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Simulation tests and measurements of crankshaft deformations by the symmetric method

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Abstract
The crankshaft is liable to deformation due to inaccurate positioning of its main journals in the bearings. This article presents results of simulated tests of such deformations. The test results and methods for the verification of crankshaft mounting in the main bearings are assessed. A new method of measurement of crankweb deformations is proposed, the so called symmetric method, that allows the correct assessment of the condition of the crankshaft mounting in the bearings.

Introduction

Crankshafts are essential components of the crank-piston engine system. Although medium- and slow-speed marine engine crankshafts have large mass and dimensions, plus a complex form, they are slender elements liable to flexural deformations. Such shafts are characterized by small cross-sectional areas relative to their length, and have additional features that distinguish them from straight shafts. Surface areas in many cross-sections perpendicular to the main axis differ, and their centres of gravity lie in various directions and at various distances relative to the crankshaft axis. For these reasons, deflections of shafts supported on main journals vitally depend on how accurately they are mounted in the engine block. Those accuracies affect the performance of the crank-piston system, and consequently, the whole working machine. It is therefore necessary to regularly examine the geometric shape of crankshafts at the manufacturing stage, and the quality of mounting in the bearings during assembly and later in service. Problems relating to the measurement of components of large machines are somewhat neglected in the metrology of geometrical parameters. This branch of metrology focuses on measurements of elements of small size, for which it is *a priori* assumed that deformations under their own weight are slight, and do not depend on supporting conditions. This contention refers specifically to workshop measurements. Marine engine manufacturers have developed and used procedures of crankshaft control, which generally make use of universal measuring equipment (Łukomski, 1972). The use of these procedures may be inadequate in terms of required accuracy and the correct assessment of the geometry of a measured object (Wärtsilä, 1998; Specification of engine MAN B&W, 2010).

Measurements of crankshaft bearing errors

Inaccuracy at the manufacturing stage, as well as in the bearing mounting of crankshafts, results in elastic deformations that vary in sign and value due to changes in shaft stiffness during rotation. Since direct measurement of shaft deformations is problematic, indirect measurement methods are frequently used for this purpose (Łukomski, 1972; Piaseczny, 1992). One common method for assessing the mounting of crankshafts is the measurement of crankweb angles performed at specific angular positions of the rotated crankshaft. This measurement, referred to as the measurement of springing, is carried out by means of a displacement gauge set between shaft cranks. The gauge, in housing via centre points, is fixed in spots drilled by the shaft maker on internal surfaces on the cranks.

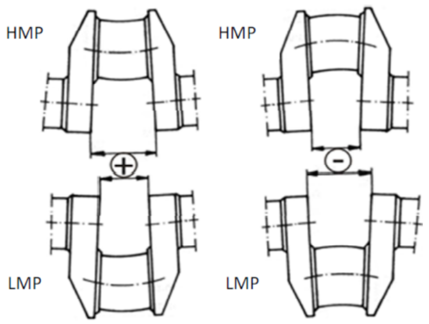

Figure 1. Examples of various shaft crank deformation conditions

The measure of springing, principally determined in the horizontal and vertical planes, is assumed to be the difference of gauge readouts at two extreme opposite positions of the cranks during shaft rotation (Figure 1). For the vertical plane, the two positions are referred to as HMP (*high maximum position*) and LMP (*low maximum position*). For the horizontal plane, the two extreme positions are denoted as SS (*starboard side)* and PS (*port side*).

The basic assumption in this type of measurement is that crankweb deformation is symmetric to the axis of crank symmetry. This assumption results from the conditions and method of measurements. As a consequence, the interpretation of springing measurement results leads to a recommendation, if the acceptable springing values are exceeded, that the axis of main bearings adjacent to the crank should be lowered or raised by half of the measured springing value. Note that in such measurements there is no permanent measurement base, as the base moves uncontrolled during the measuring process. This interpretation fails to ascertain whether or not deformation may be due to the deteriorated condition of one bearing adjacent to the crank. It is also hard to interpret how the measured springing value is affected by the interaction of adjacent cranks deformed to varying degrees. Consequently, the results of measurements are frequently misinterpreted.

Simulation tests

The preceding remarks provide a basis for performing simulation tests of crankshaft deformations, in which possible inaccuracies in the mounting of shaft main journals in bearings are introduced. The tests were carried out using Nastran FX 2010, a program for strength computations. The examined object, the crankshaft of a medium-speed marine engine, was modeled by means of 136,303 finite elements. The model was used to examine shaft deformations caused by inaccurate bearing mounting. Figures 2 through 6 illustrate possible deviations of relative axis positioning in the analysis, and the resulting elastic deformations of cranks and journals, which are illustrated along with a part of the modeled crankshaft. The assumed deviations are special cases that may have a spatial distribution, while these considerations refer to the vertical plane. Nevertheless, the examples correspond to possible, typical deviations of the crankshaft main journal axes' relative positions, known as misalignment and non-parallelism (PKN, 2006).

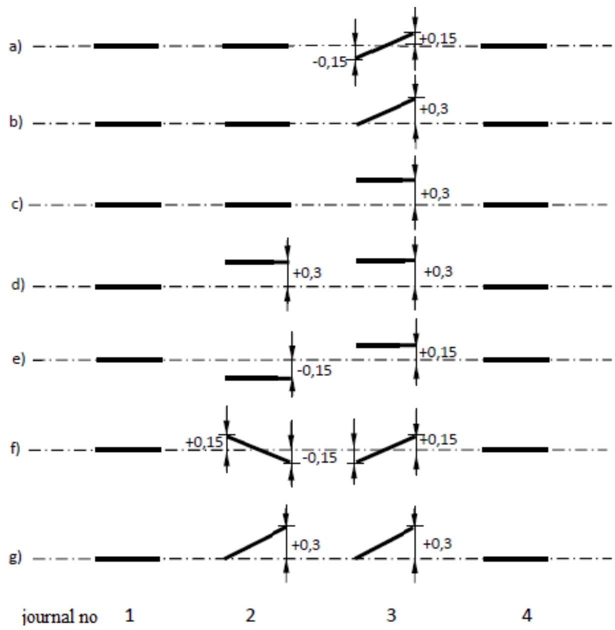

Figure 2. Graphic interpretation of geometric deviations of main journal axes assumed for the analysis of crankshaft elastic deformations

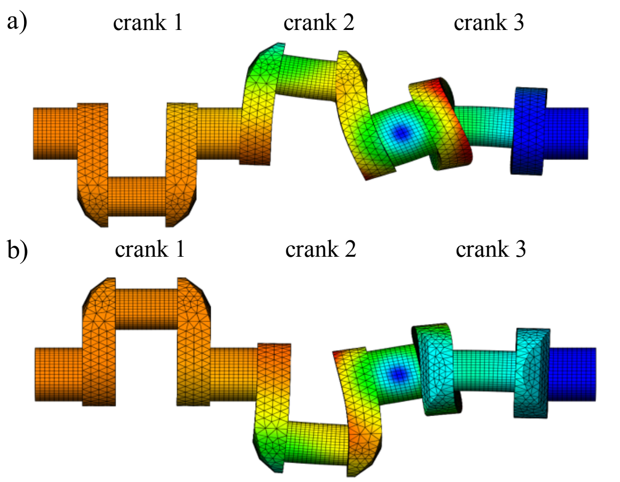

Figure 3. Deformations of a crankshaft part after the introduction of geometric deviations of main journal axes shown in Figure 2a – crank 2 at two positions a) HMP, b) LMP

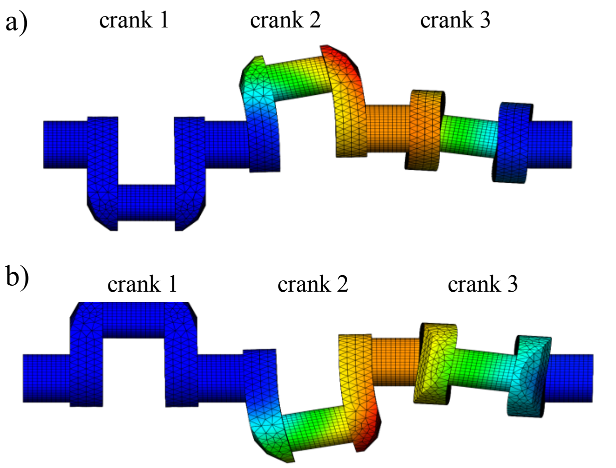

Figure 4. Deformations of a crankshaft part after the introduction of geometric deviations of main journal axes shown in Figure 2c – crank 2 at two positions a) HMP, b) LMP

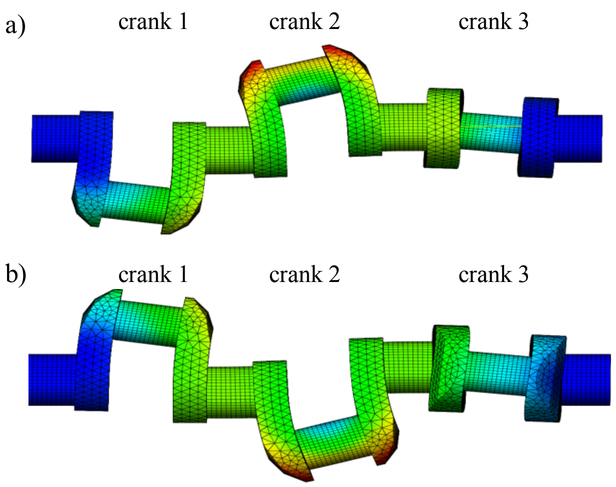

Figure 5. Deformations of a crankshaft part after introducing geometric deviations of main journal axes shown in Figure 2e – crank 2 at two positions a) HMP, b) LMP

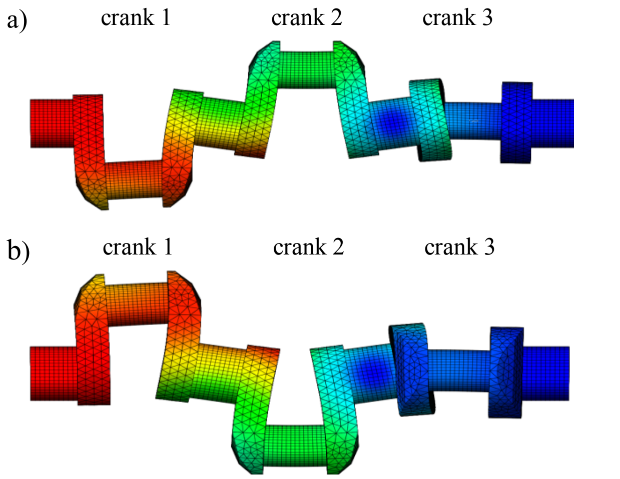

Figure 6. Deformations of a crankshaft part after introduction of geometric deviations of main journal axes shown in Figure 2f – crank 2 at positions a) HMP, b) LMP

Table 1 presents the values of crank deformations for the assumed deviations of axis position. It also contains calculated values of springing determined as the difference of crankwebs widening at HMP and LMP for the vertical plane, and SS and PS for the horizontal plane.

Test results assessment

An analysis of the presented test results leads to the observation that even a substantial displacement of a journal axis (assumed 0.3 mm) corresponds to a slight measurable value of shaft springing. On the other hand, essential differences of measurable crank deformations occur in case of symmetric or non-symmetric axis skewing. This regularity occurs regardless of the deviations: whether they refer to changed position of only one journal axis

Table 1. Simulated values of crankweb deformations and springing Δ for the assumed deviations of main journal axes positions

		Vertical plane [mm]			Horizontal plane [mm]		
		HMP	LMP	Δ_{vert}	SS	PS	Δ_{horiz}
Symmetric skewing of journal No. 3 axis ± 0.15 mm (Figure 2a)	crank 2	132.4556	131.5448	+0.9108	132.0041	131.9965	+0.0076
	crank 3	131.5442	132.4563	–0.9121	131.5472	132.4577	–0.9150
One-sided skewing of journal No. 3 axis + 0.3 mm (Figure 2b)	crank 2	132.4499	131.5501	+0.8998	132.0028	131.9974	+0.0054
	crank 3	131.5389	132.4622	–0.9233	131.5380	132.4630	–0.9250
Displacement of journal No. 3 axis + 0.3 mm (Figure 2c)	crank 2	131.9893	132.0113	–0.0220	131.9982	132.0024	–0.0042
	crank 3	131.9890	132.0115	–0.0225	131.9902	132.0129	–0.0277
One-sided skewing of journals' No. 2 and 3 axes + 0.3 mm (Figure 2d)	crank 2	132.9372	131.0628	+0.8744	131.9995	132.0004	–0.0009
	crank 3	131.5266	132.4739	–0.0527	132.0116	131.9889	+0.0227
Displacement of journals' No. 2 and 3 axes + 0.3 mm (Figure 2e)	crank 2	131.9553	132.0447	–0.0894	131.9984	132.0022	–0.0038
	crank 3	132.0115	131.9888	+0.0227	131.9848	132.0158	–0.0310
Displacement of journal No. 2 axis – 0.15 mm and journal No. 3 axis + 0.15 mm (Figure 2f)	crank 2	132.0006	131.9988	+0.0008	132.0003	131.9996	+0.0007
	crank 3	131.9843	132.0157	–0.0314	131.5266	132.4739	–0.9473
Parallel skewing of journals' No. 2 and 3 axes +0.3 mm (Figure 2g)	crank 2	131.9749	132.0268	–0.0519	132.0083	131.9944	+0.0139
	crank 3	131.5648	132.4362	–0.8714	131.5648	132.4739	–0.9091

relative to the other journals, or mutual misalignment concerning all axes of the main journals. This analysis has also proved that due to varying stiffness and non-uniform distribution of the centers of gravity in subsequent cross-sections of the crankshaft, crankshafts are subject to flexural deformations as well as crankweb torsion (Nozdrzykowski, 2008; Nozdrzykowski & Hryniewicz, 2003; Nozdrzykowski & Kuźniewski, 2001). Therefore, the results indicate that the magnitude of crankweb widening measured at a given angular position of the shaft cannot be regarded as a geometric parameter situated in a vertical or horizontal plane, but spatially. This conclusion acquires additional meaning if we consider the fact that simulation tests have been performed for the assumed bearing errors in the vertical plane, while the test results have revealed crankweb deformations in both vertical and horizontal plane.

If we adopt the spatial system of dimensioning with the origin located at one of the points between which the crankweb widening is measured, this quantity can be described by three components defining its position in space. The values and sign of these components allow the unequivocal assessment of the positions of opposite cranks, and consequently, the positions of the axes of main journals adjacent to particular cranks. However, making such measurements is in fact very difficult. It requires the use of a measuring system enabling precise measurement of absolute values of three components of the measured distance of the cranks' widening. Bearing this in mind, the author proposes an improved version of shaft springing measurement, the so-called symmetric method. The method is a modification of the previously proposed method, which has the advantage of providing a constant measuring base. Measurements by the symmetric method may employ one or two displacement gauges set on a jib of the instrument mounted to the crank journal at its half-length (Figure 7). Changes in the readouts of the gauge during shaft rotation depict crankweb deformations relative to the crank symmetry axis for which the gauge is set.

For comparison, crankweb deformations were also measured by the traditional method and by the symmetric method, with changed shaft support conditions (Figure 8). To diversify the defor-

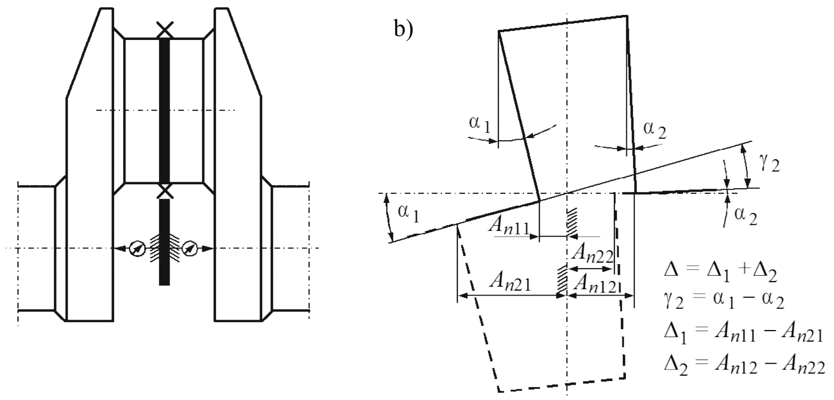

Figure 7. Measurement of shaft springing by the symmetric method (a), interpretation of the results (b)

a) b)

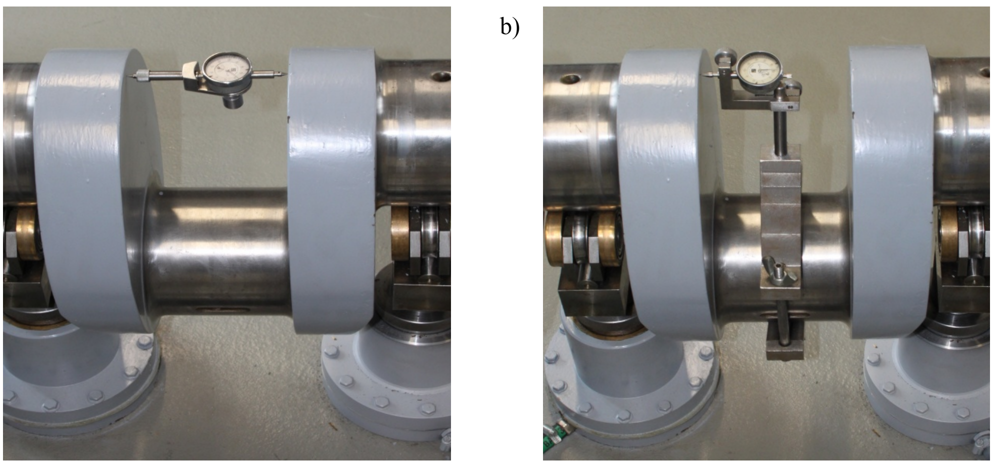

Figure 8. Measurements of shaft crank deformations by the traditional a) and symmetric methods b) at a test bed

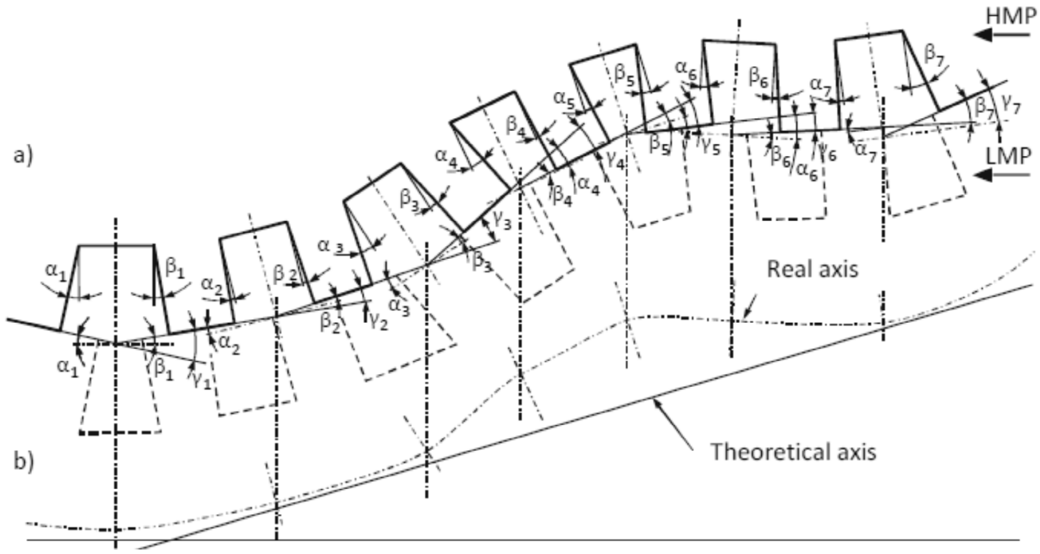

Figure 9. Geometric interpretation of crank deformation results obtained from measurements by the symmetric method

mations, the measurements were performed at a test bed equipped with special elastic supports that allowed shaft support conditions to vary. These conditions were changed by shifting the support points and changing the pressures in supporting air powered cylinders to vary the reaction forces applied by the supports. As the crankwebs may shift relative to each other, constant contact of the gauge plunger with the drilled spots on the internal surfaces of the crankwebs was maintained by fitting the with a spherical tip. It turned out that the measurement error due to the fact that the gauge was not adjusted to the bores between which springing was being measured was negligibly small, less than 1% of the measured magnitude.

The tests have confirmed that the proposed symmetric method of crankshaft springing measurements was used properly (Nozdrzykowski, 2013). The method offers two advantages: correct measurements of crankweb deformations caused by bearing mounting errors, and proper assessment of crankshaft positioning over the whole 360° range of its rotation. The measurement results permit the determination of the relative positions of the main journal axes and the line of shaft deflection. It also allows for correcting the distribution of shaft supports for measurements. In the case of a crankshaft mounting in the engine block, bearing positioning can be corrected to eliminate shaft deformations (Figure 9).

Conclusions

This analysis illustrated the complexity of problems relating to crankshaft deformations caused by bearing errors. Moreover, the analysis and test results showed that the proposed method of measurements and the interpretation of the results used in assessing crankshaft positioning may lead to improper correction of the main bearings. The proposed symmetric method for measuring crankweb deformations eliminates these shortcomings, and is practicable for correctly assessing of crankshaft positioning in the engine block.

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