

MACROGEOMETRIC MEASUREMENT OF CAMSHAFTS OF INTERNAL COMBUSTION ENGINES

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Abstract: In this work, cam profiles of a camshaft are measured by a roundness measurement machine. First, the measured cam profiles are transformed into their actual sizes, based on the measurement of the bearing locations. The 8 cams of the camshaft are of two types. From the 4–4 cam profiles of each type an approximate profile is created by fitting them to one another using their base circles as reference, and calculating the center of gravity of the cumulative points of these fitted profiles corresponding to an arc segment.

KEYWORDS: Cam profile, profile matching, Helmert transform, profile comparison, reverse engineering

1 Introduction

Already in 1965 J. H. Nourse provided [1] a thorough review of camshaft measurements. There the measurement problem is defined as how the deviation of the special cam profile from the nominal profile can be determined by measuring circular runout and angular rotation assuming a tolerance field of $\pm 0.001''$ (± 0.0254 mm). Runout scanning is still one of the standard methods for cam profile measurements.

The measurements required for this work were also carried out with a roundness measuring device, namely with TALYROND365, which was considered state-of-the-art 20 years ago. With its profile tracking method, it made possible to measure cams in addition to measuring objects with circular symmetry. With the TALYROND595 [2], which is currently considered state-of-the-art, it is now possible to perform calculations (evaluations) related to cam measurement based on the manufacturer's specification.

In relation to the measurement of a camshaft, the geometric measurement of at least the cams and the radial bearings are to be considered, but other objects, such as gear are also present. In our example, the 8 cams should be evaluated according to their size, shape and position: in this connection it is also necessary to measure the radial bearings. The 8 cams of the measured camshaft have two different sizes and shapes. Since the nominal cam profiles are not available to us, a common, average profile of the 4 cams are derived, which can be considered as an approximation of the true profile, i.e., as the basis for the comparison. The difference in size, shape and position of each cam is compared to this approximate average cam profile, and the difference in size, shape and position of the two types of cams is also obtained by comparing the approximate profiles.

The article is organized the following way. In Section 2 the measurements with a roundness measuring device, the effects of the eccentricity to the size and shape of the objects, and their corrections are described. Next, in Section 3, the comparison of the cams is given: the fitting

methodology of using a two-level limited domain Helmert transform for the base circles and the tips of the cams, and the creation of the approximating, average cam profiles are explained and the comparing is carried out. Finally, Section 4 summarizes the work.

2 Camshaft measurement with circular shape testing equipment



Fig. 1. Camshaft circular runout measurement

Figure 1 shows the runout measurement of the 1st radial bearing of the camshaft of an internal combustion engine using roundness measuring equipment TALYROND365. When measuring with roundness measuring equipment, the workpiece under test performs a rotating movement on a rotary table, the probe is fixed to a stationary arm and it moves only due to the shape and position deviation of the actual surface from the rotating basis surface. This is the essential idea behind the measurement and detection. For the measurement, the axis of rotation of the workpiece must be positioned to the axis of rotation of the rotary table. The direction of the rough positioning is provided by the bearing of the face plane of the drive gear of the camshaft on the face surface of the 3 clamping chuck jaws. The chuck jaws center the camshaft on a cylindrical surface that does not need to be measured. The chuck is centered on the round rotary table by 3 balls of the same diameter placed in the 3 grooves spaced at 120° intervals of the round table.

The fine positioning of the camshaft is carried out by measuring the runout of the first and last radial bearings (No. 1 and No. 5), the equipment determines the eccentricity of their approximate circles, and by shifting and tilting the rotary table axis in two directions (x and y)

the device brings these eccentricity below a given limit in several iterative steps. (Center/Level). As this setting has a limited correction possibility, it is essential, that the axis of rotation of the workpiece should be placed as close as possible to the axis of rotation of the measuring device.

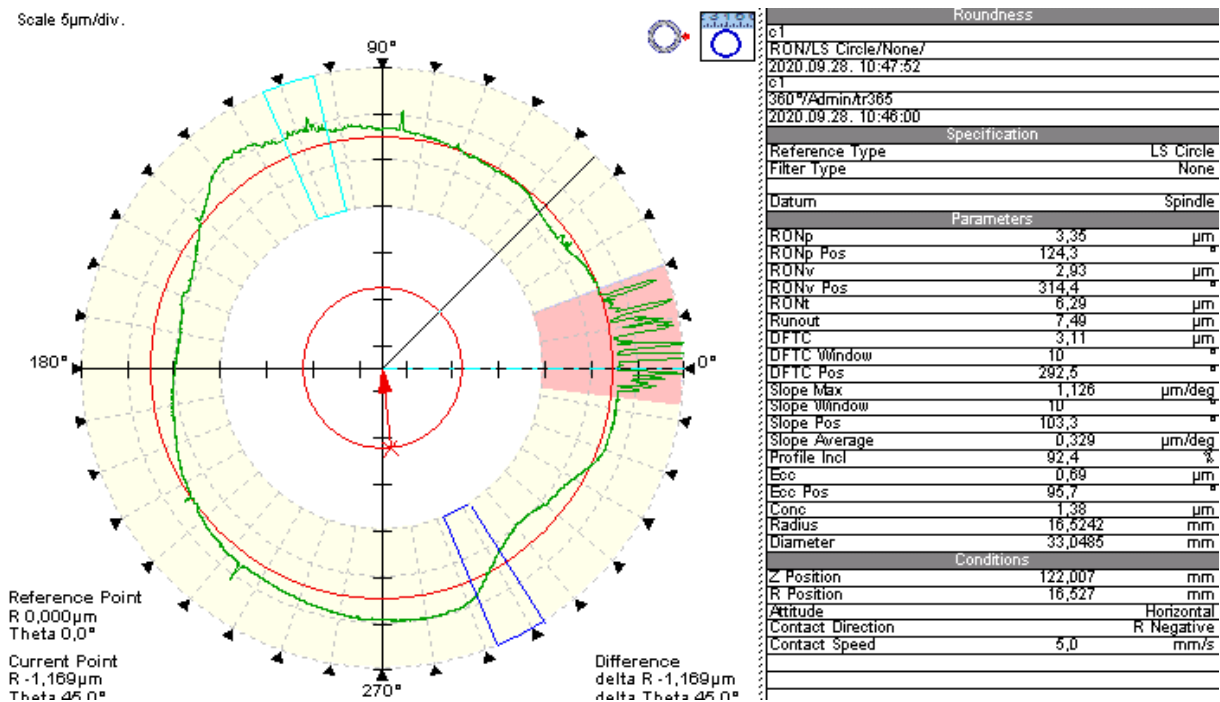


Fig. 2. Evaluation of the 1st radial bearing for diameter, roundness and eccentricity (TALYROND365)

In Figure 2, the green line represents the (slightly triangle-like) shape of the 1st radial bearing with such a magnification that the distance of the concentric dashed-line scale circles corresponds to the value of 5 µm. The red line is the approximate circle of the measured profile determined by the method of least squares.

2.1 The effect of camshaft eccentricity on the measurement

Yunlong Liu and his colleagues dealt with the problem of eccentricity in runout measurement [3] and used this as a basis for optical cam measurements [4]. If a circular profile is rotated around a point offset from its center by a distance Ecc and an angular position $EccPos$ (i.e., $x_0 = Ecc * \cos(EccPos)$ and $y_0 = Ecc * \sin(EccPos)$), then the received profile is not a circle, but a distorted profile with the following polar coordinates r and α according to the offset center of rotation,

$$r = \sqrt{(x - x_0)^2 + (y - y_0)^2}$$

$$\alpha = \arctan \frac{y - y_0}{x - x_0}$$

where x and y are the Cartesian coordinates of the measured profile points, and x_0 and y_0 are the rotation center's coordinates. Figures 3-5 gives an example with a large offset to make the effect more visible.

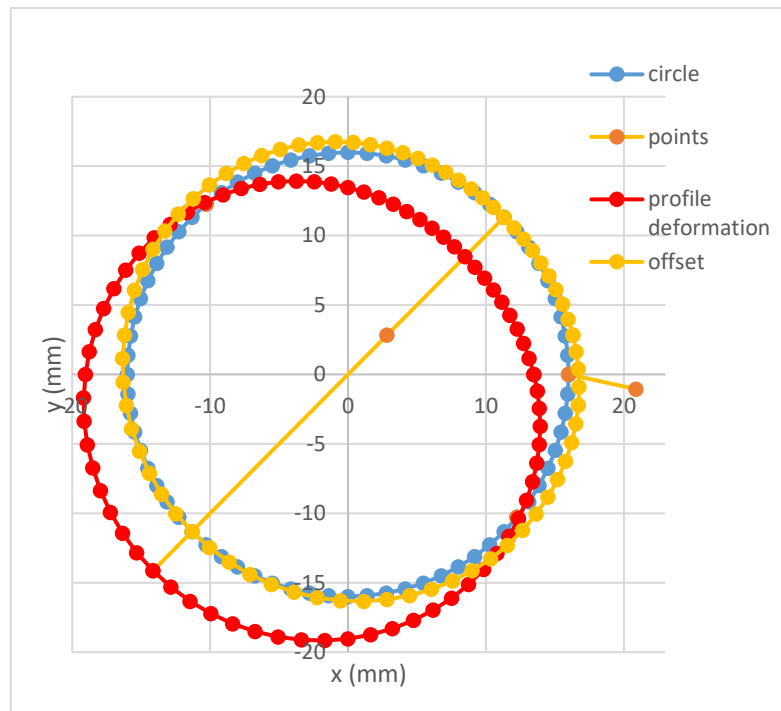


Fig. 3. Circle centered at the origin with $\varnothing 32$ mm (blue), center of rotation (2.83;2.83) (orange dot) and the probe (orange dot pair), the corresponding circular runout profile (red) and its shifted image (yellow) for comparison.

Figure 3 shows a circle with 72 points evenly distributed along the blue line with a center at the origin and a diameter of 32 mm. The 3 orange points are the center of the rotation (its polar coordinates are $r = 4$ mm, $\alpha = 45^\circ$ counterclockwise from the x axis), while the slanted dot pair connected by a line drawn to the point (0;16) indicates the radial sensor of the measuring device, which points toward the center of rotation. The red point series shows the 72 points of the profile according to the model measuring device, i.e., this profile, when rotated around the origin, gives the same circular runout diagram (Figure 4) as the blue circle.

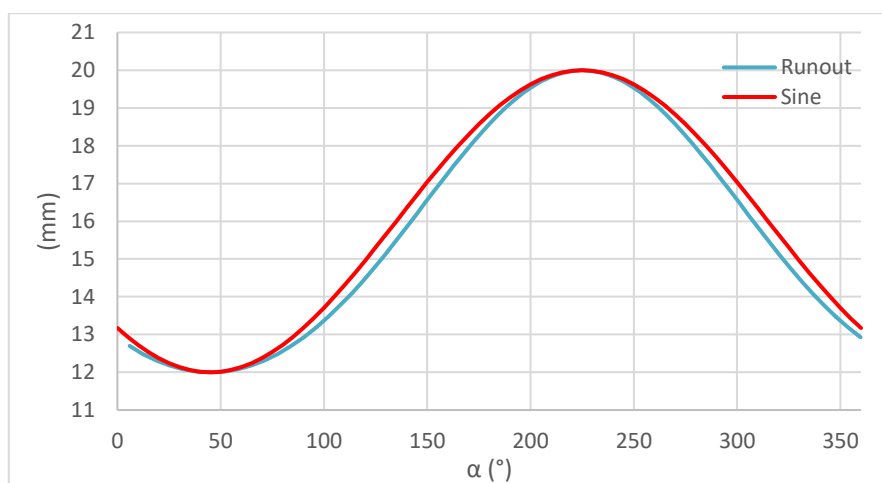


Fig. 4. Runout diagram of the $\varnothing 32$ mm circle, rotated according to Figure 3. As a comparison a sine curve is also plotted to show the difference

Figure 3 also compares the measured red profile to the original blue circle by moving the its 72 points from the origin to the center of rotation shown by yellow color to demonstrate, how the off-centered measured profile deviates from the circle. Figure 4 shows the runout diagram of the circle (blue) and a sine curve (red) to demonstrate that it deviates from the sine function.

The approximating circle of the distorted profile is also determined using the method of least squares. Figure 5 shows the distorted profile and the approximating circle, as well as the circular shape errors of the distorted profile.

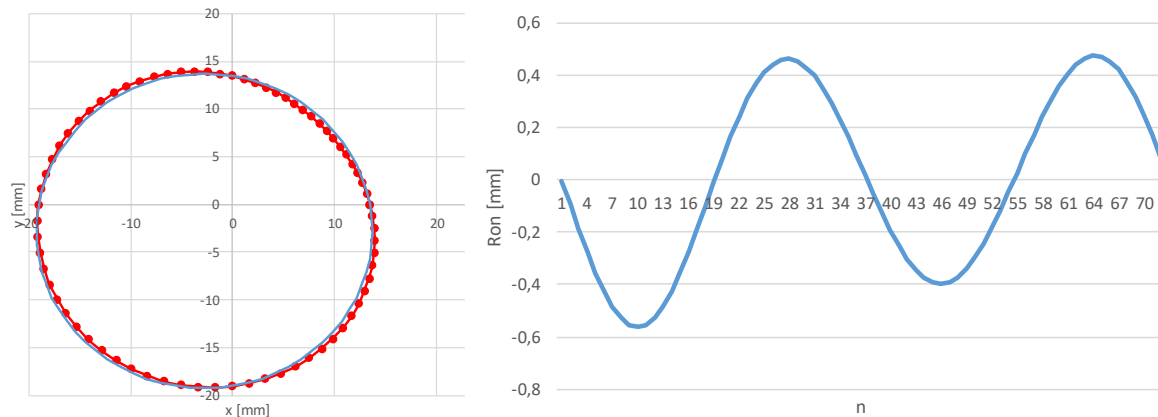


Fig. 5. The approximate circle of the distorted profile and the circle shape errors of its points

Therefore, if a 32 mm diameter circle is rotated around a point 4 mm offset from its center and the original circle is deduced from such a runout measurement, then the measurement results in a diameter 0.96 mm larger than the original, and a circle shape error of $RON_v = -0.56$ mm, $RON_p = 48$ mm and $RON_t = 1.04$ mm. Moreover, the resulting offset of the approximate circle (-2.77 ; -2.77) is only approximately as large as the real eccentricity of the rotation (2.83 ; 2.83). However, the eccentricity is not of great importance in terms of size and shape errors in practice, because the effect of eccentricity on size and shape errors is not linearly but exponentially proportional.

Figure 6 shows the eccentricity of the radial bearings of the camshaft under test. The measured eccentricities of the radial bearings (compared to the axis of rotation of the measurement) are larger (maximum $42.4 \mu\text{m}$) than compared to the operating axis of rotation (maximum $25.1 \mu\text{m}$), if the operating axis of rotation is the common axis of the 5 radial bearings. The measurement and operational eccentricities of the bearings are listed in Table 1.

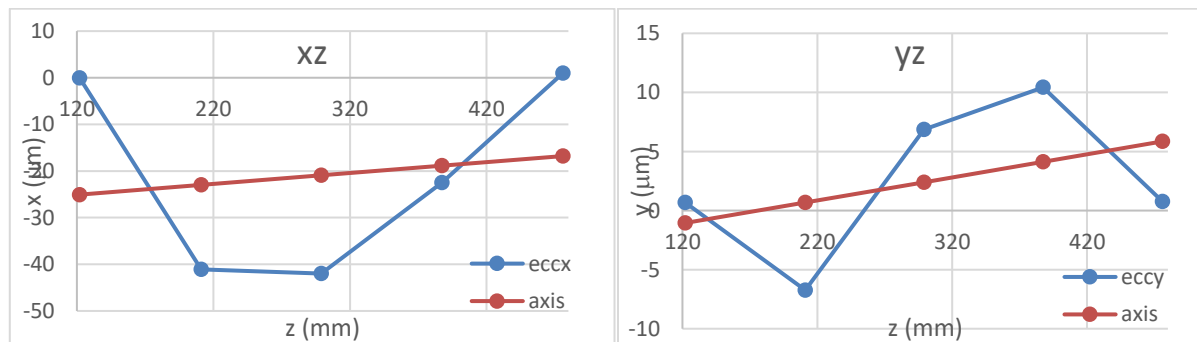


Fig. 6. Eccentricities of the 5 radial bearings in the two coordinate planes

Table 1: The position of the radial bearings in the axial direction (Z), the diameter of the approximate circle (D), the roundness error ($Ront$), the measured eccentricity (Ecc) and its angular position ($EccPos$), the Eccentricity in the xz and yz planes ($eccx$ and $eccy$), the operational eccentricities ($EccOp$) and their angular positions ($EccOpPos$)

	Z	D	$Ront$	Ecc	$EccPos$	$eccx$	$eccy$	$EccOp$	$EccOpPos$
	mm	mm	μm	μm	$^{\circ}$	μm	μm	μm	$^{\circ}$
c1	122.007	33.0485	6.29	0.69	95.7	-0.069	0.687	25.056	182.4
c2	210.962	33.0568	6.93	41.66	189.3	-41.112	-6.732	19.586	178.3
c3	299.082	33.0342	10.63	42.54	170.7	-41.981	6.875	21.525	173.5
c4	387.359	33.0308	7.52	24.76	155.1	-22.458	10.425	7.254	167.7
c5	475.995	33.0463	7.18	1.25	37.4	0.993	0.759	18.499	160.8

Based on the above consideration, it is sufficient, if the measurement is set up in such a manner, that the eccentricity of the sample is not greater than the order of magnitude of the roundness error during measurement. In our case, the eccentricity of $40\text{ }\mu\text{m}$ causes a $0.1\text{ }\mu\text{m}$ roundness error and also increases the size of the approximating circle by $0.1\text{ }\mu\text{m}$. This difference in size and shape is negligible from the point of view of measurement.

2.2 Determining the actual dimensions from the relative dimensions

The roundness measuring device does not give absolute dimensions, but only relative dimensions. To overcome this feature, the bearing locations were also measured with a dial snap meter (DSM) and a coordinate measuring machine (CMM). The snap meter measurement measures the distance between two planes, however, by rotating the camshaft and –if a non-constant value is detected – by taking the average value, it can be applied to the entire circle. The mean value of the diameter measurement of the 5 bearing locations with a snap meter and the mean value of the coordinate measuring machine measurement were considered as the base size. The uncertainty of the snap meter measurement is less than $1\text{ }\mu\text{m}$, while that of the coordinate measuring machine is less than $0.3\text{ }\mu\text{m}$. The difference between the mean diameters according to the two types of measurements is $2\text{ }\mu\text{m}$. The base value was taken as the average of the DSM and CMM measurements. The deviation of the average of the 5 radii measured by the roundness measuring equipment from this base value gives the radius difference, which has to be used as a correction for the values measured by the roundness measuring equipment to obtain actual dimensions.

2.3 Measuring the 8 cams

The roundness measuring equipment measures cam profile in a more complex way compared to the radial bearings, as the cam profile lift height of the internal combustion engines of passenger cars does not fit into the inductive sensor's 2 to 4 mm measuring range. In cam measurements, the radial position of the inductive sensor is controlled by the signal of the inductive radial sensor. When measuring a circle, the radial sensor is fixed, however, when measuring a cam, it moves in the radial direction so that the inductive sensor always stays in the middle of the measuring range. The radial dimensions of the cam measurement are not given by the sensitive inductive sensor, but by the electronic length measuring system of the device, which has a large (300 mm) measuring range for determining the radial position of the sensor, with a far worse resolution ($\sim 1\text{ }\mu\text{m}$) than the inductive sensor.

3 Geometrical comparisons of the 8 cams

3.1 Comparison of individual measured profiles

Figure 7 shows the measured profiles of the 8 cams in a Cartesian and polar coordinate systems: the successive cams, controlling one cylinder each, are denoted by the same color, i.e., 1-2 (red), 3-4 (blue), 5-6 (green) and 7-8 (black). The starting point of the polar diagram is indicated by a blue dot, the direction of rotation is counter-clockwise. It can be seen that the 2 sets of 4 cams have two different sizes and shapes, and that the angular positions of the cams within each set differ by 90°. The 4 even numbered and 4 odd numbered cams are basically the same in terms of size and shape.

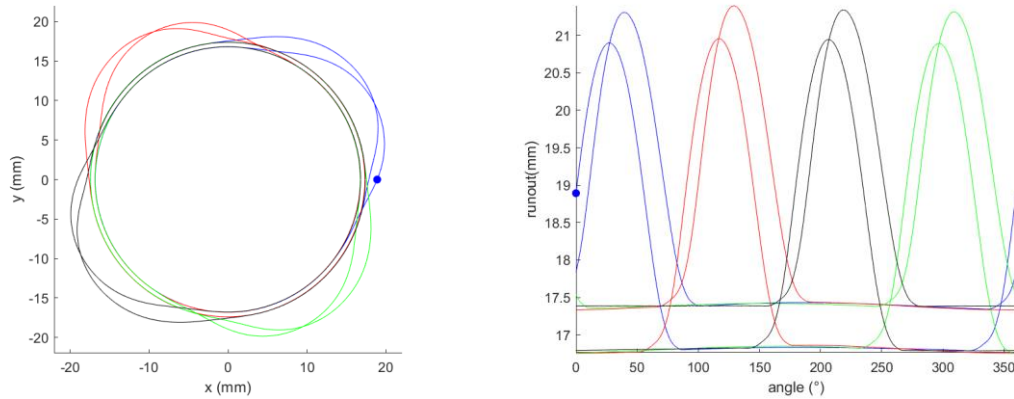


Fig. 7. The measured points of the 8 cams in Cartesian and polar coordinate systems

For the simplest geometric measurement comparison technique of the two types of cams, an example the odd and even numbered cams must be superimposed and compared. For this purpose Helmert transformation is used.

The Helmert transform is a geometrical transformation of a set of points using only one magnifying parameter beside the translation and rotation parameters. In two dimensions, the Helmert transform (X, Y) of a point (x, y) can be described by

$$\begin{pmatrix} X \\ Y \end{pmatrix} = \begin{pmatrix} C_x \\ C_y \end{pmatrix} + \mu \begin{pmatrix} \cos \phi & \sin \phi \\ -\sin \phi & \cos \phi \end{pmatrix} \cdot \begin{pmatrix} x \\ y \end{pmatrix},$$

where C_x, C_y are the translation vector components, μ is the scale factor and ϕ is the rotation angle. If at least 4 point pairs from two supposedly the same, but transformed profiles with coordinates (x_i, y_i) and (X_i, Y_i) are available, then the Helmert transformation parameters C_x, C_y, μ , and ϕ can be calculated, i.e., the profiles can be fitted to each other.

It is also possible to match profiles with little deviations compared to each other by the means of the smallest least square, and use the transformation in geometrical measurements [5].

Since cams 1 and 8 have the lowest eccentricity, the points of cam 8 are aligned to the points of cam 1. Figure 8 shows the fit of cam 8 to cam 1: rough fit red curve, fit made with Helmert transformation green curve. The second subplot contains the deviations of the points from cam 1 using the same color as the first subplot.

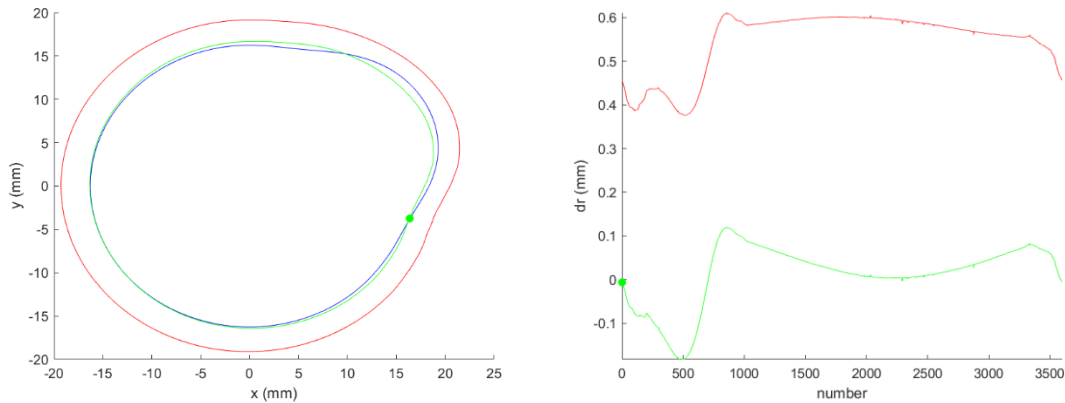


Fig. 8. Fitting of the 8th cam to the 1st cam

This fitting is not satisfactory because there is an unreasonably large deviation of nearly $100\text{ }\mu\text{m}$ in the base circle section of the cams, while it is known from a structural and manufacturing point of view that the base circle of the cam is circular with very high precision. The fitting is therefore not carried out simply by aiming for the minimum deviation according to all the cam points, but in two steps. First, the base circle section of the 8th cam is fitted to the base circle section of the 1st cam, then the 8th cam is rotated around the center of its base circle so that the deviation would be minimal on the cam part as well.

Figure 9 shows the fitting of cam 8 to cam 1, in terms of size and eccentricity based on the base circle runout profiles, i.e., only in terms of the angular positions corresponding to the base circle. When fitting according to the base circle, the fitted cam is smaller than when fitting according to all points.

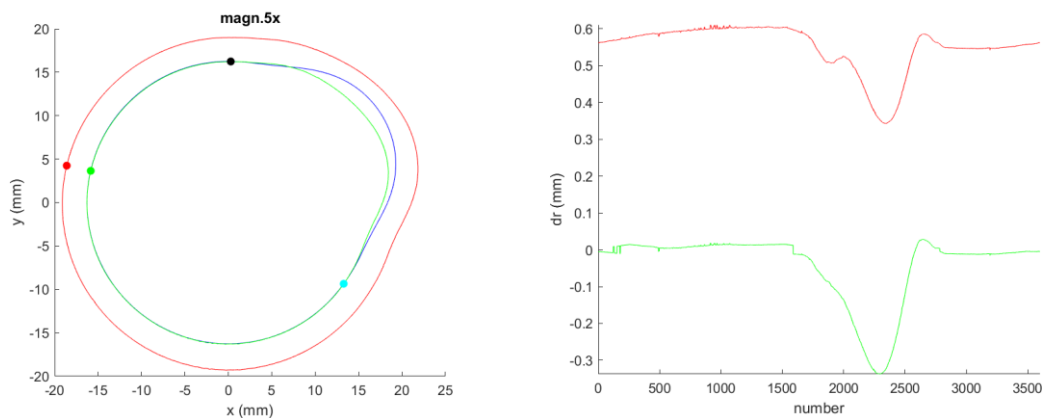


Fig. 9. Matching cam 8 to cam 1 based on the basic circle profile

3.2 Calculating averaged, ideal profiles

We also take advantage of the fact that 4 of both cams are available. We fit the 3rd, 5th and 7th cams onto the first cam according to the base circle, and from these points we determine an approximate cam profile for the odd cams.

When determining the approximate cam profile from the points of the 4 measured cams, we use the property of these cams that, in addition to the base circle, the cam itself can be approximated with a lifting, a peak, and a lowering circle. Shan Lin and his colleagues comprehensively dealt with cams by fitting 4 circular arcs to the cam profile [6], too.

When determining the derived, average cam profile from the points of the 4 measured cams, we make use of that property of these cams that they can be approximated by 4 circle segments, namely, in addition to the base circle, a lifting, a tip and a sinking circle. Of these 4 circular arcs, the base circle does not take part in the control of the functionality of the valves, but the other 3 arcs influence the mechanical and heat losses in the working cycle of the cylinder [7].

Figure 10 shows that the smallest deviations from the circle that occur in the base circle area, here the circular shape error is less than 0.01 mm, and there is a position error of 0.01 mm, in the lifting, tip and sinking sections there are circular deviations of 0.04 to 0.08 mm.

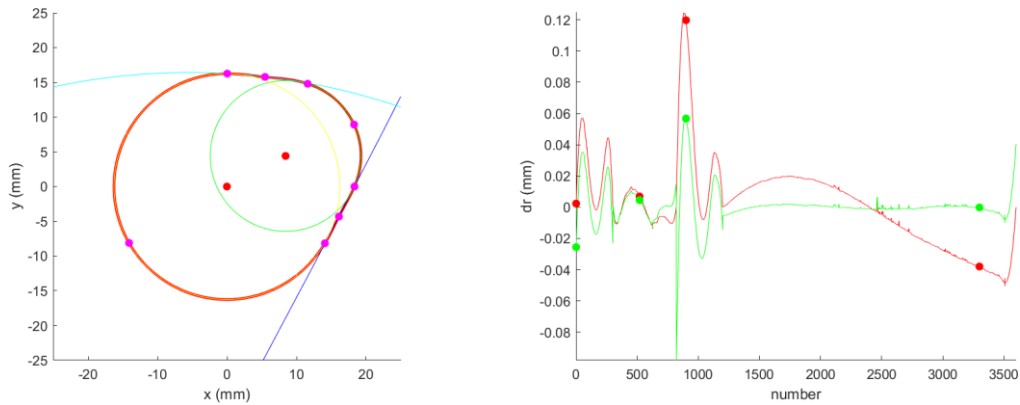


Fig. 10: The 4 circles that approximate the profile of the 1st cam and the deviations of the cam points from the approximation circles

A derived, average cam profile is determined from the 4 superimposed cam profiles by dividing the resulting point cloud into 4 sections based on the 4 circular areas: base circle, elevation, tip and sink. These sections are divided into equal angular sections in all 4 circle segment areas in such a way that almost the same number of points from the 4 cams would fall into each section. The points of the derived, average cam are determined for each of these angular sections by calculating the center of gravity of the 4 cam points that fall into them. Figure 14 shows the deviations of the original, superimposed cam points from the derived cam profile of the 4 odd-numbered cams at 100 $\times$ magnification. On the base circle section, the deviations of the points are less than $\pm 5 \mu\text{m}$ and on the other sections they fall into the -20 to $+25 \mu\text{m}$ domain.

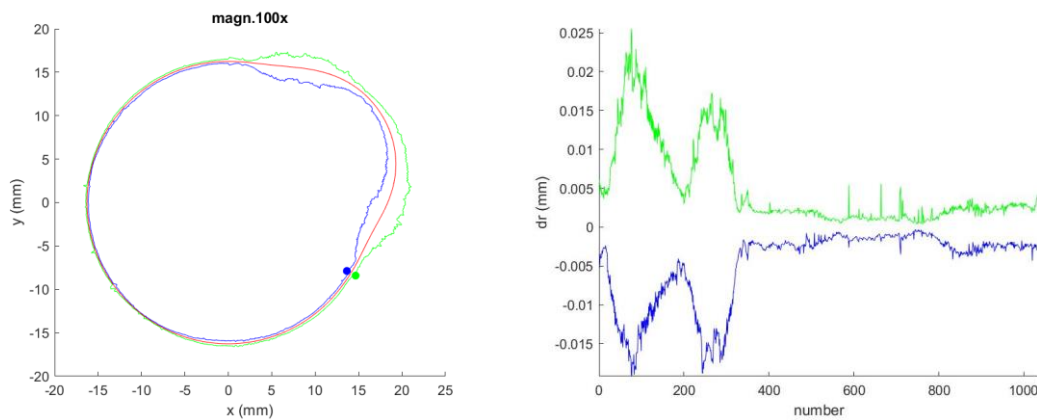


Fig. 11: The deviation of the points of the 4 odd-numbered cams from the derived, average cam

To determine the profile of the derived, average cam, a total of 1032 angular sections were created evenly for each section, with the points of the 4 cams ranging between 11 and 16 according to Figure 12.

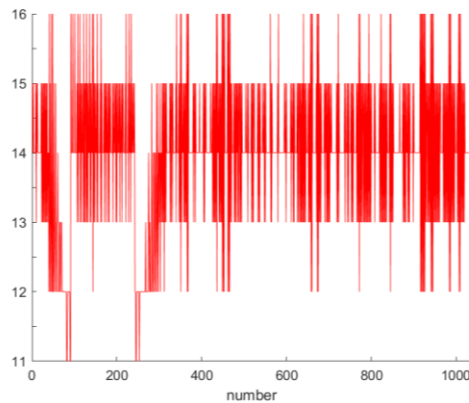


Fig. 12: The number of profile points of the 4 odd-numbered cams that fall into 1032 angle sections

In the same way, the derived cam profile of the 4 even numbered cams were determined.

3.3 Comparison of averaged, ideal profiles

The two derived, average cam profiles can be compared by fitting them primarily according to their base circle and secondarily according to the other profile parts, similarly to the method described in Section 3.1, which is shown in Figure 13, where the green and black points are the starting and ending points of the base circle.

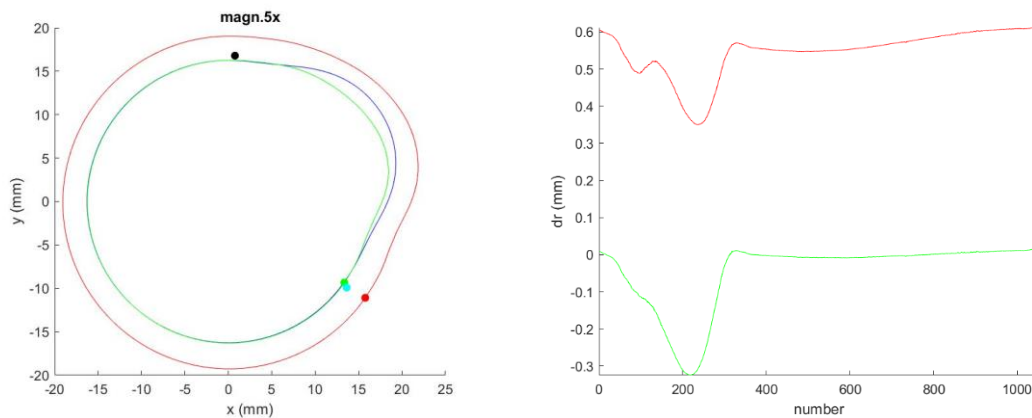


Fig. 13: Comparison of the two derived, average cam profiles adjusted according to the base circles

The deviations of the average cam profiles on the base circle sections are less than $\pm 5 \mu\text{m}$. In the other segments there is no major difference compared to the original comparison 8 to 1, from the one in Section 3.1 ($-35 \mu\text{m}$), but the result of the comparison of the two cam types is much clearer both metrologically and functionally and therefore less uncertain.

The size of the 2nd derived cam profile is 1.111 mm larger than the 1st derived cam profile in relation to the base circle diameter.

The shape deviations of the derived, average cams are $\pm 5 \mu\text{m}$ in the base circle section, while in the other sections the profile of the 2nd derived cam runs below the profile of the 1st, the largest deviation is $-32 \mu\text{m}$ (the cam lift height is $\sim 4 \text{ mm}$), the opening and closing points of the valve are the same, but the 2nd derived, average cam opens the valve slightly less.

The position deviation of the derived cams results from the position deviation of the underlying 1st and 8th cams. The position deviation of the 2nd derived cam from the 1st derived cam is due to the offset of the base circle centers, which is $-13 \mu\text{m}$ in the x direction and $-5.8 \mu\text{m}$ in the y direction, which means an eccentricity of $14.3 \mu\text{m}$ with an angular position of 204.2° . On the other hand, the angular position of the 2nd derived cam compared to the 1st derived cam is 167.03° , which means that the angular position of the intake and exhaust cams belonging to the same cylinder is $180 - 167.03 = 12.97$, i.e. $\sim 13^\circ$.

CONCLUSION

For the described methods (calibration, profile fitting, determination of size, shape and position), the manufacturers of measuring instruments provide their customers with effective procedures for which they provide as much information as is necessary for use. With an individual initiative, the use of measuring devices can be made more professionally aware, the measurement results can be better utilized, more information can be obtained from them, and the usability can be extended. With the described procedures, we reached the measurement of the cam and the determination of the average cam profiles from the measurement profile points. In the course of further work, based on the average cam profile, it would be possible to determine a profile that, based on the first derivative of the lift curve, the speed curve, and the second derivative, the acceleration curve, results in a cam profile that also meets the construction criteria.

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