SOCIETY OF AUTOMOTIVE ENGINEERS, INC.
485 Lexington Avenue, New York 17, N. Y.

Recent Developments In Cam Profile Measurement and Evaluation

J. H. Nourse, Engineering Consultant
Camcheck and Cam Design Company

SOCIETY OF AUTOMOTIVE ENGINEERS

International Automotive Engineering Congress
Detroit, Michigan
January 11-15, 1965

964A

TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

ABSTRACT

New techniques are presented for cam profile measurement and evaluation based upon recently derived analytical methods and electronic computer programs. The new methods include the mathematical refinement of profile raw lift data and obtain the following advantages over current practice:

1. Accuracy—Cam profile lift data accuracy is improved by a factor of ten to one hundred times.
2. Repeatability—The profile measurements and evaluations are repeatable within the new limits of accuracy.
3. Evaluation—"Camcheck"* computer programs yield new information which has optimum usefulness to quality control and engineering design development.
4. Efficiency—The new analytical methods essentially eliminate camshaft manual set-up procedures for profile measurement—and also substantially reduce the engineering time required for profile evaluation.

In conclusion, new acceptance criteria for cam profile quality control, and the direction for the further development of cam profile measurement and evaluation methods and techniques are suggested.

* "Camcheck" is a trade mark of the Camcheck Company.

PART I

INTRODUCTION

Modern technology, especially the development and widespread use of electronic computers in science and industry, has made possible a giant step forward in the craft of automotive engine cam profile measurement and evaluation (CPM&E). In view of the rapid technological development which has occurred in most industries during the last decade, a revolution in CPM&E should not surprise anyone; indeed, an estimate from the present vantage point suggests that the new development in cam profile metrology has been too long delayed.

A major trend in the automotive industry lies in the direction of automation and a greatly improved effectiveness in quality control. The new cam profile metrology is directly in step with this trend. It is the key to a highly improved cam profile quality control and at the same time involves procedures subject to automation.

The overall objectives of CPM&E are easily defined. Applied to production cam manufacture, the objective is to pass (by approval) every cam profile and every camshaft that will meet certain requirements for engine performance—and alternately, reject every profile that will not meet such requirements. Quite obviously there is in this definition of objectives the serious problem of stating cam profile tolerances and specifications in a way that will obtain effective control. The problem of profile tolerance is followed immediately by the requirement for profile measurement and evaluation. Such methods must obtain levels of accuracy sufficient to make the profile tolerances meaningful. Certain cam profile measurement procedures, which are used in current practice, were developed several decades ago for the profile tolerances of that time. In recent years, however, engineering tolerances have become more restrictive in line with improved engine performance and an effort toward improved quality control.

The analytical effort directed toward the new CPM&E methods grew directly from extensive experience with internal combustion engine cam design problems. Early in this development, it was observed and verified analytically that certain profile measurement procedures introduce errors larger by a factor of ten than present cam profile tolerance levels. One of these procedures is the method used for determining the zero degree position at the top of the cam rise—see detailed explanation, page 13. A second procedure is the method used for compensating the profile lift data for base circle run-out—see page 10.

The basic concept that makes the new CPM&E possible starts from a recognition of the simple fact that associated with each measurement there is an error. That is, there is an error associated with the cam profile lift (displacement) measurement—and a second error associated with the angular displacement required to rotate the cam to some new measurement position. When these errors are examined carefully, they are found to consist of two parts—a random error part and a systematic error part. Certain statistical and other mathematical procedures can be used to smooth the random error. Following this, additional procedures can be used to evaluate the systematic error and correct the profile lift data. Because of the vast amount of arithmetic involved, it is found that electronic computing methods are a practical necessity.

It is the foregoing development from which evolved the very highly specialized "Camcheck" computer programs—and has led to the methods of cam profile measurement and evaluation offered by the Camcheck Company. The objective of this paper is to present and explain the new CPM&E methods in some detail, to contrast these with current practice and, in conclusion, to present certain ideas and concepts which may point the direction for further improvements and future development.

PART II

A STATEMENT OF THE CAM PROFILE MEASUREMENT AND EVALUATION PROBLEM

The beginning step in the solution of the cam profile measurement and evaluation problem, as in any engineering problem, is the task of stating or defining the problem clearly; that is the objective of this section of the paper. The first part of this problem, cam profile measurement, is defined in the paragraphs below from typical profile engineering tolerances and standard gaging practice. The second part of this problem, profile evaluation, is defined from the requirements of quality control and also the requirements of cam design and development.

The Cam Profile Measurement Problem

The simplest statement of the CPM problem is that the profile "as made" must be measured at consecutive angular intervals with sufficient accuracy to allow a meaningful comparison with the profile lift values "as designed." Both direct measurements and certain procedures are involved; these are lift measurements, angular measurements, a procedure for orienting the measured data to a common zero position index with the design data, and a procedure for referencing the measured data to the true center of the cam base circle. The total sum of the errors from both the measurements and procedures will determine the overall accuracy. This accuracy should be in accord with standard gage practice.

Production Cam Tolerances

A typical cam profile with a statement of the production tolerances is shown in Fig. 1. These tolerances are given as average and typical of those presently used in industry. The tolerances used on any particular profile may be somewhat less demanding for an engine of relatively lesser performance or more rigid for an engine of higher performance. The tolerance consists of two kinds of statements: First, there is a maximum allowable deviation (or bandwidth) from which the profile "as made" can be permitted to depart from the design profile. Normally, this bandwidth changes with the location along the profile. The second kind of statement is a profile waviness specification. The intent of this tolerance is to limit the rate at which the profile "as made" can be permitted to deviate from the design values. This information is frequently furnished in chart form as shown in Fig. 2.

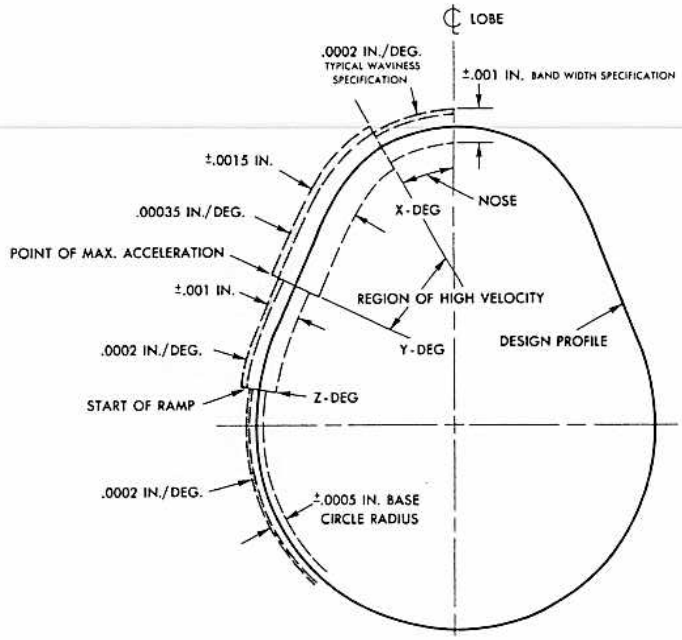


FIGURE 1. TYPICAL CAM PROFILE PRODUCTION TOLERANCES

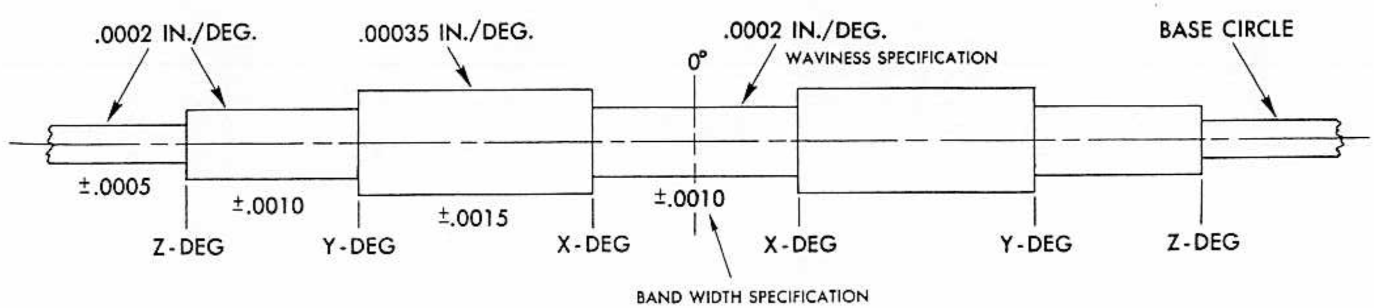


FIGURE 2. TYPICAL CAM PROFILE PRODUCTION TOLERANCES - CHART FORM

From the foregoing, it can be seen that the orders of magnitude (see Table I) of the engineering tolerances for the production cam profile are as follows:

Bandwidth specification . . .	.00100 inches
Waviness specification	.00010 in/deg

Table I

The following table shows the order of magnitude corresponding with a given range of numerical values. By definition, the dimensional units can be any; in this paper the units are inches. The first line reads as follows, "Numerical values between 50.0 and 5.0 have an order of magnitude of 10."

Range of Values	Order of Magnitude
50.0 – 5.0	10.0
5.0 – .50	1.0
.50 – .050	.10
.050 – .0050	.010
.0050 – .00050	.0010
.00050 – .000050	.00010
.000050 – .0000050	.000010

Standard Gage Practice

The means (instrument and/or method) used to perform a specific measurement must have an accuracy equal to or better than the accuracy expected in that measurement. If the measurement involves a dimensional tolerance (as in a manufactured part) then the measurement means must have significantly greater accuracy than the tolerance. The accepted standard[1] established for gaging practice is that the accuracy of the measurement means should exceed the tolerance by one order of magnitude For example, a tolerance of ± 1.0 inch would require the measurement accuracy to be $\pm .10$ inches; a tolerance of $\pm .001$ inches would require the measurement accuracy to be $\pm .0001$ inches.

Linear Displacement—Measurement Accuracy

Based upon normal gaging standards, the measurement of a cam profile engineering tolerance bandwidth specification in the order of .00100 inches requires that the instrument and methods used for the measurement have an absolute accuracy in the order of .00010 inches. An "absolute" accuracy is specified because in the bandwidth specification, a comparison between two different sets of data is intended, i.e., measured cam profile lift data is to be compared with design lift data.

A cam profile waviness specification in the order of .00010 inches per degree requires instrumentation and methods with a relative accuracy in the order of .00001 inches. A "relative" accuracy (as distinct from absolute) is specified because a comparison between two points in the same set of data is intended, i.e., each measured cam profile lift data point is to be compared with that taken at the next previous angular position.

Angular Displacement—Measurement Accuracy

Angular displacement measurements are also involved in the profile measurement problem. By considering compatibility with linear displacement tolerances and corresponding gaging accuracies, the minimum accuracy for angular displacements can be determined. An additional fact concerning the maximum slope likely to occur in the design of an internal combustion engine cam profile is required; the slope .010 inches per degree is such a maximum.[2] The gage requirement of an absolute accuracy of .00010 inches (when divided by a .010 inches per degree profile slope) corresponds with an angular displacement absolute accuracy of .010 degrees. The relative accuracy limit of .00001 inches corresponds with an angular displacement relative accuracy of .001 degrees.

The interpretation of the foregoing is that the angular displacement gage accuracy between consecutive degree positions should be .001 degrees, but that errors of this magnitude are accumulative up to an absolute maximum of .010 degrees between any two widely-spaced angular positions about the cam profile.

Measurement Accuracy—Production Cam

In summary, production cam tolerances and standard gage practice determine that the order of accuracy to be achieved by instrumentation and methods in production cam measurement should be:

Linear Displacement	Absolute Accuracy	.00010 inches
	Relative Accuracy	.00001 inches
Angular Displacement	Absolute Accuracy	.010 degrees
	Relative Accuracy	.001 degrees

Measurement Accuracy—Prototype Cam

Engineering tolerances for the prototype cam do not have an established practice in the automotive industry. The purpose of the prototype cam is to test a particular cam design, and this purpose is served best if the deviation from the design profile is held to the practical minimum value. This minimum

[1] See Reference 1 and also Reference 8, pages 18-21.

(based on the author's experience) will be approximately ±.00030 inches and, therefore, has the order of magnitude of the production cam waviness specification. On this basis, the accuracy that should be achieved in prototype cam measurement is

Linear Displacement } Absolute Accuracy .00001 inches

Angular Displacement } Absolute Accuracy .001 degrees

The Cam Profile Evaluation Problem

While the overall objectives of the Quality Control Department and the Engineering Department are identical, namely, to accept every profile that will meet the requirements for engine performance—and alternately, reject every profile that will not meet such requirements, the profile evaluation criteria applied by Quality Control is fundamentally different from the evaluation criteria that Cam Design and Development Engineering find most valuable.

Quality Control Evaluation

In accord with acceptance criteria established from the profile engineering tolerances (bandwidth and waviness specifications), Quality Control will require data which shows the difference between the cam profile "as made" and the profile "as designed." These differences data must show the local departure from the design profile at each data point as required for the bandwidth specification and must also show the rate of departure as required for the waviness specification. Ideally, this information should be given graphically as in Fig. 3. The horizontal coordinate shown in the center of the graph is a line representing the design profile (zero departure), while the differences from that design profile are plotted above or below the line as determined by whether the "as made" profile is oversize or undersize. The vertical line in the center of the graph is the zero degree angular index position; the number of degrees from zero on the opening side is shown to the left and, similarly, the closing side of the profile is shown to the right. With plotted differences data, it is simple to evaluate the departure from the design profile at each data point and also to evaluate the rate or slope of the differences line.

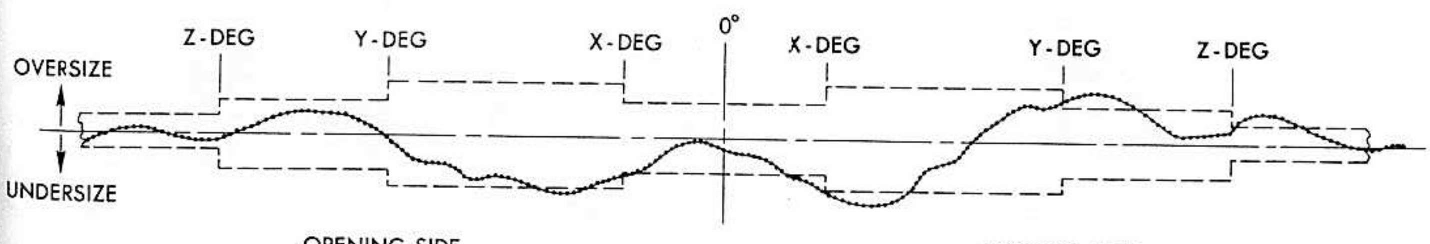


FIGURE 3. PROFILE "AS MADE" MINUS "AS DESIGNED" DIFFERENCES DATA (LOCAL DEPARTURE AND RATE OF DEPARTURE)

An adequate solution to the quality control cam profile evaluation problem would provide profile lift differences data with an accuracy specified by gaging practice and presented in plotted form as shown in Fig. 3.

Cam Engineering Evaluation

The evaluation problem as viewed by cam design and development engineering will consider as primary information the acceleration diagram for the cam profile "as made." Specifically, the acceleration diagram for a given cam profile is in direct proportion to the forces that are applied by the cam to the valve train. Since these forces are normally very great (i.e., at engine design speed, 400 to 600 g's), the rate at which these forces are applied and removed from the valve train is critical to the performance of the engine. Indeed, it is the acceleration diagram, more than any other single factor, that designs the cam profile. It is the acceleration diagram that the engine senses most directly and which, therefore, determines whether the valve train will behave satisfactorily, i.e., dynamic response characteristics. A typical acceleration diagram for an automotive cam profile is shown in Fig. 4. It can be observed that the acceleration modifies smoothly from one end to the other; there are no discontinuities or sharp corners. This is equivalent to the statement that the forces are applied and removed smoothly and in a controlled manner. Of course, a successful cam design has many necessary characteristics associated with the acceleration diagram in addition to smoothness.[2]

For cam design and development engineering, the information of greatest value is the acceleration diagram for the cam profile "as made." The engineering evaluation is based on a comparison with the acceleration diagram for the profile "as designed"—see Appendix E. It is important for the information to be quantitative so that deviations in the acceleration diagram can be evaluated for size and location.

[2] See Reference 2.

If the deviation should require profile correction, it is desirable to have quantitative information that shows quite exactly where and how much the profile is in error.

Profile Dynamic Analysis Background

The concept of evaluating the dynamic performance of a cam profile from an analysis of the acceleration diagram has been recognized and applied for many years. The original work on this subject was done by Mr. M. Turkish of the Eaton Manufacturing Company. Mr. Turkish's paper[3] appeared in the Eaton Forum in March, 1950. The method employed for obtaining the acceleration diagram is mechanical and electronic. It performs sufficiently well such that a number of engine manufacturers are using instrumentation of this kind for profile evaluation at the present time. There are, however, certain difficulties which limit its usefulness. One difficulty is that the information obtained is qualitative in substance rather than quantitative and, therefore, an operator with considerable experience is required to perform the profile evaluation.

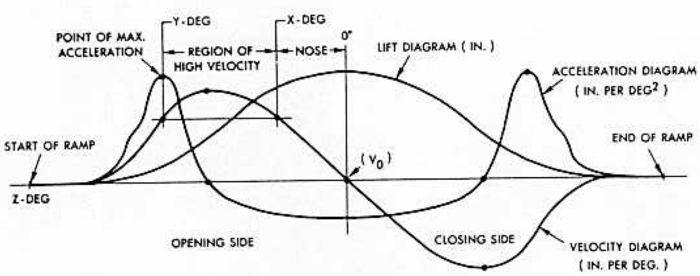


FIGURE 4. TYPICAL CAM FOLLOWER LIFT, VELOCITY, AND ACCELERATION DIAGRAMS

Engineering Evaluation Summary

Quantitative information on the acceleration diagram is of greatest interest and use in the engineering evaluation of the profile "as made." Also of interest, however, is quantitative information on the ramp heights at the timing points and the ramp velocity compared with design values, etc.

For the foregoing engineering evaluations, precise quantitative information on lift, velocity and acceleration for the profile "as made" needs to be provided in tabular form. The information is more easily evaluated if presented in plotted form. See Appendix E, pages 40 through 46.

Definitions for Accuracy versus Precision

It is desirable to define the special meaning that is attached to the words "accuracy" and "precision." Consider Fig. 5 on which are illustrated three bullseyes as used for rifle practice. (Credit for this illustration is given to Robert Esken of Sheffield Corporation.) In the illustration at the left, it

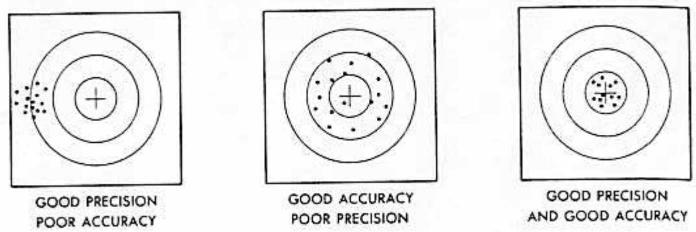


FIGURE 5. ILLUSTRATION FOR "ACCURACY" VS "PRECISION"

will be noticed that the shots are very closely spaced but that all are to the left of the target center; this is an illustration of good precision but poor accuracy. In the center illustration, the shots are scattered evenly about the center of the target area; this is an illustration of relatively good accuracy but poor precision. In the illustration on the right, the shots are closely spaced in the center of the target, representing both good precision and good accuracy.

The terms accuracy and precision are sometimes[4] used to define or distinguish between systematic and random errors. If a set of measurement data has small systematic errors, it is understood to have good accuracy; if small random errors, it is understood to have good precision. The definitions for random versus systematic errors are illustrated in Fig. 6. See Reference 4, page 3, paragraph 3.

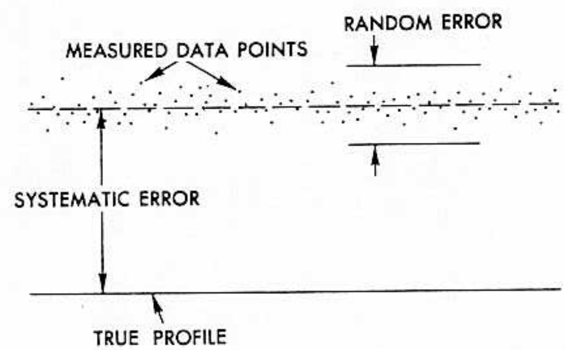


FIGURE 6. ILLUSTRATION FOR RANDOM ERROR VS SYSTEMATIC ERROR

[3] See Reference 3.

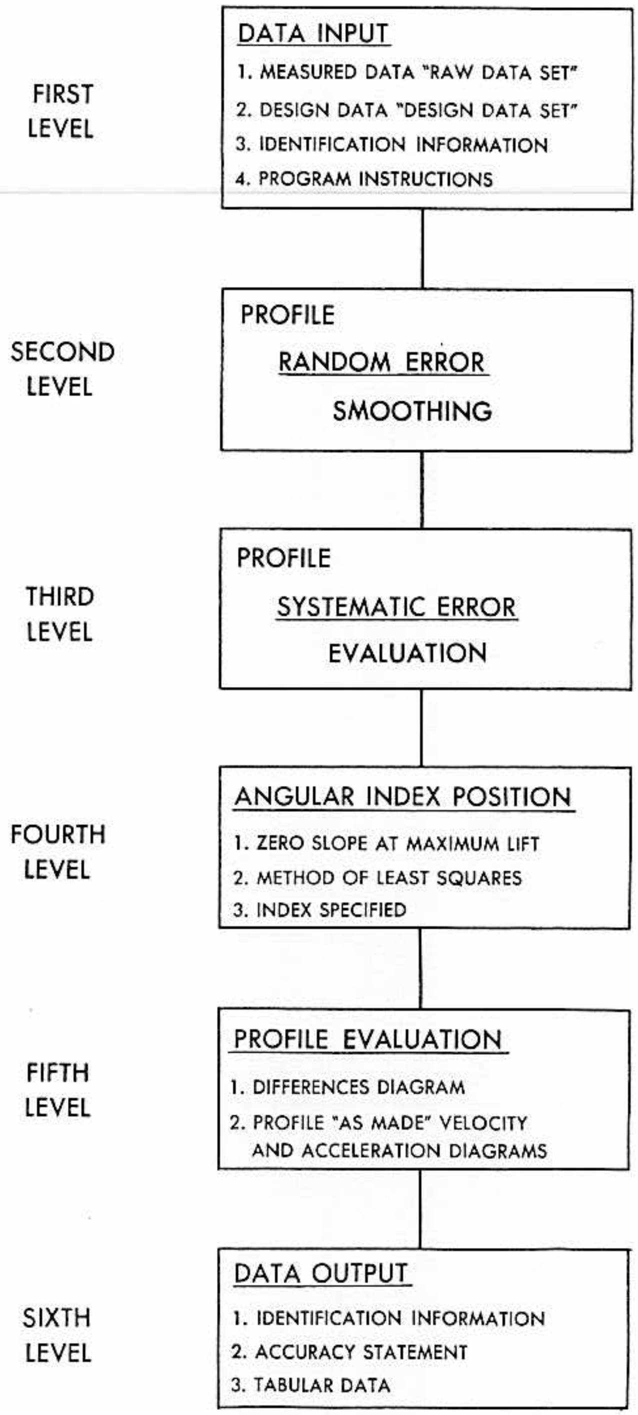
[4] See Reference 4.

PART III

A SOLUTION TO THE CAM PROFILE MEASUREMENT AND EVALUATION PROBLEM

It is the intent of this section of the paper to explain how analytical methods are used to obtain a solution to the cam profile measurement and evaluation problem and to contrast these methods with the older techniques. The new methods have as an objective the achievement of certain accuracy limits as defined in the previous section; a further objective is the determination of certain evaluation data also previously defined. A flow chart showing the order of the operations through the analytical method and the Camcheck computer program is given in Fig. 7. A description of how the solution is obtained, the required input information, the analytical methods employed by the Camcheck program, with a description of the final output follow the order given by the flow diagram.

FIGURE 7. FLOW CHART "CAMCHECK" COMPUTER PROGRAM



Data Input to the Camcheck Computer Program—Flow Chart, First Level

The solution begins with the preparation of a table of cam follower lift data for the cam profile "as made" which is identified as the "raw data set." This information is one of four types of data prepared for input to the program as follows:

1. Profile measured lift data--"raw data set."
2. Profile design lift data—"design data set."
3. Format heading and cam identification type information.
4. Program instructions.

The profile design lift data is normally taken directly from the table of lift values shown on the engineering drawing. Program instructions are required because (in the operation of the Camcheck program) there are a number of options that determine the manner in which the data is to be handled or processed. These options are discussed as they occur under the several flow chart levels.

As stated above, the solution begins with the preparation of a table of measured profile lift data. In contrast with previous cam profile measurement methods, the measured data is permitted to start from any location around the profile; the "zero degree" index location will be determined in a later step by the program. Further, the measured data is taken without a (special set-up) bearing support to minimize cam base circle run-out. Base circle run-out is a periodic systematic error; as will be discussed later, it is evaluated and read out of the data more accurately with mathematics than it is practical to do mechanically. The advantage of the new method for preparing measured data is to essentially eliminate set-up time and lead into analytical methods which greatly improve the overall accuracy of the final solution.

Cam Profile Random Error Smoothing and the Camcheck Program— Flow Chart, Second Level

The concept underlying the mathematics which makes the refinement of the "raw data set" possible is the fact that associated with each measurement there is an error. That is, there is an error associated with the cam profile lift, and a second error associated with the rotation of the profile to the new measurement position. When these errors are examined, they are found to consist of two kinds—random and systematic errors. This concept was illustrated in Fig. 6 and attention was drawn to the similarity between this illustration and Fig. 5 used to define the terms "accuracy" and "precision."

The recognition of an error associated with each cam profile measurement, coupled with the necessity for an improved accuracy, leads directly to the science of statistical mathematics—a recent but very highly developed mathematics which deals (in part) with the statistical treatment of raw measurement data (see References 4 through 7). The methods of this mathematics involve an analysis of the relative magnitude and distribution of measurement errors. Data such as profile lift measurements have random errors with a "Gaussian Distribution." Based on this particular distribution and a "Principle of Maximum Likelihood," a very powerful tool for random error smoothing has been derived and identified as the "Method of Least Squares." This method is used extensively in the Camcheck computer program.

The following illustration is intended to provide an explanation of the profile random error smoothing method of statistical mathematics without the burden of equations. Assume a cylinder which is perfectly round and perfectly smooth; also, let a series of lift measurements be taken with instrumentation similar to that used for cam profile measurement. Let it be further assumed that the test conditions are such as to produce a zero systematic error but allow a finite random error. The profile lift data for the cylinder might plot (orthographically) as shown in Fig. 8. Since the cylinder is both perfectly round and smooth, it is known that the measured data without random error should plot as a straight line. Based on this fact, and the method of least squares, the true location of the cylinder profile within the measured data can be determined as shown in Fig. 9.

Several important observations should be made from this demonstration. The actual measurements with random error are approximately evenly scattered above and below the smoothed profile; stated conversely, the profile is the smoothest path that can be drawn through the raw data with random error considered. Next, the data could be scanned for the maximum value of random error. Of much greater importance, however, is an index number called the "Standard Deviation." This number describes the average size of the random error in any

FIGURE 8. MEASURED DATA POINTS SHOWING RANDOM ERROR

particular data set. In a calibration program (see a later paragraph below) a similar number was determined called " Mean Standard Deviation;" this number is an index of the average random error size produced by a particular instrumentation system.

The analytical plan for profile random error smoothing consists, therefore, of determining the smoothest profile that can be drawn through the measured data points with random error considered. The magnitude of the random error is normally specified to the program with a numerical value for the "Mean Standard Deviation." The profile random error smoothing is accomplished in the Camcheck program by describing the profile with some large number of overlapping polynomial equations and permitting the profile to move by adjusting the data points in a series of iterative steps. The maximum movement is limited by the specified random error

FIGURE 9. MEASURED DATA POINTS AS IN FIGURE 8 WITH PROFILE LOCATED BY "METHOD OF LEAST SQUARES"

limit. Polynomial equations are used to describe the profile because such equations are analytic, i.e., the first and higher order derivatives are smooth and continuous. The "smoothest profile" is defined mathematically as that profile, within the random error limit, for which the higher order derivatives have the least numerical values. By this means, a profile path is determined for which the acceleration diagram will have the least curvature and also the least rate of change in curvature. This will correspond as nearly as possible with the profile which will fit the measured data within the limit of the random error, and which also will apply and remove the forces from the valve train as smoothly as possible.

In summary, the analytical method for profile random error smoothing depends upon first, a preassigned numerical value for the "Mean Standard Deviation" which specifies the magnitude of the random errors; second, the profile defined by analytic equations; and third, the data points given a controlled movement in a series of iterative steps. The logic underlying the movement (of data points) seeks to minimize the higher order derivatives of the profile equations; the movement is limited by the magnitude of random error evaluated through the continuous application of the "Method of Least Squares."

Sources for Data Random Error

The sources for random error in the data are numerous and depend to some high degree upon the design of the cam profile measurement instrumentation. The following are typical:

1. Operator reading error (which assumes an operator is required to read and set verniers and/or vernier adjustments).
2. Round-off error in automatic read out instrumentation.
3. Any displacements or rotations in the several parts of the cam profile measurement instrumentation which do not follow an identical path for every data point measurement.
4. Any roughness or wobble in the instrumentation live bearing center.
5. Mechanical vibration during measurement.
6. Roll follower run-out.
7. Dirt or dust on the profile surface.
8. Profile surface roughness.

Profile Surface Roughness

The profile surface roughness appears in the data as a random error but is, in fact, part of the actual measurement, i.e., an apparent random error. To make the point clear, consider Fig. 10 and visualize a large wagon wheel (the spherical or roll-radiused follower) as it is moved along a very rough road (the profile surface). The measurements that are taken are the displacement of the axle. Notice that as the wheel is moved along the road, the axle will be displaced when the wheel moves over any bump, but will not similarly show small depressions because these are bridged.

Random Error Calibration

An evaluation of the profile surface roughness "apparent" random error was important to the CPM&E solution; this effort was extended to include the calibration for the "Mean Standard Deviation" for the Camcheck instrumentation system working in standardized environmental conditions. A vital part of the calibration procedures was obtained through the direct assistance of the Micrometrical Division of The Bendix Corporation. The Proficorder, a product of this company, is an instrument used to record surface roughness, waviness and total profiles. The Proficorder produced the information used as a standard for the Camcheck calibrations.

The first step was the preparation of a cylinder gage about two inches in diameter and ten inches long—with a finish ground surface (8 - 10 r.m.s.) equivalent to typical prototype cam specifications. By means of the Micrometrical Proficorder, a cylinder cross-section was measured for surface roughness with a .0005-inch stylus at .5 gram pressure. Next, the .0005-inch radius stylus was replaced by a 1.000-inch stylus and recordings were taken at print loadings of 50, 100, 200 and 400 grams. The "wagon wheel" effect on surface roughness was clearly evident with the peak to peak

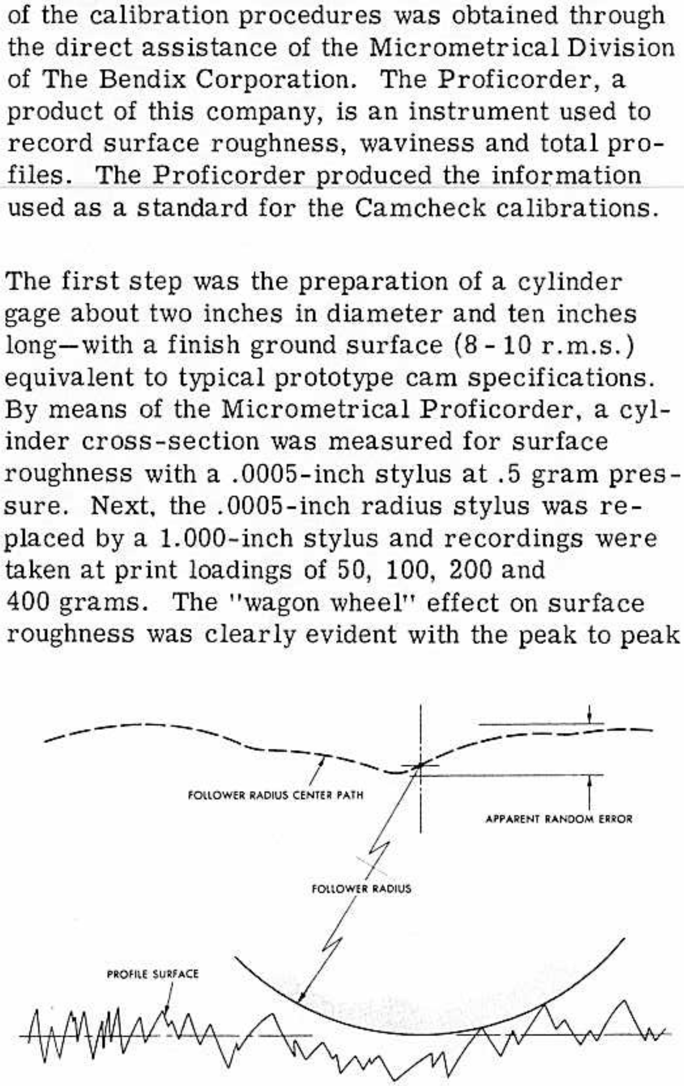


FIGURE 10. LIFT DATA, APPARENT RANDOM ERROR DUE TO PROFILE SURFACE ROUGHNESS

roughness reduced from 50-millionths to about 3- to 5-millionths; also, the effect was found to be practically independent of print loading over the range 100 to 400 grams. Next, the stylus was replaced with an infinite radius (optical flat) and a recording taken at a 200-gram print loading. The surface roughness was again 3- to 5-millionths and was thus shown to be relatively independent of follower radius over the range 1.000-inch to infinity with a print loading of 200 grams, although at the infinite radius, considerable difficulty was experienced with atmospheric dust.

In a continuing step of the calibration procedures, the cylinder was temperature stabilized followed by lift data measurements in the Camcheck gageroom. Initially, three independent sets of raw lift data were taken. The validity of the raw data measurements was enhanced by using a pair of centers in the calibration cylinder which had an eccentricity from the true centers of .12336 inches. Thus, the cylinder was caused to wobble, which in turn exercised the displacement measuring instrumentation and made the lift values unpredictable by the machine operator. The raw data sets were analyzed in the Camcheck program; the off-center data, of course, exercised the "systematic error" part of the program. In this manner the "Mean Standard Deviation" for the Camcheck instrumentation was determined and found to be thirteen-millionths (.000013) inches.

Random Error—Program Options

It will be appreciated that after a certain amount of experience with the Camcheck program, the range of numerical values for the higher order derivatives for normal production profiles will be obtained. Based on this experience, and the assumption that some given profile will have higher order derivatives similar to the normal range, an unfamiliar set of "raw lift data" can be analyzed for the numerical value of the "Standard Deviation." Further, the raw lift data can be scanned for that single data point which lies furthest from the smoothed profile. Execution of the Camcheck program in the manner described here is a program option and is useful to approximate the quality of data produced by an unknown instrumentation system.

Cam Profile Systematic Error and the Camcheck Program—Flow Chart, Third Level

There are several kinds of systematic error involved in the "raw data set" of cam profile measurement. The first kind of systematic error is one which is periodic and when plotted yields a simple sinusoid with a period of 360 degrees. This systematic error is identified as the "cam base circle run-out." It is easily evaluated with a high degree of accuracy by the Camcheck computer program. Other kinds of systematic error may be non-periodic and/or non-linear; these are not predictable and, therefore, cannot be evaluated. For this reason, it is of first importance that such errors be excluded from the cam profile measurement as discussed in later paragraphs.

Sources of Simple Periodic Error

The sources of a simple sinusoidal type of systematic error in the measured data are numerous and occur in both the camshaft and the measurement instrumentation, such as:

1. A bend or strain (dog-leg) in the camshaft. This source is always present in some degree and is normally the largest single error.
2. A misalignment of the camshaft centers with respect to the true center of the base circle of the profile being measured.
3. The live center of the measuring instrument will have some misalignment between the axis of the center cone and the axis of rotation.

There will be other sources, of course, depending upon the design and condition of the cam profile measurement instrumentation. For this discussion, it is not necessary that each source is identified, only that the existence of a simple, periodic, systematic error is recognized.

Cam Base Circle Run-Out Correction—Camcheck Analytical Method

An explanation of how the analytical method evaluates numerically the simple, periodic error (cam base circle run-out) requires a consideration of two ideas: First, examine Fig. 11 which, for simplicity, shows the end of a cylinder. The rotation of the

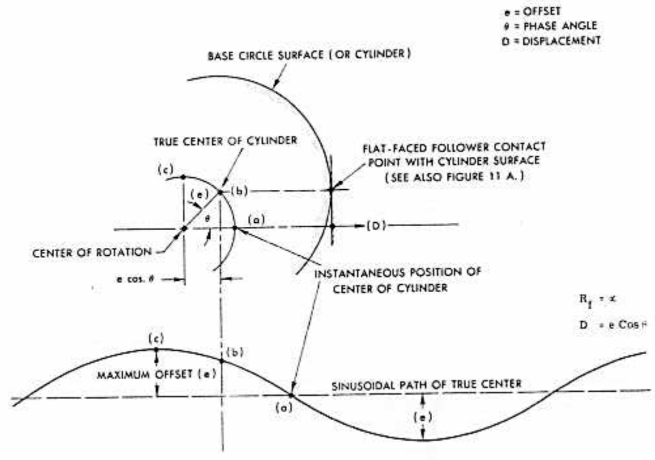


FIGURE 11. DISPLACEMENT OF BASE CIRCLE CENTER ABOUT CENTER OF ROTATION

cylinder about a point displaced from the true center is shown in a dotted line. It will be appreciated that a "raw data set" measured on the cylinder with the center of rotation offset, will develop a sinusoid when diagrammed as in the figure. Notice that the amplitude of the wave equals the offset and that the phase relationship with respect to any particular data point (or zero position) is directly determinable.

Second, consider that each separate source of periodic error will have, in general, a particular offset and phase relationship to a zero position which is different from every other source. The only characteristic in common is that the periods (wave length of one cycle) are identical. It turns out mathematically that for the special case of identical wave lengths, the amplitude of the separate sinusoids can be added algebraically with the result that a new single sinusoid is produced. The composite has some new amplitude (offset) and phase relationship to the original data (zero position)—see Fig. 12. The importance of this fact is that even though a number of periodic systematic errors are involved in the measured data, and since the effects of all need to be corrected, the mathematics of that evaluation are simplified by having to consider only a single sinusoidal wave form. The Camcheck program performs the arithmetic required to evaluate the composite sinusoid and determine its amplitude and phase relationship.

The actual numerical operation involved in the arithmetic computation occurs in a series of iterative steps. Based on a first coarse approximation to the smoothed measured data, the program chooses a sinusoid having a particular amplitude and phase relation to that data. The differences between the ideal sinusoid and the actual smoothed data, point by point, are calculated. The degree of

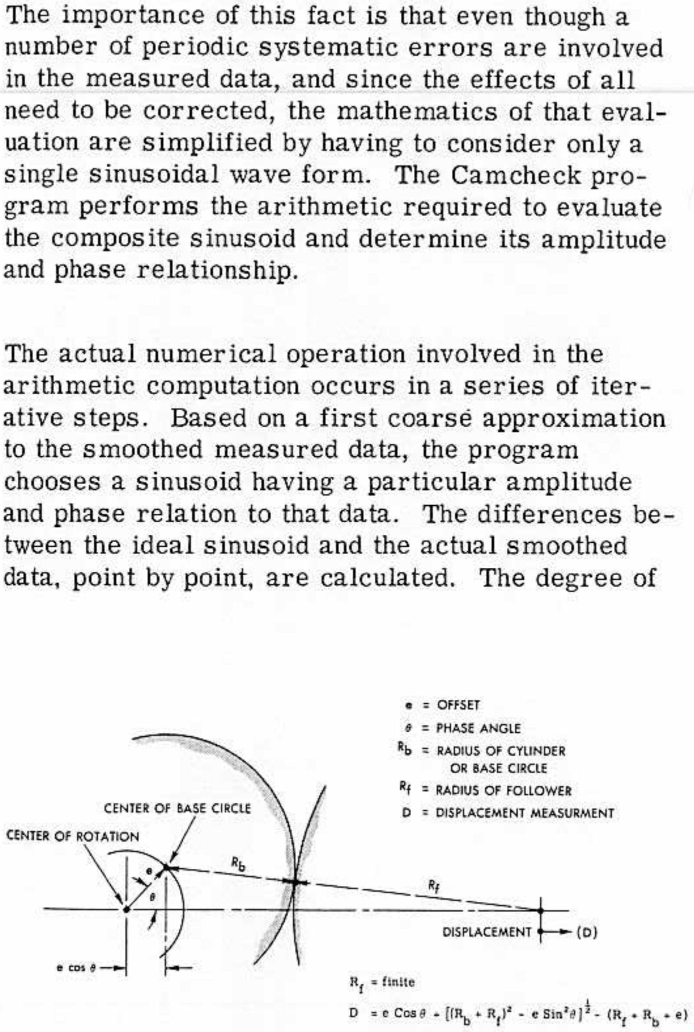


FIGURE 11A. DISPLACEMENT OF BASE CIRCLE CENTER ABOUT CENTER OF ROTATION

fit is established from the total sum of the squares of these differences. Next, the program chooses a new phase position (one degree away) and recalculates the total sum of the squares of the differences. If the sum decreases, the fit is better and a new step is taken in the same direction. After the best phase location is bracketed (in one degree steps), a similar series of trials occur for the amplitude (offset) starting with .01-inch steps. With every trial the fit is evaluated, data point by data point, seeking the least sum of the squares of the differences. Following the amplitude fit, the phase is readjusted in .1-degree steps; then amplitude is readjusted with .001-inch steps. This typical iterative

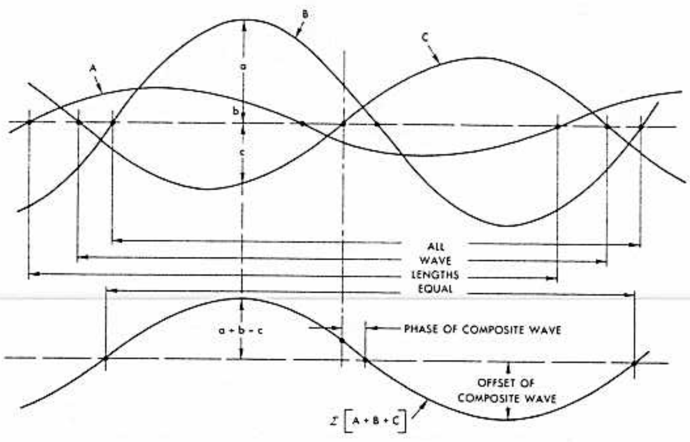


FIGURE 12. THE SUMMATION OF SINUSOIDS HAVING EQUAL WAVE LENGTHS

process is continued until the phase is located to the nearest .001 degree and the offset to the nearest .00001 inches. It can be shown that, in general, if the phase angle is located to the nearest .010 degree, the offset must exceed .060 inches for the error in the lift data to exceed .000010 inches.

Having thus evaluated the cam base circle run-out, the smoothed profile lift data is corrected to the true center of the cam base circle. At this point in the calculations, the measured profile lift data has been referenced to the base circle center as is the design lift data.

Cam Base Circle Run-Out Correction—Mechanical Method

Engineers experienced in the problem of cam profile measurement will be familiar with the set-up procedure in which the camshaft is provided with a center support. The support is adjusted to make the base circle run as true as possible. The reason for this is, obviously, to obtain lift data referenced to the center of the base circle to correspond with the design data. It is usual in the listing of the cam profile measured data to make note of the run-out remaining in the base circle after set up. (See Appendix C, Fig. 1.) The true accuracy achieved in the center support (mechanical) method of correction is not known and would be difficult to evaluate.

The uncorrected run-out remaining in the set up is usually noted on the listing of the measured data and often has a value like .0005 inches—an error fifty times larger than the desired gaging accuracy.

Sources of Non-Periodic, Non-Linear Systematic Error

It was stated in an earlier paragraph that a second kind of systematic error is non-periodic and/or non-linear; that it is not predictable and, therefore, cannot be evaluated from a "raw data set" with mathematics. In the demand for accuracy, this type of error must be excluded from the cam profile measurements.

Two important sources for such error have been observed:

1. Temperature—The first of these is a temperature gradient or a temperature change (drift) over the period of time required to obtain the profile measurement data. The magnitude of error introduced into the data due to temperature effects will depend, of course, upon the time interval, the temperature change, instrumentation design and many other factors. It is significant that a measured data drift of over one hundred millionths has been observed in the Camcheck gage room (over an eight-hour period) due to environmental changes too slight to be noticeable to the operator. The way in which the temperature drift is observed is to simply zero the instrumentation at some particular measurement position, then observe the drift as a function of time. The method requires instrumentation sensitive and readable to a few millionths. A somewhat better method is to prepare a raw data set and observe the difference by which the data fails to close after a 360-degree rotation. See Fig. 13. To be successful, this method requires instrumentation sensitive and readable to differences of ten-millionths and with also a low random error. A method of correcting the data by assuming the temperature drift to be a linear function of time suggests itself; however, a study of the problem shows that this assumption does not agree with temperature drift behavior and, therefore, a linear correction cannot be justified.

   The gage room can be temperature controlled within very narrow limits. The Camcheck gage room is temperature (and humidity) controlled to the gage standard ($68° \pm \frac{1}{2}°$). All instrumentation and camshafts are temperature stabilized for twenty-four hours prior to measurement. A second method to avoid the temperature drift problem is to obtain the measured data so rapidly that a sensible drift is unlikely to occur. One of the most recent developments in cam profile measurement instrumentation—see Appendix B—obtains data in one degree intervals at five data points per second; a 360-degree profile with some overlap is measured in less than eighty seconds.

2. Follower Radius Tolerance—A second important source of non-periodic, non-linear systematic error occurs in an approximation often made with respect to the radius of cam followers (particularly large radius cam followers). It is usual that the cam will be designed for a spherical radius tappet where that radius may have a nominal value of, for example, 35.000 inches, or some other large value. If the tappet has a barrel diameter in the order of an inch, a spherical radius of 35.000 inches is almost unnoticeable—and the approximation of equating this radius to a flat-faced cam follower is often made. This approximation is a serious blunder, both from the standpoint of cam design and cam profile measurement.

   To make the point clear, consider a cam profile which has been designed to obtain

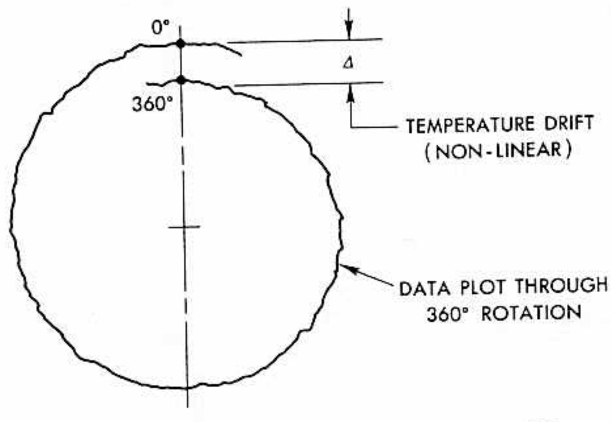


FIGURE 13. EFFECT OF TEMPERATURE GRADIENT ON PROFILE LIFT DATA

certain specific characteristics with, for example, a nominal 35.000-inch spherical-radius follower. A table of cam design lift values for the 35.000-inch follower is determined. Next, let that profile be fixed and a new table of lift values determined as required to generate the identical profile with a flat-faced follower. Such a listing is shown in Appendix A. It will be observed that at the zero degree position (i.e., the maximum lift point), the spherical tappet lift and the flat-faced follower lift are identical. However, at about forty degrees from top center in the region of the profile where the velocity (slope) and eccentricity are maximum, the difference between the radius follower lift and the flat-faced follower lift has become, in this example, .00261 inches. The very obvious implication of this fact is that an analytical method for either cam design or for cam profile measurement which must be concerned about accuracies in the order of .00001 inches cannot make the approximation that a large spherical radius follower can be replaced by a flat-faced follower with negligible error.

The Camcheck gage facility uses radius followers made with high accuracy for all cam profile measurements. In the preceding example where the follower spherical radius has a nominal value of 35.000 inches, it can be shown that a lift measurement accuracy of .00001 inches requires a radius tolerance equal to or less than ±.134 inches. Therefore, the Camcheck specification for this follower radius is 35.000 ±.100 inches.

Index Position (Zero Degree) Determination and the Camcheck Program—Flow Chart, Fourth Level

The function performed at this location in the Camcheck program is the determination of the "zero degree" angular index position for the measured profile data. This index position is used for the angular alignment (orientation) of the measured profile data with the design data and is necessary to the continuing step for profile evaluation.

Advantages of Computer Methods Over Mechanical

The first and over-riding advantage of the analytical method for determining the index position in the measured data as compared with the mechanical method is accuracy. It was shown in the problem statement that the maximum allowable absolute error for angular position is .010 degrees, that a maximum relative error between consecutive degree positions should be in the order of .001 degrees. In the Camcheck computer programming, the conservative position is taken with the zero position calculated to the nearest .001 degrees and is sufficient, therefore, for prototype cam profile measurement and evaluation. The mechanical method for determining the zero position normally produces an error greater than .10 degrees, i.e., more than ten times greater than the maximum allowable error. The large error inherent to the mechanical method was one of the important reasons for initiating the new development. The difficulty with the mechanical method is examined in a separate discussion below.

Other advantages of the analytical method for index positioning over the mechanical method are the time saved at set up (from five to twenty minutes), the independence from manual skills, and the direct involvement of the data with the continuing steps for evaluation.

The Camcheck Program Method

A necessary condition to the analytical method used to find the index position in the measured data is that the index position must be defined in a manner identical with that used in the corresponding cam design. There are three ways used in current cam design practice for defining the "zero degree" index position; therefore, the Camcheck program provides three options. Any particular option is selected by a command in the program input.

Recall that at this level in the program operation, the following operations to the initial "raw data set" will have been completed:

1. Profile random error smoothing with the profile defined by analytic functions.
2. The periodic systematic error evaluated for offset and phase relationship, with the profile lift data corrected to the true center of the cam base circle.

First Option—Profile Zero Slope

The design data set for the internal combustion engine cam normally (but not always) identifies the profile maximum lift point as the "zero degree" position—as in the examples, Appendices A and D. A typical lift, velocity and acceleration diagram for a cam of this type was shown in Fig. 4. The essential point in the design definition is that the "zero degree" index position occurs at maximum lift and zero profile slope, i.e., that maximum lift point defined by a zero value in the velocity diagram.

The first option program operation is:

1. Scan the profile lift data and find the region of maximum lift.
2. Calculate, from the profile equations, the first derivative of the profile over this region, i.e., by definition, the velocity diagram.
3. Set the velocity equal to zero and solve for the angular displacement position of that zero position (V_0) with respect to a preassigned data point.
4. Specify the (V_0) point as the "zero degree"

index position and calculate the numerical value of the corresponding maximum profile lift.

5. Starting from the (V_0) position, calculate at equal angular incremental spacings the corresponding profile lift values. Note: The size of the incremental spacing is a program option and is chosen to correspond with the spacing of the design data—normally every half degree.

Second Option—Method of Least Squares

This option is used when a constant radius occurs at maximum profile lift as in certain diesel engine cam designs. It is also used for cams (other than internal combustion engine) where the profile may vary continuously through 360 degrees; the method provides for the "best fit" between the "as made" and design data.

The second option program operation is:

1. Accept from the program data input an initial value zero position for a first trial registration with the design data.
2. Calculate the differences between the measured data and the design data for every data point over the 360 degrees of cam rotation; then calculate the total sum of the squares of the differences.
3. Index the initial zero position in the measured data .100 degrees clockwise and recalculate a new complete set of lift data points by means of the equations for the smoothed profile.
4. As in Step 2 above, calculate the sum of the squares of the differences.
5. Compare the sum obtained in Step 4 with the sum of Step 2. If the sum in Step 4 is less, Step 3 is repeated with an index of .100 degrees clockwise. If the sum in Step 4 is greater, the index is counterclockwise.
6. The foregoing procedures are repeated with .100 degrees indices until the angular position for the least sum of the squares of the differences is bracketed.
7. The size of the index is changed to .010 degrees and the foregoing procedures are repeated within the region bracketed as in Step 6.
8. The size of the index is changed to .001 degrees and the foregoing is again repeated within the region bracketed in Step 7. [Note: The terminating minimum size of the index is a program option.]

Third Option—Index Position Specified

In this third option, the program accepts any preassigned value for the index position from the program input data. The registration between the measured data and the design data is based on the preassigned value.

The Analytical and Mechanical Methods for Index Position Contrasted

The mechanical method for finding the zero position on the "as made" profile is illustrated in Fig. 14. The profile lift is balanced at two points, usually about thirty degrees on either side of top center, with the zero position considered to be at the midpoint between them. The basic assumption involved in the method is that the cam profile "as made" has zero deviation (or exactly equal deviation) at the two balance points. This assumption is, of course, obviously false. As shown in Fig. 14, if the deviation of only one of the balance points is set at the normal engineering tolerance limit (.001 inches) and the other balance point deviation is zero, the error introduced into the zero degree index position determination is .10 degrees. The

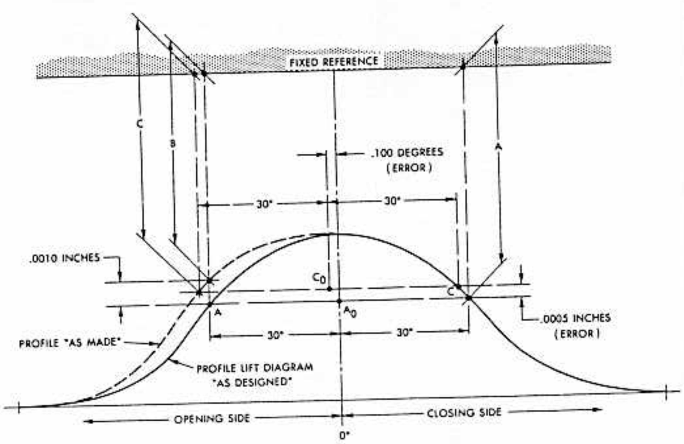


FIGURE 14. MECHANICAL METHOD FOR PROFILE (ZERO DEGREE) INDEX POSITION LOCATION

Explanation of Fig. 14

The "A" measurements are "balanced" if the profile "as made" has zero error (also assumes a zero measurement error)—the true zero index position is at the mid-point (A_0). The "B" measurement will be read if the profile has an oversize deviation of .001 inches—as shown, "B" is less than "A" and the measurements are "unbalanced." The "C" measurements show the "as made" balance points—the corresponding zero index position is (C_0). If the cam profile slope is .005 inches per degree, the zero index position error between (A_0) and (C_0) is .100 degrees.

error in the cam profile lift introduced by this misalignment of the zero position is .0005 inches. This is an error fifty times larger than the desired gaging accuracy and is clearly unacceptable. Camcheck programming has been used to determine the mechanical method zero positioning error in a large number of "raw data sets." The average error was found to be approximately .20 degrees; the least error observed in any data set was .085 degrees.

Profile Evaluation and the Camcheck Computer Program— Flow Chart, Fifth Level

At the fifth level, the program calculates the information for profile evaluation as specified in the problem definition.

Quality Control Evaluation

The primary quality control evaluation information is the "differences diagram" [see "Quality Control Evaluation," page 5], i.e., the numerical value of the cam profile lift "as made," minus the lift "as designed." An illustration of the "differences diagram" was shown in Fig. 3. Numerical data in tabular form from the Camcheck program is shown in Appendix E, page 45; this data is then plotted to scale on page 46.

The Camcheck program data given in Appendix E is an actual solution to a typical prototype cam profile measurement and evaluation problem. The identical profile was also checked by another company, a company that specializes in this type of measurement and uses instrumentation and methods of long-established practice. The cam profile lift measurements furnished by that company as the final report are given (photocopy) in Appendix C, Fig. 1. The notation for base circle run-out is shown in the lower right-hand corner; the zero degree angular index position was determined by the mechanical method. It is usual that the differences between the measured and design data will be calculated by hand, then plotted as shown in Appendix C, Fig. 2. A direct comparison can be made for the identical profile between this "differences diagram" and that provided by the new CPM&E methods as shown in Appendix E, page 46.

Cam Design and Development Evaluation

The primary cam design and development evaluation information is the acceleration diagram for the cam profile "as made." Numerical data in tabular form from the Camcheck program is shown in Appendix E page 44; a comparison between the acceleration diagram for a profile "as made" with that "as designed" is plotted to scale on page 46.

The assumption is made occasionally that the velocity and acceleration diagrams for a profile "as designed" or "as made" can be determined by taking the simple differences of the lift data. It turns out, however, that the simple differences method when applied to the profile "as designed" produces velocity and acceleration diagrams that are badly distorted—when applied to "as made" data, the resulting diagram bears no resemblance to reality. The acceleration diagram calculated by the "second differences method" is shown in Appendix C, page 28. A direct comparison can be made for the identical profile between this acceleration diagram and that produced by the new CPM&E methods shown in Appendix E, page 46.

It will be appreciated that certain tests had to be designed for the analytical methods program development. This was necessary to determine the accuracy with which the computer program would reproduce the acceleration diagram corresponding with a given set of profile lift data. This is the most severe requirement imposed upon the analytical method for profile analysis. The first (and simplest) test was to reproduce the acceleration diagram starting from cam design lift values where the true diagram was known in advance with great accuracy from the cam design work [i e., as in Appendix D, item (z_0'')]. It should be noted that design data can be described as very "well-ordered" smooth data The continuing and more difficult test was to reproduce the acceleration diagram for the profile "as made " This test depends upon measured, "raw lift data" not well ordered, having both random and systematic type errors.

In the typical "Camcheck" cam profile measurement and evaluation final report of Appendix E, the profile was manufactured from flat-faced follower lift data. The "as made" acceleration diagram was determined from 35.000-inch follower "raw lift data"--see figure, Appendix E.

Camcheck Computer Program Output— Flow Chart, Sixth Level

The Camcheck program output in tabular form is identified as the "processed data set." A typical cam profile measurement and evaluation final solution is shown in Appendix E.

The principal objectives of this paper have been to present and explain the concepts and new methods developed for cam profile measurement and evaluation. In retrospect it will be appreciated that the major step for an improvement derives from the application of statistical mathematics to the refinement and interpretation of profile raw lift data measurements. The minimum level of acceptable accuracy for a profile measurement system (instrumentation plus techniques for refinement) was determined from profile normal tolerance specifications and the application of the standards for good gaging practice. It is, of course, axiomatic that the overall accuracy of the final "processed lift data" will be directly dependent upon the quality of the initial "raw data set." The measure of that quality with respect to random error is the numerical value of the "Standard Deviation;" the quality with respect to systematic error must be evaluated separately.

Error Evaluation for the New CPM&E Methods with Camcheck Instrumentation and Computer Programs

Recall from the problem statement that the total sum of the errors from both the lift measurements and certain checking procedures determines the overall accuracy of any given CPM&E system. The following is an evaluation of the errors for Camcheck profile measurement and evaluation.

	Random Error— Mean Standard Deviation (σ_m) . . . . (Based on calibration procedures with Camcheck instrumentation located within a controlled environment.)	.000013 (inches)
		Max. Error (Inches)
1.	Cam profile, random error smoothed . . . . (Based on cylinder calibration.)	.000013
2.	Base circle run-out . . . . (Residual error after lift data correction based on program limits.)	.000020
3.	Index (zero degree) position . . (Assumes .010 in/deg cam slope, error based on program limits.)	.000010
4.	Systematic error . . . residual (Based on follower radius tolerance, etc.)	.000010
	Possible total sum	.000053

It will be appreciated that for each of the foregoing components of error, the actual numerical value must lie within a range, (minus limit) ≤ error ≤ (plus limit), i.e. there is an equal probability for a positive or negative value. Also, the probability of a numerical value near the center of the range is relatively high, near either limit, relatively low. Thus, the possible total error sum of .000053 inches depends upon the very remote probability that all components of error have the same sign and that all lie at the extreme limit of the range. An evaluation of the greatest likelihood for the maximum error can be based on a normal error function distribution. For Camcheck CPM&E final solutions,

68.3% will have maximum errors less than	.000017 inches
95.4% will have maximum errors less than	.000034 inches
99.7% will have maximum errors less than	.000050 inches

Future Development— Cam Tolerance Specifications

Traditionally, engineering has provided tolerance specifications based on dimensional limits. The profile tolerances in Part II of this paper represent this type of normal standard specification. In automotive engine cam profiles, however, the valve train senses and responds primarily to the profile acceleration diagram. This fact suggests that there should be some measure of the profile acceleration reflected in the tolerance specification. Indeed, if the engine valve train has been found to behave properly with a particular profile "as designed," there should be some simple way to compare the "as made" and the "as designed" acceleration diagrams. The acceptance criteria or tolerance specification should be written to include this comparison.

Based on information which has been made available by the new methods of CPM&E, the observation can be made that the difference between the acceleration diagrams for the profile "as made" and "as designed" is directly proportional to the curvature of of the profile lift differences diagram. Consider Appendix E, page 46, which shows the acceleration diagrams for a profile "as made" and "as designed;" the figure also shows the profile lift differences diagram. Notice that each deviation between the acceleration diagram corresponds exactly with a sharp curvature (small radius of curvature) in the differences diagram at that location. The mathematical relationship between profile lift differences curvature and profile acceleration departure is shown graphically in Fig. 15.

The logical extension of the foregoing concept is that the radius of curvature of the profile lift differences diagram could be calculated by the Camcheck program with the curvature data given in table form; this calculation could be accomplished very simply based on the present program information. The new engineering tolerance would specify the minimum allowable curvature as a function of location along the cam profile.

At any particular (θ)

Let, $\frac{d^2}{d\theta^2}(z_o) = C_o$ — C_o is the numerical value of acceleration "as designed"

$\frac{d^2}{d\theta^2}(z_m) = C_m$ — C_m is the numerical value "as made"

Then, the difference $(C_o - C_m) = \Delta C$

or, $\frac{d^2}{d\theta^2}(\Delta z) = \Delta C$

Following integration,

$$\frac{d}{d\theta}(\Delta z) = \Delta C\theta + \text{Constant}$$

Let = 0

$$\Delta z = \frac{\Delta C}{2}\theta^2 + \text{Constant}$$

Let = 0

Solved for three typical values of (ΔC) as shown. To apply, the scale must be chosen identical to the graph showing the profile acceleration diagram.

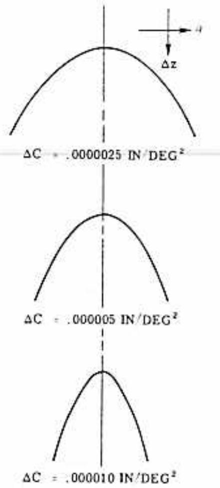


FIGURE 15. CURVATURE IN LIFT DIFFERENCES DIAGRAM CORRESPONDING WITH DIFFERENCES IN ACCELERATION DIAGRAM

Future Development— An Automated Cam Profile Measurement and Evaluation System

An entirely automated cam profile measurement and evaluation system is suggested as a possible reality based upon methods and instrumentation within the present state of the art. The following system is suggested as a "blue sky" solution to the CPM&E problem; it represents a possible system but one that is not likely to be found economic at the present time. The suggestion is made because of the dramatic evolution in method possible compared with methods in current practice; it is thought that certain intermediate solutions, given study and evaluation, might be found to be both practical and economic. The "blue sky" system could have the following features:

1. Automatic camshaft loading (and unloading) to (and from) the profile lift measurement instrumentation.
2. Automatic raw lift data measurement—all cam lobes measured simultaneously—approximate elapsed time for measurement, 60 seconds.
3. Raw lift data read out—direct transmission of data to computer center, read on magnetic tape.
4. Raw lift data processing and cam profile evaluation based on Camcheck programs and methods—approximate time for data processing, 30 seconds.
5. Final profile evaluation based on engineering tolerance specifications with a "pass" or "reject" decision—performed by computer with a direct transmission of that decision to the cam measurement location. The reason for a "reject" decision could be given by the computer and would be in tabular form similar to that shown in Appendix E.

A Summary of the Primary Advantages of the New Cam Profile Measurement and Evaluation Methods

1. Accuracy—Cam profile lift data accuracy is improved over accuracies obtained in current practice by a factor of ten to one hundred times. This improvement was shown necessary to apply the profile engineering tolerances used in current practice in accord with the normal requirements for standard gaging practice.
2. Repeatability—Following raw lift data refinement, profile measurement and evaluation are repeatable within the new limits of accuracy. Specifically, two or more raw lift data sets taken from the same profile, but taken independently, will not normally be recognizable as data from the same profile; following data refinement, those raw data sets provide identical profile measurements and evaluation.
3. Evaluation—Camcheck refinement of raw lift data yields precise, quantitative information for profile evaluation which has optimum usefulness. For Quality Control, this information is "profile lift differences data," i.e., profile lift "as made" minus profile lift "as designed." For Cam Design and Development Engineering, this information is profile "as made" velocity and acceleration diagrams.
4. Efficiency—The new analytical methods essentially eliminate camshaft manual set-up procedures, and also substantially reduce the time required for profile evaluation. The new methods make possible automated cam profile evaluation systems.