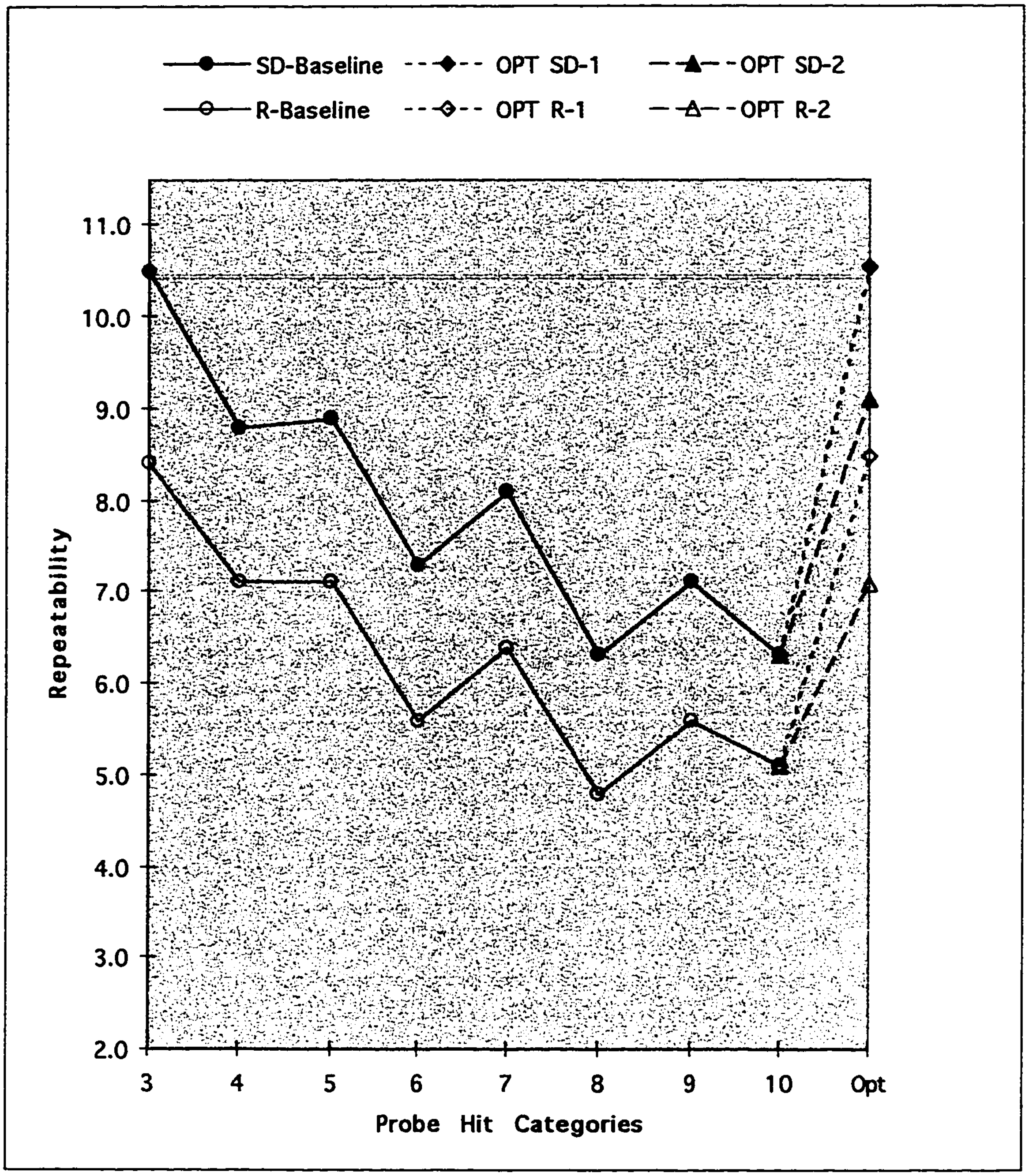


Figure 17. XY Plane: SB(3-10) Optimization. Note. All repeatability values are expressed in inches (x 10^{-5}).

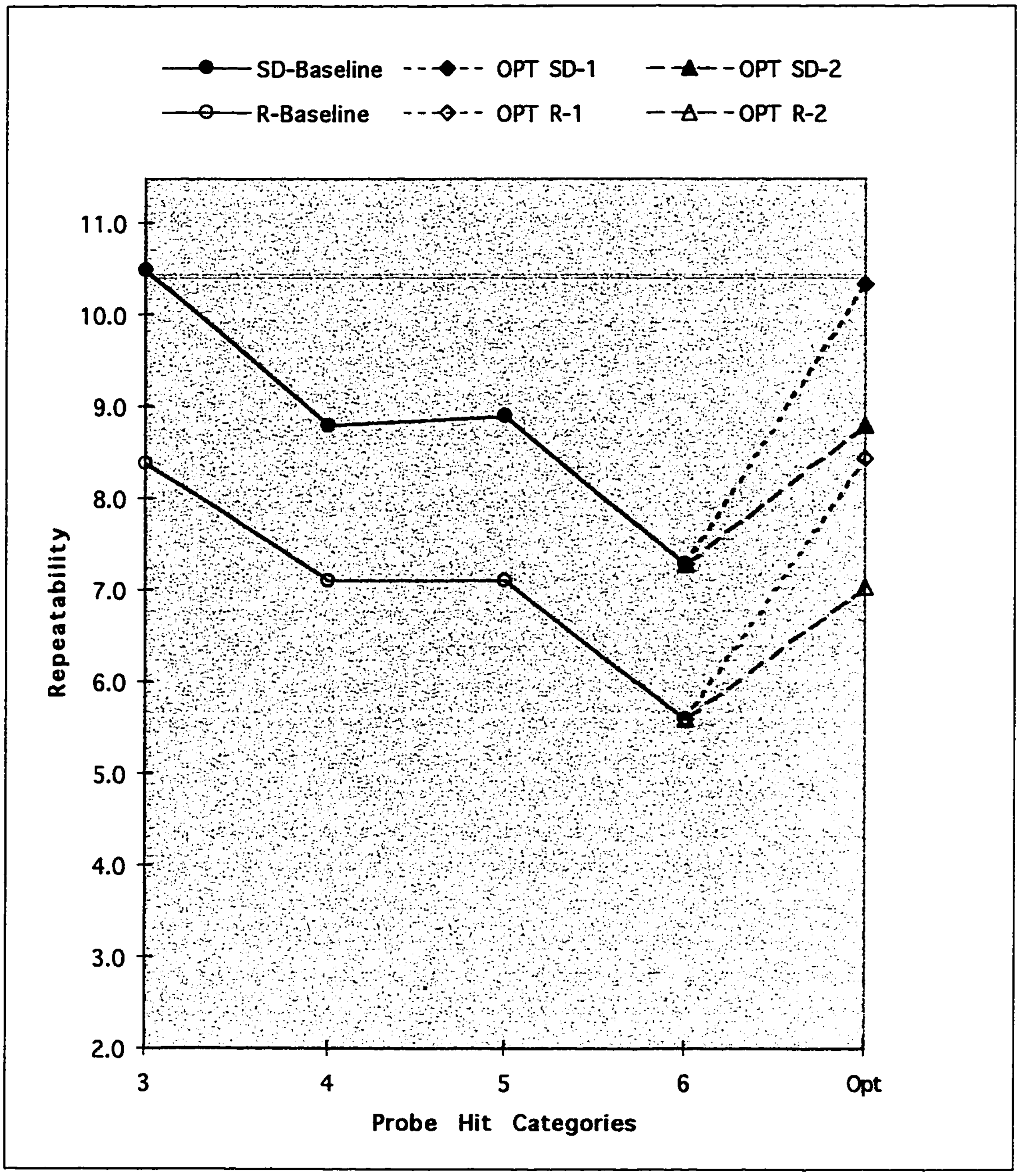


Figure 18. XY Plane: SB(3-6) Optimization. Note. All repeatability values are expressed in inches (x 10^{-5}).

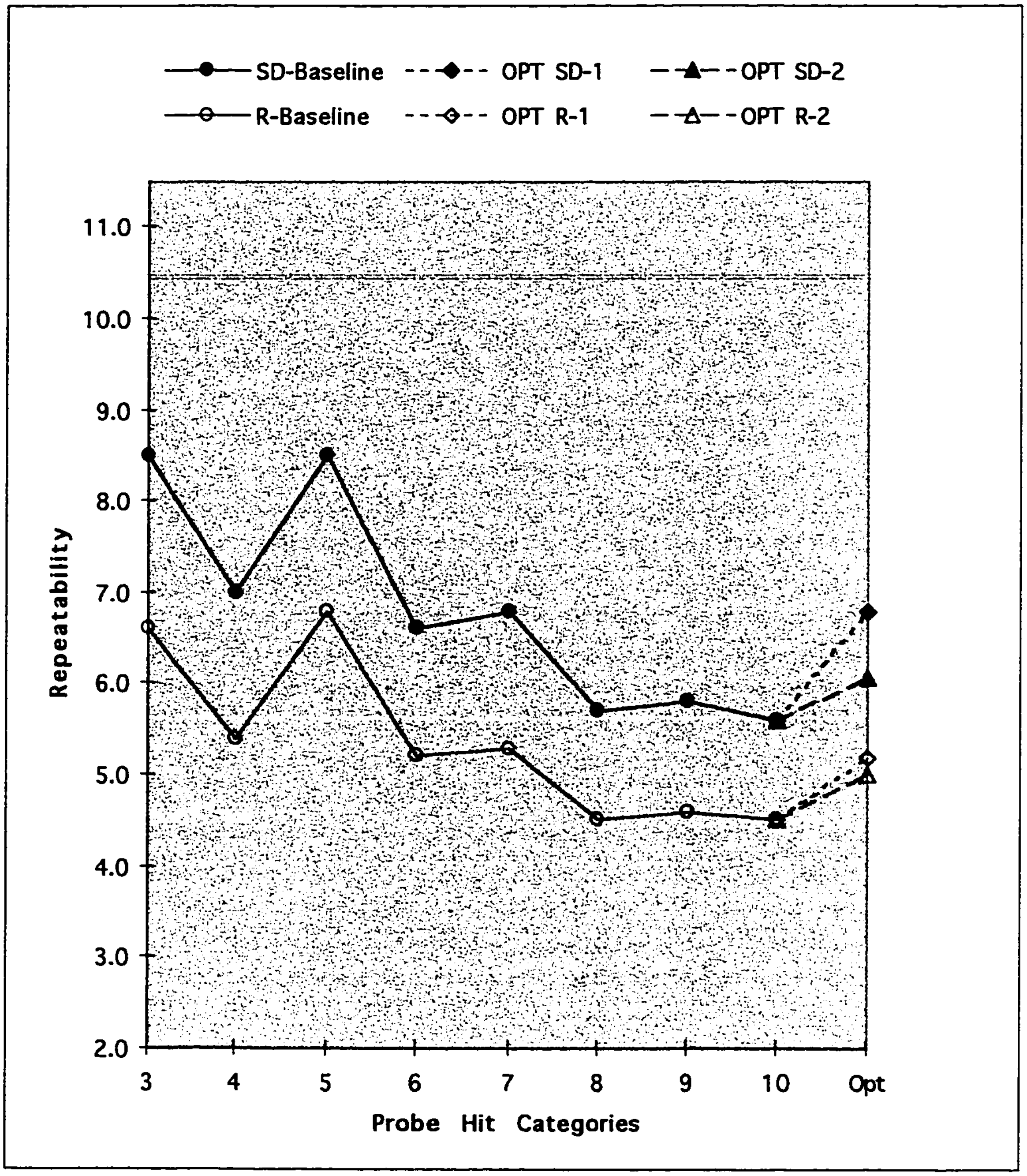


Figure 19. XZ Plane: MB(3-10) Optimization. Note. All repeatability values are expressed in inches (x 10^{-5}).

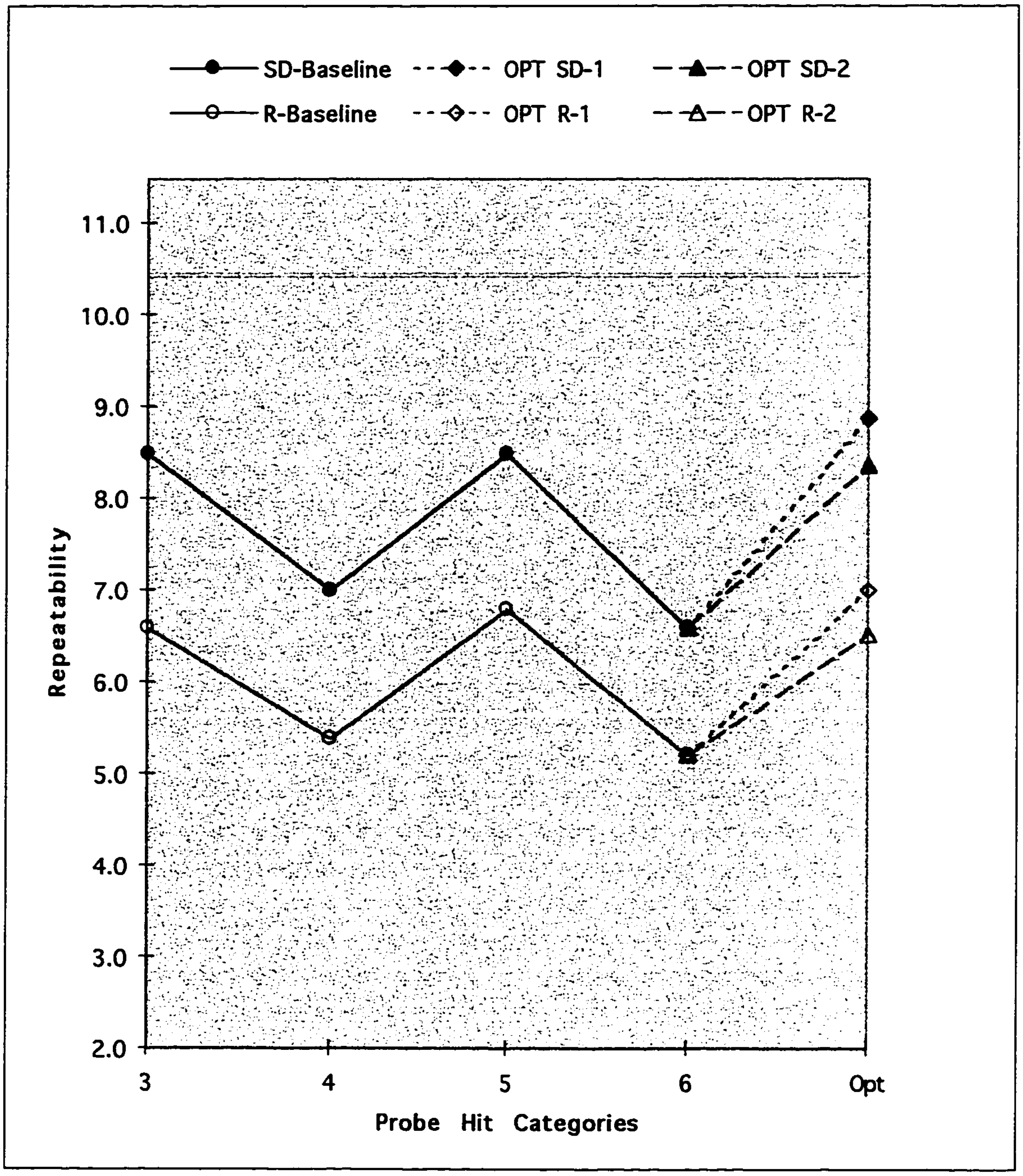


Figure 20. XZ Plane: MB(3-6) Optimization. Note. All repeatability values are expressed in inches (x 10^{-5}).

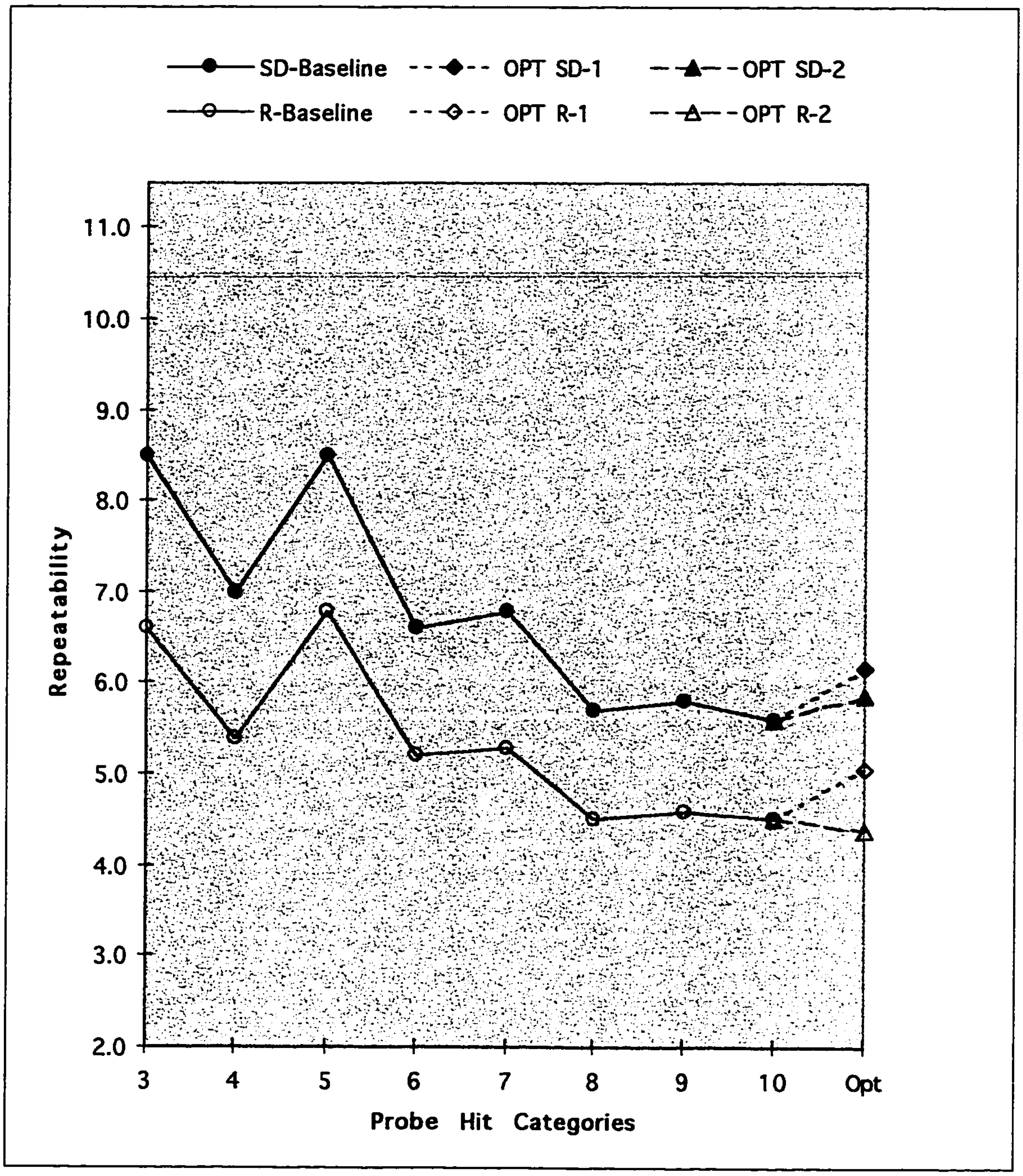


Figure 21. XZ Plane: SB(3-10) Optimization. Note. All repeatability values are expressed in inches (x 10^{-5}).

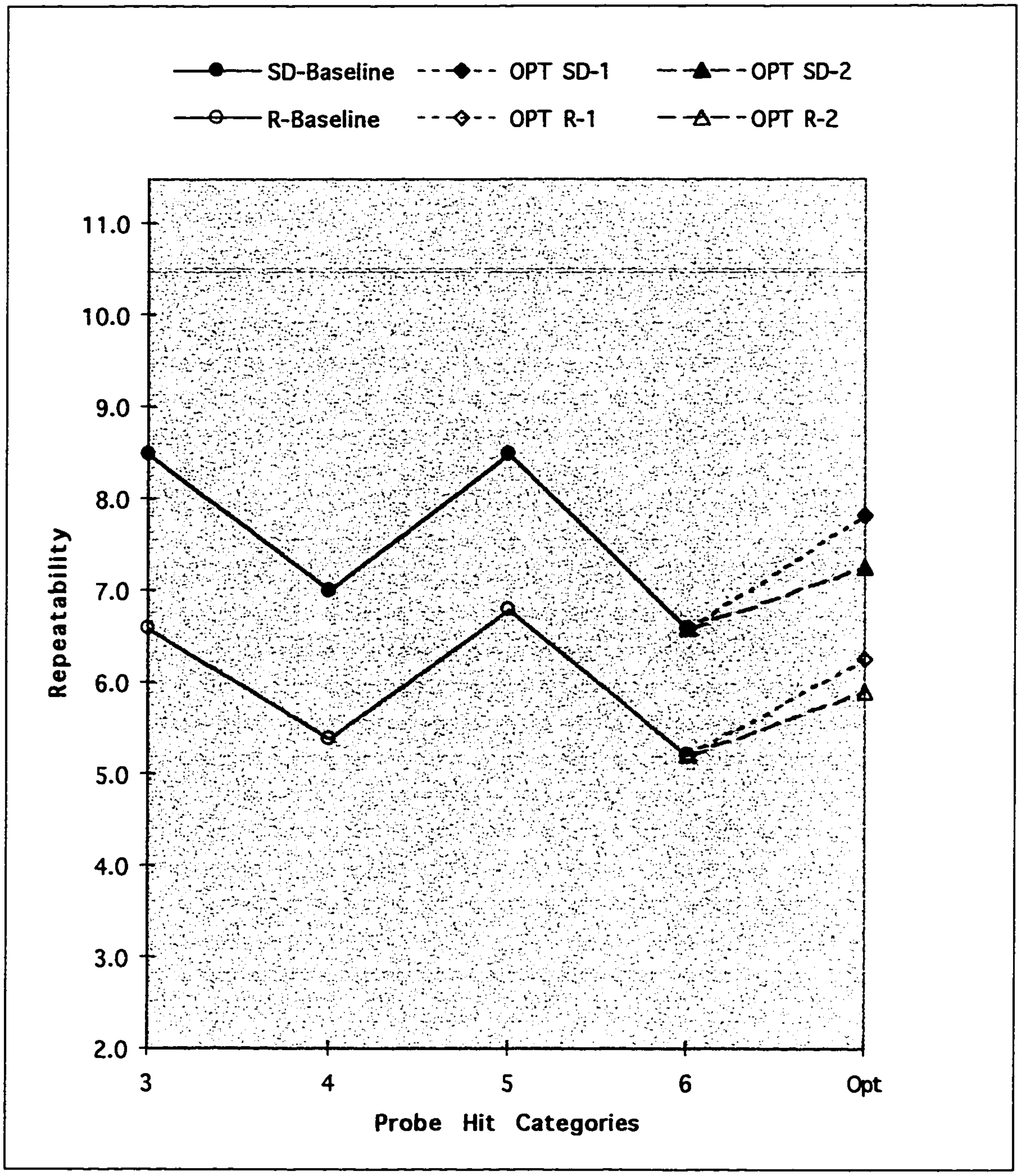


Figure 22. XZ Plane: SB(3-6) Optimization. Note. All repeatability values are expressed in inches (x 10^{-5}).

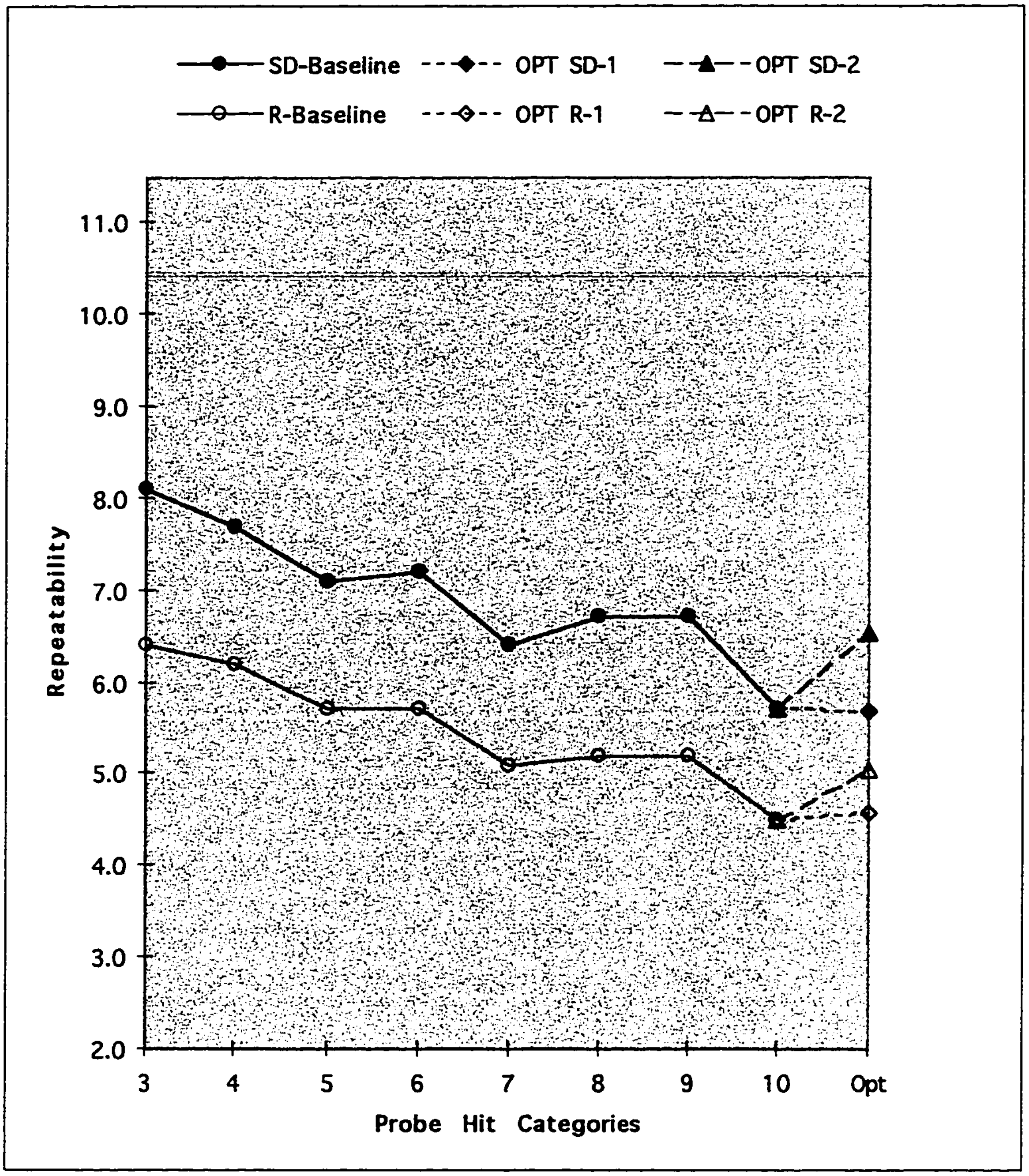


Figure 23. YZ Plane: MB(3-10) Optimization. Note. All repeatability values are expressed in inches (x 10^{-5}).

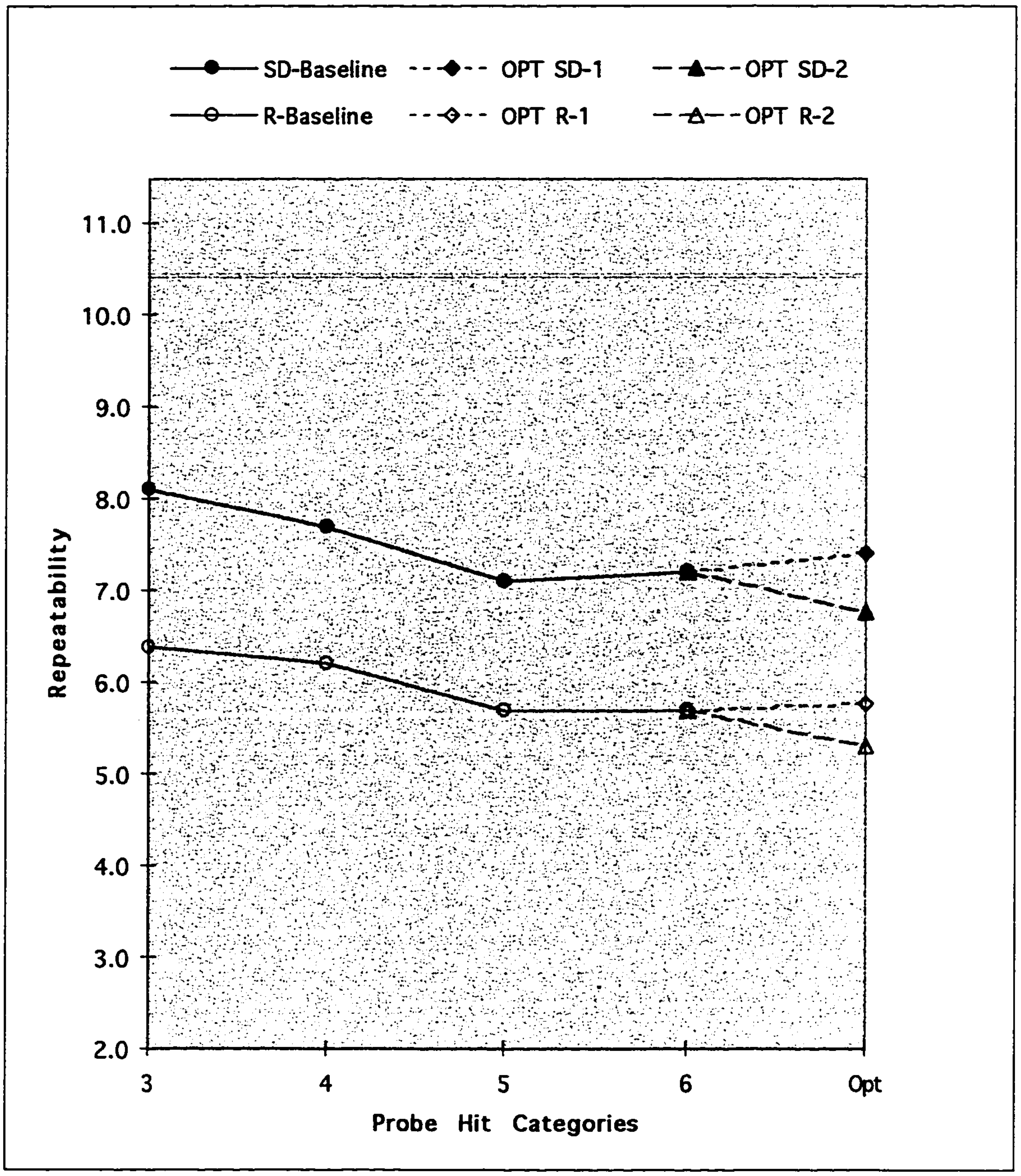


Figure 24. YZ Plane: MB(3-6) Optimization. Note. All repeatability values are expressed in inches (x 10^{-5}).

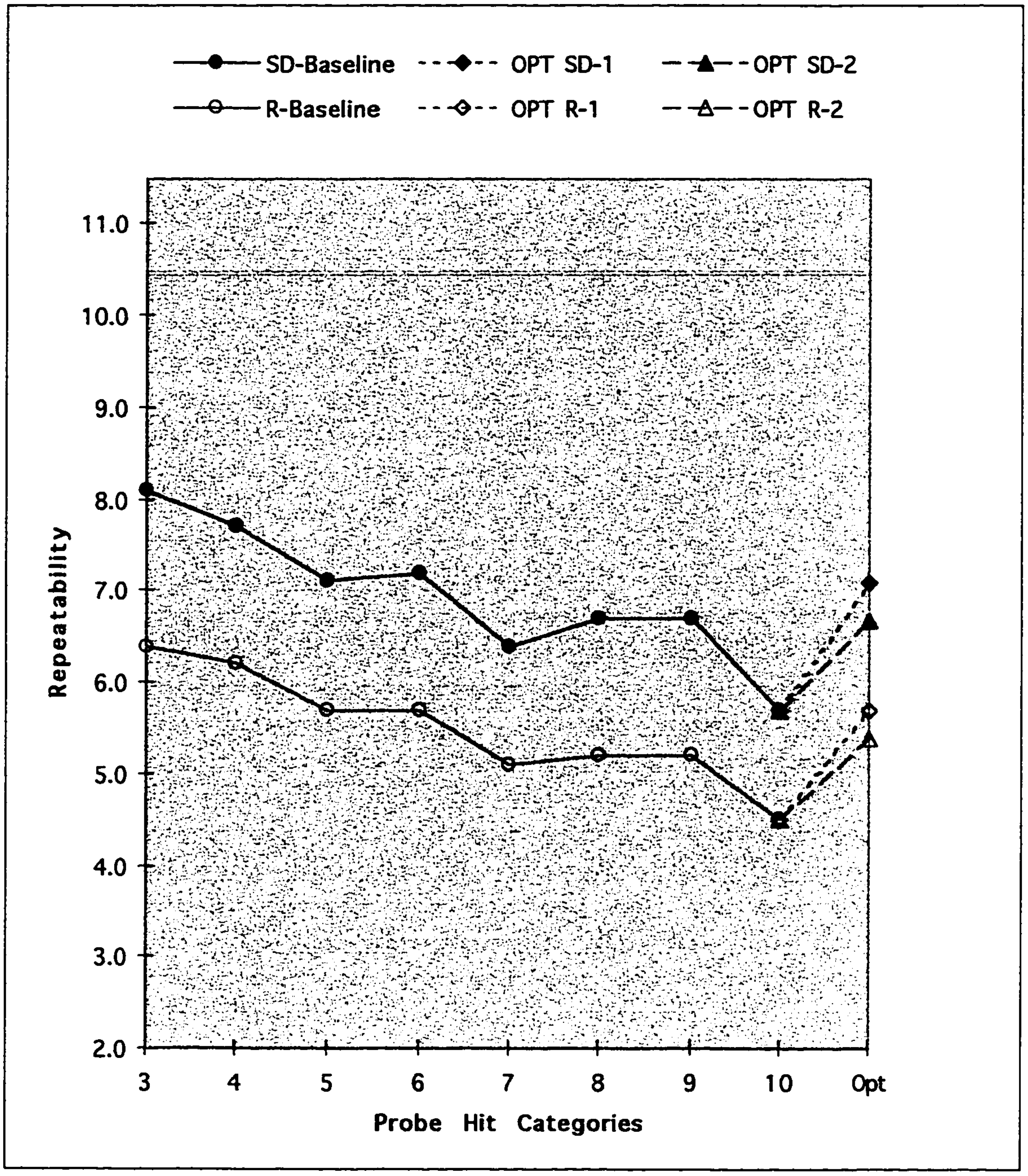


Figure 25. YZ Plane: SB(3-10) Optimization. Note. All repeatability values are expressed in inches (x 10^{-5}).

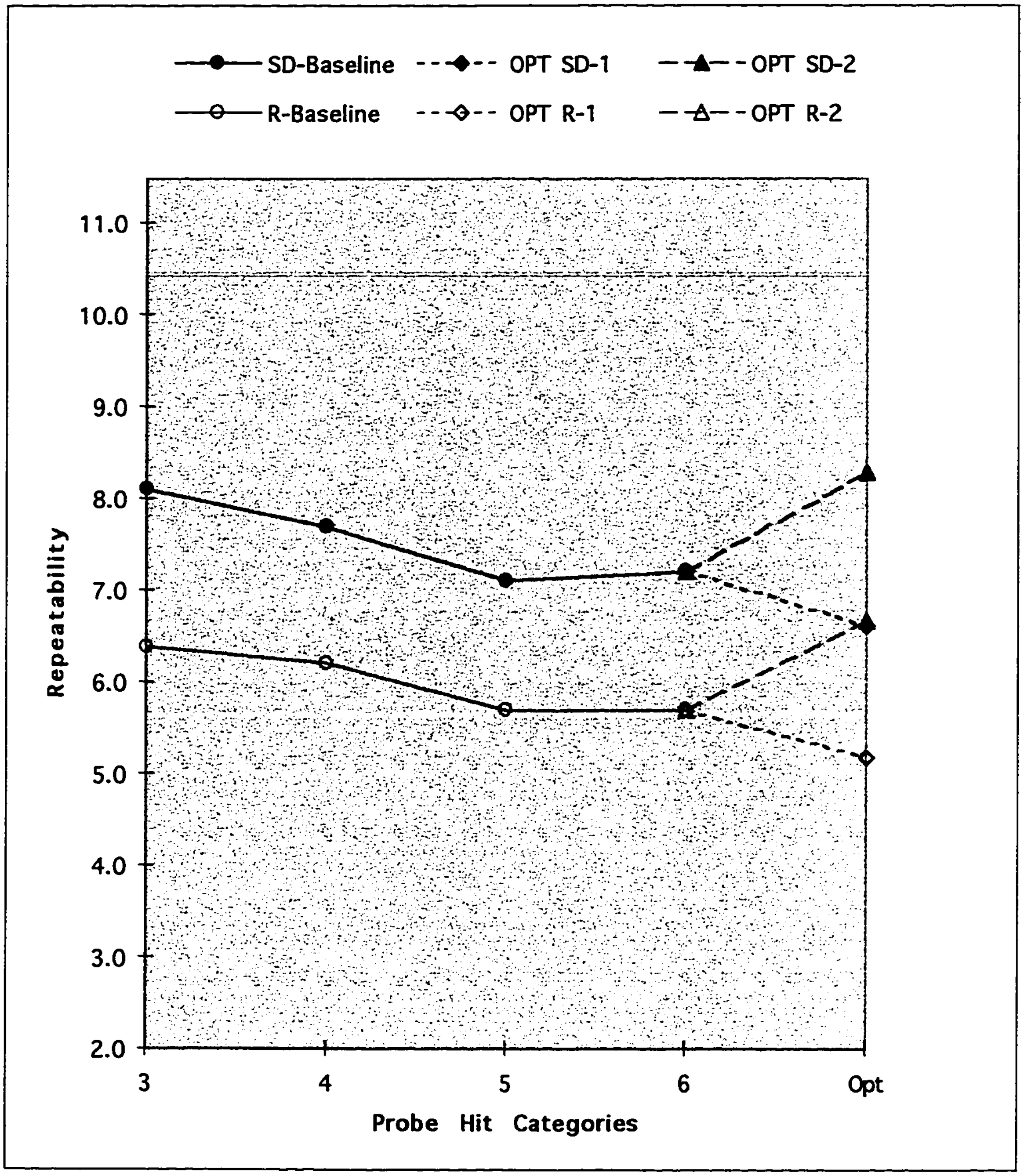


Figure 26. YZ Plane: SB(3-6) Optimization. Note. All repeatability values are expressed in inches (x 10^{-5}).

Table 41

Summary of Multi-Baseline, SD-Based Repeatability (x 10^{-5})

Probe Hit Category	XY Plane	XZ Plane	YZ Plane
	3-10 Probe Hit Range		
3-pt.	10.5	8.5	8.1
4-pt.	8.8	7.0	7.7
5-pt.	8.9	8.5	7.1
6-pt.	7.3	6.6	7.2
7-pt.	8.1	6.8	6.4
8-pt.	6.3	5.7	6.7
9-pt.	7.1	5.8	6.7
10-pt.	6.3	5.6	5.7
MB(3-10)-1	6.7	6.8	5.7
MB(3-10)-2	6.4	6.1	6.6
	3-6 Probe Hit Range		
3-pt.	10.5	8.5	8.1
4-pt.	8.8	7.0	7.7
5-pt.	8.9	8.5	7.1
6-pt.	7.3	6.6	7.2
MB(3-6)-1	9.0	8.9	7.4
MB(3-6)-2	9.4	8.4	6.8

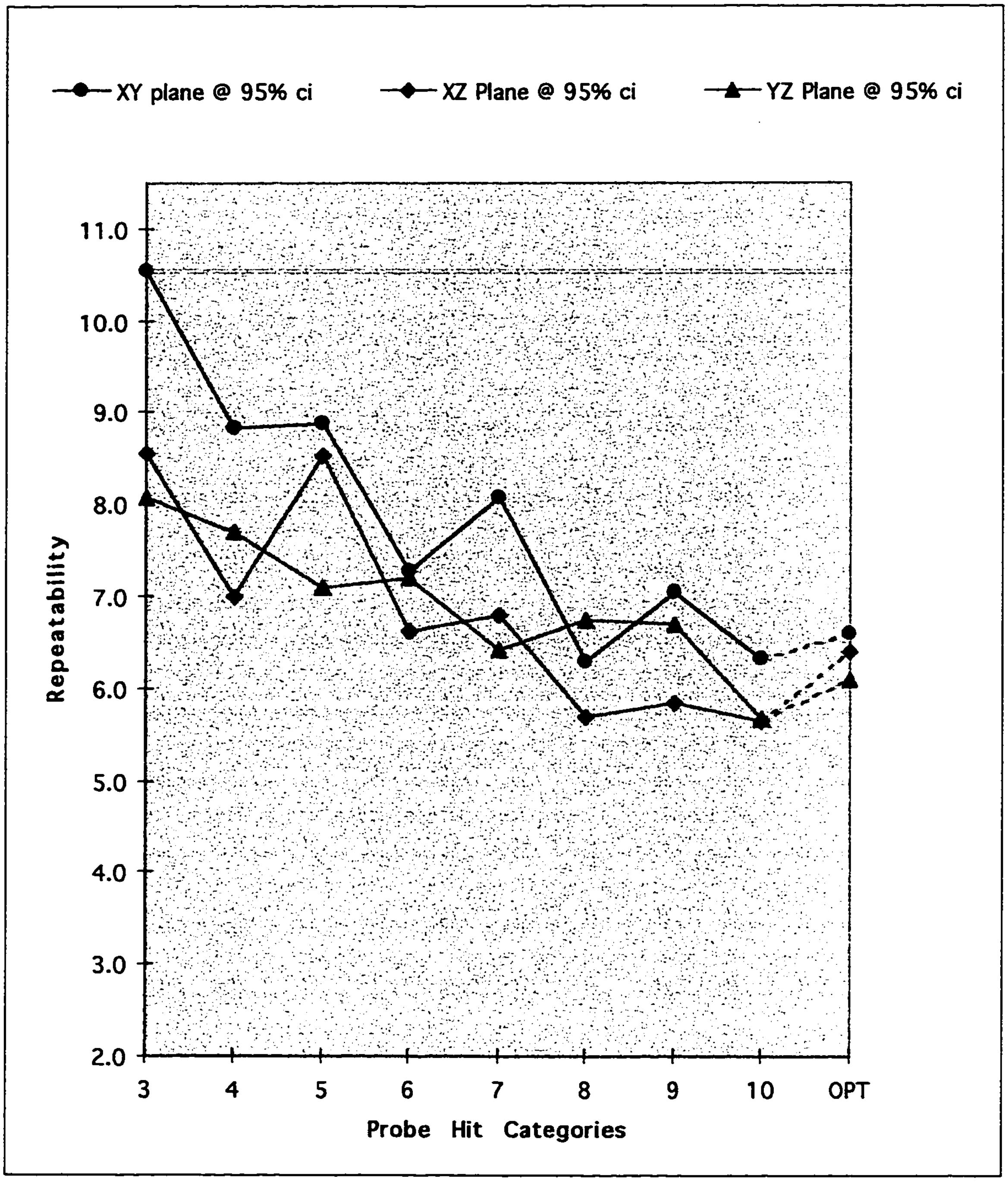


Figure 27. SD-based, mean probe hit repeatability and MB(3-10) repeatability optimization. Note. All repeatability values are expressed in inches (x 10^{-5}).

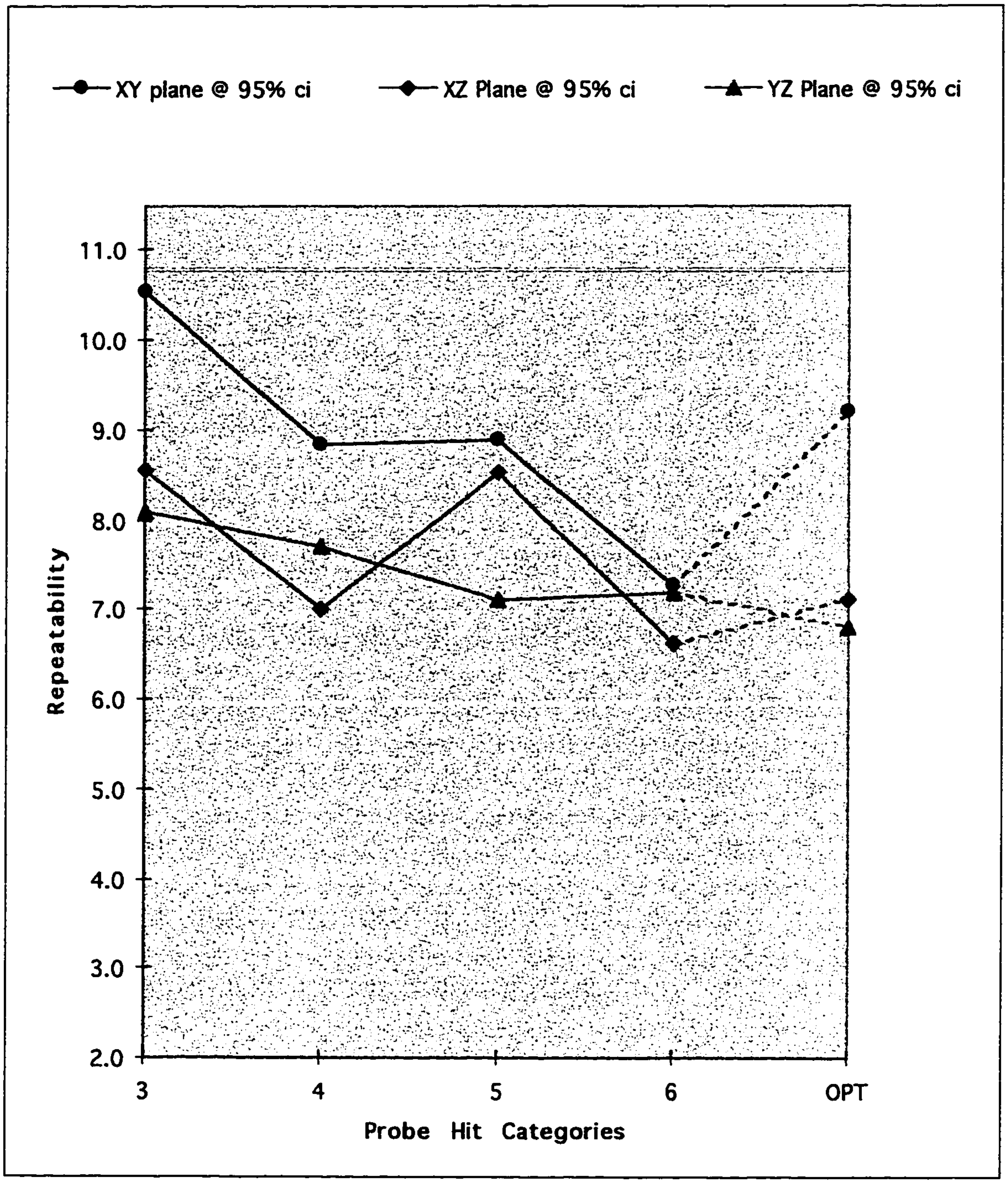


Figure 28. SD-based, mean probe hit repeatability and MB(3-6) repeatability optimization. Note. All repeatability values are expressed in inches (x 10^{-5}).

Table 42

Summary of Multi-Baseline, Range-Based Repeatability (x 10^{-5})

Probe Hit Category	XY Plane	XZ Plane	YZ Plane
	3-10 Probe Hit Range		
3-pt.	8.4	6.6	6.4
4-pt.	7.1	5.4	6.2
5-pt.	7.1	6.8	5.7
6-pt.	5.6	5.2	5.7
7-pt.	6.4	5.3	5.1
8-pt.	4.8	4.5	5.2
9-pt.	5.6	4.6	5.2
10-pt.	5.1	4.5	4.5
MB(3-10)-1	4.7	5.2	4.6
MB(3-10)-2	5.3	5.0	5.2
	3-6 Probe Hit Range		
3-pt.	8.4	6.6	6.4
4-pt.	7.1	5.4	6.2
5-pt.	7.1	6.8	5.7
6-pt.	5.6	5.2	5.7
MB(3-6)-1	7.3	6.5	5.8
MB(3-6)-2	7.4	7.0	5.3

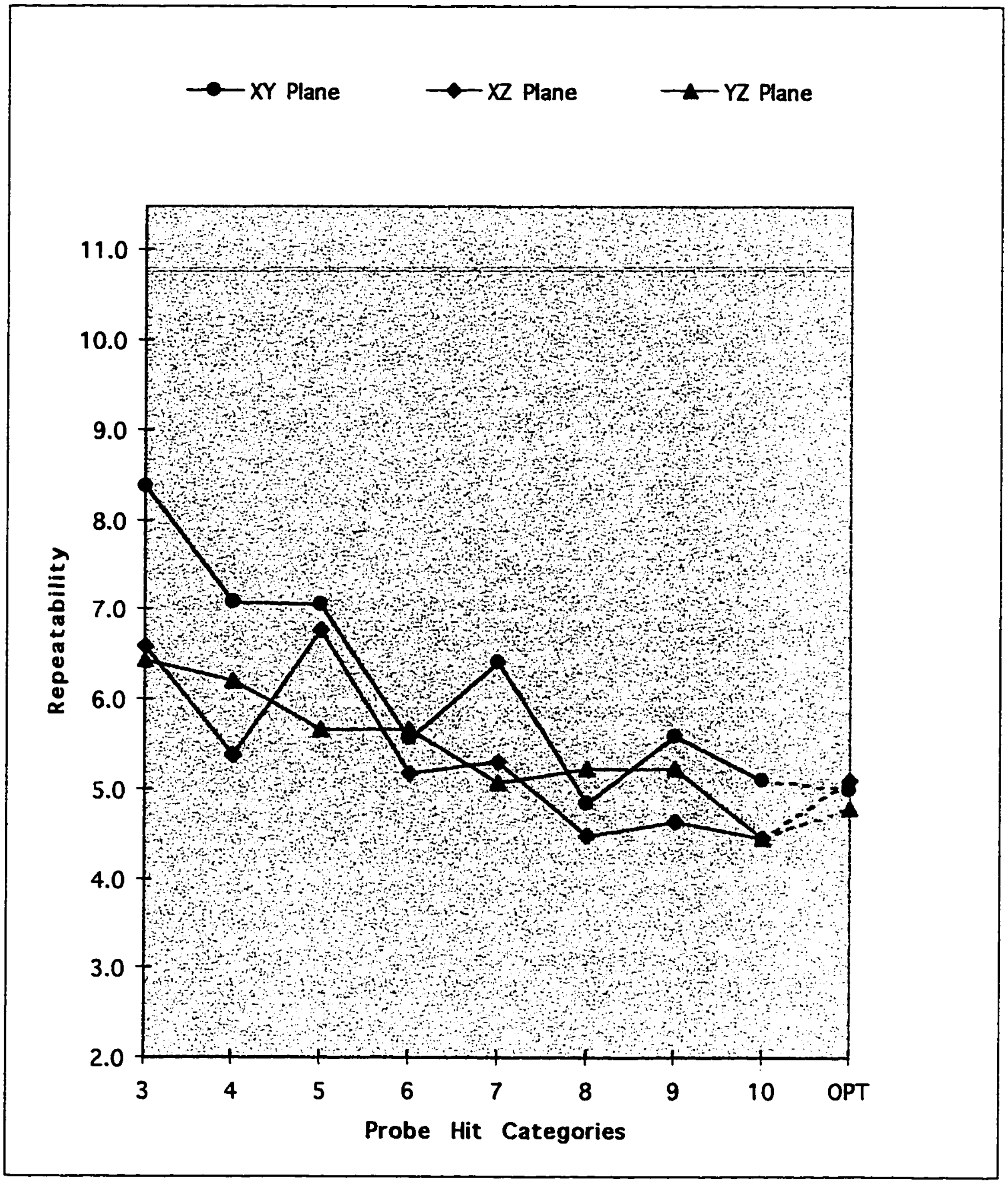


Figure 29. Range-based, mean probe hit repeatability and MB(3-10) repeatability optimization. Note. All repeatability values are expressed in inches (x 10^{-5}).

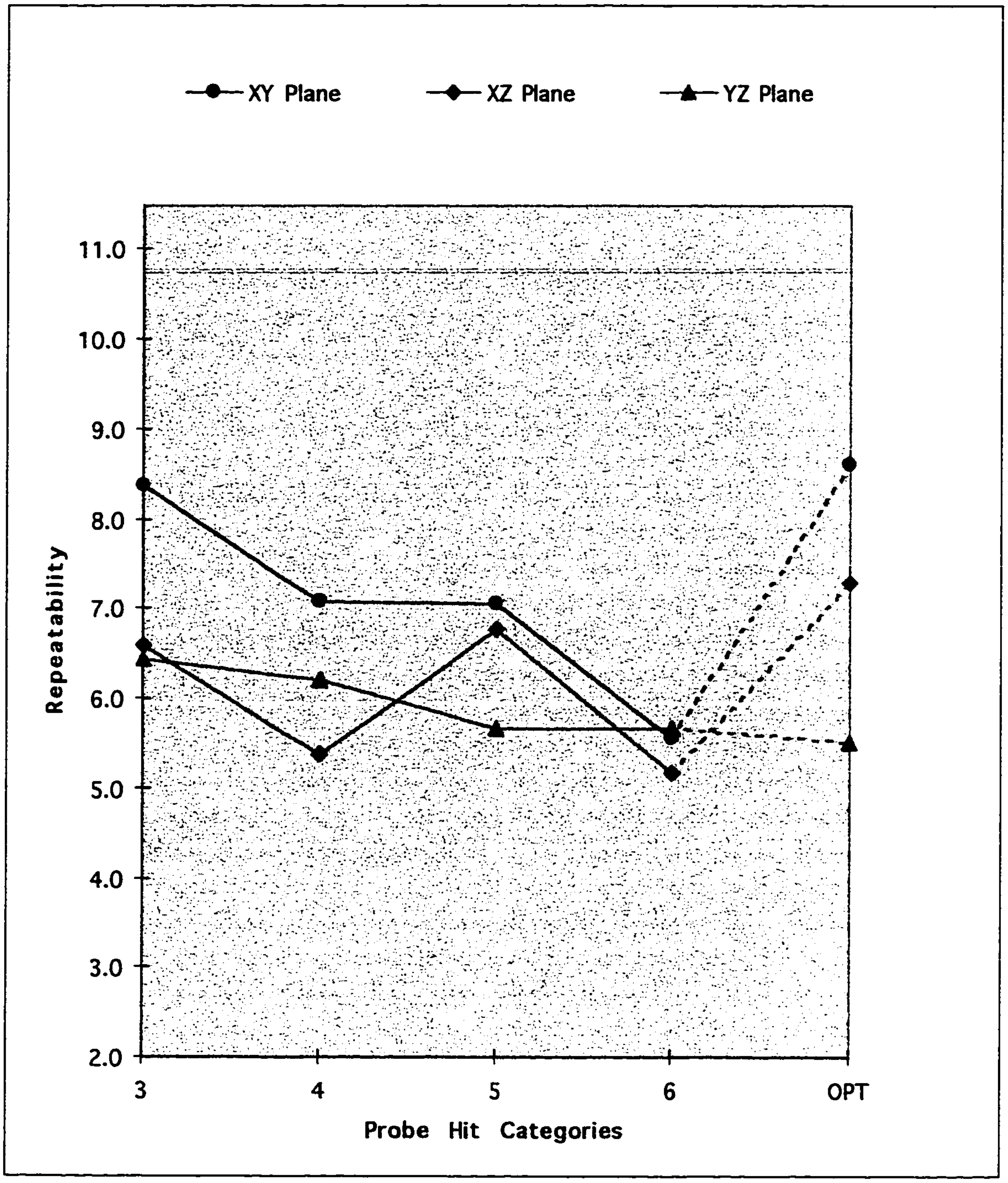


Figure 30. Range-based, mean probe hit repeatability and MB(3-6) repeatability optimization. Note. All repeatability values are expressed in inches (x 10^{-5}).

Table 43

Summary of Single Baseline, SD-Based Repeatability (x 10^{-5})

Probe Hit Category	XY Plane	XZ Plane	YZ Plane
	3-10 Probe Hit Range		
3-pt.	10.0	9.5	7.7
4-pt.	8.3	7.6	7.5
5-pt.	9.1	8.0	7.1
6-pt.	7.2	6.7	6.9
7-pt.	7.4	6.4	6.1
8-pt.	6.1	5.4	5.9
9-pt.	6.9	5.4	6.0
10-pt.	6.1	5.2	5.6
SB(3-10)-1	10.5	6.2	7.1
SB(3-10)-2	9.1	5.9	6.7
	3-6 Probe Hit Range		
3-pt.	10.0	9.5	7.7
4-pt.	8.3	7.6	7.5
5-pt.	9.1	8.0	7.1
6-pt.	7.2	6.7	6.9
SB(3-6)-1	10.3	7.8	6.6
SB(3-6)-2	8.8	7.3	8.3

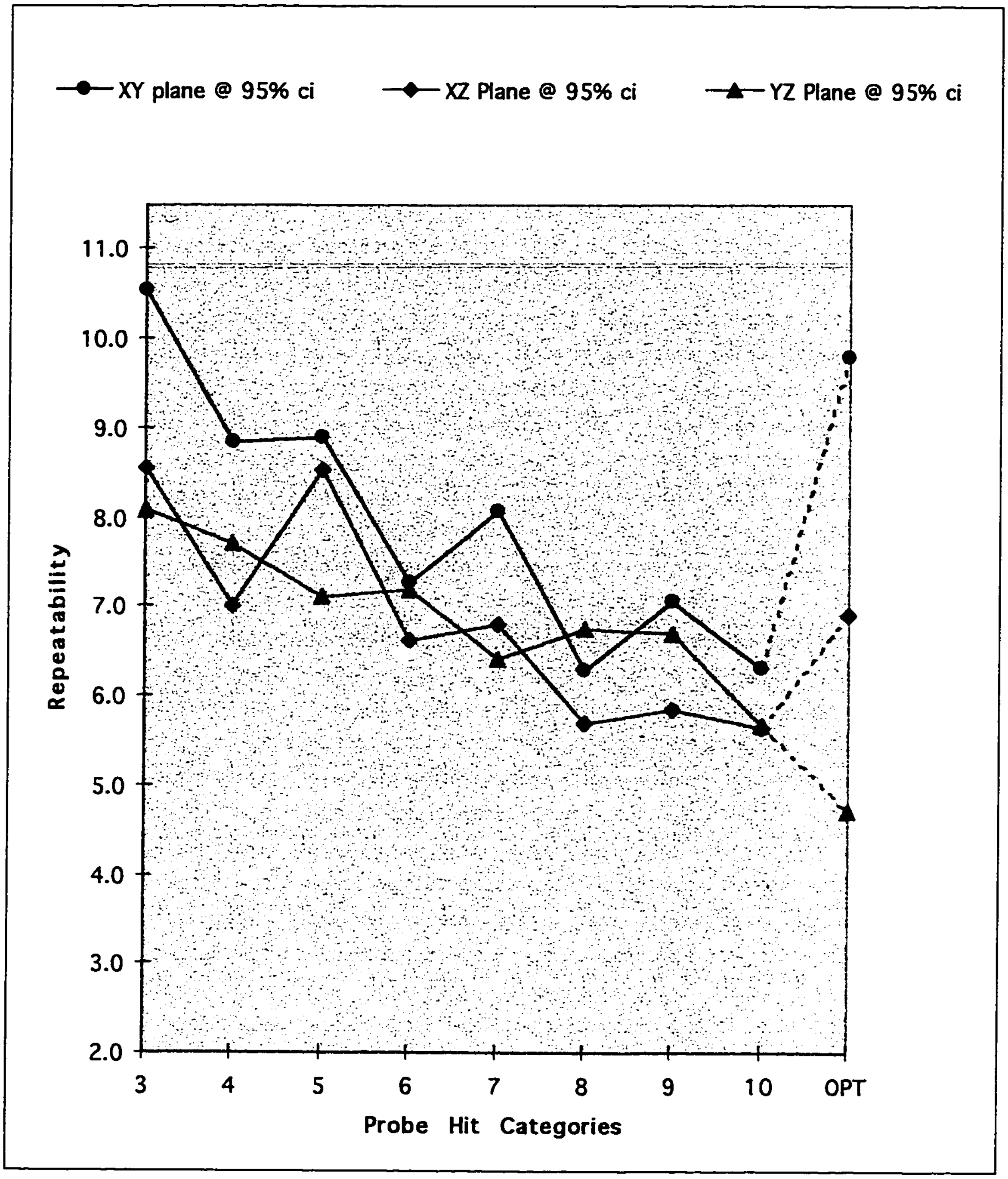


Figure 31. SD-based, mean probe hit repeatability and SB(3-10) repeatability optimization. Note. All repeatability values are expressed in inches (x 10^{-5}).

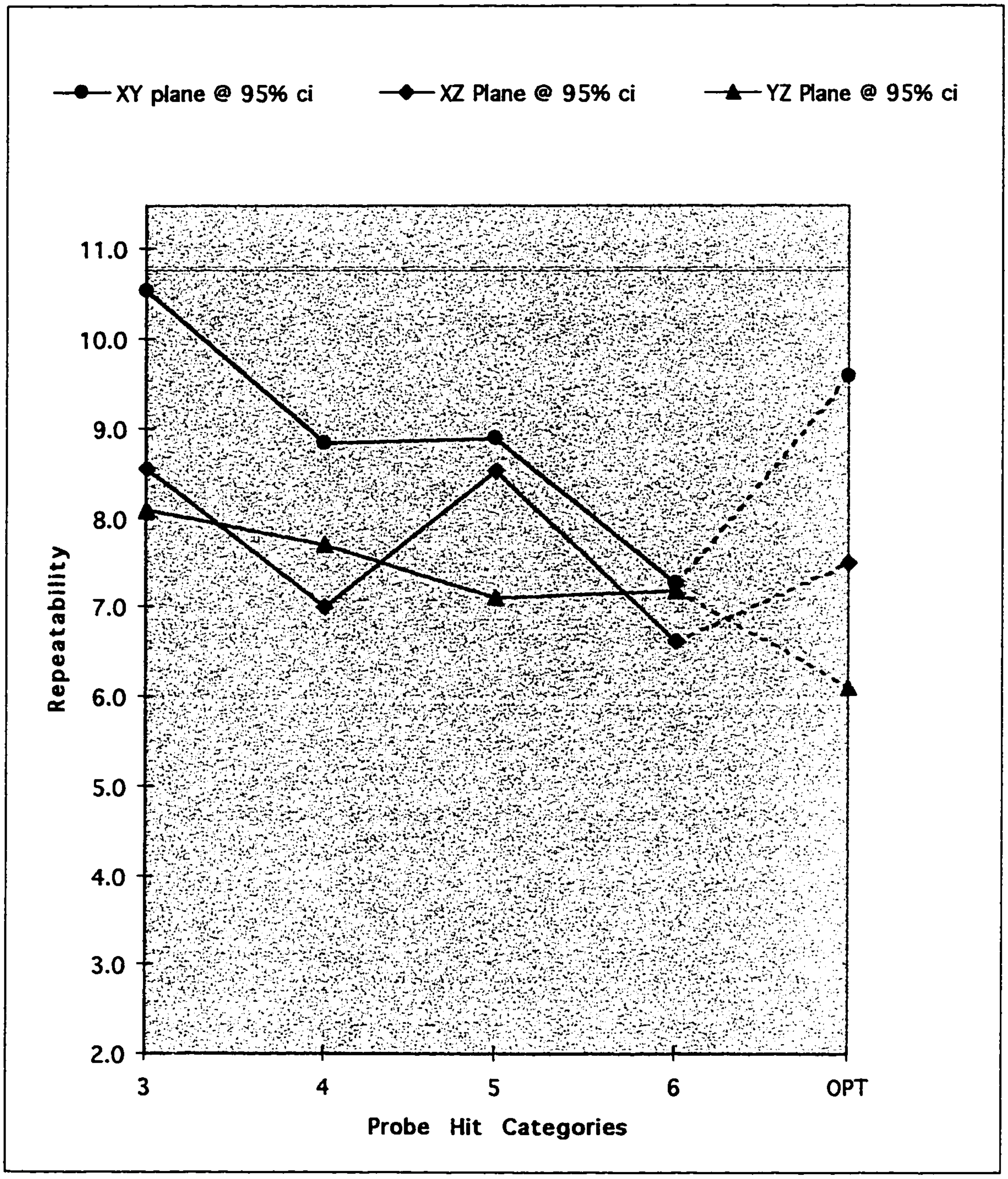


Figure 32. SD-based, mean probe hit repeatability and SB(3-6) repeatability optimization. Note. All repeatability values are expressed in inches (x 10^{-5}).

Table 44

Summary of Single Baseline, Range-Based Repeatability (x 10^{-5})

Probe Hit Category	XY Plane	XZ Plane	YZ Plane
	3-10 Probe Hit Range		
3-pt.	8.0	7.3	6.1
4-pt.	6.7	5.8	6.0
5-pt.	7.3	6.3	5.5
6-pt.	5.3	5.1	5.4
7-pt.	6.0	5.0	4.8
8-pt.	4.7	4.2	4.6
9-pt.	5.4	4.3	4.6
10-pt.	4.8	4.1	4.4
SB(3-10)-1	8.5	5.0	5.7
SB(3-10)-2	7.1	4.4	5.4
	3-6 Probe Hit Range		
3-pt.	8.0	7.3	6.1
4-pt.	6.7	5.8	6.0
5-pt.	7.3	6.3	5.5
6-pt.	5.3	5.1	5.4
SB(3-6)-1	8.4	6.3	5.2
SB(3-6)-2	7.0	5.9	6.7

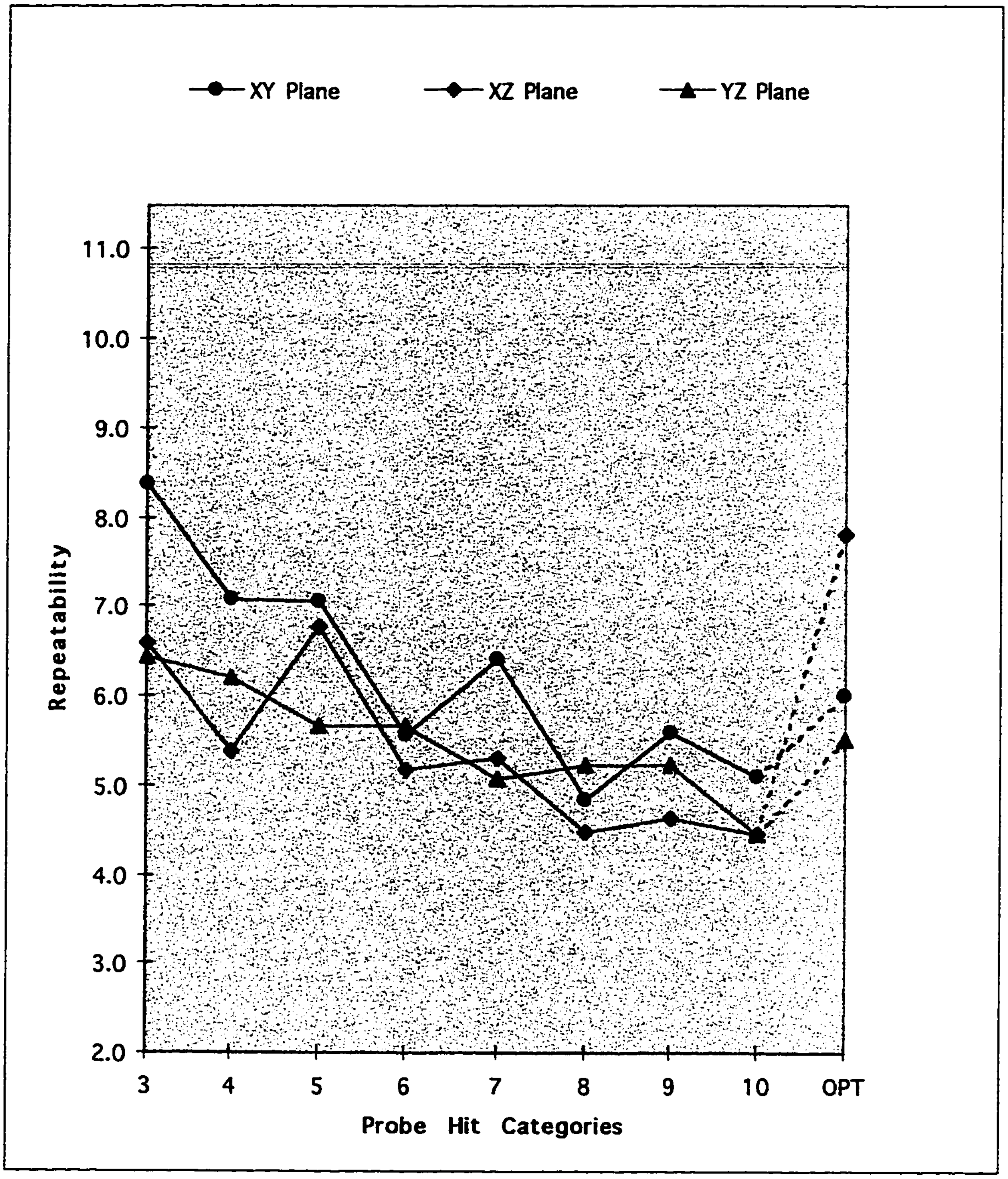


Figure 33. Range-based, mean probe hit repeatability and SB(3-10) repeatability optimization. Note. All repeatability values are expressed in inches (x 10^{-5}).

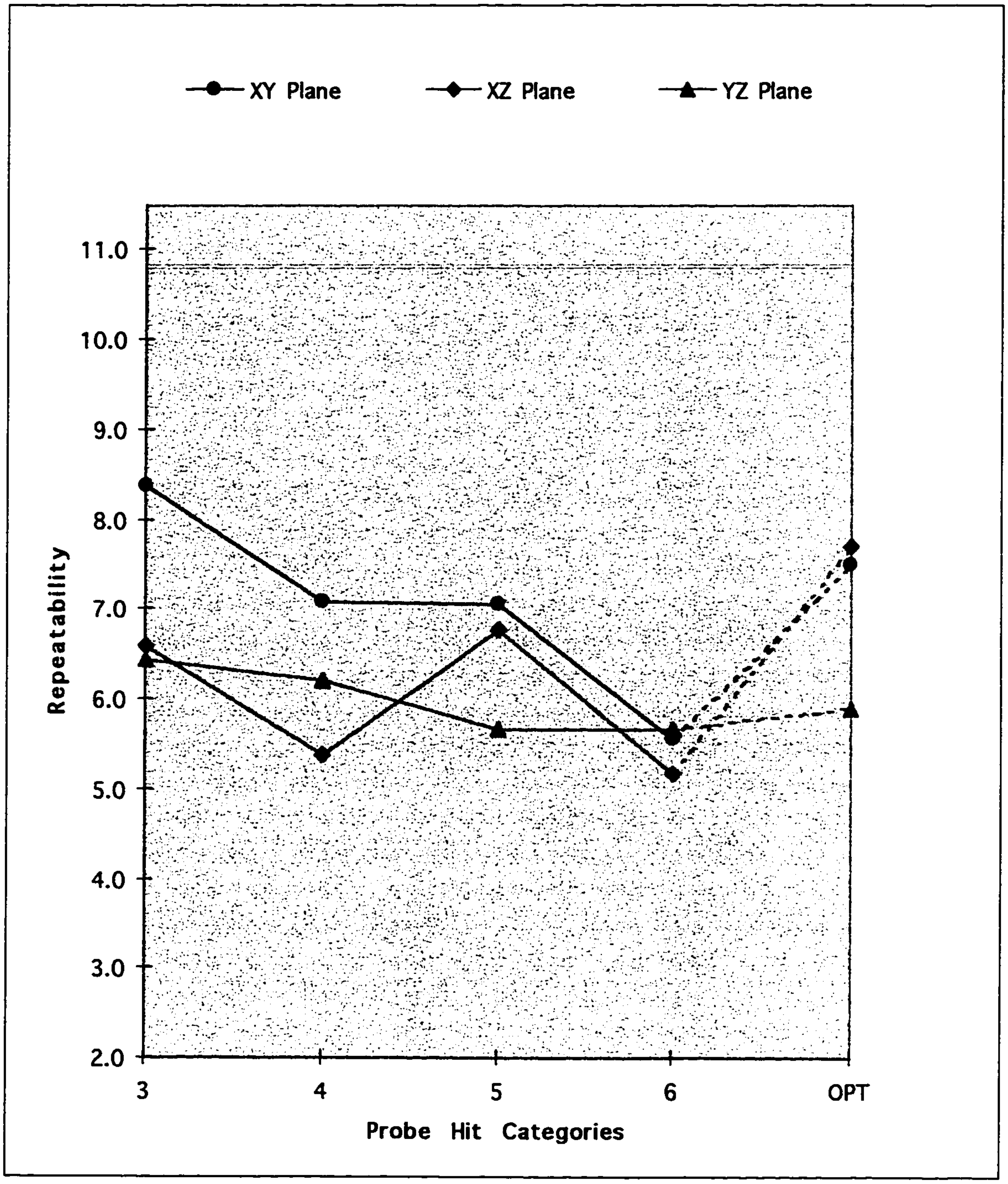


Figure 34. Range-based, mean probe hit repeatability and SB(3-6) repeatability optimization. Note. All repeatability values are expressed in inches (x 10^{-5}).

results of repeated optimization programs indicated instability in repeatability in many of the diameter/probe hit categories. It should be noted that these two findings were further substantiated on the XZ and YZ planes. The research hypothesis also indicated that repeatability improvement would be deemed significant if the time required to complete one measurement pass of each test specimen plate in the optimization programs was less than the time required to complete one measurement pass of each test specimen plate of the baseline probe hit category with the "best" average probe hit repeatability within the given probe hit range. The term "best" implies the category with the smallest numeric average repeatability value. Since data collected from the multi-baseline optimization programs did not indicate repeatability improvement, no time analysis was performed other than a tabular listing of baseline and multi-baseline optimization inspection times (see Table 45.).

Inferential analysis is a useful approach for formulating generalizations about a given population based on samples of the population. One frequently used method in inferential analysis is the t-statistic test. In this hypothesis testing method, a large discrepancy between the sample means will lead to a rejection of the null hypothesis (Ho:). This rejection can be caused by either random chance or a true effect. One variation of the t-statistic test is the single sample t-test. In this test the mean of a given sample is compared to a given constant to determine the degree to which future samples can be expected to be greater than or less than the given constant. Since the repeatability data from the optimization programs failed to support the research hypothesis (multi-baseline repeatability optimization will yield average repeatability values less than the "best" probe hit categories from counterpart baseline programs with a 95% confidence level), further analysis using single sample t-testing was not deemed relevant.

With respect to the third research hypothesis, the repeatability results indicated that no improvement in diameter measurement repeatability was achieved through both multi-baseline repeatability assessment and optimization. In essence, the null hypothesis was shown to be valid (no significant improvement in diameter measurement repeatability would be achieved through multi-baseline repeatability assessment and optimization). The results of the single baseline repeatability optimization analysis, on the other hand, validated the XY Plane findings of the 1993 diameter repeatability study. This finding was further substantiated on the XZ and YZ planes as well. It is important to note that repairs to the CMM were performed between baseline data collection and optimization data collection. The potential impact of these repairs on the optimization data is discussed in more detail in Chapter V.

Restatement of Hypothesis 4

The fourth research hypothesis states that differences would be noted in the general structure of each planar optimization program but would not be noted in calculated average repeatability and mean probe hit values. Structural differences and average repeatability and mean number of probe hit similarities would be deemed significant if:

4a. The time required to complete one measurement pass of all test specimens were distinctly different between planar optimization programs.

4b. The mean number of probe hits between planar optimization programs with identical probe hit ranges were the same.

The null hypothesis associated with this research hypothesis states that no significant difference will be noted in the general structure of planar optimization programs but will be noted in the calculated average repeatability and mean probe hit values.

Results of Hypothesis 4

The structure of the multi-baseline optimization programs were developed using repeatability data supplied by the baseline programs. Once formalized, these optimization programs were analyzed to determine (a) the time required to complete one measurement pass of all test specimens and (b) the mean number of probe hits of each optimization program. The results of the time analysis for the multi-baseline (3-10) and (3-6) optimization programs can be seen in Table 45. The results presented in this table shows minor differences in plate inspection times between planes. It also shows table that all optimization programs yielded inspection times less than greater than the 7-pt. probe hit category but less than the 8-pt. probe hit category. Although these inspection time differences do not appear to be significant, these differences over the course of a day, week, month, or year could add up and present a significance difference or potential time savings.

The results of the mean probe hit analysis on each optimization program for the multi-baseline (3-10) and (3-6) optimization programs can be seen in Tables 46 and 47, respectively. The results presented in these two tables show identical probe hit means between planes. With respect to the fourth research hypothesis, the results of the analysis performed on the structure of the multi-baseline optimization programs indicated minor differences in plate inspection times between inspection planes. Although these inspection time differences did not appear to be significant, these minor differences over the course of a day, week,

Table 45

Test Specimen Plate Inspection Times (seconds)

Probe Hit Category	Plate A Times	Plate B Times	Plate C Times	Plate D Times	Total Time
		3-10 Probe Hit Range			
3-pt.	108	79	73	91	351
4-pt.	120	88	81	102	391
5-pt.	133	97	89	112	431
6-pt.	144	103	94	121	462
7-pt.	154	110	100	130	494
8-pt.	165	117	105	138	525
9-pt.	175	123	110	146	554
10-pt.	185	129	116	154	584
		Multi-Baseline (3-10)			
XY: MB(3-10)	165	104	105	132	501
XZ: MB(3-10)	163	111	104	134	515
YZ: MB(3-10)	165	109	97	135	506
		Multi-Baseline (3-6)			
XY: MB(3-6)	125	92	92	115	424
XZ: MB(3-6)	127	86	84	116	433
YZ: MB(3-6)	134	88	83	109	414

Table 46

Multi-Baseline (3-10) Diameter Probe Hits (##-pt.)

Diameter	XY Plane	XZ Plane	YZ Plane
0.25	9	7	8
0.50	5	5	10
0.75	9	3	5
1.00	9	9	6
1.25	9	4	8
1.50	10	7	10
1.75	3	7	3
2.00	10	7	10
2.25	7	10	5
2.50	7	8	9
2.75	8	6	8
3.00	8	9	6
3.25	4	10	10
3.50	10	9	6
3.75	10	9	10
4.00	6	10	10
4.25	9	9	10
4.50	6	5	7
4.75	4	10	6
5.00	5	8	10
5.25	8	9	8
5.50	10	7	6
5.75	10	7	5
Mean Probe Hits	8	8	8

Table 47

Multi-Baseline (3-6) Diameter Probe Hits (##-pt.)

Diameter	XY Plane	XZ Plane	YZ Plane
0.25	3	6	6
0.50	5	4	3
0.75	6	3	5
1.00	4	6	6
1.25	5	4	5
1.50	4	4	4
1.75	3	4	3
2.00	4	4	6
2.25	6	4	5
2.50	3	4	6
2.75	5	6	3
3.00	5	6	6
3.25	4	3	3
3.50	4	5	6
3.75	6	6	4
4.00	6	4	5
4.25	6	6	5
4.50	6	5	3
4.75	6	5	6
5.00	5	6	3
5.25	6	3	4
5.50	5	5	6
5.75	6	3	5
Mean Probe Hits	5	5	5

month, or year could add up and present a significance difference. On the other hand, the results of the mean probe hit analysis on each multi-baseline optimization program indicated identical probe hit means between planes. Both of these findings, supported the research hypothesis that differences would be noted in the general structure of each planar optimization program but would not be noted in mean probe hit values. One aspect of the research hypothesis that was not supported by the research findings was the expectation that average repeatability within each multi-baseline optimization grouping (SD-based 3-10, SD-based 3-6, Range-based 3-10, and Range-based 3-10) would be the same between planes.

With respect to the fourth research hypothesis, the results of the analysis performed on the structure of the multi-baseline optimization programs indicated minor differences in plate inspection times between inspection planes. Although these inspection time differences did not appear to be significant, these minor differences over the course of a day, week, month, or year could add up and present a significance difference. On the other hand, the results of the mean probe hit analysis on each multi-baseline optimization program indicated identical probe hit means between planes. Both of these findings, supported the research hypothesis that differences would be noted in the general structure of each planar optimization program but would not be noted in mean probe hit values. One aspect of the research hypothesis that was not supported by the research findings was the expectation that average repeatability within each multi-baseline optimization grouping (SD-based 3-10, SD-based 3-6, Range-based 3-10, and Range-based 3-10) would be the same between planes.

Summary of Findings and Analyses

This chapter presented the findings of the research hypotheses. The findings of the four research hypotheses can be summarized in the following manner:

1. Similarities were noted in the direction and magnitude of the relationship between average probe hit repeatability and probe hit variations between repeated baseline programs and baseline programs of different planes. In short, all baseline inspections indicated a moderate to high negative correlation between average probe hit repeatability and probe hit variations for both SD-based and range-based repeatability. Another way to perceive this relationship is that diameter measurement repeatability, regardless of measurement plane, improves as the number of probe hits used in the inspection process is increased. This finding was substantiated through the correlational values associated with mean probe hit repeatability of each planar baseline program (XY-M, XZ-M, and YZ-M). It should be noted that recorded variations in the correlational values between repeated baseline inspections could be viewed as an indicator of significant instability in repeatability within selective diameter/probe hit categories. Consequently, the correlational values associated with mean baseline repeatability tend to reflect more accurately the true nature of the relationship between average probe hit repeatability and probe hit variations in diameter measurement. It was also noted in the XY and XZ baseline repeatability analyses that probe hit categories based on an even number of contact hits (4, 6, 8, and 10) yielded better average repeatability (Note: a smaller numeric repeatability value is an indicator of lower measurement variability, thus better repeatability).

2. The repeatability difference assessments between repeated baseline programs indicated that measurement stability was not significant within all diameter/probe hit categories. In other words, instances occurred in which identical or near-identical repeatability values were not obtained in any probe hit category of a given test specimen between repeated baseline inspections. When these instances occurred, the diameter/probe hit category with the least instability was selected for repeatability optimization. It should be noted that these instances occurred with a greater frequency in SD-based repeatability difference assessment and not range-based difference assessments.

3. The repeatability results of the multi-baseline optimization programs indicated no significant improvement in measurement repeatability. It must be noted, however, that repairs were made to the CMM between baseline data collection and optimization data collection. The potential impact of these repairs on the results of the multi-baseline optimization programs is discussed in more detail in Chapter V. The results of the single baseline repeatability optimization analysis, on the other hand, validated the XY plane findings of the 1993 diameter repeatability study. This finding was further substantiated on the XZ and YZ planes as well. It should be noted that these results may have also been influenced by the CMM repairs.

4. The results of the analysis performed on the structure of the multi-baseline optimization programs indicated minor differences in plate inspection times between inspection planes. Although these inspection time differences did not appear to be significant, these differences over the course of a day, week, month, or year could add up and present a significance difference. The results of the mean probe hit

analysis on each multi-baseline optimization program indicated identical probe hit means between planes (XY, XZ, and YZ). Both of these findings, supported the research hypothesis that differences would be noted in the general structure of each planar optimization program but would not be noted in mean probe hit values. One aspect of the research hypothesis that was not supported by the research findings was the expectation that average repeatability within each multi-baseline optimization grouping (SD-based 3-10, SD-based 3-6, Range-based 3-10, and Range-based 3-10) would be the same between planes. It must be noted that repairs were made to the CMM between baseline data collection and optimization data collection. The impact of these repairs on the results of the optimization programs are discussed in more detail in Chapter V.

CHAPTER V

SUMMARY, CONCLUSIONS, IMPLICATIONS, AND RECOMMENDATIONS

This chapter presents the conclusions of the investigation into the effects of multi-baseline repeatability assessment on the optimization of planar diameter measurement repeatability using a direct computer-controlled coordinate measuring machine (DCC/CMM), specific diameter test specimens, and different probe hit inspection routines. To reflect the extent of the subject matter, this chapter was organized around a overview of the study followed by the conclusions, implications, and recommendations.

Summary

Success in manufacturing today requires a commitment to a philosophy of manufacturing excellence. This philosophy, commonly termed World-Class Manufacturing (WCM), is characterized by several strategies, three of which are continuous improvement, improvement in manufacturing flexibility, and product variability reduction. Changes in manufacturing practices due to the implementation of these strategies has been the driving forces behind the evolution of coordinate measuring machines (CMMs).

To contend with changing market requirements and quality-based competition, manufacturers have taken a more aggressive stand to reduce manufacturing variability, commonly referred to as process variability. Process variability is a quantitative assessment of the accumulated effects of all sources of variability, including gage variability. Through the integration of computer-controlled gaging systems and the improved accuracy and repeatability these systems provide over traditional measuring instruments, manufacturers are provided a truer estimation of actual process variability.

Although computer-controlled gaging system provide numerous advantages over manual gaging systems, these advantages can be further enhanced when potential sources of gage variability and instability are investigated. In other words, a gage capability study is a useful tool for identifying and analyzing sources of variability and instability so that steps can be taken to eliminate the cause of the variability or at the very least bring it under statistical control. Smith (1991) indicated the importance of gage capability studies when he identified four gage characteristics that can be assessed from these studies: accuracy, repeatability, reproducibility, and stability. Smith also indicated that repeatability errors are generally one of the largest contributors of gage variability.

Sources of gage variability in CMMs are diverse and included factors such as temperature change, vibration, probing systems, part fixturing, and dirt and dust. One area of gage variability that has not be adequately investigated is inspection methodology. The potential for measurement variability in this area can be attributed, in part, to the capability of CMMs to measure various features with a multitude of inspection methodologies based on varying numbers of probe hits. Research into this area can yield important information on (a) the extent of measurement repeatability that is lost or gained due to inspection methodology (probe hit variations), (b) the number of probe hits that should be used to measure other circular-based features such as cylinders and cones, (c) a methodology that could be used to assess stability in measurement repeatability (optimal performance signatures), and (d) selective part orientations that can yield improvements in Gage R&R results.

Conclusions

Based on the findings of the study, several conclusions were reached. These conclusions have been divided in two categories, hypothesis-based and indirect observations. The first category, hypothesis-based, incorporate conclusions that were drawn directly from the research findings. The second category, indirect observations, incorporate conclusions that were drawn from the research findings but influenced by unexpected results and personal opinions.

Hypothesis-Based

With respect to the individual research hypotheses, the following conclusions were reached:

1. With regards to research hypothesis #1, similarities were noted in the direction and magnitude of the relationship between average probe hit repeatability and probe hit variations between repeated baseline programs and baseline programs of different planes. In short, all baseline inspections indicated a moderate to high negative correlation between average probe hit repeatability and probe hit variations for both SD-based and range-based repeatability. Another way to perceive this relationship is that diameter measurement repeatability, regardless of measurement plane, improves as the number of probe hits used in the inspection process is numerically increased. The downside to this conclusion is that improved repeatability requires a price, an increase in inspection time. This conclusion was based on (a) the average repeatability results of the three measurement planes using eight probe hit categories and two

repeatability determination methods and (b) the correlational values associated with the relationship between probe hit repeatability and probe hit variation on each of the three measurement planes.

2. With regards to research hypothesis #2, the repeatability difference assessments between repeated baseline programs indicated that measurement stability was not significant within all of the diameter/probe hit categories. In other words, instances occurred in which identical or near-identical repeatability values were not obtained in any probe hit category of a given test specimen between repeated baseline inspections. Although measurement stability was not deemed significant within a limited number of test specimens, difference data of different planes did indicate stability within a similar percentage of diameter/probe hit categories. For example, repeatability difference values of 1.0×10^{-5} or less were noted in 27% of the diameter/probe hit categories on the XY plane, 30% of the diameter/probe hit categories on the XZ plane, and 26% of the diameter/probe hit categories on the YZ plane. The assessment of baseline repeatability also indicated that the diameter/probe hit categories selected for repeatability optimization varied between measurement planes. It should be noted that although the established structure of each optimization varied between measurement planes, the mean number of probe hits for each optimization program was the same in both multi-baseline (3-10) and (3-6) optimization programs and varied slightly in the single baseline (3-10) and (3-6) programs. The results of the multi-baseline repeatability assessments gave credence to the existence of an optimal performance signature for this particular CMM. The existence of this signature also gave credence to the fact that this information could be used to stabilize

and/or improve stability in repeatability through the development of plane-specific optimization programs. Additional findings that gave credence to the existence of an optimal performance signature were: (a) the indication that the 6-pt. category had the "best" measurement stability between the three measurement planes and (b) the indication that the XY and XZ planes had better average repeatability with an even numbers of probe hits over an odd numbers of probe hits. The stability within the 6-pt. category was confirmed on all planes and through both repeatability assessment methods (SD and range) while the even/odd phenomena was only noted on the XY and XZ planes. It should be noted that these results may have also been influenced repairs performed to the CMM between baseline data collection and optimization data collection.

3. With regards to research hypothesis #3, the repeatability results of the multi-baseline optimization programs indicated no significant improvement in measurement repeatability. The primary reason for the lack of improvement in repeatability is that the diameter/probe hit categories with the least instability did not necessarily possess the "best" repeatability. The assessment of baseline repeatability specific to the structure of each multi-baseline optimization program indicated that minor improvements could be obtained in average measurement repeatability while significant improvements could be obtained in measurement stability (reductions in average difference values). For example, the "best" probe hit category on the XZ plane (the 10 pt. category) indicated an average repeatability of 5.6×10^{-5} with an average difference of 2.3×10^{-5}. The theoretical values of the MB(3-10) optimization program, on the other hand, indicated that an average

repeatability of 5.5 x 10^{-5} with an average difference of 0.5 x 10^{-5} could be obtained through repeatability optimization. Although the values indicated by the XZ MB(3-10) optimization program are strictly theoretical, they did indicate a potential benefit that could be derived from multi-baseline repeatability assessment and optimization. The results of the single baseline repeatability optimization analysis, on the other hand, validated the XY plane findings of the 1993 diameter repeatability study. This finding was substantiated on both the XZ and YZ planes as well. It should be noted that these results may have also been influenced by the CMM repairs.

4. With regards to research hypothesis #4, the results of the analysis performed on the structure of the multi-baseline optimization programs indicated minor differences in plate inspection times between inspection planes. Although these inspection time differences did not appear to be significant, these differences over the course of a day, week, month, or year could add up and present a significance difference. The results of the analysis performed on the structure of the multi-baseline optimization programs indicated minor differences in plate inspection times between inspection planes. Although the differences were not significant, these differences over the course of a day, week, month, or year could present a significance time and cost savings. The results of the mean probe hit analysis on each multi-baseline optimization program indicated identical probe hit means between planes, an 8 pt. mean for the MB(3-10) optimization program and a 5 pt. mean for the MB(3-6) optimization program. This finding supports the assertion that differences would be noted in the general structure of each planar optimization program but would not be noted in mean probe hit values.

In other words, probe hit optimization is plane-specific. One aspect that was not supported by the findings was the expectation that average repeatability between measurement planes--within identical optimization groupings, MB(3-10) and MB(3-6)--would be similar. It must be noted that the repairs made to the CMM between baseline and optimization data collection could have influenced the results relative to this expectation.

Indirect Observations

During the analysis and formulation of the research findings, several indirect observations or conclusions were identified. These conclusions, supported indirectly by the research findings, were:

1. Multi-baseline repeatability assessment has been shown to be a viable approach for identifying diameter/probe hit categories with inherent stability as well as a potential method for improving diameter measurement stability through the use of repeatability/stability optimization. Although the results of the multi-baseline optimization tests failed to validate the repeatability improvement supposition, this methodology should not be discounted. The basis for this assertion is that repairs performed on the CMM between the time frame of baseline data collection and optimization data collection could have caused a shift in the repeatability signature that was established through baseline repeatability assessment. If this theory is correct, any change in the repeatability signature will impact established signatures and influence optimization program results. The specific repairs that were performed to the CMM in between the collection of baseline and optimization data were: (a) replacement of the Y-axis motor, (b) replacement of the controller board, and (c) recalibration of the Y-axis. One should also

take note that the diameter/probe hit categories with the least instability may not possess the "best" repeatability, thus improvements in repeatability beyond that of the "best" single category baseline inspection may not be possible.

2. Since the definition for an outlier is a value that exceeds the six sigma limits and since the distribution of diameter measurement error rarely exceeded the four sigma limits, an extreme value that does not meet the criteria for classification as an outlier but is significantly different from the other measurement error values can influence the assessment of range-based repeatability. As a result, the use of the standard deviation method for repeatability determination should be given preference over the range method when CMM repeatability studies are being conducted. This recommendation is made based on the understanding that the standard deviation method assesses repeatability utilizing all members of the distribution whereas the range method only utilizes two members of the distribution, the maximum and minimum values. Consequently, one extreme measurement error value will not significantly alter repeatability when the standard deviation method is used but will when the range method is used.

3. The average repeatability values calculated through the range method were approximately equal to a 3.29 sigma spread of the standard deviation of the measurement error. This sigma spread equates to a confidence interval of approximately 90%.

Implications

Companies large and small have used CMMs for inspections to the point of unquestioned reliance. This unquestioned reliance, according to Watts & Prout (1991), is often expressed by users through the following statement: "It must be right, I checked it on the CMM" (p. 25). In some respects, the major question is not whether the measurement is right or wrong but whether measurement repeatability is acceptable or unacceptable and stable or unstable. The implications presented by the findings and conclusions of this study tend to reflect the importance for a greater awareness and understanding of automated inspection system and the nature of their measurements. The major implications of this study are:

1. The results of the range-based repeatability assessment indicated that repeatability based on this methodology yields a repeatability value that is approximately equal to a SD-based repeatability value with a 90% confidence interval (3.29 sigma spread). This is an important aspect since repeatability assessments based on the use of the range method do not provide users with an indication of the degree of confidence that can be placed in measurement results. An addition implication of this study is that affords CMM purchasers a greater understanding of the assessment methodology under which their CMM may have been assessed during the final stages of production as well as the methodology under which future recalibrations may be conducted.

2. The multi-baseline repeatability assessment methodology gives CMM users a tool that can be used to (a) evaluate the inspection methodology under which different features will be inspected, (b) evaluate the plane (part orientation) under which different features will be inspected, (c) assess optimal performance signatures upon which machine wear and tear can be tracked or monitored, or (d) assess machine signatures upon which repeatability comparison studies can be conducted. In short, the multi-baseline repeatability assessment

methodology is a assessment tool that can be used to identify the presence of measurement variability, the factors that influence measurement variability, and the validity of theorized and/or tested solutions.

3. The results of the study give CMM users a greater understanding of the assessment methodology under which their CMM may have been assessed during the final stages of manufacturing. It also gives CMM users a greater understanding of the assessment methodology under which future recalibrations may be conducted.

Recommendations

Based on the conclusions and implications of this study, the following recommendations are made:

1. Repeatability assessment and optimization is, in many respects, a realistic approach for evaluating measurement repeatability when repeatability differences are noted within different inspection methodologies. Consequently, further research in diameter measurement as well as other types of features is needed to help identify the cause of measurement variability due to inspection methodology. Additional repeatability studies utilizing the multi-baseline approach should be conducted to determine if similar variability exists in other brands and models of CMMs.

2. Since a lack of research exists on the effects of diameter and probe hit variations on diameter measurement repeatability using the computer-controlled, contact-driven CMMs, further research is needed to validate the results of this study. It is also speculated that diameter measurement repeatability is a machine-specific characteristic much like signatures and fingerprints are to people. If this signature notion proves

to be true and high precision measuring activities are to be performed using the CMM, then CMM users may desire to assess their particular machines and determine the particular inspection methodology that yields optimal performance from their CMM.

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APPENDIX A.

CMM SPECIFICATIONS

Description

THE XCEL

The Xcel Coordinate Measuring Machine (Figure 2-1) features an ultra-light bridge structure with a rigid unitary table and base, both made of granite.

These machines are designed to measure parts at a rate of more than 50 hits per minute with exceptional repeatability. When combined with the power of AVAIL, the industry's most advanced geometric measurement software, they offer a machine of exceptional speed and accuracy.

The Xcel series of machines incorporates the following features:

- An ultra-light aluminum alloy bridge structure that provides minimum thermal distortion and predictable and rapid recovery after a temperature change.
- A granite worktable and base that provide a precision measuring surface that is practically maintenance free. The unit's low center of gravity effectively reduces the influence of vibrations that can disturb accuracy.
- Air bearings that are extremely stable and stiff at any speed and operate with a minimal clearance without contamination.
- A effective inertial damping system that assures fast settling after long, high-speed movements.

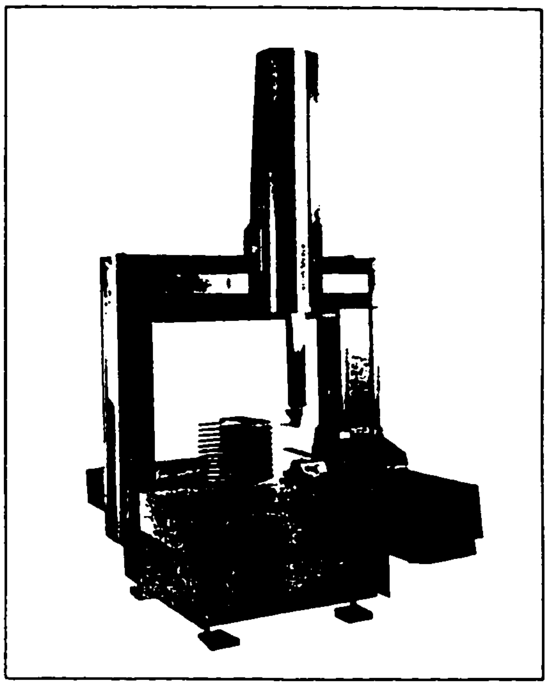


Figure 2-1

- A pneumatic counterbalance system for fast, backlash-free and distortion-free Z-axis travel.
- An advanced manual joystick control that emulates the repeatability of DCC measuring and isolates the operator's body temperature from the probe and workpiece to prevent compromising the machine's accuracy.
- Positive axis drives with backlash eliminated.
- Glass scales that deliver .000020" resolution.

Description

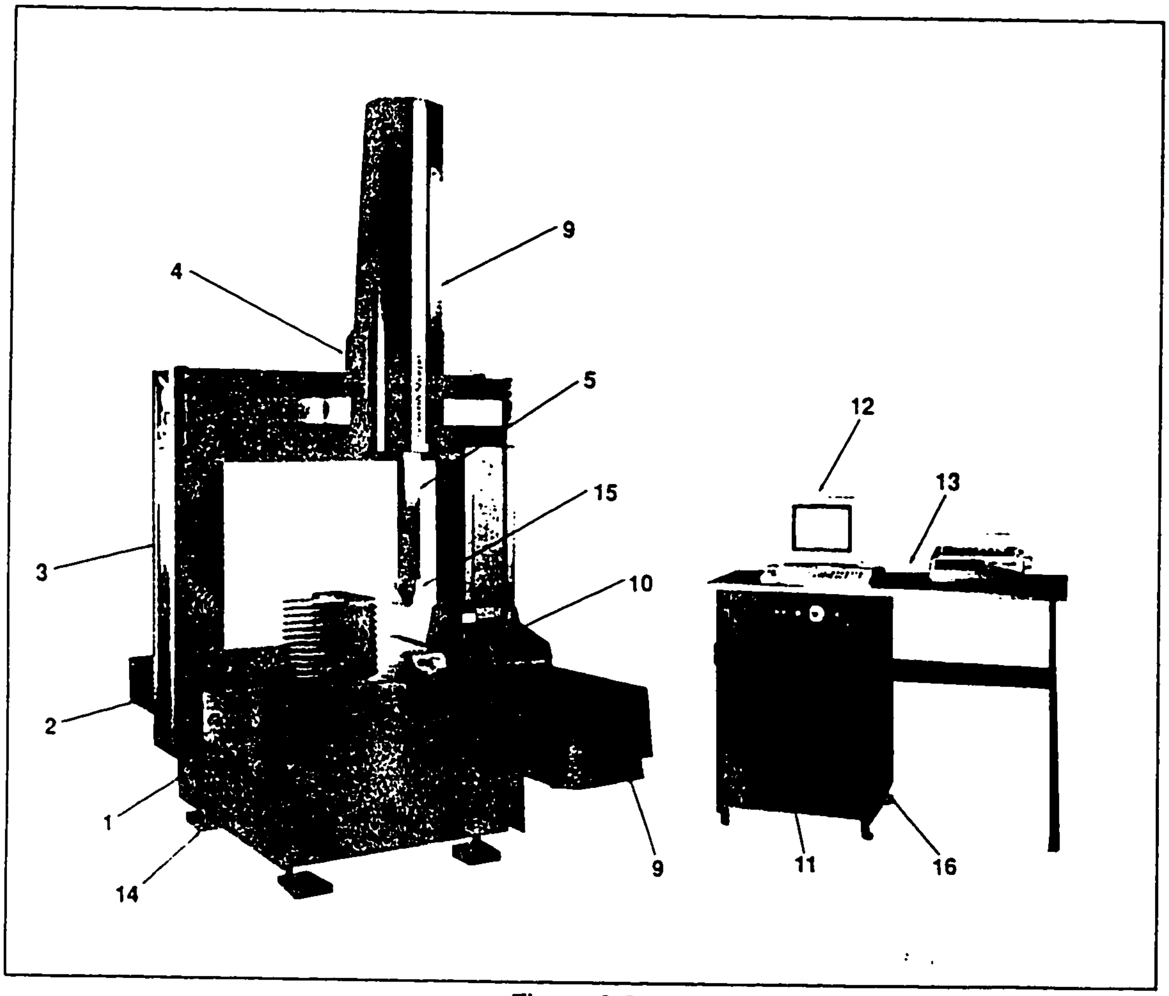


Figure 2-2

The Xcel CMM system consists of the following main components:

1. Base
2. Table
3. Bridge
4. X-Z Carriage
5. Z-Rail
6. Air Bearings (Not shown)
7. Measuring System (Not shown)
8. Air Supply (Not Shown)
9. Covers
10. Joystick Remote Control
11. Controller
12. Monitor
13. Workstation
14. Machine Leveling Feet
15. Probe
16. Electronic Cabinet.

Courtesy of Brown and Sharpe Mfg. Co.

Description

1. BASE - A granite support that provides an extremely low center of gravity. Four isolation pads that support the base, help to minimize vibrations during measuring cycles and prevent vibrations from being transmitted from the floor to the machine.

2. TABLE - A flat, granite surface that provides a means for supporting, locating and clamping parts. The table shoulders serve as the Y-Axis rails. The table is permanently bonded to the base block forming a rigid unit.

3. BRIDGE - A movable structure that consists of left and right legs and the X-Axis rail. The bridge is constructed of ultra-light, cryogenically stress relieved, aluminum alloy that moves on the Y-Axis rails. The X-Axis rail forms the top portion of the bridge and provides the means for guiding the X-Z carriage in an accurate and straight line along the X-Axis. A seismic damper, attached internally to the left top of the bridge, provides for fast settling of vibrations during the measurement cycle. The drive mechanism for the bridge is mounted on the under side of the right leg's foot.

4. X-Z CARRIAGE - The carriage is constructred of ultra-light aluminum alloy and moves along the X-Axis. The carriage contains the air bearings for the X-Axis as well as the air bearings for the Z-rail. The carriage also contains the X and Z drive units.

5. Z-RAIL - A pneumatically counterbalanced rail, constructred of aluminum alloy, that moves vertically in the carriage for making Z-Axis measurements. The rail pneumatic counterbalance cylinder, mounted inside the Z-rail, provides symmetrical rail support and is piped to an accumulator. This provides quick air redistribution within the counterbalance system at high speed with minimal resistance. The counterbalance is factory pre-set for Z-rail weight and average probe weight. The Z-rail is fitted with a holder for attaching various probes. A seismic damper, attached internally to the bottom of the Z-rail on 12-20-10 size machines, provides dynamic stability of the X-Y system.

6. AIR BEARINGS - The air bearings provide for noncontact, frictionless movement of the bridge, carriage, and Z-rail along their respective ways.

7. MEASURING SYSTEM - A highly accurate, opto-electric system, consisting of a scale and an encoder head, which sends electronic position signals to the computer as it moves along the scale.

8. AIR SUPPLY - Provides and distributes air to the air bearings for smooth, frictionless travel of the bridge, carriage and Z-rail. The air supply is also used for the Z-rail counterbalance system. The pneumatic control system provides for safe machine operation and stops operation whenever the air supply pressure is below pre-set limits.

Courtesy of Brown and Sharpe Mfg. Co.

Description

9. COVERS - The covers on the Xcel CMM are both fabricated and molded construction. They are designed to provide ease of access, functional styling, safe operation and protect sensitive machine components.

10. JOYSTICK REMOTE CONTROL - Provides the operator with a remote means of controlling the movement of the probe along the coordinate axes minimizing setup time. It also contains an XYZ axis position display.

11. CONTROLLER - Housed in a fully enclosed cabinet, it supplies the main power source required to operate the Xcel CMM. The cabinet also contains a set of master controls.

12. MONITOR - A CRT with large, easy to read characters. The display provides XYZ readouts, software menu selections and data input capabilities depending on the software used..

13. WORKSTATION - Provides the operator with a convenient desktop work area. The workstation houses the electronic enclosure, the printer, paper, and the monitor.

14. MACHINE LEVELING FEET - Isolation and vibration absorbing type leveling pads that are used to level the machine as well as help prevent transmission of floor borne vibrations to the machine and improve machine dynamic stability.

15. PROBE - Probes are touch trigger types and are used to take hits on the piece being measured.

16. ELECTRONIC CABINET - The cabinet houses the controller and other electrical components.

Courtesy of Brown and Sharpe Mfg. Co.

Specifications

XCEL 7•6•5

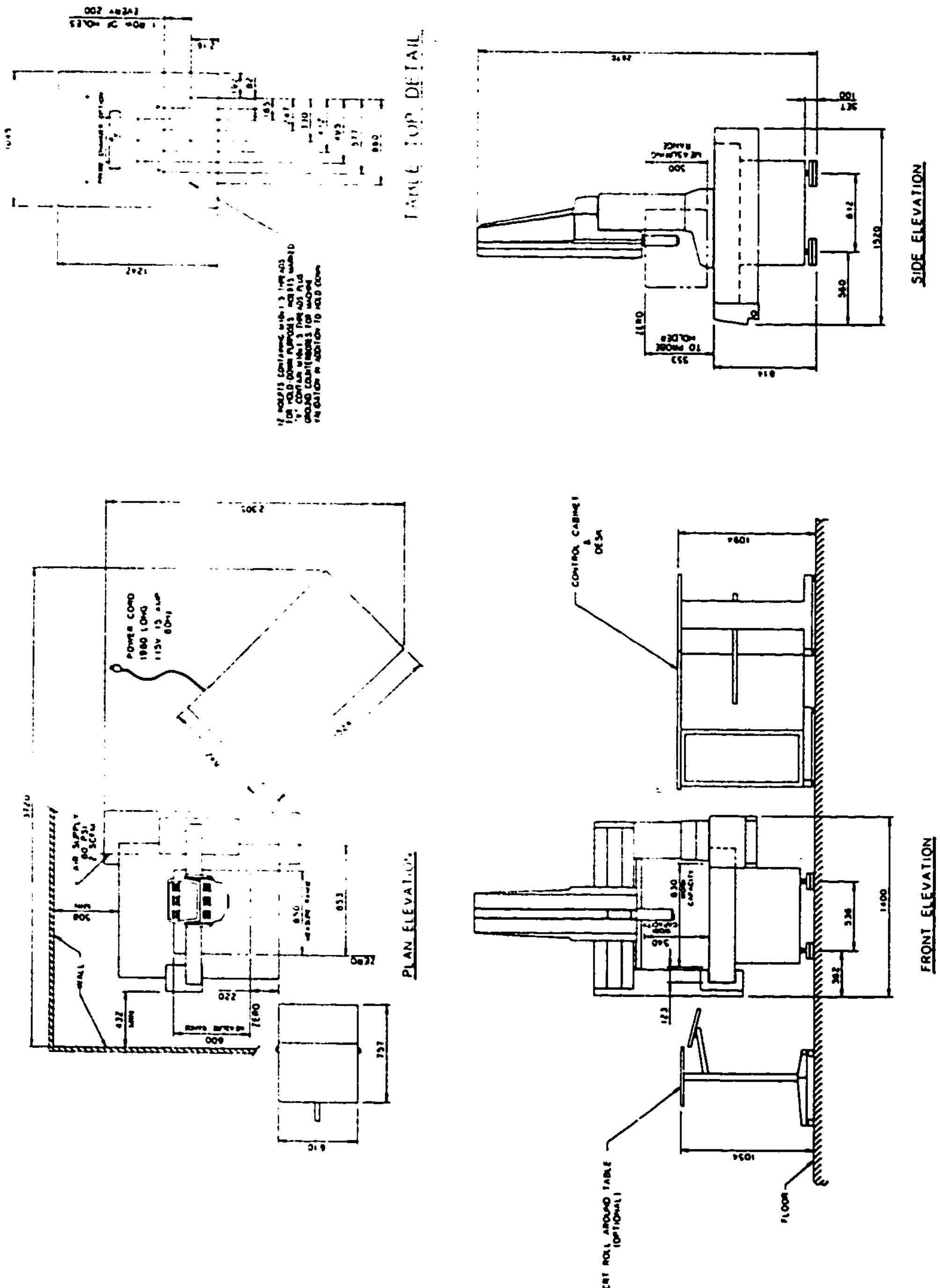
PERFORMANCE	METRIC	ENGLISH
Repeatability B-89	0.0035 mm	0.00014 in.
Volumetric Accuracy	0.011 mm/400 mm	0.0004 in./15.75 in.
Resolution	0.0005 mm	0.00002 in.
Display Range	+/-9999.999 mm	+/-999.9999 in.
Measuring Speed (SCS)	0-25 mm/sec	0-1 in/sec
Rapid Speed (SCS)	0-500 mm/sec	0-20 in/sec
Measuring Speed (MJC)	0-10 mm/sec	0-0.4 in/sec
Rapid Speed (MJC)	0-125 mm/sec	0-5 in/sec
DIMENSIONS		
Measuring Range	650 x 600 x 500 mm	25.6x23.6x19.7in.
Length - Y-Axis	1520 mm	59.8 in.
Width - X-Axis	1400 mm	55.1 in.
Height - Z-Axis	2670 mm	105.12 in.
Weight (Machine only)	1818 kg	4000 lbs
Weight (Complete system)	2000 kg	4400 lbs
Shipping Weight	2454 kg	5400 lbs
Maximum Part Weight	1136 kg	2500 lbs
Part Size Capability (X,Z)	830 x 540 mm	32.7 x 21.26 in.
OPERATIONAL REQUIREMENTS		
Operating Temperature Range	20°C±1°C	68°F±1.8°F
Superimposed Temp. Cycle*	±1°C	±1.8°F
Relative Humidity	20-80%	20-80%
Storage Temperature	-30° to 60°C	-22° to 140°F
Minimum Air Input Pressure	5.2 BAR	75 psi
Operating Air Pressure	4.5 BAR	65 psi
Air Consumption	55 NL (18 L/min)	2 SCFM (0.7 CFM)
Power Requirements (DCC)	110/120 VAC-15A 1PH 50/60 HZ 220/440 VAC-6A 1PH 50/60 HZ	110/120 VAC-15A 1PH 50/60 HZ 220/440 VAC-6A 1PH 50/60 HZ
Power Requirements (MJC)	110/120 VAC-15A 1 PH 50/60 HZ 220/440 VAC-6A 1PH 50/60 HZ	110/120 VAC-15A 1 PH 50/60 HZ 220/440 VAC-6A 1PH 50/60 HZ
Power Consumption incl. Computer (DCC)	1150 W Max. @115VAC 1380 W Max. @ 230VAC	1150 W Max. @ 115VAC 1380 W Max. @ 230VAC
Power Consumption (MJC) (Control only)	345 W Max. @115VAC 345 W Max. @ 230VAC	345 W Max. @ 115VAC 345 W Max. @ 230VAC
Floor Vibration (3-20 Hz)	0.0005mm Pk/Pk	.00002 in. Pk/Pk
Floor Vibration (over 20 Hz)	0.001mm Pk/Pk	.00004 in. Pk/Pk

* Minimum 4 cycles per hour.

Courtesy of Brown and Sharpe Mfg. Co.

Dimensions

Xcel 7•6•5



Courtesy of Brown and Sharpe Mfg. Co.

APPENDIX B.

TEST SPECIMEN LAYOUTS

The circular test specimens used in this study were laid out on four 12" x 12" x 3/4" aluminum plates. These four plates were labelled Plate A, B, C, and D and encompassed the following test specimen configurations:

Plate A

Specimen Identification	Approx. Diameter (in.)	XY Center
Circle 2	0.50	6.563 , 9.156
Circle 4	1.00	6.685 , 2.220
Circle 6	1.50	6.313 , 5.594
Circle 8	2.00	9.406 , 1.969
Circle 10	2.50	9.406 , 5.406
Circle 12	3.00	9.438 , 9.344
Circle 14	3.50	3.063 , 2.719
Circle 16	4.00	3.063 , 8.781

Plate B

Specimen Identification	Approx. Diameter (in.)	XY Center
Circle 5	1.25	1.625 , 3.625
Circle 7	1.75	4.125 , 1.875
Circle 13	3.25	9.375 , 9.375
Circle 20	5.00	8.500 , 3.500
Circle 23	5.75	3.875 , 8.125

Plate C

Specimen Identification	Approx. Diameter (in.)	XY Center
Circle 9	2.25	9.875 , 9.875
Circle 11	2.75	2.375 , 2.375
Circle 21	5.25	8.375 , 3.625
Circle 22	5.50	3.250 , 8.750

Plate D

Specimen Identification	Approx. Diameter (in.)	XY Center
Circle 1	0.25	5.625 , 5.625
Circle 3	0.75	6.725 , 6.725
Circle 15	3.75	9.125 , 9.125
Circle 17	4.25	3.125 , 3.125
Circle 18	4.50	8.750 , 3.250
Circle 19	4.75	3.375 , 8.625

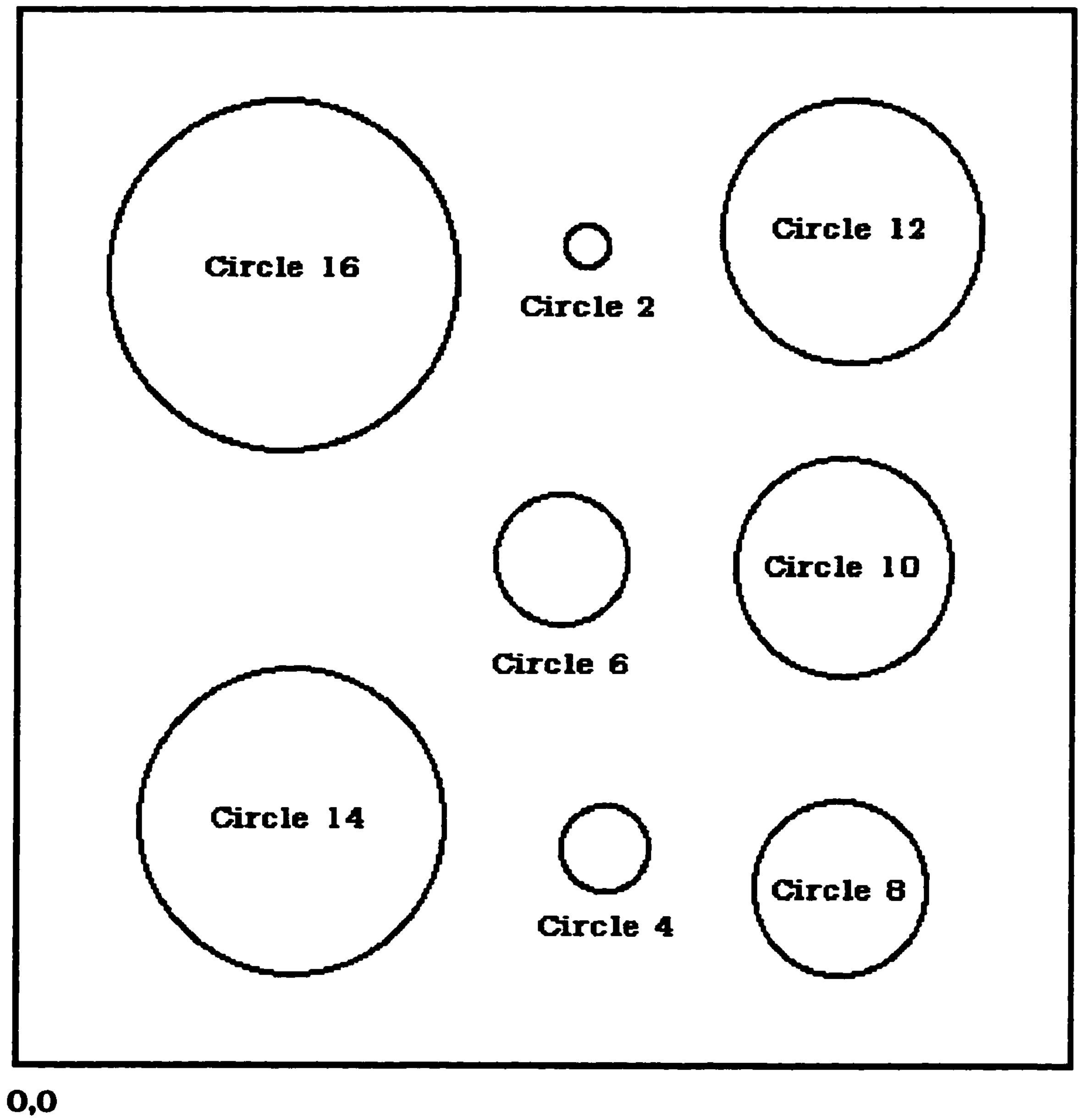


Plate A

Scale: 1/2" = 1.0"

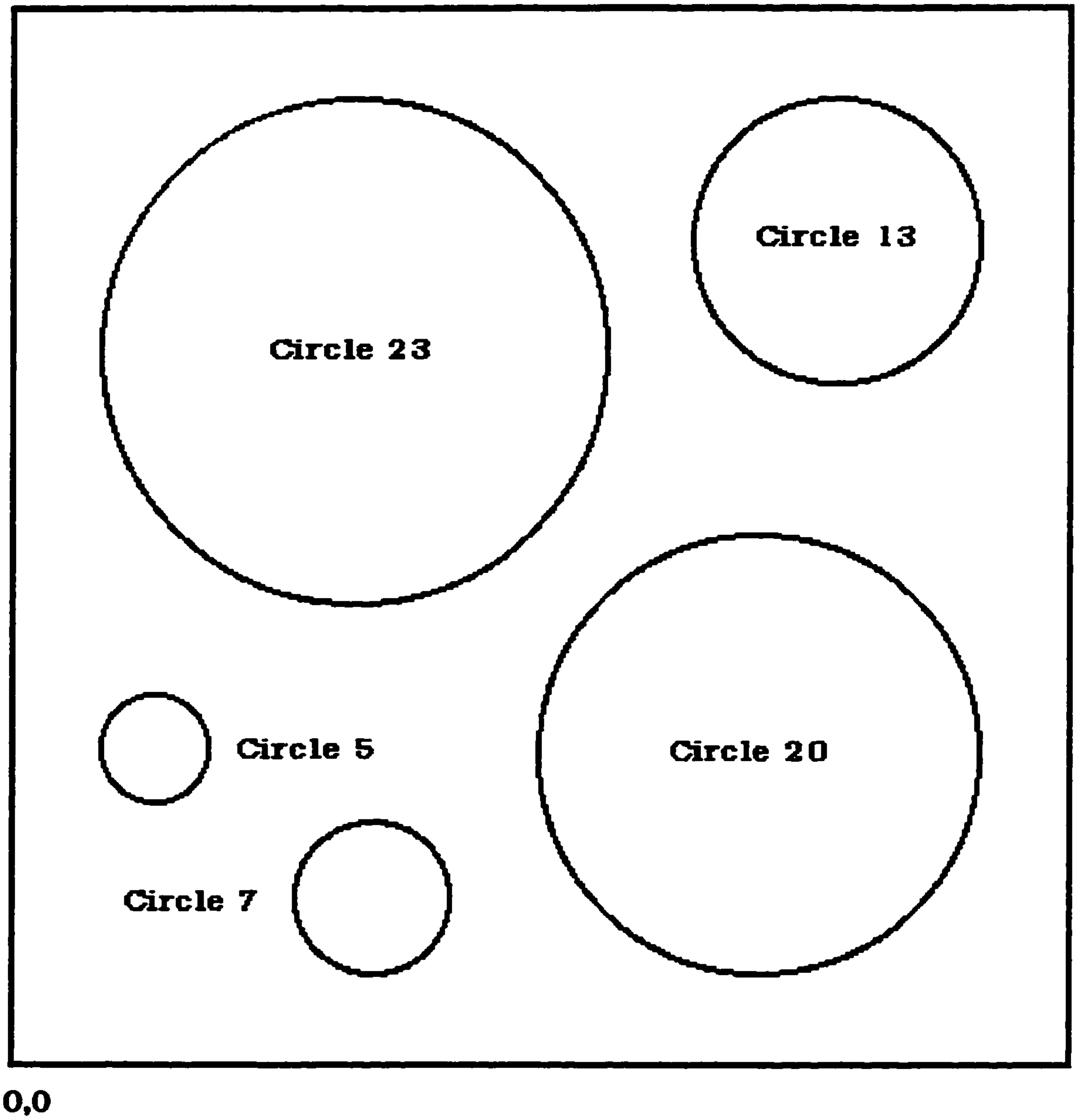


Plate B

Scale: 1/2" = 1.0"

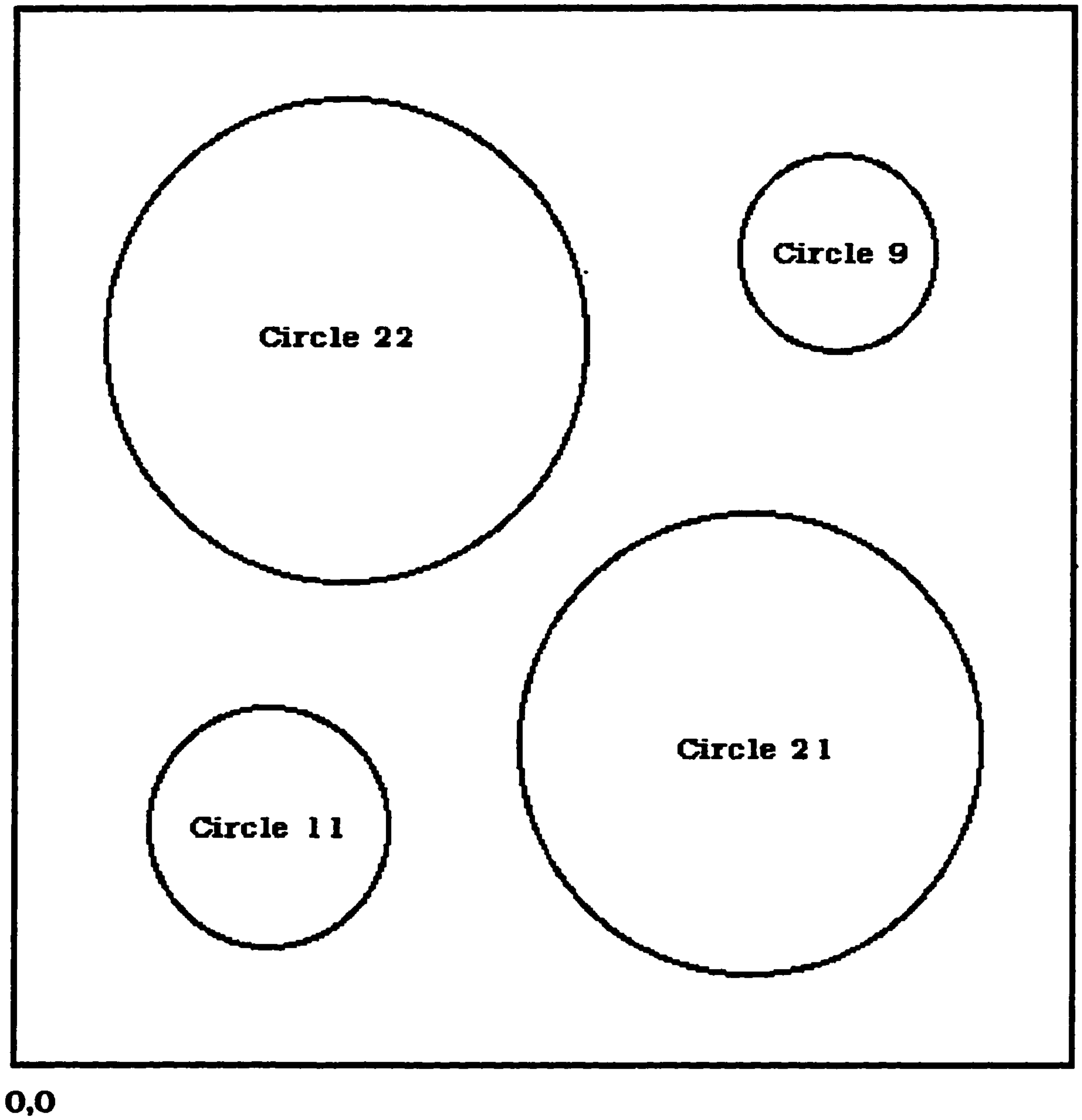


Plate C

Scale: 1/2" = 1.0"

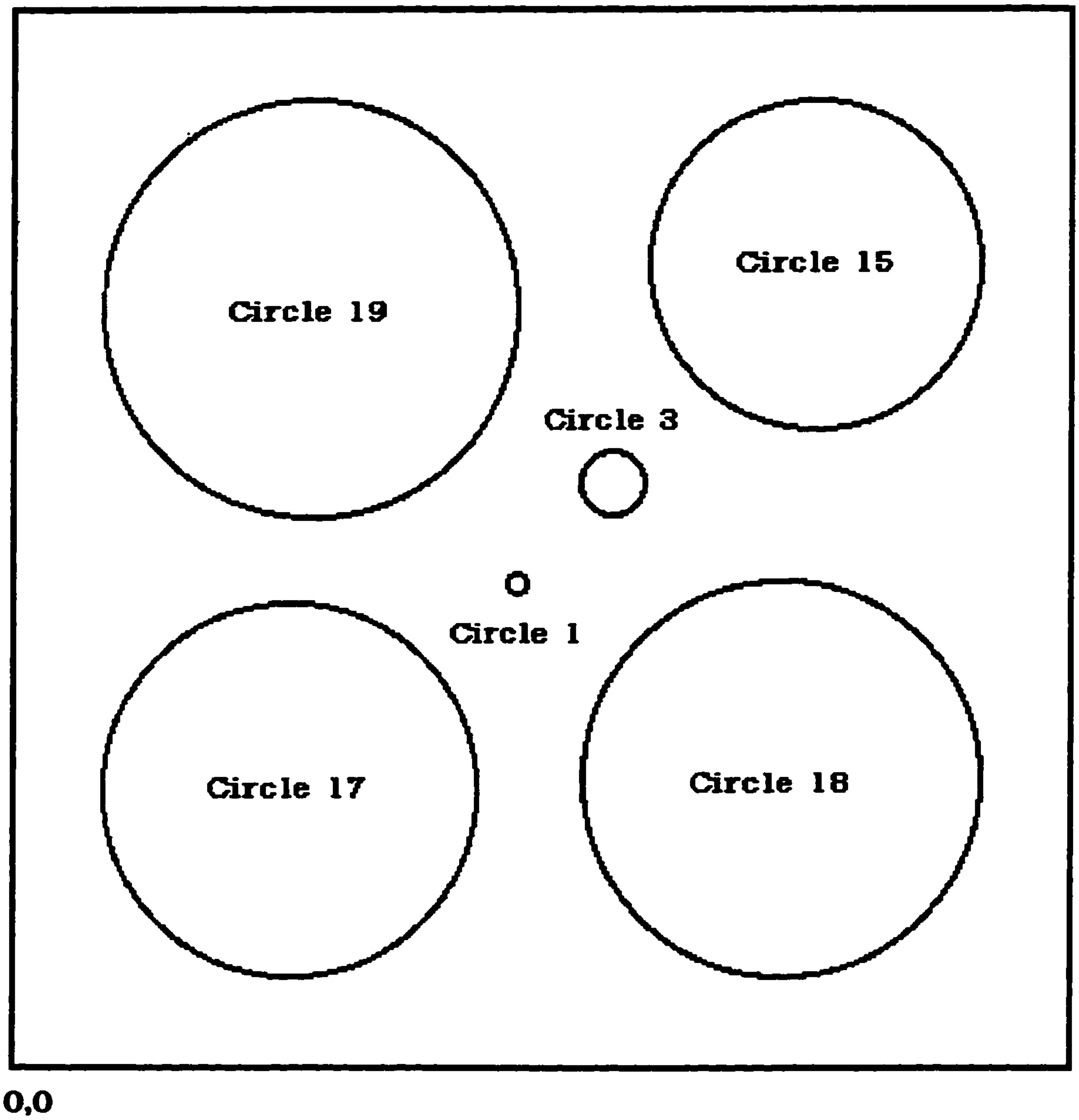
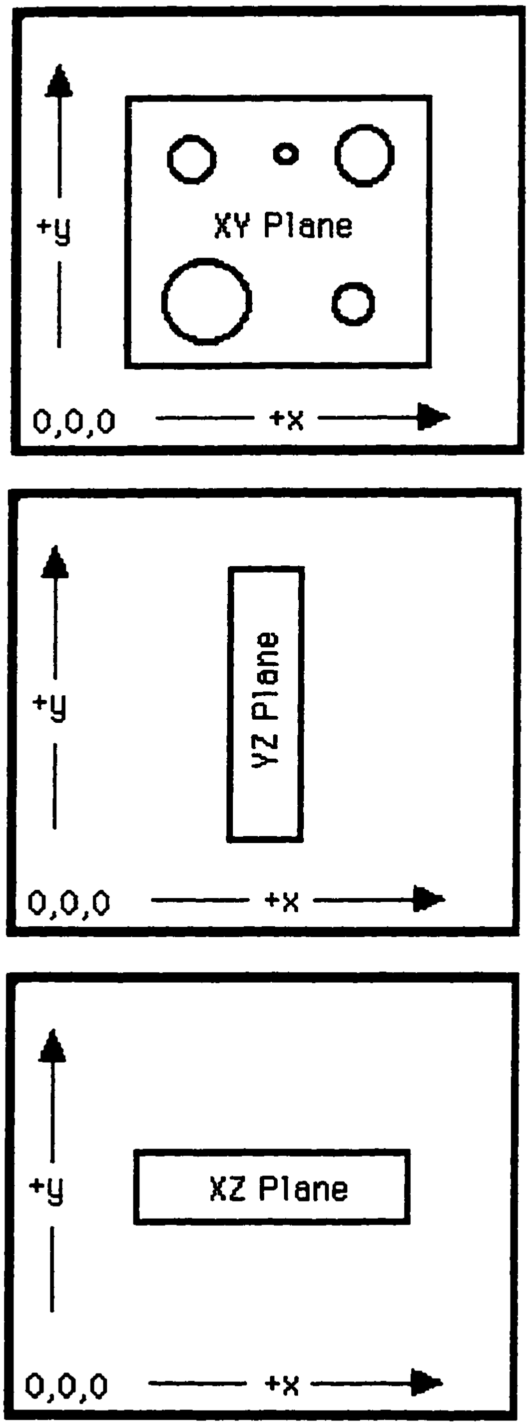


Plate D

Scale: 1/2" = 1.0"

Top View of CMM

Note. Z Plane comes out of the granite table



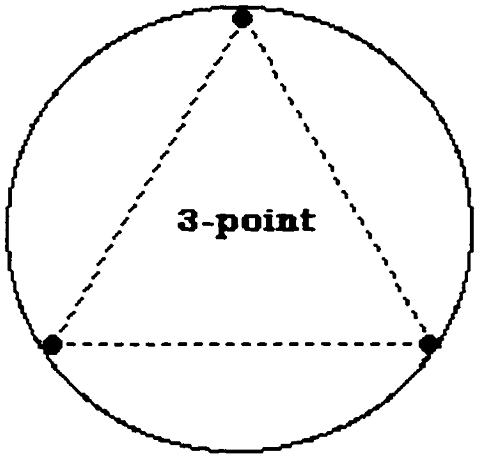
Test Specimen Layout on XY, YZ, and XZ Planes

APPENDIX C.

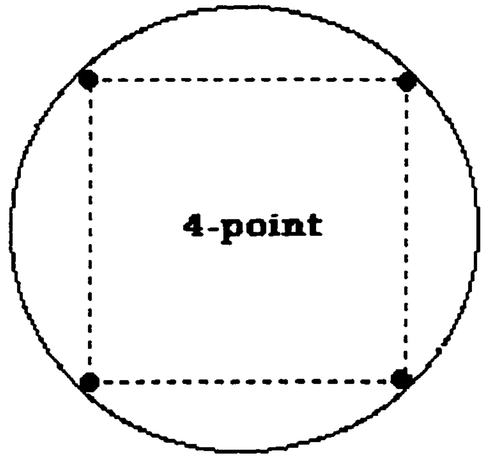
PROBE HIT MEASUREMENT PATTERNS

PROBE HIT CATEGORIES

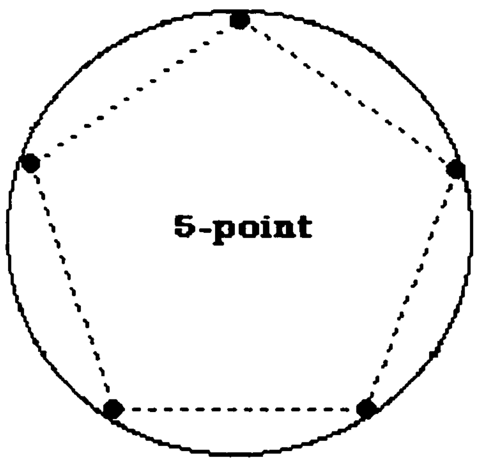
Probe Hits 3 to 6



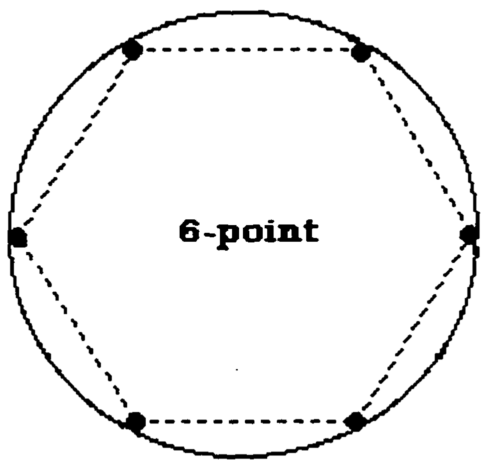
120 degree increments



90 degree increments



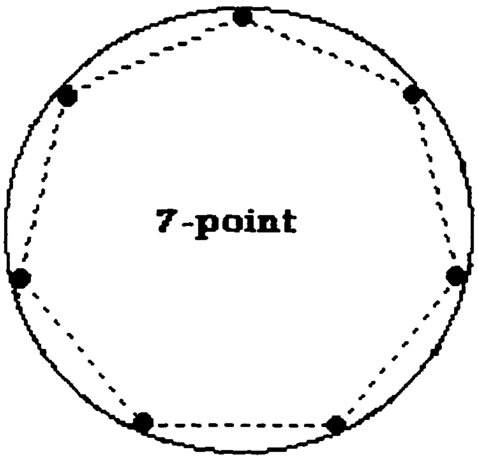
72 degree increments



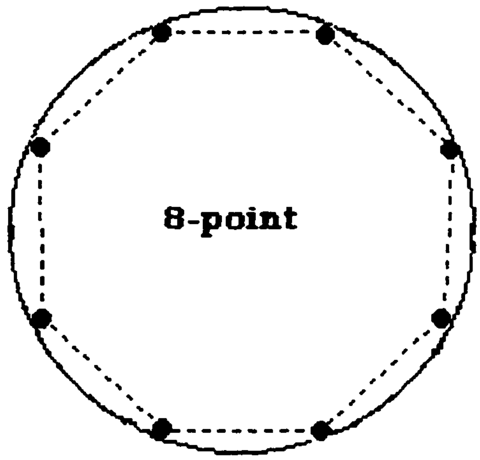
60 degree increments

PROBE HIT CATEGORIES

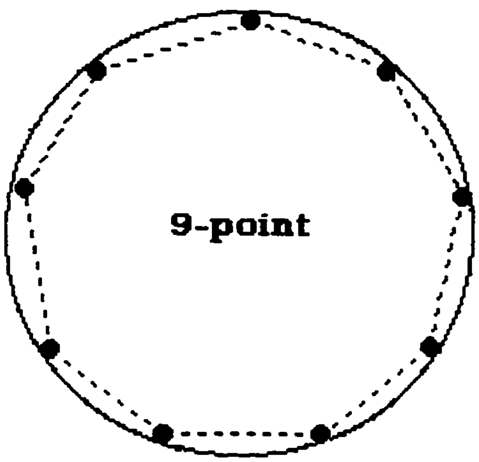
Probe Hits 7 to 10



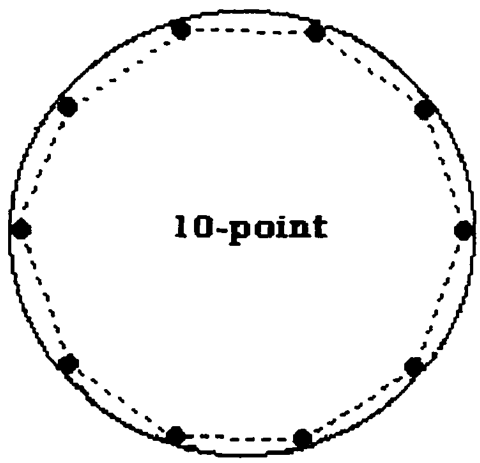
51.4 degree increments



45 degree increments



40 degree increments



36 degree increments

APPENDIX D.

DIAMETER INSPECTION PROGRAMS

In this study, fifteen inspection programs were utilized. Three of the programs were baseline and twelve were optimization. The three baseline programs were developed based on the planes upon which the inspections were conducted. For example, the baseline program that was used to carry out inspections on the XY plane was developed specifically for the XY plane and labelled as XY Plane Baseline Inspection Program. Except for differences in the XYZ coordinates of the individual circular test specimens, the three baseline inspection programs were identical in most respects. Consequently, only the XY Plane Baseline Inspection Program was included in this section.

With regards to the optimization programs, one optimization program was used to conduct four optimization inspections. The program structure that made this consolidation possible was that the inspection parameters for the MB(3-10), MB(3-6), SB(3-10), and SB(3-6) optimization programs on a specific plane were identified as variables within the program and accessed by the program itself. Since each of the planar optimization programs had many similarities, only the XY Plane Optimization Program was included in this section.

Section 1.

XY Plane Baseline Inspection Program

```
! VARIABLES USED
! 1.  RUNS.SC1  = TEXT PROMPT FOR LOOP REPITIONS
! 2.  HITS.SC1  = NUMBER OF PROBE HITS TO BE USED
!                 DURING MEASUREMENT
! 3.  ANG.SC1   = ENDING ANGLE FOR AUTO/CIR EXPRESSION
! 4.  LPHT.SC1  = LAST PROBE HIT TEST CATEGORY
! 5.  COUNT.SC1 = LOOP COUNTER
!
! 6.  SEGS.SC1  = NUMBER OF ARC SEGMENTS WITHIN PROBE
!                 HIT CATEGORY
! 7.  LESS.SC1  = NUMBER OF ARC SEGMENTS IN PROBE HIT
!                 CATEGORY MINUS ONE

      VERSION/NUMBER:2.900000
      UNITS/ENGLISH:
      QUALIFY/RECALL:TIP526
      QUALIFY/OLD_TIP:1
      SETUP/PARAMETERS:20.2.5,20,0.1,100.0.100.0,3.0

PLA.SC1 = CALCULATION/COPY:1
PLB.SC1 = CALCULATION/COPY;2
PLC.SC1 = CALCULATION/COPY:3
PLD.SC1 = CALCULATION/COPY;4

RUNS.SC1 = TEXT/PROMPT:(
HOW MANY MEASUREMENT REPETITIONS OF EACH CIRCLE ARE TO BE MADE?
)

.START_A = LABEL/:
OUTPUT/NEW_PAGE:1

PLATE.SC1 = TEXT/PROMPT:(
WHAT PLATE ID NUMBER IS BEING MEASURED? (ENTER 1, 2, 3, OR 4)
)
          TEXT/DISPLAY:(
FIRST, PLACE THE PLATE ON THE GRANITE SURFACE WITH THE
       SCRIBED ARROW OF THE PLATE FACING FORWARD AND TO
       THE LEFT.

SECOND, MAKE SURE THE PROBE TIP IS IN THE VERTICAL POSITION.

THIRD, TAKE FOUR HITS ON THE TOP OF THE PLATE. ONE HIT IN
       EACH CORNER
)
          PAUSE/:

PLN1 = GEOMETRIC/PLANE:
       MANUAL/:4
       DONE/:

       TEXT/DISPLAY:(
TAKE TWO HITS ON THE FRONT SIDE OF THE PLATE FROM LEFT TO RIGHT.
)

         PAUSE/:
X_AXIS = GEOMETRIC/2D LINE:PLN1
         MANUAL/:2
```

```
          DONE/:

          TEXT/DISPLAY:(
TAKE TWO HITS ON THE LEFT SIDE OF THE PLATE FROM FRONT TO BACK.
)

          PAUSE/:
Y_AXIS = GEOMETRIC/2D LINE;PLN1
          MANUAL/:2
          DONE/:

          ZERO = INTERSECT/POINT;X_AXIS,Y_AXIS
          ALIGNMENT/PART;PLN1,X_AXIS.ZERO.XYZ
          ALIGNMENT/SAVE;LABRUN.ALG1

          TEXT/DISPLAY:(
MOVE PROBE HEAD TO A POSITION APPROXIMATELY 5 INCHES
ABOVE THE LEFT FRONT CORNER OF THE PLATE.
)

          OUTPUT/DELETE:TFILE
          OUTPUT/DELETE:SFILE
          PAUSE/:
          MOVE/BY:0.0.3

LPHT.SC1 = CALCULATION/COPY;10
HITS.SC1 = CALCULATION/COPY;3
ANG.SC1 = CALCULATION/COPY;240

START_B = LABEL/:
COUNT.SC1 = CALCULATION/COPY;0

START_C = LABEL/:
COUNT.SC1 = CALCULATION/ADD;COUNT.SC1,1

      TEXT/REPORT:PLATE.SC1,,HITS.SC1,,RUNS.SC1,,COUNT.SC1 (
PLATE ID NUMBER:

PROBE HIT CATEGORY:

TOTAL MEASUREMENT REPETITIONS:

REPETITION NUMBER:
)

IFTEST/NE:PLATE.SC1.PLA.SC1,START_D
MOVE/TO;3.109,2.659,-.1

CIR14 = AUTO/CIR:PLN1.IS,HITS.SC1,3.109,2.659,-.1,3.5.0,ANG.SC1
          MOVE/TO;3.109,2.659,-.1
          MOVE/BY:0,0,.6
          MOVE/BY:-0.082.6.060,0
          MOVE/TO:3.027.8.719,-.1
          DONE/:

CIR16 = AUTO/CIR:PLN1.IS,HITS.SC1,3.027.8.719.-.1.4.0,ANG.SC1
          MOVE/TO:3.027,8.719,-.1
          MOVE/BY:0.0,.6
          MOVE/BY:3.494,0.424,0
          MOVE/TO:6.521,9.143,-.1
```

```
          DONE/:

CIR2 = AUTO/CIR;PLN1,IS,HITS.SC1,6.521,9.143,-.1,0.5,0,ANG.SC1
          MOVE/TO:6.521,9.143,-.1
          MOVE/BY:0,0,.6
          MOVE/BY:-0.201,-3.566,0
          MOVE/TO:6.320,5.577,-.1
          DONE/:

CIR6 = AUTO/CIR:PLN1,IS,HITS.SC1,6.320,5.577,-.1,1.5,0,ANG.SC1
          MOVE/TO:6.320,5.577,-.1
          MOVE/BY:0,0,.6
          MOVE/BY;0.375,-3.375,0
          MOVE/TO:6.740,2.208,-.1
          DONE/:

CIR4 = AUTO/CIR;PLN1,IS,HITS.SC1,6.740,2.208,-.1,1.0,0,ANG.SC1
          MOVE/TO:6.740,2.208,-.1
          MOVE/BY:0,0,.6
          MOVE/BY:2.722,-0.213,0
          MOVE/TO:9.462,1.995,-.1
          DONE/:

CIR8 = AUTO/CIR:PLN1,IS,HITS.SC1,9.462,1.995,-.1,2.0,ANG.SC1
          MOVE/TO:9.462,1.995,-.1
          MOVE/BY:0,0,.6
          MOVE/BY:-0.047,3.436,0
          MOVE/TO:9.415,5.431,-.1
          DONE/:

CIR10 = AUTO/CIR:PLN1,IS,HITS.SC1,9.415,5.431,-.1,2.5,0,ANG.SC1
           MOVE/TO:9.415,5.431,-.1
           MOVE/BY:0,0,.6
           MOVE/BY:-0.022,3.937,0
           MOVE/TO:9.393,9.368,-.1
           DONE/:

CIR12 = AUTO/CIR:PLN1,IS,HITS.SC1,9.393,9.368,-.1,3.0,0,ANG.SC1
           MOVE/TO:9.393,9.368,-.1
           MOVE/BY:0,0,.6
           MOVE/BY:-6.284,-6.709,0
           MOVE/TO:3.109,2.659,-.1
           DONE/:

           TEXT/PRINTER:{
PLATE ID NUMBER:
}
           OUTPUT/PRINT:PLATE.SC1
           TEXT/PRINTER:{
PROBE HIT CATEGORY:
}
           OUTPUT/PRINT;HITS.SC1
           TEXT/PRINTER:{
TOTAL MEASUREMENT REPETITIONS:
}
           OUTPUT/PRINT:RUNS.SC1
           TEXT/PRINTER:{
REPETITION NUMBER:
}
           OUTPUT/PRINT:COUNT.SC1
```

```
        OUTPUT/LFEED:2

PRINT_OPTION/AXES:D
REPORT/:CIR2
REPORT/:CIR4
REPORT/:CIR6
REPORT/:CIR8
REPORT/:CIR10
REPORT/:CIR12
REPORT/:CIR14
REPORT/:CIR16

RESET/OUTPUT:
OUTPUT/NEW_PAGE:1

IFTEST/NE:COUNT.SC1.RUNS.SC1,START_C
IFTEST/EQ:HITS.SC1,LPHT.SC1,FINISH_A

HITS.SC1 = CALCULATION/ADD:HITS.SC1.1
SEGS.SC1 = CALCULATION/DIVIDE:360.HITS.SC1

LESS.SC1 = CALCULATION/SUB:HITS.SC1.1
ANG.SC1 = CALCULATION/MULTIPLY:SEGS.SC1.LESS.SC1

GOTO/LABEL:START_B
FINISH_A = LABEL/:
MOVE/BY:0.0.6
GOTO/LABEL:TERM
GOTO/LABEL:START_A


START_D =LABEL/:
IFTEST/NE:PLATE.SC1.PLB.SC1.START_E

MOVE/TO:3.833,8.152,-.1

CIR23 = AUTO/CIR:PLN1,IS,HITS.SC1,3.833,8.152,-.1,5.75,0,ANG.SC1
          MOVE/TO:3.833,8.152,-.1
          MOVE/BY:0,0,.6
          MOVE/BY:-2.239,-4.527,0
          MOVE/TO:1.594,3.625,-.1
          DONE/:

CIR5  = AUTO/CIR:PLN1.IS,HITS.SC1.1.594.3.625,-.1.1.25.0.ANG.SC1
          MOVE/TO:1.594.3.625,-.1
          MOVE/BY:0,0,.6
          MOVE/BY:2.500,-1.757,0
          MOVE/TO:4.094,1.868,-.1
          DONE/:

CIR7 = AUTO/CIR;PLN1,IS.HITS.SC1,4.094.1.868,-.1,1.75.0,ANG.SC1
          MOVE/TO:4.094,1.868,-.1
          MOVE/BY:0,0,.6
          MOVE/BY:4.416,1.641,0
          MOVE/TO:8.500,3.509,-.1
          DONE/:

CIR20 = AUTO/CIR:PLN1,IS,HITS.SC1,8.500.3.509,-.1,5,0,ANG.SC1
          MOVE/TO:8.500,3.509,-.1
          MOVE/BY:0,0,.6
```

```
          MOVE/BY;0.815,5.907,0
          MOVE/TO;9.315,9.416,-.1
          DONE/:

CIR13 = AUTO/CIR;PLN1,1S,HITS.SC1,9.315,9.416,-.1,3.25,0,ANG.SC1
          MOVE/TO;9.315,9.416,-.1
          MOVE/BY;0,0,.6
          MOVE/BY;-5.482,-1.264,0
          MOVE/TO;3.833,8.152,-.1
          DONE/:

          TEXT/PRINTER:{
PLATE ID NUMBER:
}

          OUTPUT/PRINT;PLATE.SC1
          TEXT/PRINTER:{
PROBE HIT CATEGORY:
}
          OUTPUT/PRINT;HITS.SC1
          TEXT/PRINTER:{
TOTAL MEASUREMENT REPETITIONS:
}
          OUTPUT/PRINT;RUNS.SC1
          TEXT/PRINTER:{
REPETITION NUMBER:
}
          OUTPUT/PRINT;COUNT.SC1
          OUTPUT/LFEED:2

PRINT_OPTION/AXES;D
REPORT/:CIR3
REPORT/:CIR7
REPORT/:CIR13
REPORT/:CIR20
REPORT/:CIR23

RESET/OUTPUT:
OUTPUT/NEW PAGE:1

IFTEST/NE:COUNT.SC1,RUNS.SC1,START_C
IFTEST/EQ;HITS.SC1,LPHT.SC1,FINISH_B

HITS.SC1 = CALCULATION/ADD;HITS.SC1,1
SEGS.SC1 = CALCULATION/DIVIDE;360,HITS.SC1

LESS.SC1 = CALCULATION/SUB;HITS.SC1,1
ANG.SC1 = CALCULATION/MULTIPLY;SEGS.SC1,LESS.SC1

GOTO/LABEL;START_B
FINISH_B = LABEL/:
MOVE/BY;0,0,6
GOTO/LABEL;TERM
GOTO/LABEL;START_A


START_E =LABEL/:
IFTEST/NE;PLATE.SC1,PLC.SC1,START_F
MOVE/TO;8.336,3.647,-.1
```

```
CIR21 = AUTO/CIR:PLN1.IS.HITS.SC1.8.336.3.647.-.1.5.25.0.ANG.SC1
        MOVE/TO:8.336,3.647,-.1
        MOVE/BY;0,0,.6
        MOVE/BY;1.437,6.237,0
        MOVE/TO:9.773.9.884,-.1
        DONE/:

CIR9 = AUTO/CIR;PLN1,IS,HITS.SC1,9.773,9.884,-.1,2.217,0,ANG.SC1
        MOVE/TO:9.773,9.884,-.1
        MOVE/BY:0,0,.6
        MOVE/BY:-6.230,-1.339,0
        MOVE/TO:3.543,8.485,-.1
        DONE/:

CIR22 = AUTO/CIR;PLN1,IS,HITS.SC1.3.543,8.485,-.1,5.5,0,ANG.SC1
        MOVE/TO:3.543.8.485,-.1
        MOVE/BY:0,0,.6
        MOVE/BY:-1.213,-6.096,0
        MOVE/TO:2.330,2.389,-.1
        DONE/:

CIR11 = AUTO/CIR:PLN1.IS.HITS.SC1.2.330.2.389.-.1.2.75.0,ANG.SC1
        MOVE/TO:2.330,2.389,-.1
        MOVE/BY:0,0,.6
        MOVE/BY:6.006,1.258,0
        MOVE/TO:8.336,3.647,-.1
        DONE/:

        TEXT/PRINTER;{
PLATE ID NUMBER:
}

        OUTPUT/PRINT;PLATE.SC1
        TEXT/PRINTER:{
PROBE HIT CATEGORY:
}
        OUTPUT/PRINT:HITS.SC1
        TEXT/PRINTER:{
TOTAL MEASUREMENT REPETITIONS:
}
        OUTPUT/PRINT:RUNS.SC1
        TEXT/PRINTER:{
REPETITION NUMBER:
}
        OUTPUT/PRINT:COUNT.SC1
        OUTPUT/LFEED:2

PRINT_OPTION.AXES:D
REPORT/:CIR9
REPORT/:CIR11
REPORT/:CIR21
REPORT/:CIR22

RESET/OUTPUT:
OUTPUT/NEW_PAGE:1

IFTEST/NE:COUNT.SC1.RUNS.SC1.START_C
IFTEST/EQ:HITS.SC1,LPHT.SC1,FINISH_C
```

```
HITS.SC1 = CALCULATION/ADD;HITS.SC1,1
SEGS.SC1 = CALCULATION/DIVIDE;360,HITS.SC1

LESS.SC1 = CALCULATION/SUB;HITS.SC1,1
ANG.SC1 = CALCULATION/MULTIPLY;SEGS.SC1,LESS.SC1

GOTO/LABEL:START_B
FINISH_C = LABEL/:
MOVE/BY:0,0,.6
GOTO/LABEL:TERM
GOTO/LABEL:START_H


START_F =LABEL/:
IFTEST/NE:PLATE.SC1,PLD.SC1,FINISH_D
MOVE/TO:8.661,3.276,-.1

CIR18 = AUTO/CIR:PLN1,IS,HITS.SC1,8.661,3.276,-.1,4.5,0,ANG.SC1
        MOVE/TO:8.661,3.276,-.1
        MOVE/BY:0,0,.6
        MOVE/BY:0.387,5.860,0
        MOVE/TO:9.048,9.136,-.1
        DONE/:

CIR15 = AUTO/CIR;PLN1,IS,HITS.SC1,9.048,9.136,-.1,3.75,0,ANG.SC1
        MOVE/TO:9.048,9.136,-.1
        MOVE/BY:0,0,.6
        MOVE/BY:-2.361,-2.410,0
        MOVE/TO:6.687,6.726,-.1
        DONE/:

CIR3 = AUTO/CIR:PLN1,IS,HITS.SC1,6.687,6.726,-.1,0.75,0,ANG.SC1
       MOVE/TO:6.687,6.726,-.1
       MOVE/BY:0,0,.6
       MOVE/BY:-1.127,-1.099,0
       MOVE/TO:5.560,5.627,-.1
       DONE/:

CIR1 = AUTO/CIR:PLN1,IS,HITS.SC1,5.560,5.627,-.1,0.25,0,ANG.SC1
       MOVE/TO:5.560,5.627,-.1
       MOVE/BY:0,0,.6
       MOVE/BY:-2.585,-2.511,0
       MOVE/TO:2.975,3.116,-.1
       DONE/:

CIR17 = AUTO/CIR:PLN1,IS,HITS.SC1,2.975,3.116,-.1,4.15,0,ANG.SC1
       MOVE/TO:2.975,3.116,-.1
       MOVE/BY:0,0,.6
       MOVE/BY:0.269,5.498,0
       MOVE/TO:3.244,8.614,-.1
       DONE/:

CIR19 = AUTO/CIR;PLN1,IS,HITS.SC1,3.244,8.614,-.1,4.60,0,ANG.SC1
        MOVE/TO;3.244,8.614,-.1
        MOVE/BY:0,0,.6
        MOVE/BY;5.417,-5.338,0
        MOVE/TO:8.661,3.276,-.1
        DONE/:

        TEXT/PRINTER:(
```

```
PLATE ID NUMBER:
}
          OUTPUT/PRINT:PLATE.SC1
          TEXT/PRINTER:{
PROBE HIT CATEGORY:
}
          OUTPUT/PRINT;HITS.SC1
          TEXT/PRINTER:{
TOTAL MEASUREMENT REPETITIONS:
}
          OUTPUT/PRINT:RUNS.SC1
          TEXT/PRINTER:{
REPETITION NUMBER:
}
          OUTPUT/PRINT:COUNT.SC1
          OUTPUT/LFEED:0

PRINT_OPTION/AXES:0
REPORT/:CIR1
REPORT/:CIR3
REPORT/;CIR15
REPORT/:CIR17
REPORT/:CIR18
REPORT/:CIR19

RESET/OUTPUT:
OUTPUT/NEW_PAGE:1

IFTEST/NE:COUNT.SC1,RUNS.SC1,START_C
IFTEST/EQ:HITS.SC1.LPHT.SC1,FINISH_D

HITS.SC1 = CALCULATION/ADD:HITS.SC1,1
SEGS.SC1 = CALCULATION/DIVIDE;360,HITS.SC1

LESS.SC1 = CALCULATION/ADD:HITS.SC1,1
ANG.SC1 = CALCULATION/MULTIPLY:SEGS.SC1,LESS.SC1

GOTO/LABEL:START_C
FINISH_D = LABEL/:
MOVE/BY:0,0,6
TERM = LABEL/:
ENDOF/PROGRAM:
```

Section 2.

XY Plane Optimization Program

```
! VARIABLES USED
! 1.  RUNS.SC1 = TEXT PROMPT FOR LOOP REPETITIONS
! 2.  HIT?.SC1 = NUMBER OF PROBE HITS TO BE USED
!                DURING MEASUREMENT
! 3.  AN?.SC1  = ENDING ANGLE FOR AUTO/CIR EXPRESSION
! 5.  COUNT.SC1 = LOOP COUNTER

      VERSION/NUMBER;2.900000
      UNITS/ENGLISH;
      QUALIFY/RECALL;T1PS26
      QUALIFY/OLD_TIP;;
      SETUP/PARAMETERS;20.2.5.20.0.1,100.0.100.0,3.0

PLA.SC1 = CALCULATION/COPY;1
PLB.SC1 = CALCULATION/COPY;2
PLC.SC1 = CALCULATION/COPY;3
PLD.SC1 = CALCULATION/COPY;4

RUNS.SC1 = TEXT/PROMPT;{
HOW MANY MEASUREMENT REPETITIONS OF EACH CIRCLE ARE TO BE MADE?
}

OPT.SC1 = CALCULATION/COPY;1
OPTA.SC1 = CALCULATION/COPY;1
OPTB.SC1 = CALCULATION/COPY;2
OPTC.SC1 = CALCULATION/COPY;3
OPTD.SC1 = CALCULATION/COPY;4


START_A = LABEL/;
OUTPUT/NEW_PAGE;1

PLATE.SC1 = TEXT/PROMPT;{
WHAT PLATE ID NUMBER IS BEING MEASURED? (ENTER 1, 2, 3, OR 4)
}
             TEXT/DISPLAY;{
FIRST, PLACE THE PLATE ON THE GRANITE SURFACE WITH THE
       SCRIBED ARROW OF THE PLATE FACING FORWARD AND TO
       THE LEFT.

SECOND, MAKE SURE THE PROBE TIP IS IN THE VERTICAL POSITION.

THIRD, TAKE FOUR HITS ON THE TOP OF THE PLATE, ONE HIT IN
       EACH CORNER
}
            PAUSE/;

PLN1 = GEOMETRIC/PLANE;
       MANUAL/;4
       DONE/;

       TEXT/DISPLAY;{
TAKE TWO HITS ON THE FRONT SIDE OF THE PLATE FROM LEFT TO RIGHT.
}

           PAUSE/;
X_AXIS = GEOMETRIC/2D_LINE;PLN1
```

```
            MANUAL/;2
            DONE/;

          TEXT/DISPLAY;{
TAKE  TWO HITS ON THE LEFT SIDE OF THE PLATE FROM FRONT TO BACK.
}

            PAUSE/;
Y_AXIS = GEOMETRIC/2D_LINE;PLN1
            MANUAL/;2
            DONE/;

            ZERO = INTERSECT/POINT;X_AXIS,Y_AXIS
            ALIGNMENT/PART;PLN1,X_AXIS,ZERO.XYZ
            ALIGNMENT/SAVE;LABRUN,ALG1

            TEXT/DISPLAY;{
MOVE PROBE HEAD TO A POSITION APPROXIMATELY 5 INCHES
ABOVE THE LEFT FRONT CORNER OF THE PLATE.
}

          OUTPUT/DELETE;TFILE
          OUTPUT/DELETE;SFILE
          PAUSE/;
          MOVE/BY;0,0,3


START_B = LABEL/;
COUNT.SC1 = CALCULATION/COPY;0

' %%%%%%% OPTIMIZ[illegible] %%%%%%%%

IF TEST.NE;[illegible]

ANA.SC1  = CALCULATION/COPY;320
ANB.SC1  = CALCULATION/COPY;288
ANC.SC1  = CALCULATION/COPY;320
AND.SC1  = CALCULATION/COPY;320
ANE.SC1  = CALCULATION/COPY;320
ANF.SC1  = CALCULATION/COPY;324
ANG.SC1  = CALCULATION/COPY;240
ANH.SC1  = CALCULATION/COPY;324
ANI.SC1  = CALCULATION/COPY;308.57
ANJ.SC1  = CALCULATION/COPY;308.57
ANK.SC1  = CALCULATION/COPY;315
ANL.SC1  = CALCULATION/COPY;315
ANM.SC1  = CALCULATION/COPY;270
ANN.SC1  = CALCULATION/COPY;324
ANO.SC1  = CALCULATION/COPY;324
ANP.SC1  = CALCULATION/COPY;300
ANQ.SC1  = CALCULATION/COPY;320
ANR.SC1  = CALCULATION/COPY;300
ANS.SC1  = CALCULATION/COPY;270
ANT.SC1  = CALCULATION/COPY;288
ANU.SC1  = CALCULATION/COPY;315
ANV.SC1  = CALCULATION/COPY;324
ANW.SC1  = CALCULATION/COPY;324

HITA.SC1  = CALCULATION/COPY;[illegible]
HITB.SC1  = CALCULATION/COPY;5
```

```
HITC.SC1 = CALCULATION/COPY;9
HITD.SC1 = CALCULATION/COPY;9
HITE.SC1 = CALCULATION/COPY;9
HITF.SC1 = CALCULATION/COPY;10
HITG.SC1 = CALCULATION/COPY;3
HITH.SC1 = CALCULATION/COPY;10
HITI.SC1 = CALCULATION/COPY;7
HITJ.SC1 = CALCULATION/COPY;7
HITK.SC1 = CALCULATION/COPY;8
HITL.SC1 = CALCULATION/COPY;8
HITM.SC1 = CALCULATION/COPY;4
HITN.SC1 = CALCULATION/COPY;10
HITO.SC1 = CALCULATION/COPY;10
HITP.SC1 = CALCULATION/COPY;6
HITQ.SC1 = CALCULATION/COPY;5
HITR.SC1 = CALCULATION/COPY;6
HITS.SC1 = CALCULATION/COPY;4
HITT.SC1 = CALCULATION/COPY;5
HITU.SC1 = CALCULATION/COPY;8
HITV.SC1 = CALCULATION/COPY;10
HITW.SC1 = CALCULATION/COPY;10

GOTO/LABEL;START_C


' %%%%%%%% OPTIMIZATION VARIABLES FOR M/B (3-6) %%%%%%%%

OP_B = LABEL/;
IFTEST/NE;OPT.SC1,OPTB.SC1,OP_C

ANA.SC1 = CALCULATION/COPY;240
ANB.SC1 = CALCULATION/COPY;288
ANC.SC1 = CALCULATION/COPY;300
AND.SC1 = CALCULATION/COPY;[illegible]
ANE.SC1 = CALCULATION/COPY;288
ANF.SC1 = CALCULATION/COPY;270
ANG.SC1 = CALCULATION/COPY;240
ANH.SC1 = CALCULATION/COPY;270
ANI.SC1 = CALCULATION/COPY;300
ANJ.SC1 = CALCULATION/COPY;240
ANK.SC1 = CALCULATION/COPY;285
ANL.SC1 = CALCULATION/COPY;289
ANM.SC1 = CALCULATION.COPY;270
ANN.SC1 = CALCULATION/COPY;270
ANO.SC1 = CALCULATION/COPY;300
ANP.SC1 = CALCULATION/COPY;300
ANQ.SC1 = CALCULATION/COPY;300
ANR.SC1 = CALCULATION/COPY;300
ANS.SC1 = CALCULATION/COPY;300
ANT.SC1 = CALCULATION/COPY;288
ANU.SC1 = CALCULATION/COPY;300
ANV.SC1 = CALCULATION/COPY;288
ANW.SC1 = CALCULATION/COPY;300

HITA.SC1 = CALCULATION/COPY;3
HITB.SC1 = CALCULATION/COPY;5
HITC.SC1 = CALCULATION/COPY;6
HITD.SC1 = CALCULATION/COPY;4
HITE.SC1 = [illegible]
HITF.SC1 = [illegible]
```

```
HITG.SC1  = CALCULATION/COPY;[illegible]
HITH.SC1  = CALCULATION/COPY;4
HITI.SC1  = CALCULATION/COPY;6
HITJ.SC1  = CALCULATION/COPY;3
HITK.SC1  = CALCULATION/COPY;5
HITL.SC1  = CALCULATION/COPY;5
HITM.SC1  = CALCULATION/COPY;4
HITN.SC1  = CALCULATION/COPY;4
HITO.SC1  = CALCULATION/COPY;6
HITP.SC1  = CALCULATION/COPY;6
HITQ.SC1  = CALCULATION/COPY;6
HITR.SC1  = CALCULATION/COPY;6
HITS.SC1  = CALCULATION/COPY;6
HITT.SC1  = CALCULATION/COPY;5
HITU.SC1  = CALCULATION/COPY;6
HITV.SC1  = CALCULATION/COPY;5
HITW.SC1  = CALCULATION/COPY;6

GOTO/LABEL;START_C


' ********* OPTIMIZATION VARIABLES FOR S/B (3-10) *********

OP_C = LABEL :
IFTEST/NE;OP[illegible].SC1,[illegible].SC1,OP_D

ANA.SC1  = CALCULATION/COPY;308.5[illegible]
ANB.SC1  = CALCULATION/COPY;324
ANC.SC1  = CALCULATION/COPY;300
AND.SC1  = CALCULATION/COPY;324
ANE.SC1  = CALCULATION/COPY;308.57
ANF.SC1  = CALCULATION/COPY;315
ANG.SC1  = CALCULATION/COPY;308.57
ANH.SC1  = CALCULATION/COPY;240
ANI.SC1  = CALCULATION/COPY;270
ANJ.SC1  = CALCULATION/COPY;324
ANK.SC1  = CALCULATION/COPY;31[illegible]
ANL.SC1  = CALCULATION/COPY;[illegible]
ANM.SC1  = CALCULATION/COPY;[illegible]
ANN.SC1  = CALCULATION/COPY;300
ANO.SC1  = CALCULATION/COPY;315
ANP.SC1  = CALCULATION/COPY;300
ANQ.SC1  = CALCULATION/COPY;324
ANR.SC1  = CALCULATION/COPY;324
ANS.SC1  = CALCULATION/COPY;320
ANT.SC1  = CALCULATION/COPY;308.57
ANU.SC1  = CALCULATION/COPY;324
ANV.SC1  = CALCULATION/COPY;324
ANW.SC1  = CALCULATION/COPY;308.[illegible]

HITA.SC1  = CALCULATION/COPY;7
HITB.SC1  = CALCULATION/COPY;10
HITC.SC1  = CALCULATION/COPY;6
HITD.SC1  = CALCULATION/COPY;10
HITE.SC1  = CALCULATION/COPY;7
HITF.SC1  = CALCULATION/COPY;8
HITG.SC1  = CALCULATION/COPY;7
HITH.SC1  = CALCULATION/COPY;3
HITI.SC1  = CALCULATION/COPY;4
HITJ.SC1  = CALCULATION/COPY;10
```

```
HITK.SC1  = CALCULATION/COPY;[illegible]
HITL.SC1  = CALCULATION/COPY;5
HITM.SC1  = CALCULATION/COPY;6
HITN.SC1  = CALCULATION/COPY;6
HITO.SC1  = CALCULATION/COPY;8
HITP.SC1  = CALCULATION/COPY;6
HITQ.SC1  = CALCULATION/COPY;10
HITR.SC1  = CALCULATION/COPY;10
HITS.SC1  = CALCULATION/COPY;9
HITT.SC1  = CALCULATION/COPY;7
HITU.SC1  = CALCULATION/COPY;10
HITV.SC1  = CALCULATION/COPY;10
HITW.SC1  = CALCULATION/COPY;[illegible]

GOTO/LABEL;START_L

' ********** DEFINITION VARIABLES FOR [illegible] **********

OP_D = LABEL  ;
IFTEST/NE;OPT.SC1,[illegible].SC1,FINISH_A

ANA.SC1  = CALCULATION/COPY;[illegible]
ANB.SC1  = CALCULATION/COPY;270
ANC.SC1  = CALCULATION/COPY;300
AND.SC1  = CALCULATION/COPY;270
ANE.SC1  = CALCULATION/COPY;270
ANF.SC1  = CALCULATION/COPY;[illegible]
ANG.SC1  = CALCULATION/COPY;240
ANH.SC1  = CALCULATION/COPY;240
ANI.SC1  = CALCULATION/COPY;270
ANJ.SC1  = CALCULATION/COPY;240
ANK.SC1  = CALCULATION/COPY;300
ANL.SC1  = CALCULATION/COPY;258
ANM.SC1  = CALCULATION/COPY;300
ANN.SC1  = CALCULATION/COPY;300
ANO.SC1  = CALCULATION/COPY;300
ANP.SC1  = CALCULATION/COPY;300
ANQ.SC1  = CALCULATION/COPY;240
ANR.SC1  = CALCULATION/COPY;[illegible]
ANS.SC1  = CALCULATION/COPY;[illegible]
ANT.SC1  = CALCULATION/COPY;[illegible]
ANU.SC1  = CALCULATION/COPY;[illegible]
ANV.SC1  = CALCULATION/COPY;240
ANW.SC1  = CALCULATION/COPY;300

HITA.SC1  = CALCULATION/COPY;6
HITB.SC1  = CALCULATION/COPY;4
HITC.SC1  = CALCULATION/COPY;6
HITD.SC1  = CALCULATION/COPY;4
HITE.SC1  = CALCULATION/COPY;4
HITF.SC1  = CALCULATION/COPY;4
HITG.SC1  = CALCULATION/COPY;[illegible]
HITH.SC1  = CALCULATION/COPY;[illegible]
HITI.SC1  = CALCULATION/COPY;4
HITJ.SC1  = CALCULATION/COPY;3
HITK.SC1  = CALCULATION/COPY;6
HITL.SC1  = CALCULATION/COPY;5
HITM.SC1  = CALCULATION/COPY;6
HITN.SC1  = CALCULATION/COPY;6
HITO.SC1  = CALCULATION/COPY;6
```

```
HITP.SC1  = CALCULATION/COPY;6
HITQ.SC1  = CALCULATION/COPY;3
HITR.SC1  = CALCULATION/COPY;5
HITS.SC1  = CALCULATION/COPY;5
HITT.SC1  = CALCULATION/COPY;5
HITU.SC1  = CALCULATION/COPY;6
HITV.SC1  = CALCULATION/COPY;3
HITW.SC1  = CALCULATION/COPY;6

GOTO/LABEL;START_C

! XXXXXXXX END OF VARIABLE IDENTIFICATION XXXXXXX

START_C = LABEL/;
COUNT.SC1  = CALCULATION/ADD;COUNT.SC1,1

      TEXT/REPORT;PLATE.SC1,,OPT.SC1,,RUNS.SC1,,COUNT.SC1 (
PLATE ID NUMBER:

OPTIMIZATION PROGRAM NUMBER:

TOTAL MEASUREMENT REPETITIONS:

REPETITION NUMBER:
)

IFTEST/NE;PLATE.SC1,PLA.SC1,START_D
MOVE/TO;3.109,2.659,-.1

CIR14  = AUTO/CIR;PLN1,IS,HITN.SC1,3.109,2.659,-.1,3.5,0,ANN.SC1
         MOVE/TO;3.109,2.659,-.1
         MOVE/BY;0,0,.6
         MOVE/BY;-0.082,6.060,0
         MOVE/TO;3.027,8.719,-.1
         DONE/;

CIR16  = AUTO/CIR;PLN1,IS,HITP.SC1,3.027,8.719,-.1,4,0,ANP.SC1
         MOVE/TO;3.027,8.719,-.1
         MOVE/BY;0,0,.6
         MOVE/BY;3.494,0.424,0
         MOVE/TO;6.521,9.143,-.1
         DONE/;

CIR2  = AUTO/CIR;PLN1,IS,HITB.SC1,6.521,9.143,-.1,0.5,0,ANB.SC1
        MOVE/TO;6.521,9.143,-.1
        MOVE/BY;0,0,.6
        MOVE/BY;-0.201,-3.566,0
        MOVE/TO;6.320,5.577,-.1
        DONE/;

CIR6  = AUTO/CIR;PLN1,IS,HITF.SC1,6.320,5.577,-.1,1.5,0,ANF.SC1
        MOVE/TO;6.320,5.577,-.1
        MOVE/BY;0,0,.6
        MOVE/BY;0.375,-3.375,0
        MOVE/TO;6.740,2.208,-.1
        DONE/;

CIR4  = AUTO/CIR;PLN1,IS,HITD.SC1,6.740,2.208,-.1,1.0,0,AND.SC1
        MOVE/TO;6.740,2.208,-.1
        MOVE/BY;0,0,.6
```

```
        MOVE/BY;2.722,-0.213,0
        MOVE/TO;9.462,1.995,-.1
        DONE/;

CIR8 =  AUTO/CIR;PLN1,IS,HITH.SC1,9.462,1.995,-.1,2,0,ANH.SC1
        MOVE/TO;9.462,1.995,-.1
        MOVE/BY;0,0,.6
        MOVE/BY;-0.047,3.436,0
        MOVE/TO;9.415,5.431,-.1
        DONE/;

CIR10 =  AUTO/CIR;PLN1,IS,HITJ.SC1,9.415,5.431,-.1,2.5,0,ANJ.SC1
         MOVE/TO;9.415,5.431,-.1
         MOVE/BY;0,0,.6
         MOVE/BY;-0.022,3.937,0
         MOVE/TO;9.393,9.368,-.1
         DONE/;

CIR12 =  AUTO/CIR;PLN1,IS,HITL.SC1,9.393,9.368,-.1,3.0,0,ANL.SC1
         MOVE/TO;9.393,9.368,-.1
         MOVE/BY;0,0,.6
         MOVE/BY;-6.284,[illegible],0
         MOVE/TO;3.109,[illegible],-.1
         DONE/;

         TEXT/PRINTER;{
PLATE ID NUMBER:
}
         OUTPUT/PRINT;PLATE.SC1
         TEXT/PRINTER;{
OPTIMIZATION PROGRAM NUMBER:
}
         OUTPUT/PRINT;OPT.SC1
         TEXT/PRINTER;{
TOTAL MEASUREMENT REPETITIONS:
}
         OUTPUT/PRINT;RUNS.SC1
         TEXT/PRINTER;{
REPETITION NUMBER:
}
         OUTPUT/PRINT;COUNT.SC1
         OUTPUT/LFEED;2

PRINT_OPTION/AXES;D
REPORT/;CIR2
REPORT/;CIR4
REPORT/;CIR6
REPORT/;CIR8
REPORT/;CIR10
REPORT/;CIR12
REPORT/;CIR14
REPORT/;CIR16

RESET/OUTPUT;
OUTPUT/NEW_PAGE;1

IFTEST/NE;COUNT.SC1,RUNS.SC1,START_C

IFTEST/EQ;OPT.SC1,OPTD.SC1,FINISH_A
OPT.SC1 = CALCULATION/ADD;OPT.SC1,1
```

```
GOTO/LABEL;START_B
FINISH_A = LABEL/;


MOVE/BY;0,0,6
GOTO/LABEL;TERM


START_D =LABEL/;
IFTEST/NE;PLATE.SC1,PLB.SC1,START_E

MOVE/TO;3.833,8.152,-.1

CIR23 = AUTO/CIR;PLN1,IS,HITW.SC1,3.833,8.152,-.1,5.75,0,ANW.SC1
          MOVE/TO;3.833,8.152,-.1
          MOVE/BY;0,0,.6
          MOVE/BY;-2.239,-4.527,0
          MOVE/TO;1.594,3.625,-.1
          DONE/;

CIR5  = AUTO/CIR;PLN1,IS,HITE.SC1,1.594,3.625,-.1,1.25,0,ANE.SC1
          MOVE/TO;1.594,3.625,-.1
          MOVE/BY;0,0,.6
          MOVE/BY;2.500,-1.757,0
          MOVE/TO;4.094,1.868,-.1
          DONE/;

CIR7 = AUTO/CIR;PLN1,IS,HITG.SC1,4.094,1.868,-.1,1.75,0,ANG.SC1
         MOVE/TO;4.094,1.868,-.1
         MOVE/BY;0,0,.6
         MOVE/BY;4.416,1.641,0
         MOVE/TO;8.500,3.509,-.1
         DONE/;

CIR20 = AUTO/CIR;PLN1,IS,HITT.SC1,8.500,3.509,-.1,5,0,ANT.SC1
          MOVE/TO;8.500,3.509,-.1
          MOVE/BY;0,0,.6
          MOVE/BY;0.815,5.907,0
          MOVE/TO;9.315,9.416,-.1
          DONE/;

CIR13 = AUTO/CIR;PLN1,IS,HITM.SC1,9.315,9.416,-.1,3.25,0,ANM.SC1
          MOVE/TO;9.315,9.416,-.1
          MOVE/BY;0,0,.6
          MOVE/BY;-5.482,-1.264,0
          MOVE/TO;3.833,8.152,-.1
          DONE/;

          TEXT/PRINTER;<
PLATE ID NUMBER:
>

          OUTPUT/PRINT;PLATE.SC1
          TEXT/PRINTER;<
OPTIMIZATION PROGRAM NUMBER:
>
          OUTPUT/PRINT;OPT.SC1
          TEXT/PRINTER;<
TOTAL MEASUREMENT REPETITIONS:
>
```

```
          OUTPUT/PRINT;RUNS.SC1
          TEXT/PRINTER;(
REPETITION NUMBER:
)
          OUTPUT/PRINT;COUNT.SC1
          OUTPUT/LFEED;2

PRINT_OPTION/AXES:D
REPORT/;CIR5
REPORT/;CIR7
REPORT/;CIR13
REPORT/;CIR20
REPORT/;CIR23

RESET/OUTPUT;
OUTPUT/NEW_PAGE;1

IFTEST/NE;COUNT.SC1,RUNS.SC1,START_C

IFTEST/EQ;OPT.SC1,OPTD.SC1,FINISH_A
OPT.SC1 = CALCULATION/ADD;OPT.SC1,1
GOTO/LABEL;START_B
FINISH_A = LABEL/;

MOVE/BY;0,0,6
GOTO/LABEL;TERM

START_E =LABEL/;
IFTEST/NE;PLATE.SC1,PLC.SC1,START_F
MOVE/TO;8.336,3.647,-.1

CIR21 = AUTO/CIR;PLN1,IS,HITU.SC1,8.336,3.647,-.1,5.25,0,ANU.SC1
          MOVE/TO;8.336,3.647,-.1
          MOVE/BY;0,0,.6
          MOVE/BY;1.437,6.237,0
          MOVE/TO;9.773,9.884,-.1
          DONE/:

CIR9 = AUTO/CIR;PLN1,IS,HIT1.SC1,9.773,9.884,-.1,2.217,0,ANI.SC1
          MOVE/TO;9.773,9.884,-.1
          MOVE/BY;0,0,.6
          MOVE/BY;-6.230,-1.339,0
          MOVE/TO;3.543,8.485,-.1
          DONE/;

CIR22 = AUTO/CIR;PLN1,IS,HITV.SC1,3.543,8.485,-.1,5.5,0,ANV.SC1
          MOVE/TO;3.543,8.485,-.1
          MOVE/BY;0,0,.6
          MOVE/BY;-1.213,-6.096,0
          MOVE/TO;2.330,2.389,-.1
          DONE/:

CIR11 = AUTO/CIR;PLN1,IS,HITK.SC1,2.330,2.389,-.1,2.75,0,ANK.SC1
          MOVE/TO;2.330,2.389,-.1
          MOVE/BY;0,0,.6
          MOVE/BY;6.006,1.258,0
          MOVE/TO;8.336,3.647,-.1
          DONE/;

          TEXT/PRINTER;(
```

```
PLATE ID NUMBER:
}

          OUTPUT/PRINT;PLATE.SC1
          TEXT/PRINTER;{
OPTIMIZATION PROGRAM NUMBER:
}
          OUTPUT/PRINT;OPT.SC1
          TEXT/PRINTER;{
TOTAL MEASUREMENT REPETITIONS:
}
          OUTPUT/PRINT;RUNS.SC1
          TEXT/PRINTER;{
REPETITION NUMBER:
}
          OUTPUT/PRINT;COUNT.SC1
          OUTPUT/LFEED;2

PRINT_OPTION/AXES;D
REPORT/;CIR9
REPORT/;CIR11
REPORT/;CIR21
REPORT/;CIR22

RESET/OUTPUT;
OUTPUT/NEW_PAGE;1

IFTEST/NE;COUNT.SC1,RUNS.SC1.START_C

IFTEST/EQ;OPT.SC1,OPTD.SC1,FINISH_A
OPT.SC1 = CALCULATION/ADD;OPT.SC1,1
GOTO/LABEL;START_B
FINISH_A = LABEL/;

MOVE/BY;0,0,6
GOTO/LABEL;TERM


START_F =LABEL/;
IFTEST/NE;PLATE.SC1,PLD.SC1,FINISH_D
MOVE/TO;8.661,3.276,-.1

CIR18 = AUTO/CIR;PLN1,IS,HITR.SC1,8.661,3.276,-.1,4.5,0,ANR.SC1
          MOVE/TO;8.661,3.276,-.1
          MOVE/BY;0,0,.6
          MOVE/BY;0.387,5.860,0
          MOVE/TO;9.048,9.136,-.1
          DONE/;

CIR15 = AUTO/CIR;PLN1,IS,HITO.SC1,9.048,9.136,-.1,3.75,0,ANO.SC1
          MOVE/TO;9.048,9.136,-.1
          MOVE/BY;0,0,.6
          MOVE/BY;-2.361,-2.410,0
          MOVE/TO;6.687,6.726,-.1
          DONE/;

CIR3 = AUTO/CIR;PLN1,IS,HITC.SC1,6.687,6.726,-.1,0.75,0,ANC.SC1
         MOVE/TO;6.687,6.726,-.1
         MOVE/BY;0,0,.6
         MOVE/BY;-1.127,-1.099,0
```

```
        MOVE/TO;5.560,5.627,-.1
        DONE/;

CIR1 = AUTO/CIR;PLN1,IS,HITA.SC1,5.560,5.627,-.1,0.25,0,ANA.SC1
        MOVE/TO;5.560,5.627,-.1
        MOVE/BY;0,0,.6
        MOVE/BY;-2.585,-2.511,0
        MOVE/TO;2.975,3.116,-.1
        DONE/;

CIR17 = AUTO/CIR;PLN1,IS,HITQ.SC1,2.975,3.116,-.1,4.15,0,ANQ.SC1
        MOVE/TO;2.975,3.116,-.1
        MOVE/BY;0,0,.6
        MOVE/BY;0.269,5.498,0
        MOVE/TO;3.244,8.614,-.1
        DONE/;

CIR19 = AUTO/CIR;PLN1,IS,HITS.SC1,3.244,8.614,-.1,4.60,0,ANS.SC1
         MOVE/TO;3.244,8.614,-.1
         MOVE/BY;0,0,.6
         MOVE/BY;5.417,-5.338,0
         MOVE/TO;8.661,3.276,-.1
         DONE/;

         TEXT/PRINTER;{
PLATE ID NUMBER:
}

         OUTPUT/PRINT;PLATE.SC1
         TEXT/PRINTER;{
OPTIMIZATION PROGRAM NUMBER:
}
         OUTPUT/PRINT;OPT.SC1
         TEXT/PRINTER;{
TOTAL MEASUREMENT REPETITIONS:
}
         OUTPUT/PRINT;RUNS.SC1
         TEXT/PRINTER;{
REPETITION NUMBER:
}
         OUTPUT/PRINT;COUNT.SC1
         OUTPUT/LFEED;2

PRINT_OPTION/AXES;D
REPORT/;CIR1
REPORT/;CIR3
REPORT/;CIR15
REPORT/;CIR17
REPORT/;CIR18
REPORT/;CIR19

RESET/OUTPUT;
OUTPUT/NEW_PAGE;1

IFTEST/NE;COUNT.SC1,RUNS.SC1,START_C

IFTEST/EQ;OPT.SC1,OPTD.SC1,FINISH_A
OPT.SC1 = CALCULATION/ADD;OPT.SC1,1
GOTO/LABEL;START_B
FINISH_A = LABEL/;

MOVE/BY;0,0,6
TERM = LABEL/;
ENDOF/PROGRAM;
```