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EFFECTIVENESS OF EVALUATION METHODS OF THE GEOMETRICAL CONDITION AND BEARING SUPPORT OF EXTRA-LARGE CRANKSHAFTS

Key words: crankshafts, evaluation methods, geometric condition, bearing support.

Abstract: The article presents an overview of known and used measurement methods on the basis of which the geometrical state of the design and bearing support of extra-large crankshafts is evaluated. These methods were evaluated both in terms of the correctness of their implementation and the interpretation of results. The article also presents a new concept of a device that permits the evaluation of the condition of the shaft bearing on the basis of measurements of the deformation of crank webs using the symmetrical method.

Efektywność metod oceny stanu geometrycznego i łożyskowania wielkogabarytowych wałów korbowych

Słowa kluczowe: wały korbowe, metody oceny, stan geometryczny, łożyskowanie.

Streszczenie: W artykule przedstawiono przegląd znanych i stosowanych metod pomiarów, w oparciu o które dokonuje się oceny stanu geometrycznego wykonania i łożyskowania wielkogabarytowych wałów korbowych. Dokonano oceny tych metod zarówno pod względem poprawności ich realizacji, jak i sposobu interpretacji wyników. Przedstawiono też nową koncepcję przyrządu umożliwiającego ocenę stanu łożyskowania wału na podstawie pomiarów odkształceń ramion wykorbień tzw. metodą symetryczną.

Introduction

In order to eliminate elastic deflections of extra-large machine components, especially flexible components of small cross-section dimensions relative to the length, such as crankshafts of marine engines, they must be provided with multi-point support. Maintenance of main bearings supporting a crankshaft in alignment within permissible deviation limits is a prerequisite for proper operation of the piston-crank system and the entire engine. Therefore, assessment of the crankshaft bearing support is a significant part of technical verification at the stage of manufacturing as well as at periodic inspections during the operation of the engine.

1. Methods of crankshaft bearing support assessment

Direct tests of the alignment of the main bearings of a crankshaft are troublesome. Therefore, indirect testing methods are applied, such as the slump test or the crank web deformation test, referred to as the “springing test.”

In order to carry out a slump test, covers of the main bearings must be dismounted. The test is performed with the use of a stencil. The slump is measured by the size of gap Δ between the protrusion of the stencil and the cylindrical surface of the crankshaft’s main journals (Fig. 1). Measurements are taken with a gap gauge. In more advanced solutions, the stencil may be equipped with a micrometre screw, which permits the measurement of the gap without the use of a gap gauge.

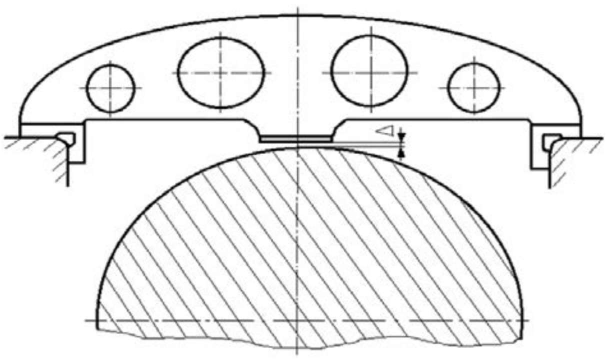

Fig. 1. Crankshaft slump test

The measurement base is provided by the lower surface of the protrusion, and indirectly by the division surfaces of main bearing housings on which the template is placed. In compliance with the recommendations [1], a slump test should be taken every time a crankshaft is set in a certain position, in order to get points of reference and compare the settings. However, to treat the results of a slump test as a criterion for the assessment of the condition of bearing support would be a simplification. The test results can be treated as approximate and local. Correct bearing support of the crankshaft is obtained with the bearings mounted. A single bearing should be understood as an assembly of the seat, the bushing, and the journal. Each of these elements has its own dimensions and deviations, and during the operation, the crankshaft bearing support condition depends on the degree of wear of each of them. Considering the characteristics of the slump test, it is done very rarely nowadays and mostly on older engines equipped with thick-walled bushings.

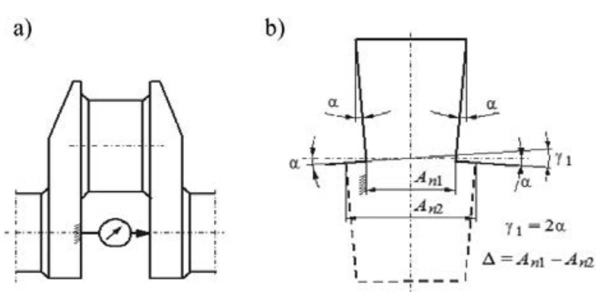

Fig. 2. Springing test by the traditional method (a), interpretation of test results (b)

Tests of crankshaft elastic strain are in common use. Springing tests are carried out while the crankshaft rotates, with the main bearings mounted (Fig. 2). The measure of springing, typically determined in the vertical and horizontal planes, is the difference between the readings of the displacement sensor mounted in a clamp between two cranks, in two opposite end positions of the cranks [1–4]. For the vertical plain, these positions are referred to as the top dead centre (TDC) and the bottom dead centre (BDC), and for the horizontal plane, they are the starboard (SB) and port (P). The basic assumption for this type of measurement is that strain of crank webs is symmetrical to the symmetry axis of the crank. The assumption follows from the testing method and conditions and affects the interpretation of the results. If the maximum permissible value of springing is exceeded, it is recommended to move the axes of the main bearings located next to a given crank up or down by a half of the measured springing value. It should be stressed here that the measurement base is not locked and moves in an uncontrollable way during the measurements. The fact that strain may be caused by a deteriorating condition of only one of the bearings next to a given crank is not taken into consideration. Moreover, it is difficult to assess how the reading of springing may be affected by the mutual reaction of cranks with a different degree of strain. These observations were confirmed by the results of simulation tests of crankshaft strain that were obtained after taking into consideration the possible inaccuracy of the bearing support of the main journals [5]. Additionally, the analysis showed that, due to variable stiffness and uneven distribution of the centres of mass in consecutive cross sections, the elastic strain of the crankshaft and the twisting of its crank webs were observed. Therefore, the test results show that the distance between the crank webs, measured in a certain angular position cannot be treated as a value in a vertical or horizontal plane, but rather as a value in space.

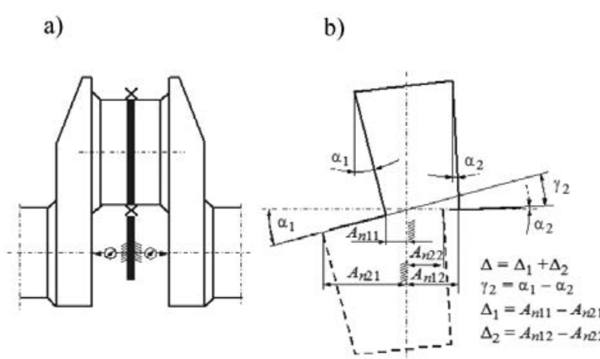

Fig. 3. Springing test by the symmetrical method – the sensor mounted on a crank pin (a), interpretation of the test results (b)

The proposed method of crank web strain tests (Fig. 3) [5, 6] permits the elimination of the many flaws of the traditional method. Among others, it eliminates the most significant flaw, which is the lack of a locked measurement base. However, in order to apply this method in operational conditions, the foot of the connecting rod must be dismounted, and the piston-crank system must be suspended in order to place the clamp of the measuring sensor mounted on the crank pin, which makes the test significantly more time-consuming.

2. New concept of crank web strain test by the symmetrical method

Based on the assumption that the workmanship of a crankshaft and its position in the main bearings can be assessed on the basis of the crankshaft strain, a new measurement system was developed. Applying the traditional method of mounting the gauge and measurement of springing, the system permits one to assess the strain of individual crank webs. The measurement base, similar to the traditional method, consists of a gauge set by means of locating pins in the (standard) punch marks on the inner parts of crank webs. However, owing to the fact that sensing pins of the gauge are equipped with caps, strain is assessed in the perpendicular direction to the measuring base. The caps, slid into place on the sensing pins, are pressed with a force of a fixed value against the inner face surfaces of crank webs. Strain is recorded continuously in the form of changes in the circumferential pressures on the face surfaces of the cap pads. The measurement is taken symmetrically in conditions equivalent to those in the traditional method. The cap pads, made of a material prone to elastic strain, have a sensitive membrane measuring surface pressures. Similar to the traditional method, a displacement sensor measures the aggregate value of crank web strain, while a collaborating circumferential pressure measurement system facilitates proportional quantitative distribution of the measured springing value between neighbouring crank webs.

The gauge, according to the concept [7] (Fig. 4a), has a body (1) to which the displacement sensor casing (2) is attached. The initial assumption is to apply a dial displacement sensor with an axial slide of the sensing pin (ultimately, a small inductive displacement sensor with an axial slide of the sensing pin will be applied, connected by wired or wireless connection to a digital display). The body (1) has a rigid pin (3). The sensing pin and the rigid pin (3), which are axially aligned, are equipped with spherical tips (4). The rigid pin (3) has a screw drive system (7) for adjusting its length. The screw drive system ensures initial tension of the sensor and simultaneously the time firm rest of the gauge, which is locked with the spherical tip pins, in the punch marks (provided by the crankshaft manufacturers) on the inner face surfaces of crank webs (Fig. 4b). Caps (9) with pressure pads (10) are slid onto the outer cylindrical surface of the rigid pin (3) and the handle part (8) of the displacement sensor (2). Handles (9a) of the pressure caps (9) facilitate the mounting and positioning of the gauge between crank webs. Face surfaces of the pressure pads (10) are equipped with pads (11) made of a material prone to flexible strain but resistant to permanent deformation. At their ends, they have a sensitive membrane (12) measuring surface pressures. Springs (13), which are set on a guide bar (14), ensure that the face surfaces of the pads (11) and membranes (12) measuring surface pressures have contact with the inner face surfaces of crank webs. The screw drive system (15 and 16) facilitates pre-tensioning of the springs (13) and the contact pressure of the caps (9). Results of the measurement of circumferential surface pressures (which depend on the value of elastic strain of the pads (11) at the contact point of the membranes (12) with the inner face surfaces of the crank webs are visualised on the computer screen in the form of a map of a scan of surface pressures. Measurement data is fed to the computer memory and processed with the use of a dedicated algorithm. The contact pressure of the locking pins (4) with the punch marks on the inner face surfaces of the crank webs and the contact pressure of the pads' face surfaces (11) (with sensitive membrane tips measuring surface pressures) with the inner face surfaces of the crank webs are realized independently.

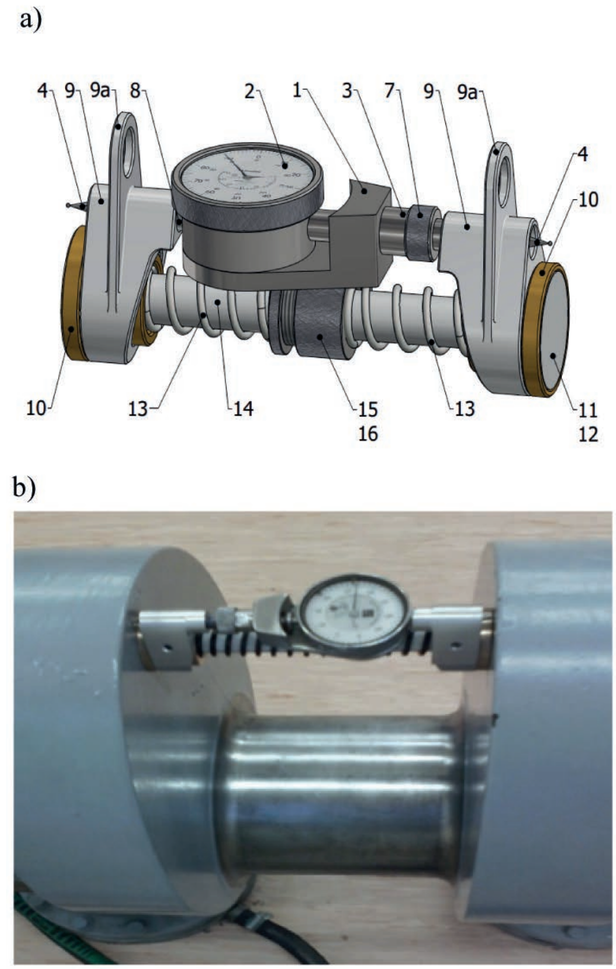

Fig. 4. New concept of gauge for testing crank web strain by the symmetrical method (a), gauge resting between cranks (b)

The mutual position of the axes of main journals located next to the measured crank can be determined on the basis of measurements. Measurements are taken in a way similar to the traditional method and recorded continuously for a shaft turn angle for which a measurement can be taken. If the piston-crank system is dismounted, measurements are recorded for the entire 360° angle. If the piston-crank system is not dismounted, measurements can be taken within the angle corresponding to two extreme positions of the gauge close to the connecting rod shank.

3. Development of test results with the use of dedicated software

A procedure of the interpretation of measurement results has been developed for the proposed test method. Geometric interpretation of results is performed with the use of dedicated software. The software performs the following steps of the algorithm for the data provided by a scanned image of surface pressures in the contact points of the membranes with the face surfaces of crank webs:

- The deletion of outliers,
- An approximation to a 3D surface, and
- The determination of normal vectors for particular surfaces.

The membrane measuring surface pressures facilitates data acquisition for the colour mapping of particular pressure forces. The map is a digital 2D image, storing the third dimension in the form deviation values. The image is processed with the use of digital image processing algorithms. Since the data acquired from the membranes may include some outlying values (outliers), at the first stage of the development of test results, the data must be cleaned. An outlier is an element which does not match the data model represented by other elements [8]. Outlying observations are caused by an imperfection of the gauge, irregularities of the crank surfaces coming in contact with the membranes, and other anomalies occurring during the measurements. Outliers are represented on the pressure map as rapid, short-term, single-tone colour changes. They hinder data analysis; therefore, they must be deleted or replaced with correct values. Too many outliers may also cause incorrect geometric interpretation of test results. Direct deletion of outliers is not recommended. Therefore, the author proposes to replace them with medians that calculated for the points under analysis and the adjacent points. Medians are more resistant to the occurrence of outliers than mean values. For this purpose, the pressure map image is divided into sub-images of arbitrary size on which the median filter is used (non-linear filtration). The size of a sub-image depends on the size of distortions. Its adjustment can be automated with the use of image segmentation methods based on local image thresholding or colour histograms. If the distribution of variables is asymmetric, the truncated (Windsor) mean is applied, which offers a compromise between the arithmetic mean and the median.

At the next stage of data processing, the map of surface pressures is approximated, i.e. its image is transformed onto a flat surface in 3D space. A normal vector is determined for this surface, which represents the inclination angle of the crank web face surface. Approximation of the map of surface pressures is performed by the least square method (Fig. 5).

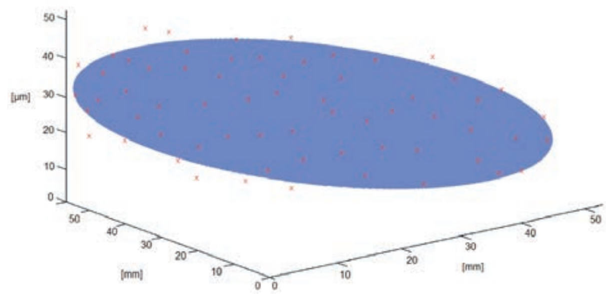

Fig. 5. Approximation by the last square method, with outliers

The direction of the inclination of the crank web face surface is represented by the normal vector *n* to the surface. A normal vector is a vector perpendicular to the surface at a point in 3D space. The approximation image of the map of surface pressures is used to determine the normal vector. The length of the normal vector is one, due to its normalization. The normal vector in 3D space is determined on the basis of the vector product of two vectors tangent to the analysed surface, and it corresponds to the axis of the cylindrical surface of the crankshaft journal (Fig. 6). Vectors tangent to the surface are determined on the basis of the surface formula created as a result of the approximation.

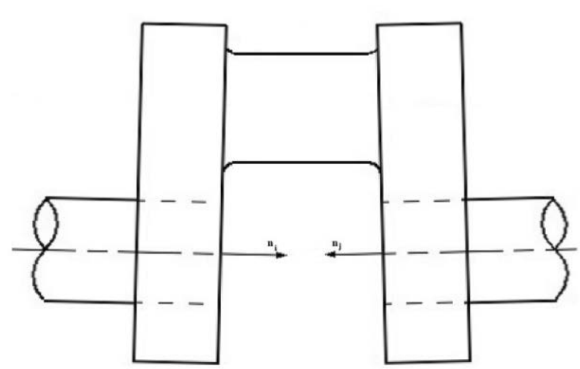

Fig. 6. Normal vectors (single crank)

Normal vectors of lateral surfaces of cranks represent the crankshaft deflection line. By creating a chain of deformed cranks (Fig. 7), the crankshaft deflection line can be determined. The data can be used for the correction of the bearing support in order to eliminate deflection of the crankshaft.

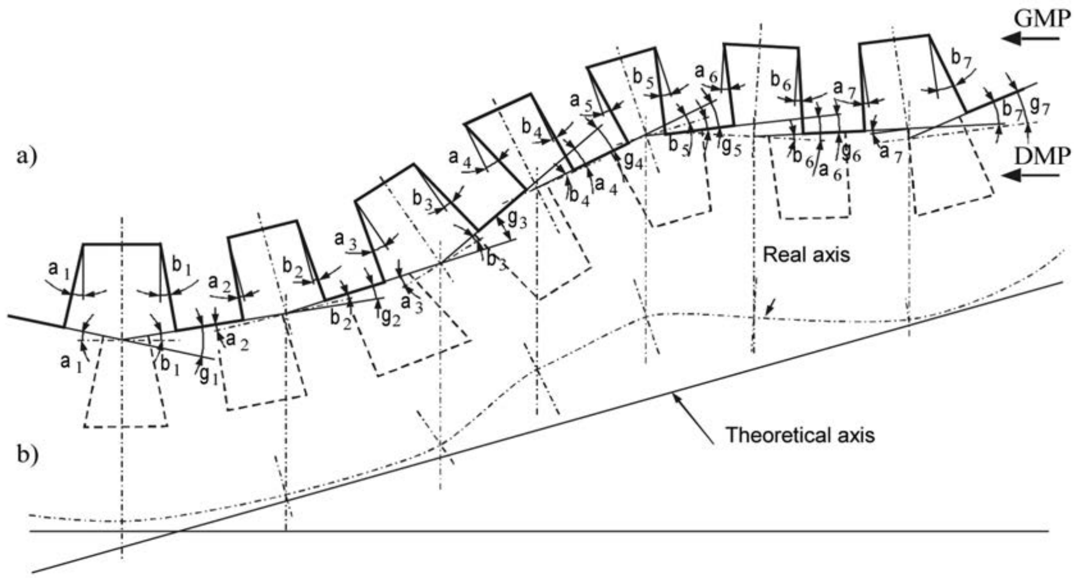

Fig. 7. Geometric interpretation of crank strain test results by the symmetrical method: a) image of crank deformation, b) determining the real axis of the crankshaft

Summary

The tests performed on a real crankshaft of a medium speed marine engine showed that a combination of the proposed measurement system with the traditional measurement method facilitates correct assessment of the condition of bearing support of crankshafts. A displacement sensor measures the aggregate value of strain on crank webs, while a collaborating circumferential surface pressure measurement system facilitates, according to the principle of proportionality of elastic strain to load, the proportional quantitative distribution of the measured springing value into the neighbouring crank webs.

The concept of test and the procedure for the interpretation of test results presented in this paper are suitable for the assessment of the geometric condition of extra-large crankshafts during the manufacturing process and for the assessment of bearing supports of crankshafts performed at fixed intervals during the operation of the engine.

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