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Aspects of using correlation calculus in comparative measurements of geometric deviations and shape profiles of main crankshaft bearing journals

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Abstract

This article discusses possible applications of correlation calculus as a universal tool enabling verification of a procedure for correct selection of elastic support system. Such system is used in measurements values of roundness deviations of main crankshaft bearing journals and assessment of shape correctness of measured roundness profiles. These profiles can be mathematically represented as a sum of terms of a Fourier trigonometric series.

Introduction

Measured profiles and deviations can be assessed quantitatively or qualitatively. The quantitative assessment consists in determining the value of a specifically defined parameter – a measure of deviation from the ideal profile. In case of roundness profiles, roundness deviation is the basic criterion of assessment. The method for determining this deviation depends on the reference element assumed as ideal, in this case reference circle (LSC, MCC, MIC, MZC). This parameter is particularly useful when determining shape deviations of regular profiles. In practice, actual profiles are irregular to a lesser or greater degree. For this reason other parameters are also used for quantitative assessment of shape deviations. Those other parameters are related to the amplitude of the actual profile course (amplitude-related parameters), or related to the speed of vibrations of the moving measuring instrument tip (dynamic parameters). Apart from the mentioned groups of parameters that may prove insufficient in describing the profile geometric condition, other parameters have been proposed, determined in accordance with the reference circle direction and parameters connected with the shape of irregularities of the measured profile [1].

As research shows, the degree of correlation between particular parameters is much varied [1]. Because of this, the use of these parameters as a measure unequivocally determining the degree of correlation between roundness profile measurements carried out by two different methods may also be insufficient.

Correlation calculus offers wide possibilities to overcome such difficulties. Both, quantitative and qualitative, assessment is in this case possible.

Examples of correlation calculus used in profile measurements

The idea to use correlation calculus for comparative assessment of roundness profiles performed by various methods is proposed and described in the studies [2, 3, 4, 5]. The concept includes the intercorrelation function for the comparison of measured profiles. The function is written in this form:

$$\rho(\gamma) = \frac{2\int_0^{2\pi} r_1(\varphi) r_2(\varphi+\gamma)\,\mathrm{d}\varphi}{\int_0^{2\pi} r_1(\varphi)^2\,\mathrm{d}\varphi + \int_0^{2\pi} r_2(\varphi)^2\,\mathrm{d}\varphi} \qquad (1)$$

The function was standardized so that:

$$-1 \le \rho(\gamma) \le 1 \qquad (2)$$

As a result, the determined value of argument γ^*, for which the intercorrelation function assumes a maximum, corresponds to a phase shift between the compared profiles and the maximum value of intercorrelation functions. The maximum value of the intercorrelation function can be taken as a value of reciprocal correlation coefficient. This procedure was applied to verify the correctness of establishing conditions for the so called elastic support of a crankshaft whose end journals were based in V-blocks (Fig. 1) [6]. Research was done by measuring roundness profiles of crankshaft journals for various support conditions provided by two different measurement systems. Apart from the measurement system with elastic shaft supports, the reference system comprised a MUK 25÷600 head and SAJD software, developed at the Department of Manufacturing and Measurement Processes, Kielce University of Technology. Measurements including a reference system were not dependent on shaft support conditions because the measuring head was set directly on examined journals.

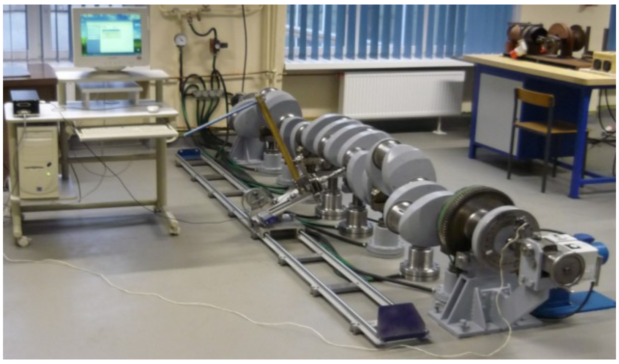


Fig. 1. A test bed for geometrical deviation measurements of crankshafts, equipped with a system of shaft elastic support

Research were performed by variation in crankshaft support condition. Changes in support conditions were made through variation in forces generation by a system of lightening supports. The function of lightening supports was to eliminate elastic deformations of the shaft due to its own weight. The measurement results showed that the forces were correctly selected in supports that satisfied assumed support criteria. These criteria, corresponding to the optimum support variant, ensured minimum deflections at the journals and permanent contact of main end journals with the V-blocks. The value of intercorrelation coefficient for measured journals determined for this variant ranged from 0.8695 to 0.9399 (Table 1), which according to J.P.Guilford's [7] assessment scale of correlation indicates high or very high correlation between the compared profiles.

Table 1. Values of roundness deviations of main bearing journals of the measured crankshaft, measured by the examined system Δ_z and reference system Δ_w, and values of intercorrelation coefficients for the compared profiles ρ

Journal number	Roundness deviation Δ_z	Roundness deviation Δ_w	Intercorrelation coefficient ρ
1	26.100	23.341	0.8989
2	31.158	30.241	0.8754
3	31.394	29.158	0.9056
4	56.053	54.207	0.9165
5	30.098	28.419	0.9126
6	41.145	39.463	0.8968
7	43.671	42.038	0.9399
8	24.116	24.154	0.8893
9	35.774	32.651	0.8695
10	43.418	44.272	0.9106

According to this assessment scale, the degree of interrelation between the examined properties is significant or very high. Any change in support conditions, comparing to the optimum variant, results in a substantial increase in deflections at the journals, and a simultaneous decrease in the value of intercorrelation coefficient. The determined phase shift value allows to present the superimposed roundness profiles and to evaluate visually the similarity of the measure examined to the reference profiles, at each stage of the verification of shaft support correctness (Fig. 2).

It is known that any roundness profile can be represented as a sum of Fourier trigonometric series terms, i.e. a finite cosine or sine transform. Therefore, any roundness profile can be represented as a discrete amplitude spectrum by determining the amplitudes and phase shifts of each harmonic. Such analysis allows to evaluate the influence of individual harmonics on the shape of measured profile.

The harmonic components of the measured profiles were compared by using the principles of reciprocal correlation calculus. Pearson's linear correlation coefficient was a measure of correlation between the compared harmonics:

$$r = \frac{\sum_{i=1}^{n}\left(Cx_{ni} - \overline{Cx}_n\right)\left(Cy_{ni} - \overline{Cy}_n\right)}{\sqrt{\sum_{i=1}^{n}\left(Cx_{ni} - \overline{Cx}_n\right)^2 \sum_{i=1}^{n}\left(Cy_{ni} - \overline{Cy}_n\right)^2}} \tag{3}$$

where:

Cx_{ni} – value of harmonic amplitude of a measured crankshaft i-th journal profile;

Cy_{ni} – value of harmonic amplitude of the reference i-th journal profile;

$\overline{Cx}_n$ – mean value of harmonic amplitude of a measured profile;

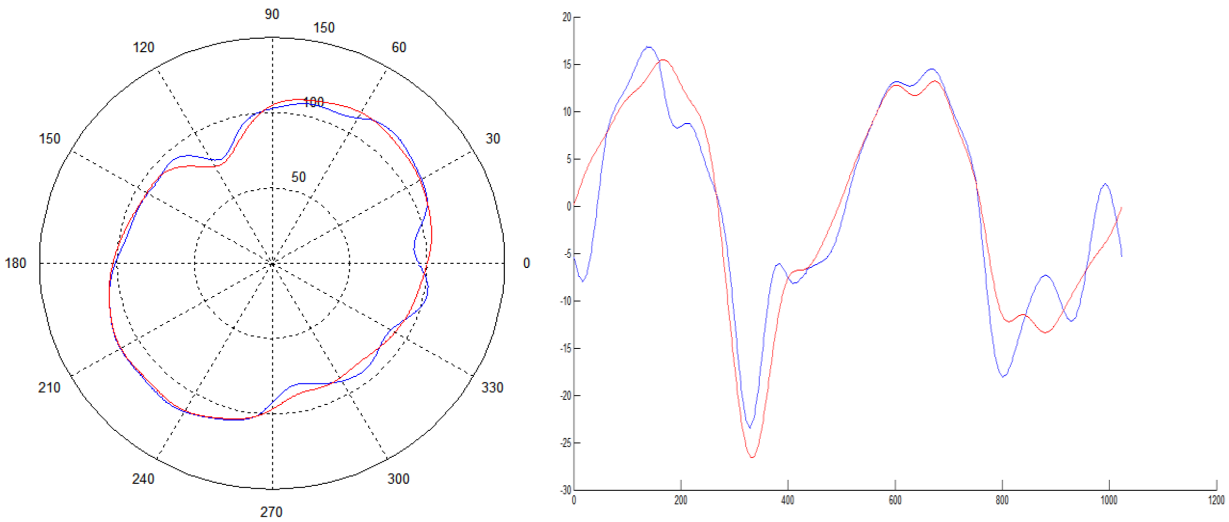


Fig. 2. Superimposed profiles, accounting for the phase shift γ*, measured transformed (color blue) and reference transformed profiles (color red) presented in the polar and Cartesian systems

$\overline{Cy}_n$ – mean value of harmonic amplitude of the reference profile.

Correlation calculations were verified using a significance test of the correlation coefficient at the level $\alpha = 0.05$ by assuming the hypothesis: no correlation – H_0: $r = 0$ relative to the alternative hypothesis: correlation exists – H_1: $r \neq 0$, using for this purpose the statistics:

$$t = \frac{r}{\sqrt{1-r^2}}\sqrt{n-2} \tag{4}$$

where: r – estimated correlation coefficient, n – sample size.

Calculated Pearson's coefficients defining the degree of correlation between the values of amplitudes and phase shifts of each harmonic of the compared crankshaft roundness profiles are given in tables 2 and 3.

From the harmonics comparison viewpoint, essential correlation coefficient values in tables 2 and 3 are these corresponding to diagonal elements of correlation matrix. These elements correspond to the correlation coefficients between amplitudes and phase shifts with the same harmonic numbers.

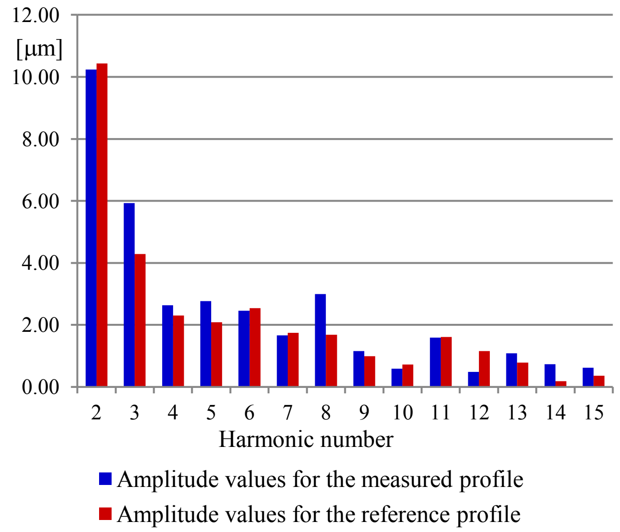
The calculations have shown that in most cases there is high or very high correlation between amplitudes of relevant harmonics (particularly the dominating amplitudes and these decisive for the profile shape, i.e. harmonics in the range $n = 2 \div 10$). For some harmonics only, $n = 14$, 15, the correlation is moderate. However, we may assume that the impact of these harmonics on the profile shape is slight. The determined coefficient values also show which component harmonics and to what extent affect the difference in the shape of compared profiles. This is confirmed by charts of the amplitude spectra. One chosen case is presented in figure 3.

Table 2. Pearson's coefficient values for harmonics amplitudes of compared roundness profiles

Harm.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.
2.	0.9601	–0.0922	0.1846	0.1657	0.1925	0.1561	–0.0364	–0.0369	–0.1220	–0.1260	–0.1978	–0.2793	0.0690	–0.0419
3.	–0.0384	0.9732	0.0776	0.5416	0.0789	0.1659	0.5993	0.3450	0.5040	0.2800	0.3382	0.0154	–0.0313	0.0741
4.	0.1012	0.7095	0.7359	0.4757	0.1967	0.4578	0.4049	0.6359	0.4918	0.1048	0.2453	–0.2139	–0.1602	–0.1433
5.	0.1258	0.6390	–0.0742	0.9734	0.1756	0.3116	0.7176	0.2696	0.4513	0.0587	0.1122	–0.3535	0.2661	0.2492
6.	0.0747	0.1609	0.2324	0.4007	0.8675	0.6865	0.6614	0.3292	0.3207	0.3185	0.1020	–0.3286	–0.1185	–0.0702
7.	0.0550	0.0872	0.2033	0.2167	0.6648	0.9136	0.3000	0.5801	0.2591	0.1474	0.1263	–0.3083	–0.2128	–0.0245
8.	0.0124	0.1197	0.0333	0.2813	0.0057	0.0766	0.7333	0.2729	0.3248	–0.0147	0.0204	–0.1492	0.1191	–0.0369
9.	0.0115	0.0305	0.0212	0.0841	–0.0056	0.5569	0.0708	0.6074	0.2250	–0.1668	0.0223	–0.1444	0.0365	0.0703
10.	–0.0203	0.0577	0.0418	–0.0086	–0.2824	–0.1626	0.0923	0.5575	0.6962	–0.0448	0.2387	0.0562	–0.0014	–0.2438
11.	–0.0242	0.0678	0.0045	–0.0005	0.1779	0.0344	0.2870	0.1189	0.4733	0.9305	0.7286	0.4852	–0.4163	0.0306
12.	–0.0077	0.0277	0.0035	0.0028	0.1428	0.1948	0.1154	0.1169	0.2268	0.8350	0.8489	0.4255	–0.5390	0.2556
13.	–0.0077	–0.0061	–0.0181	–0.0264	0.0761	0.0459	0.0185	–0.0654	–0.0500	0.3725	0.3405	0.7074	–0.5792	0.4485
14.	0.0103	–0.0141	–0.0284	0.0298	–0.0018	0.0349	–0.0306	–0.0919	–0.1629	–0.2397	–0.2833	–0.4617	0.5175	0.5310
15.	0.0051	0.0093	0.0014	0.0231	0.0793	0.0846	0.0448	0.0027	0.0157	0.1609	0.1317	0.0373	–0.2697	0.5692

Table 3. Pearson's coefficient values for harmonics phase shifts of compared roundness profiles

Harm.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.
2.	0.9918	0.5726	–0.2505	0.2948	0.2002	0.2148	0.2148	–0.4048	–0.2059	–0.1431	0.0971	–0.2551	–0.3485	0.0456
3.	0.4593	0.9052	0.5562	0.4321	0.5758	0.7948	0.1428	0.0912	0.3592	0.0779	0.0488	–0.3178	0.1231	0.5140
4.	0.0996	0.4184	0.9351	0.5324	0.6485	0.6708	–0.0372	0.2278	0.7318	0.2143	–0.0907	–0.1481	0.3065	0.2708
5.	0.2402	0.1830	0.3210	0.8021	0.7857	0.0819	0.2871	0.1272	0.1095	0.0907	0.0066	–0.0090	0.5958	0.0579
6.	–0.1184	0.3453	0.8076	0.7564	0.9147	0.3810	0.1589	0.4613	0.5692	0.3331	–0.1405	–0.0746	0.7062	0.2308
7.	0.4001	0.8482	0.6082	0.3328	0.5603	0.8628	0.1617	0.1668	0.4007	0.0892	0.0841	–0.2972	0.0886	0.6312
8.	0.3981	0.6632	0.0902	0.5348	0.5518	0.2770	0.9139	0.5461	–0.2394	0.5667	–0.0501	–0.4166	0.3948	0.5946
9.	–0.4742	–0.0262	0.5641	0.2549	0.2604	0.4158	0.3150	0.8365	0.4413	0.7322	–0.4621	–0.3578	0.3545	0.5591
10.	0.3391	0.3180	0.5854	0.4580	0.4590	0.6476	–0.0585	–0.0376	0.8745	0.2365	–0.1933	–0.3284	–0.2432	0.2196
11.	0.1722	0.2679	0.0793	0.3387	0.0970	0.4715	0.6234	0.3736	0.2146	0.9113	–0.3297	–0.6467	–0.1646	0.4414
12.	–0.0390	–0.0554	–0.0173	–0.1111	–0.0065	–0.1661	–0.1178	–0.0838	–0.0973	–0.2624	0.9576	0.4946	0.0763	–0.1594
13.	–0.1941	–0.5110	0.0123	–0.0264	–0.0348	–0.5042	–0.3188	–0.2190	–0.0246	–0.3254	0.1243	0.7537	0.1721	–0.8372
14.	–0.3982	–0.3319	–0.4509	–0.2741	–0.2375	–0.7672	0.1499	0.2285	–0.7981	–0.1649	0.2774	0.4618	0.4880	–0.2300
15.	0.0531	0.4243	0.3988	0.0446	0.1801	0.8340	0.2641	0.3861	0.3910	0.4159	–0.2184	–0.5967	–0.1518	0.8949



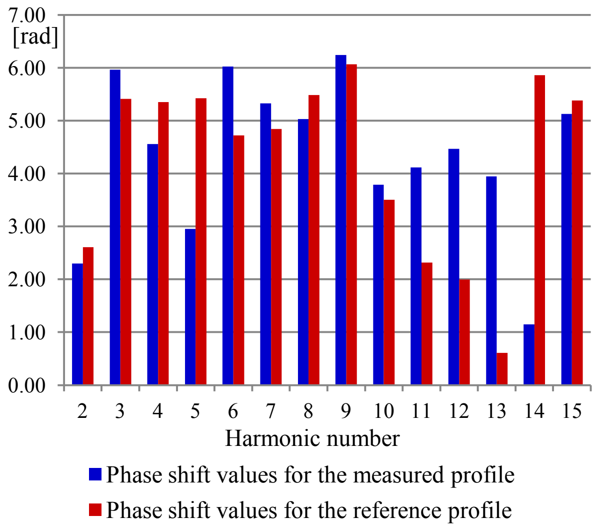


Fig. 3. Amplitude spectra charts for journal no. 2, including harmonics $n = 2 \div 15$, measurements using the shaft elastic supports system and the reference system

Conclusions

The measurement test results lead to a conclusion that the proposed system of shaft elastic supports effectively minimizes elastic deflection of the measured object. The values of intercorrelation coefficients obtained for the case of shaft support satisfying optimum conditions show a high correlation between the measured and reference profiles, which is also true for the values of Pearson's coefficients defining the degree of correlation between the harmonics of the measured profiles. As a result, the conclusion can be made that the values of geometric deviations obtained from measurements via the proposed system are correctly determined values.

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