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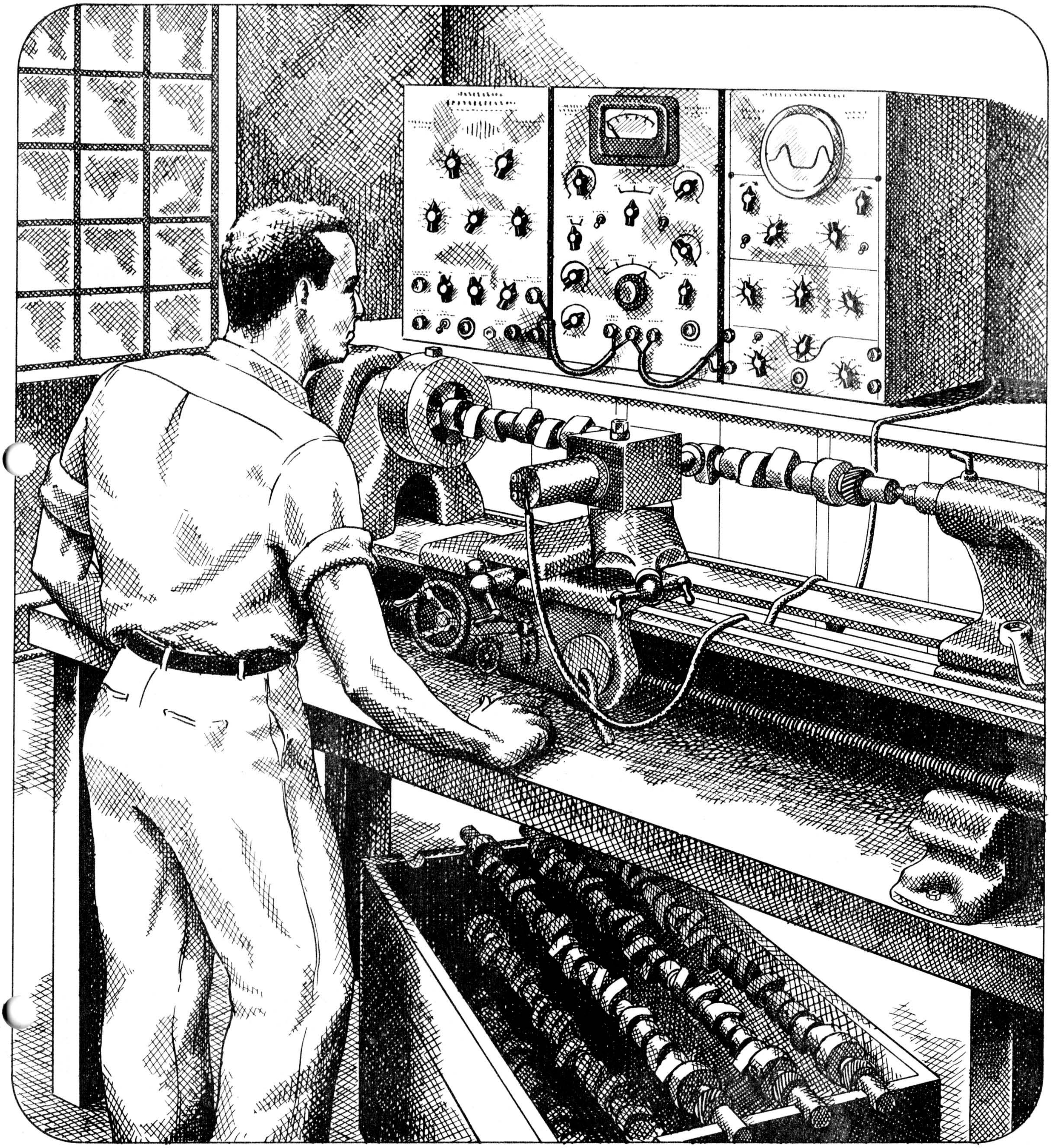


Inspection of Cam Contours by the Electronic Method

By Michael C. Turkish, B.S., M.E.

High production camshaft manufacture is generally done on special machinery designed and built for this specific purpose. The machinery for finish gringing the cam contours utilizes suitable chucking equipment for holding the camshaft while it slowly rotates and a grinding wheel grinds away the the cam lobes. The camshaft rotates slowly, while the grinding wheel rotates at a relatively much higher speed. The grinding operation requires that the camshaft be oscillated in a predetermined manner relative to the position of the grinding wheel so that the cam lobes may be formed. It is accomplished by the use of a master cam to produce the required motion which will result in the desired contour or profile of the cam lobe. As the wheel reduces in diameter from wear, the master cam needs to be changed for another which is designed to give the same desired cam contour when using the smaller grinding wheel.

Any wear in the master cams, linkages, or machine spindle bearings can produce errors in the cam contour. Uneven grinding operations, rough grinding wheels, lash, and inertia of machine members at high speeds will also produce errors which can be of sufficient magnitude in the cam contours to cause the final camshaft to perform poorly in an engine.

A cam lobe possessing a contour deviating noticeably from the theoretical can affect engine performance and cause failure of parts in the valve gear. Tappet face and cam nose failures can occur or broken valves, tappets, or springs may result which can cause the entire engine to be scrapped.

This points to the need for camshaft inspection from the standpoint of assuring reasonable accuracy in the finish of cam contours and of checking on the production machinery to insure that high standards of quality are being attained in this vital part of the internal combustion engine.

Cam contour inspection can be divided into three types: template, micrometer measurements, and electronic methods. The use of a template for comparative purposes is impractical for any real accuracy. A modified form of the template method (using a magnifying comparator employing light to cast an enlarged shadow of the profile on a ground glass screen) is much more accurate. However, this does not lend itself to non-destructive and production inspection.

Use of micrometer measurements in a suitable fixture recording the cam contour lift on a dial indicator in intervals of one or two degrees is sufficiently accurate for most inspection purposes. It provides data comparable to the design lift figures. However, contour errors are not easily found without plotting a lift curve several times size or taking differences between adjacent lift figures and plotting the resulting data which will resemble a velocity curve. One can also take differences of these difference figures to secure data which would resemble an acceleration curve. These data, when carried to this extreme, become erratic and are too sensitive to the fourth and fifth decimal places which are difficult to measure accurately. This academic method of measuring a cam contour to check a new master cam is time-consuming and is impractical for production test even when done at rather infrequent intervals. When each lobe is to be inspected on a sixteen lobe camshaft for an eight-cylinder engine, the inspection time is considerably increased. Accuracy in this method depends largely on the type of inspection fixture being used. Small errors in indexing, bearing supports for the camshaft and clearances in the tappet follower can affect the results appreciably since readings are required to .0001″ or closer if possible.

In view of the shortcomings of the two established methods of inspection, the electronic method was evolved to obtain a very rapid, accurate, and more reliable method of determining the type of motion a particular cam will produce. Due to the great amount of engine test work being done on valve gear and the frequent use of specially designed camshafts at the Eaton Laboratory, an improved method of cam contour inspection was imperative. Adoption of the electronic method permitted the rapid and accurate inspection of all the cam lobes on a camshaft. Thus a large unknown factor was eliminated from an engine test, allowing more accurate conclusions to be drawn from the results.

OUTLINE

By using the electronic method of cam contour inspection it is possible to inspect each lobe in approximately one minute. All of the cam lobes of a camshaft can be inspected and photographed in only a fraction of an hour, once the equipment is set up. This method is equally suitable for supplementing production inspection and for cam contour development work.

The electronic method of inspection permits studying the lift, velocity, or acceleration curve by only the turn of a selector switch. These three types of curves are shown in Figure 1. The versatility of this method is readily appreciated when one desires to study these individual curves without going through the process of plotting them on graph paper from data obtained from micrometer measurements. In actual inspection work the lift curve is not of much value as small errors are not apparent. The velocity curve reveals the errors more readily, whereas the acceleration curve reveals local irregularities even more readily and more accurately than obtainable by calculation from lift figures measured to .0001″.

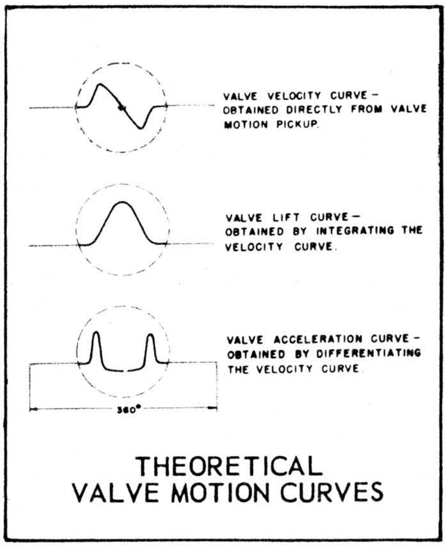


Figure 1

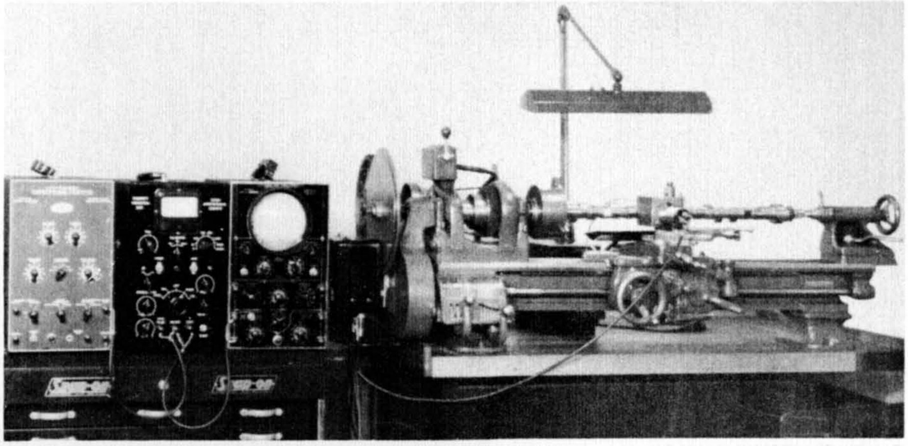


Figure 2

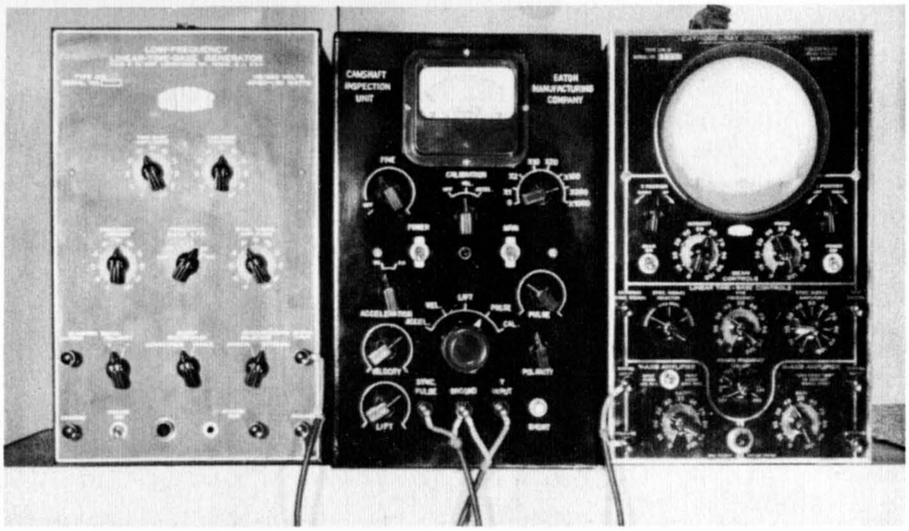
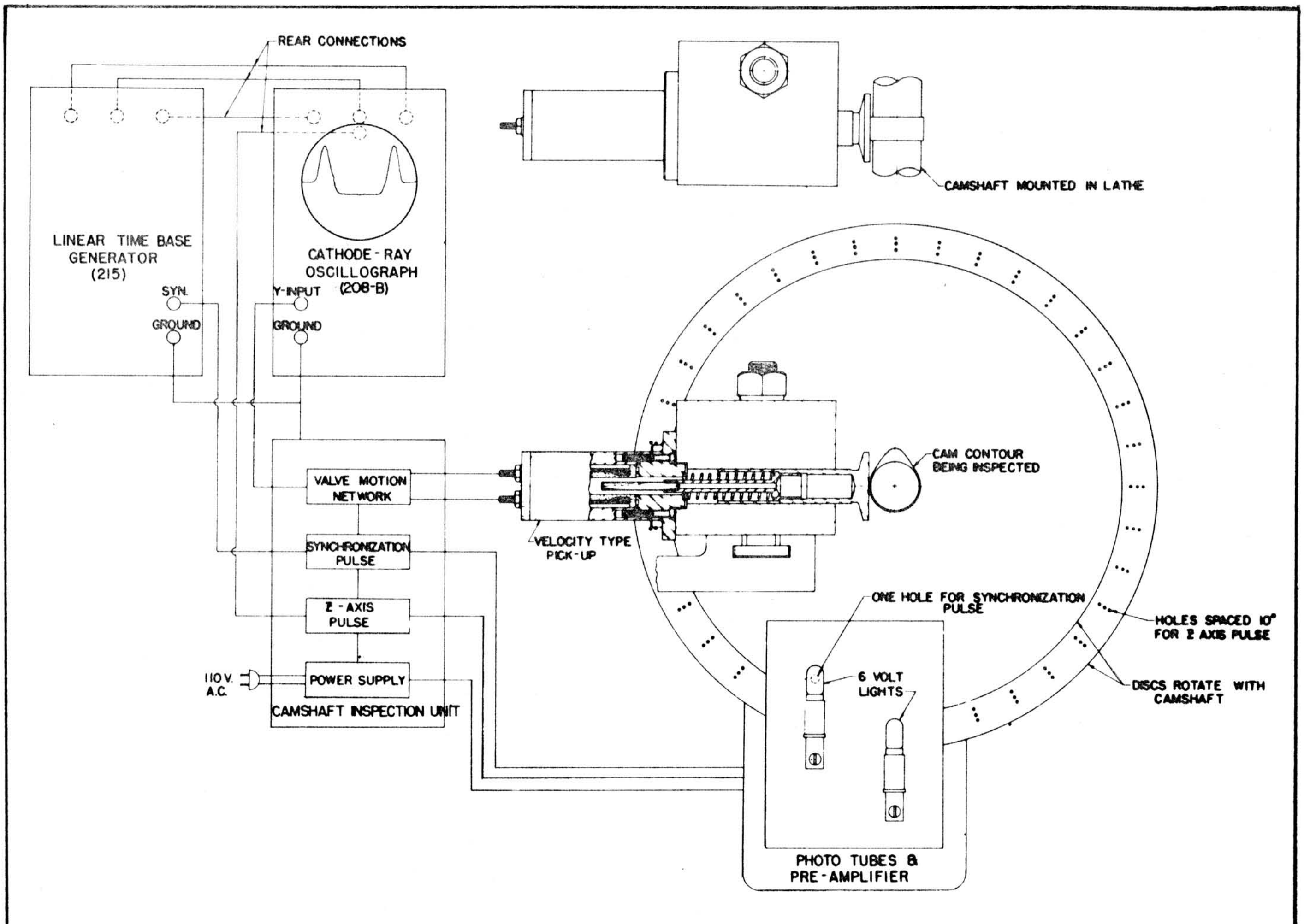


Figure 3

This method of inspection begins by mounting the camshaft in a lathe and rotating it at a given uniform low speed of approximately 200 to 400 R.P.M. A tappet follower (flat, roller, or shoe) is held against the cam lobe by means of a light spring to simulate the motion of a tappet in a valve gear. Figure 2 is a photograph of a camshaft in a lathe for this test work and also shows the electronic equipment being used. Figure 3 is a photograph giving a more detailed view of the electronic equipment used for the more elaborate inspection procedure explained in this article.

The electronic equipment comprises a cam contour inspection unit which was specially built up for this purpose, a 5″ cathode-ray oscillograph which is a 208-B DuMont unit employing a blue screen cathode-ray tube for photographic purposes, and a linear-time-base generator which is a 215 DuMont unit. The above oscillograph is well suited for this application due to its high Y-axis gain, making it possible to design a pick-up for this inspection work without the use of an additional electronic amplifier. The linear-time-base generator was employed to secure a more linear-time-base for the X-axis than was available within the oscillograph. However, a more recent model oscillograph (DuMont 304-H) does not require this extra unit in order to receive a reasonably linear X-axis time base.

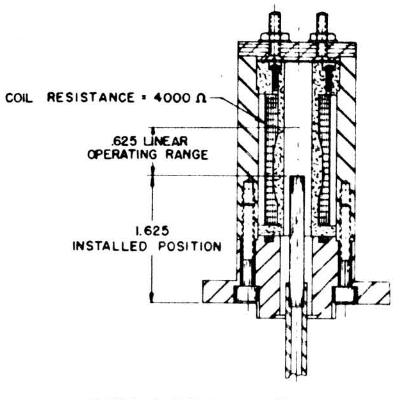


BLOCK WIRING DIAGRAM OF CAM CONTOUR INSPECTION FIXTURE

Figure 4

A drawing showing the tappet follower riding on the cam contour is shown in Figure 4. This drawing also shows the wiring diagram in block form to illustrate how the various units are functionally related. The tappet follower supports a small rod-shaped magnet which moves with it as the tappet is reciprocated by the motion imparted to it by the cam lobe.

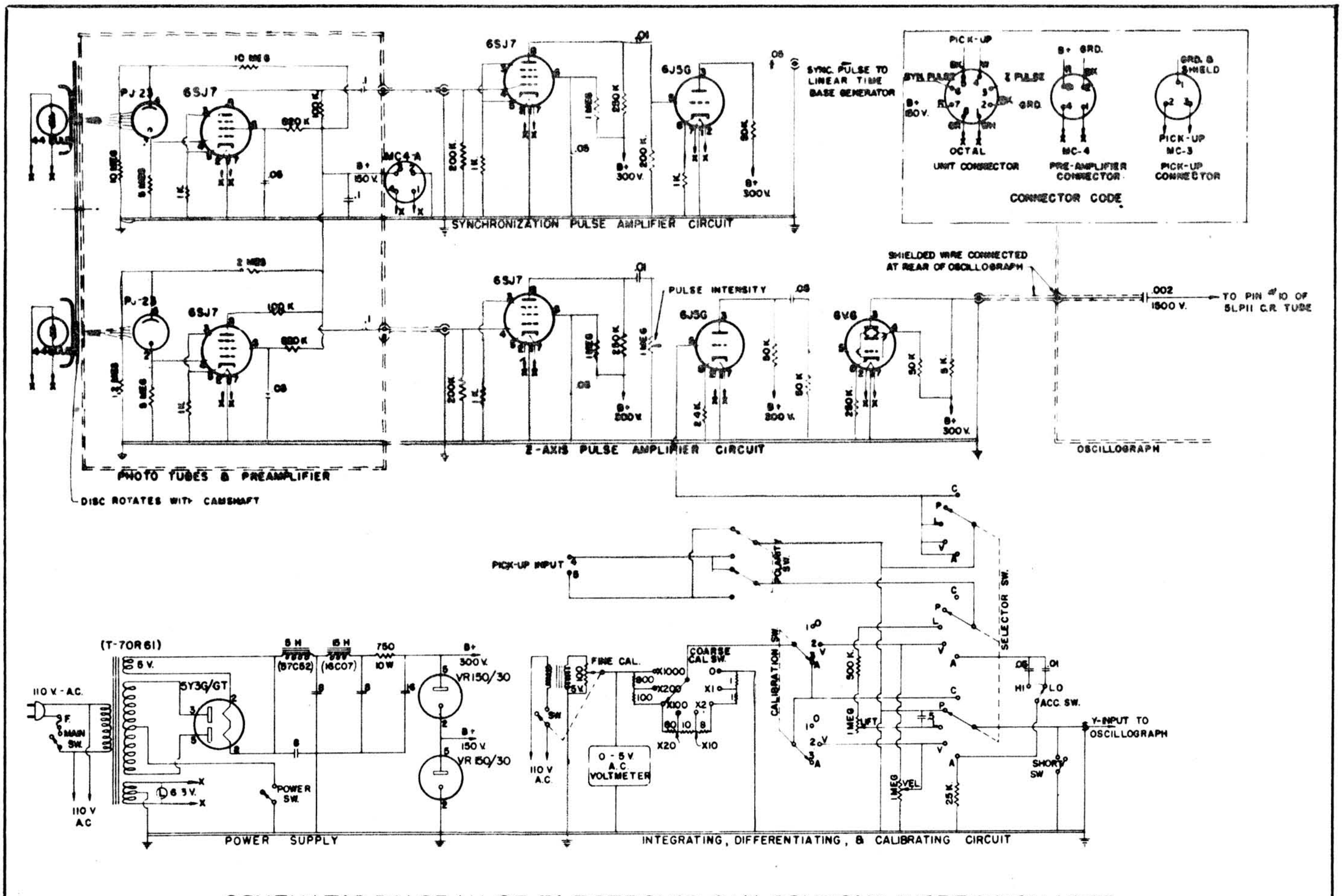
A drawing of the pick-up assembly is shown in Figure 5. It is termed a velocity type pick-up since its output produces a voltage which is directly related to the velocity of the magnet. As the tappet follower moves, following the cam contour, the small magnet generates a voltage in the pick-up coil which can be fed to the oscillograph. The voltage wave form appearing on the screen of the oscillograph is directly related to the shape of the cam contour. The wave form appearing will be the velocity curve. However, either the lift or acceleration curve may be observed by suitable electrical integrating or differentiating circuits.



VELOCITY TYPE PICK-UP ASSEMBLY

Figure 5

Figure 6 is a schemetic diagram of the electronic cam contour inspection unit and reveals these special circuits to secure the lift and acceleration curve. Note the simplicity of this portion of the cam contour inspection unit and that no electronic amplifiers are employed, even though the voltage loss in the electrical process is over 95%. This is made possible by employing the oscillograph possessing the high gain as



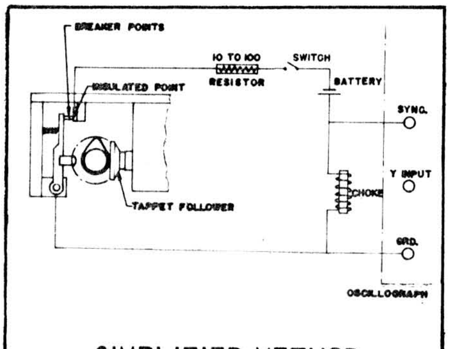
SCHEMATIC DIAGRAM OF ELECTRONIC CAM CONTOUR INSPECTION UNIT

Figure 6

mentioned and by building a very sensitive pick-up specially designed to have a high sensitivity factor and still give a linear response in its operating range.

This equipment possesses calibration controls so that measurements of the ordinates of the acceleration and velocity curves are easily done once the sensitivity factor of the pick-up is known. For critical cam contour inspection work it is best to study the acceleration curve since here errors are more readily apparent. The velocity curve is also of much value, especially in checking the ramps provided at each end of the cam contour.

The electronic circuits in the cam contour inspection unit (Figure 6) are employed in providing two types of pulse voltages: one for synchronization of the oscillograph to the rotative speed of camshaft and the other to provide ten-degree markers to the X-axis for photography use. The electronic camshaft inspection unit employes many features to permit recording data wherein the ordinates and abscissas are calibrated.



SIMPLIFIED METHOD
OF SYNCHRONIZATION
USING BREAKER POINTS

Figure 7

This is highly desirable in checking an actual velocity or acceleration curve against a theoretical one. In production applications (or where only a few cams are occasionally checked) the electronic portion of the cam contour inspection unit can be dispensed with. For synchronization purposes a pair of breaker points can be provided to be actuated by the cam lobe being inspected. Figure 7 shows the simplified wiring diagram of a synchronization circuit for use with breaker points.

THEORY

As the magnet (attached to the tappet follower) reciprocates within the wire coil, a voltage is generated across the pick-up terminals and is equal to:

measurements are easily made on the oscillograph due to the sinusoidal wave form output from the pick-up. To secure adequate sensitivity a higher speed is used for calibration than for actual cam contour inspection. Low speeds are desirable during cam contour inspection to keep inertia and spring loads to a minimum.

The output from the pick-up is fed to the cam contour inspection unit, with the acceleration switch set on low gain, and then to the oscillograph. The oscillograph Y-gain is adjusted to give a certain amplitude on the screen (2″ overall). Then the selector switch is set on "Calibration" and the calibration switch is set on "Acceleration". Finally, the fine and coarse calibration controls are adjusted to give the same height as before (2″ overall) on the oscillograph screen. The reading of the voltmeter (read in millivolts), multiplied by the appropriate multiplication factor given on the coarse calibration control, is then used to establish the sensitivity factor of the pick-up as follows:

Eccentric displacement = .376"

$E = .188''$

Calibration speed $N_c = 640$ RPM

Test speed $N_t = 226$ RPM

$$\frac{N_c}{N_t} = 2.835 \qquad \left(\frac{N_c}{N_t}\right)^2 = 8.02$$

$A_m = .30462 \cdot 10^{3} \cdot E = .0572 \cdot 10^{-3}\ ''/\text{deg}^2$

output voltage from differentiating network measured at 30.0 millivolts (RMS) at 640 RPM

Acceleration sensitivity factor for 226 RPM = K

$$K = \frac{30.0\ \text{mv.}}{8.02 \cdot .0572 \cdot 10^{-3}} = 65.3 \frac{\text{mv.}}{''/\text{deg}^2}$$

at 226 RPM

This sensitivity factor is then used for all later adjustments to the oscillograph providing:

(a) The pick-up and magnet are not altered.

(b) The test speed is held at 226 RPM (or other selected value).

(c) The differentiating circuit is not altered.

(This factor should be checked occasionally (once a year or so) to be sure that the magnet has not lost sufficient strength to introduce undesirable errors).

For actual inspection work, wherein the screen is photographed, the most practical ordinates are selected ; i.e. 1″ on the screen is equal to .0006″/deg.^{2}. The calibration controls are adjusted to give a voltage equal to J = K x H (ordinate) and the Y-gain control is adjusted to give 2″ overall pattern height to the oscillograph screen. In the instance noted, the voltage to use is:

$$J = 65.3 \cdot 10^{3} \frac{\text{mv.}}{''/\text{deg}^2} \times .0006\ ''/\text{deg}^2$$

$J = 39.2$ millivolts

VELOCITY CALIBRATION

The velocity calibration is made in very much the same manner as is the acceleration calibration. The sensitivity factor is determined in a similar manner, providing items previously listed as (a) and (b) remain the same. The calibration outline is as follows:

Eccentric displacement = .376"

$E = .188''$

$N_c = 640 \quad N_t = 226 \quad \frac{N_c}{N_t} = 2.835$

$V_m = .01745 \times E = .0033\ ''/\text{deg.}$

Output voltage measured from pickup = 1,710 millivolts (RMS) at 640 RPM

Velocity sensitivity factor for 226 RPM = M

$$M = \frac{1{,}710\ \text{mv.}}{2.835 \cdot .0033\ ''/\text{deg.}} = 183 \cdot 10^3 \frac{\text{mv.}}{''/\text{deg.}}$$

at 226 RPM

Again in actual inspection work the most practical ordinates are selected; i.e. 1″ on the screen equals .0060″/deg. The calibration controls are adjusted to give a voltage equal to L = M x H (ordinate). Once the Y-gain is set as outlined above for the acceleration calibration, it should not be disturbed and the velocity gain on the cam contour inspection unit needs to be used to adjust the height of the calibration pattern on the oscillograph screen to give an overall height of 2″. In this instance the voltage to be used is:

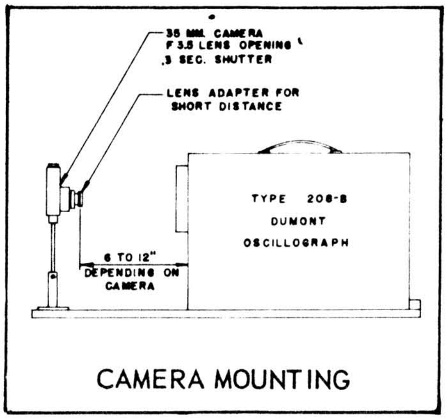
$$L = 183 \cdot 10^3 \frac{\text{mv.}}{''/\text{deg.}} \times .006\ ''/\text{deg.}$$

$L = 1100$ millivolts

It should be observed that the specific figures outlined above are only used for explanatory purposes. Another calibration done on another fixture and pick-up could employ a different displacement to the eccentric used for calibration, a different calibration and test speed, and different units may prove to be desirable for the ordinates of the acceleration and velocity curves.

X-AXIS CALIBRATION

It is also desirable to establish definite units to the abscissa or X-axis of the oscillograph screen, especially if the curves are to be photographed for further study. A typical camera mounting arrangement is shown in Figure 9. A type 5LP11 cathode-ray tube should be used in the oscillograph due to the blue short-persistance



CAMERA MOUNTING

Figure 9

screen which is much more efficient for this photographic use. The camera equipment is installed in a dark room so that so that stray light does not enter the camera. A specially built light enclosure, or a camera adapter to the oscillograph which is available, may also be used. The camera employs a 35 mm. film and is adjusted for F 3.5 lens opening with a shutter speed of approximately 1/3 second. Typical data obtainable by photographic methods are shown in Figures 10 and 11. The multiple curves shown are obtained by multiple exposure; an exposure being required for each line or pattern across the film.

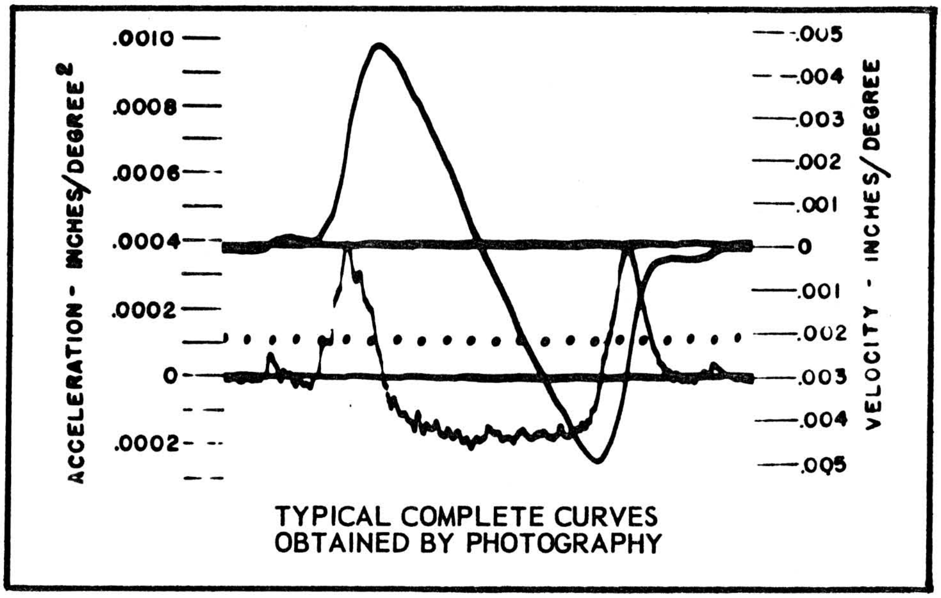


Figure 10

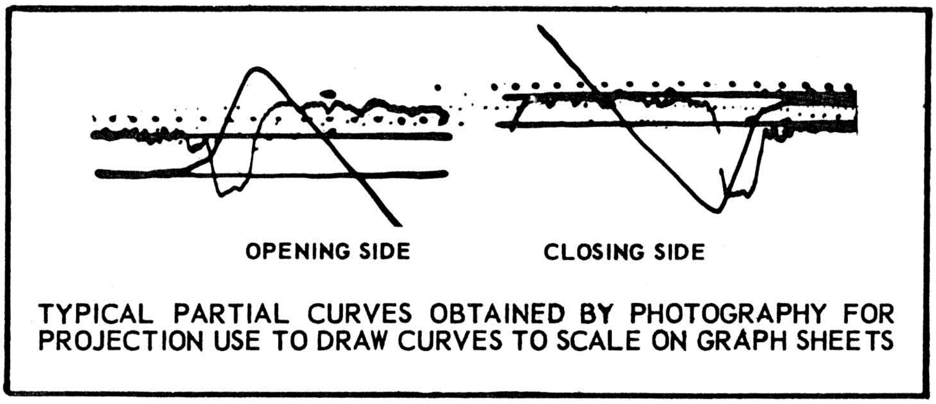


Figure 11

When the photographic results are enlarged it is desirable to have accurate X-axis calibration. This is accomplished by having a horizontal line consisting of dots every ten degrees. This dotted line is produced by introducing Z-axis pulses into the oscillograph. These pulses are spaced every ten degrees and are obtained from a series of holes drilled in a rotating disc which rotates together with the camshaft. The holes, which are located near the periphery of the disc, are used to trigger one of two photo cells enclosed in a small box mounted on the lathe as shown in Figure 2. This disc arrangement is also shown in Figures 4 and 6 and illustrates how this Z-pulse is fed to the oscillograph. The particular oscillograph used for this work (DuMont 208-B) did not have this Z-axis feature but it was quite easily incorporated. A later model oscillograph (DuMont 304-H) does not require this rework as it has a Z-axis input available.

Figure 10 is a photograph showing typical complete curves used for study of velocity and acceleration. The X-axis calibration has approximately sixty degrees to the inch and allows the entire curves to appear. Figure 11 uses thirty degrees to the inch on the X-axis and allows only one-half of the curve to appear. This is the type of photograph preferred for making enlargements and tracings to scale in order to allow accurate comparison to the theoretical curve. Typical results of this method are shown in Figures 12, 13, 14, and 15 (pages 9 and 10) and reveal the close comparison obtainable between actual and theoretical curves.

X-AXIS SYNCHRONIZATION

In order to obtain a stationary image on the oscillograph screen it is necessary that the frequency of the X-axis sweep circuit be adjusted to be slightly below the RPM of the camshaft and then to insert a synchronization voltage into the oscillograph. Exact synchronization is obtained by injecting a voltage pulse equal in frequency to the camshaft speed into the X-axis sweep generator circuit. This voltage pulse is obtained by electronic methods and employs a rotating disc to trigger light to another photo tube. The rotating disc assembly consists of two discs: one having a series of holes every ten degrees and another with only one hole. The discs are adjusted by hand so that two holes will register and will be in position to allow light to trigger the photo tube when the tappet follower is on the base circle approximately opposite the center of the cam lobe. Each time the tappet follower is moved from one cam lobe to another the discs need to be readjusted. The electronic circuit employed for this synchronization is shown in Figure 6 whereas a simplified synchronization circuit is shown in Figure 7.

SET-UP OF EQUIPMENT

The inspection fixture as built up employs a conventional lathe as illustrated in Figure 2. The tappet follower can be either a flat, roller, or curved shoe, and should be the same as the type normally used with the particular cam contour being inspected if accurate data are to be obtained for comparison with a theoretical curve. For purposes of magnifying errors appearing on the nose of the cam, a small roller follower may be used on a cam contour normally requiring a flat or large roller follower. In this instance, the wave forms will be of value for comparative purposes only in production testing and will have no direct relationship to theoretical curves.

The tappet follower is mounted in a block which is installed in place of the tool post on the lathe carriage. This makes changing from one cam lobe to another a simple operation. The tappet follower and allied parts are made small, light, and rigid to introduce a minimum of inertia load on the camshaft during testing. At the adopted test speed of 226 RPM the maximum inertia load, when inspecting a high acceleration cam, is about one pound which is quite low. During testing a light oil of about SAE-10 is continually supplied to the cam lobe to eliminate any tendency of the tappet follower to chatter. Inadequate lubrication produces rough and non-repetitive curves. For the purpose of oiling the camshaft, a small continuous supply of oil is provided by an oil pump driven by a 1/25 H.P. motor.

INSPECTION PROCEDURE

The following is an outline of the procedure employed to secure photographs suitable for enlargine purposes. It is included here to reveal briefly the sequence of operations employed to serve as a guide to others who may adopt a similar method:

1. Mount camshaft in lathe holding it in a three jaw chuck.
2. Square-up tappet follower on cam contour to be checked. Adjust so that magnet is 1 5/8″ from mounting block (Figure 5) when follower is on base circle.
3. Adjust disc so that light passes through synchronization hole when follower is on base circle opposite cam nose.
4. Operate lathe at low speed (226 RPM).
5. Adjust oil supply to be continuous.
6. Turn on oscillograph and linear-time-base generator and adjust for synchronization.
7. With acceleration gain set on "Low" and calibration "Off", proceed to calibrate X-axis.
8. With selector switch on "Pulse" and operating "Short" switch, adjust X-axis controls for desired spacing of dots (three per inch).
9. Proceed with Y-axis calibration as follows:
   - (a) Set selector to "Calibration" and calibration switch to "Acceleration".
   - (b) Set calibration controls to 39.2 millivolts and adjust Y-gain on oscillograph for 2″ pattern neight on screen.
   - (c) Turn the calibration switch to "Velocity".
   - (d) Set calibration controls to 1100 millivolts and adjust velocity control on cam contour inspection unit for 2″ pattern height on screen.
   - (e) Turn calibration and fine control to "Off".
10. Proceed to make photographs as follows:
    - (a) Set the selector on "Acceleration", centralize vertically and horizontally on the screen, and take picture of acceleration curve.
    - (b) Take picture of acceleration base line by depressing the short switch.
    - (c) Turn the selector to "Velocity", centralize vertically only on screen and take picture of velocity curve.
    - (d) Take picture of velocity base line by depressing the short switch.
    - (e) Turn selector to "Pulse", reduce intensity to a series of dots, depress short switch for a line and take picture of pulse dots.
    - (f) Turn film.
    - (g) Repeat (a) to (f) above for closing side if first curve was only for opening side.

CONCLUSIONS AND RECOMMENDATIONS

Electronic cam contour inspection as herein outlined can be carried out using one of the following three schemes:

(1) Visual inspection on the oscillograph screen of the

$e_o = k_1 \cdot N \cdot \frac{d\phi}{dt}$

where: N = number of coil turns

$\frac{d\phi}{dt}$ = rate of cutting flux lines

but: $\frac{d\phi}{dt} = k_2 \cdot V$

where: V = velocity of magnet

Therefore: $e_o = k_3 \cdot N \cdot V$

This shows that the output voltage from the pick-up is directly proportional to the velocity curve and this curve will appear on the oscillograph screen when the output terminals from the pick-up are connected directly to it. The pick-up was designed for a linear response in its normal operating range (making $d\phi / dt = k_2 \cdot V$).

To obtain a lift curve or an acceleration curve an electrical network must be employed to integrate or differentiate the velocity curve. The basic circuits by which this is accomplished are shown in Figure 8. Electrical integration is performed by utilizing an RC network with selected values to give a high ratio of resistance to capacitive reactance and a high ratio of time constant (RC) to the reciprocal of the frequency of operation (l/f). The integrated voltage appears across the terminals of the condenser. For the case of a sinusoidal voltage output from the pick-up, a vector diagram is indicated.

Electrical differentiation is also performed with an RC network as shown in Figure 8. In this instance the values are chosen to give a high ratio of capacitive reactance to resistance and a low ratio of time constant (RC) to the reciprocal of the frequency of operation (l/f). The differentiated voltage appears across the resistance. A vector diagram is shown for a sinusoidal voltage output from the pick-up. Note the large loss in voltage in both of these networks (incorporated in the circuit diagram shown in Figure 6).

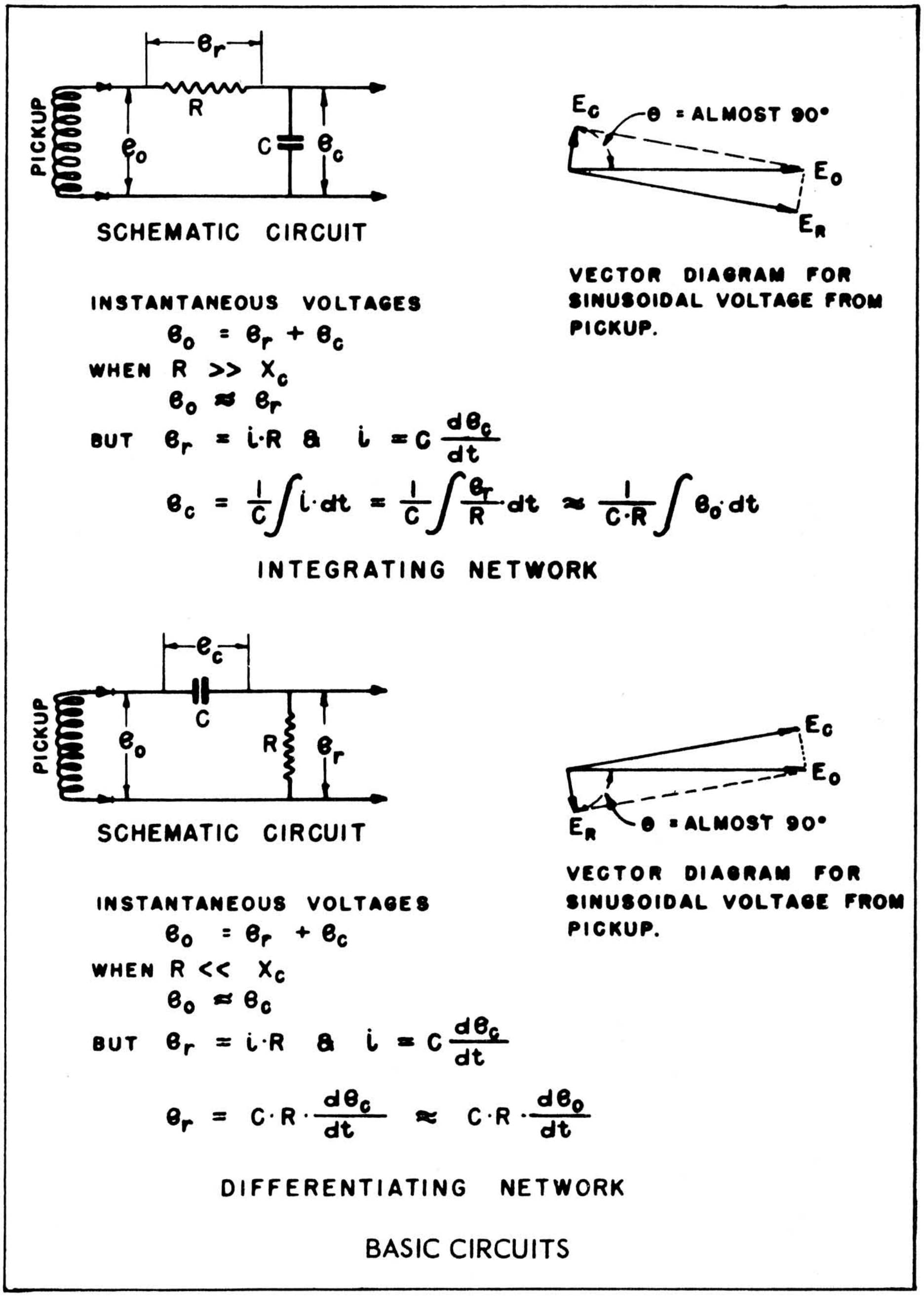


Figure 8

A sixty-cycle calibrating voltage is provided to facilitate adjusting the gain controls to predetermined settings and to secure curves on the oscillograph screen with calibrated ordinates. This requires that the pick-up be calibrated to determine its sensitivity factor by measuring the voltage generated as related to the maximum acceleration and velocity of the small reciprocating magnet. The following outline gives the sequence of operation used to calibrate the pick-up and shows how this sensitivity factor is employed in setting the controls to adjust the height of the acceleration and velocity curves on the oscillograph screen. Typical values will be cited to clarify the explanation. Each pick-up will have its own sensitivity factor.

ACCELERATION CALIBRATION

Calibration is accomplished by employing an eccentric to reciprocate the tappet follower. Here the actual acceleration of the tappet is known and voltage

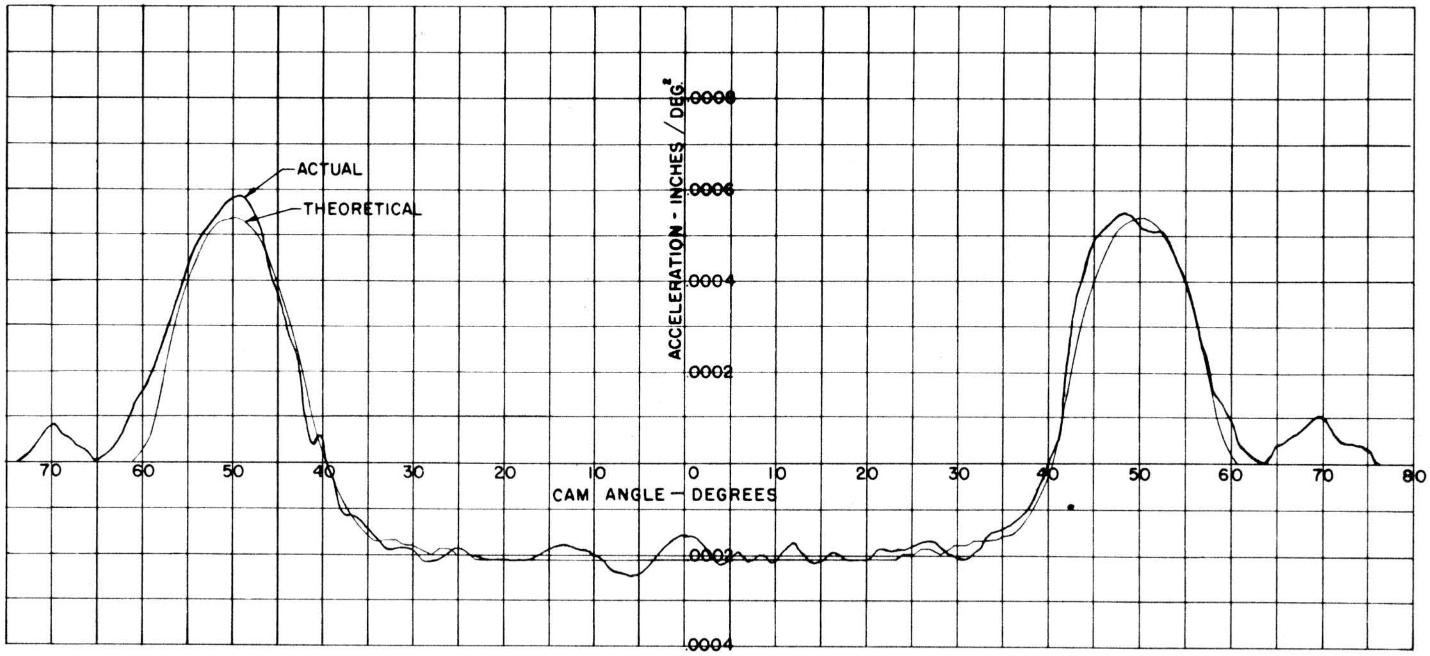


Figure 12

COMPARATIVE ACCELERATION CURVES FOR A NEW CAM CONTOUR ACCURATELY FINISH GROUND

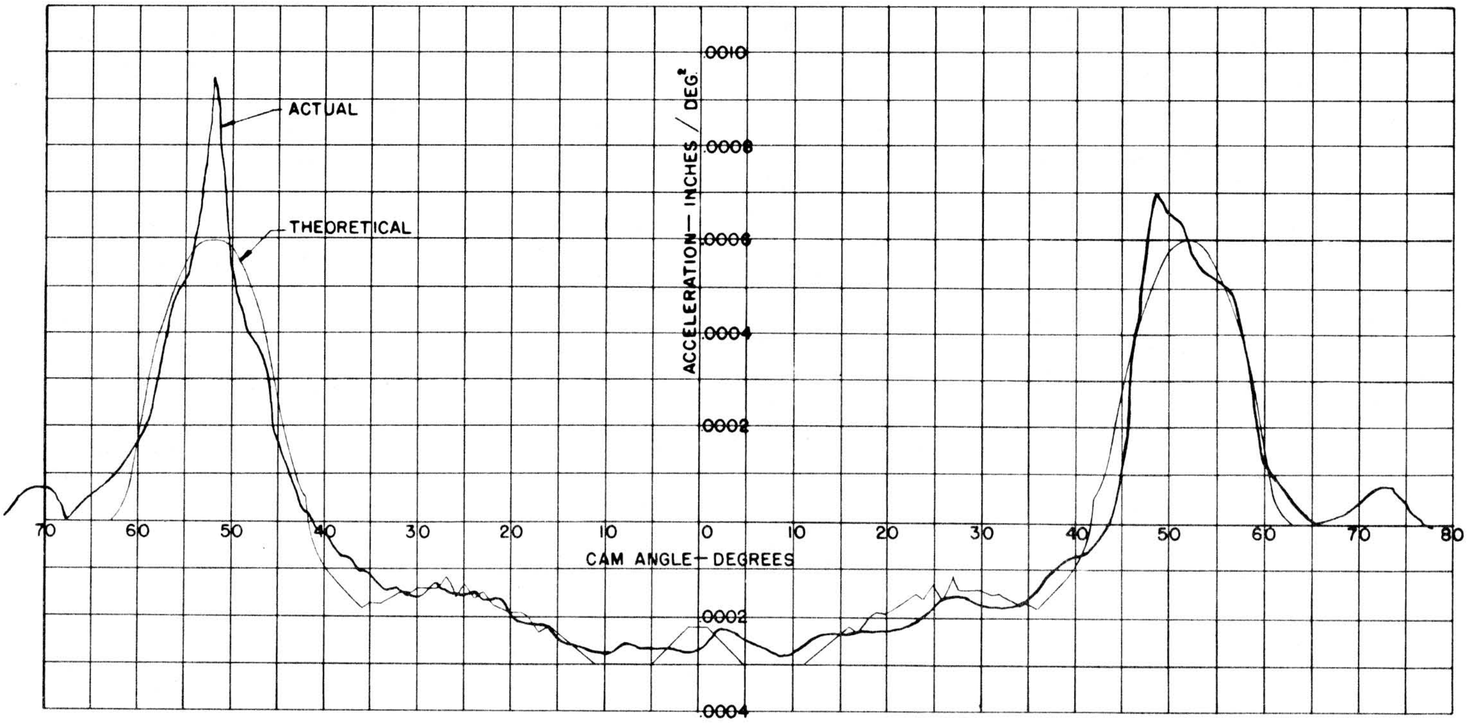


Figure 13

COMPARATIVE ACCELERATION CURVES FOR A NEW CAM CONTOUR POORLY FINISH GROUND ON THE OPENING FLANK

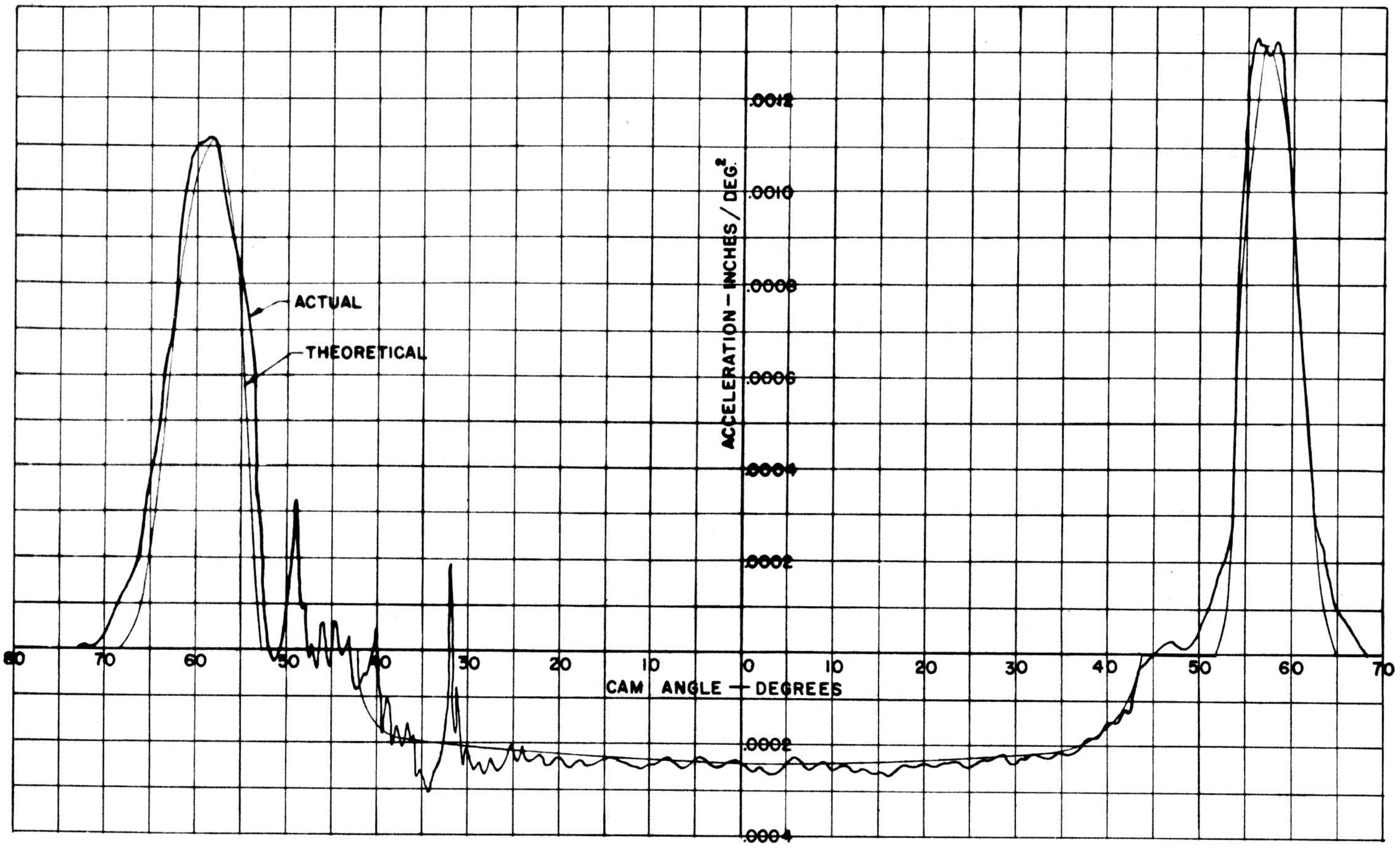


Figure 14

COMPARATIVE ACCELERATION CURVES FOR A USED CAM CONTOUR WITH A WORN SPOT ON THE OPENING SIDE OF THE NOSE

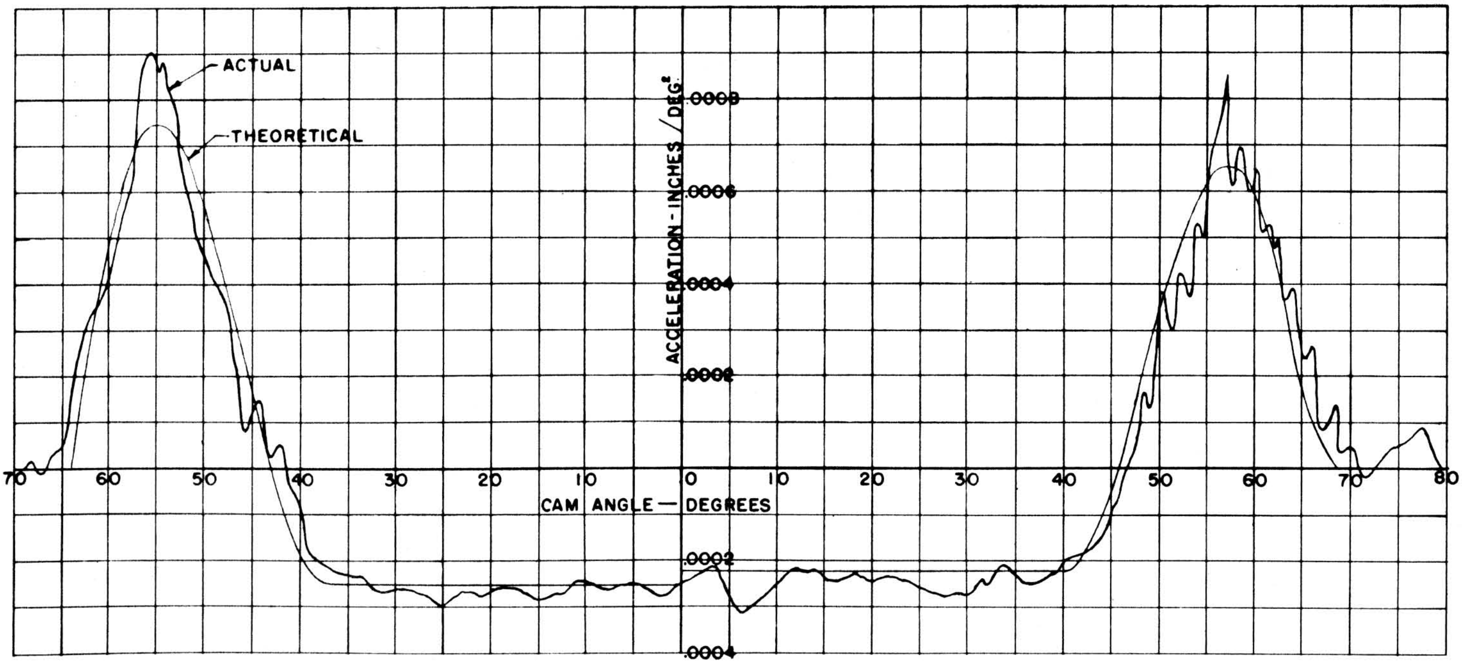


Figure 15

COMPARATIVE ACCELERATION CURVES FOR A USED CAM CONTOUR WITH A ROUGH CLOSING FLANK acceleration or velocity curve, comparing it to limits or to a curve marked on the screen. The set-up can employ the type of follower for which the cam contour was designed or can employ a follower with a small roller to magnify irregularities on the cam nose when used for production checking. This is the simplest form of inspection and requires a minimum of equipment.

(2) Photographic recording of the curves appearing on the oscillograph screen as illustrated in Figure 10 to permit closer study. This also gives a permanent record of the curves for future reference.

(3) Photographic recording of the curves as illustrated in Figure 11 for enlarging or projection use to draw actual curves for comparative purposes with the theoretical. Examples of this scheme are shown in Figures 12 through 15. Figure 12 shows a relatively accurately ground cam contour. Fairly close agreement is noted to exist between the actual acceleration curve and the theoretical one designed to have a smooth acceleration curve (parabolic cam design). Figure 13 is a curve of a new cam contour having an inaccurately ground point in the mid-portion of the opening flank. The acceleration rises sharply to about one and one-half times the theoretical value. Figures 14 and 15 are curve comparisons for cams that have been used in an engine test to show how localized wear is easily revealed. Figure 14 indicates a badly worn spot on the opening side of the cam nose whereas Figure 15 shows a relatively rough closing flank.

The electronic method has proved to be much superior to other methods of inspection in many respects. It readily reveals irregularities in the cam contour. However, it should not be construed as replacing all micrometer measurements in production inspection. A contour which may be ground considerably undersize (thus producing a very small cam nose radius) will give a good acceleration curve even though it may not be suitable for use in an engine. For this reason, some basic micrometer measurements are still essential in production inspection such as base circle radius, overall cam height, a spot check on the cam nose radius, flank radius, and cam angle. However, this method, suggested to supplement production inspection, fits into a most urgent need for research and development work in cam design.

The cost of the electronic equipment required is nominal when compared to the benefits derived from its use. It can be less than $500.00 (including the oscillograph and pick-up) when adapted to an existing lathe. The pick-up which has been especially designed for this use is available at a small cost or specifications can be furnished for building one up.

This equipment can also be employed in engine test work to observe valve motion. The use of this type or similar electronic inspection equipment will assure that more manufactured cam contours will be closer to the preferred design with the result that the component parts of the valve gear will have longer life and engine performance will be improved.

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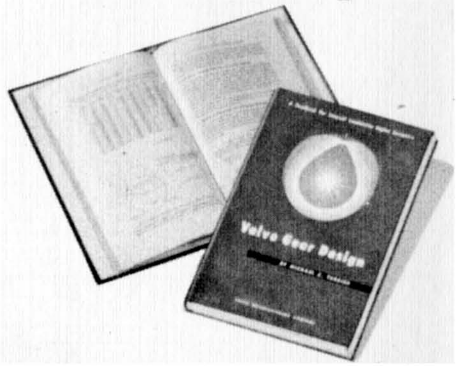
"Valve Gear Design"



The 130-page book, "Valve Gear Design", by the author of the foregoing paper, is an invaluable handbook for designers of internal combustion engines. It is the first comprehensive treatise on the designing of cams, tappets, valve springs and other units of the valve gear. Replete with formulae and diagrams, it is a concise and understandable presentation of theory combined with a working handbook. Its procedures have been used in the designing of many well-known automotive, aircraft and industrial engines.

Copies of this book have been placed in technology departments of libraries in all the principal industrial centers. It should be in the engineering library of every vehicle and engine manufacturer. They are available at $6 per copy. Address: Eaton Manufacturing Company, Valve Division, 9771 French Road, Detroit 13, Mich.