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ADJUSTMENT AND ANALYSIS OF FORCES IN A FLEXIBLE CRANKSHAFT SUPPORT SYSTEM

Key words: flexible support system, adjustment and analysis of forces, rolling resistance.

Abstract: The paper presents an innovative measurement system implementing flexible support of a crankshaft. Through adjustment of support conditions, deflection and strain of the crankshaft under its weight can be eliminated. The principles of the selection of forces in the flexible support system and an analysis of the impact of rolling resistance on the deformation of the measured object are presented.

Dobór i analiza sił w układzie elastycznego podparcia wału korbowego

Słowa kluczowe: układ elastycznego podparcia, dobór i analiza sił, opory tarcia tocznego.

Streszczenie: W artykule przedstawiono nowatorskie rozwiązanie systemu pomiarowego z tzw. elastycznym podparciem wału korbowego. Zaprezentowany sposób elastycznego podparcia umożliwia, poprzez odpowiedni dobór warunków podparcia, wyeliminowanie ugięć i odkształceń wału pod wpływem ciężaru własnego. Przedstawiono zasady doboru sił w podporach układu elastycznego podparcia oraz analizę oddziaływania oporów tarcia tocznego na odkształcenia obiektu mierzonego.

Introduction

Nowadays, research on the identification of geometric errors focuses mainly on small components commonly used in machines and other mechanisms. It is assumed, arbitrarily, that deflection and flexible strain of such elements caused by their weight are small and therefore insignificant. In practice, no analyses are conducted to eliminate their deflection or strain through the selection of proper support conditions. Similarly, the support of large machine components is also treated marginally. However, as it has been shown in [1–5], the strain of large cylindrical machine components may obtain significant values. In most cases, complete elimination of this type of distortion is impossible, especially in the case of large "slender" components (such as crankshafts or camshafts), which are highly prone to deformation. Therefore, in order to obtain reliable measurement results, strain of these elements should be analysed and, if possible, eliminated or minimized through appropriate adjustment of the support of the measured object.

The existing solutions for crankshaft testing use the support of the crankshaft on rigid V-blocks of adjustable height. The supports are adjusted vertically to eliminate deflection of the crankshaft. It is practically impossible to obtain reliable results of measurements of a crankshaft supported on rigid V-blocks, since, due to the initial deflection and geometric errors, the measurements are affected by the positive or negative flexible strain of variable values caused by changes in the stiffness of the crankshaft during its rotation.

The proposed solution of a measuring device [6] provides for setting the crankshaft on external journals in two articulated V-blocks and supporting the crankshaft at mid-section with a set of load distribution supports that provide equal and fixed load distribution forces. The solution lets the crankshaft rest freely on the supports, which significantly minimizes the change of its shape and facilitates its rotation during the measurements. Although innovative, the solution has a number of substantial flaws. It fails to eliminate possible unintended displacement of the crankshaft, since, during rotation, there is typically constant contact of the irregular rounded surface of the main journals with the heads of the articulated load distribution supports. Assuming a fixed value of pressure on all load distribution supports ensures fixed values and directions of reaction forces on the supports, but it does not eliminate deflection on the journals. Deflection on the main journals may have various values and additionally vary during the shaft's rotation. The solution may be satisfactory in the conditions of precise balancing of the crankshaft and its uniform stiffness. In practice, the stiffness of the crankshaft varies across its length, especially in the case of crankshafts of a complex shape with asymmetrically distributed main journals and cranks.

The existing measurement methods pose the difficulty of precise and unequivocal fixing of the crankshaft in position due to the high and variable reaction forces produced by the supports and the resulting deformation which depends, additionally, on the values and types of geometric errors of the measured object [7] .

1. Flexible support system – design and working principle

Taking into consideration the above mentioned difficulties in the assessment of geometric irregularities of crankshafts, an innovative measurement system has been proposed that uses the concept of the flexible support of the measured object. The system has been developed on the basis of the author's patented solution [8, 9], with the use of a dedicated measurement methodology and dedicated software for the processing of measurement results. The measurement system facilitates precise and comprehensive measurements of geometric errors of the assemblies of crankshaft journals and straight shafts. The concept of flexible support is shown in Fig. 1.

This type of support permits the elimination of the elastic deflexion of the crankshaft under its weight. Regardless whether the crankshaft rests between locking pins or on V-blocks, the flexible supports distributed across its mid-section compensate for the possible elastic deflection. The measurement system can be used for taking measurements at crankshaft manufacturing facilities, and engine mounting and engine overhaul facilities.

– The system is composed of the following:
– The flexible support and base system,
– The measurement system,
– The revolution control system, and
– The data processing and analysis system.

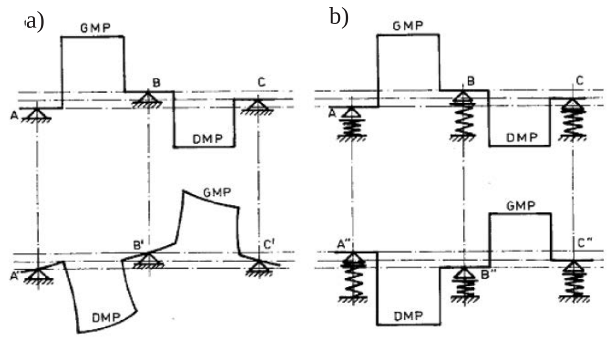


Fig. 1. (a) Strain of cranks – rigid support; (b) flexible support concept

The flexible support system is made up of a set of flexible supports of a number and distribution corresponding to the number and distribution of the main journals. Flexible supports eliminate elastic deflection of the crankshaft under its weight. Pneumatic motors can be used as flexible supports. The working medium is air. The flexible supports have the properties of self-aligning, elastic rolling V-blocks. Their elasticity compensates for deflection as well as vertical and horizontal movement of the crankshaft. The crankshaft is locked axially by means of two spherical tip pins of which one is rigid, while the other is elastic, and they set the axial direction. This type of base for the crankshaft ensures that it has continuous contact with the locking pins, regardless of any possible axial elastic strain, while the pressure force is self-adjustable.

The measurement system is composed of a truck with a tripod and a measuring sensor mounted on it. The truck moves (backlash free) along precise guide bars.

The system is equipped with a crankshaft rotation control system, which facilitates continuous recording of the measurement data and feeding it into the computer memory. Measurement results, including comprehensive data on crankshaft shape and position errors, are processed for the determination of geometric errors. Calculations are performed by proprietary software, which is an integral part of the measurement system.

Figure 2 presents the main components of the proposed system.

The main journals (2) of the crankshaft (1) rest on a set of flexible load distribution supports (5). The supports are equipped with self-aligning rolling V-block heads (6) which, in collaboration with actuators (10)

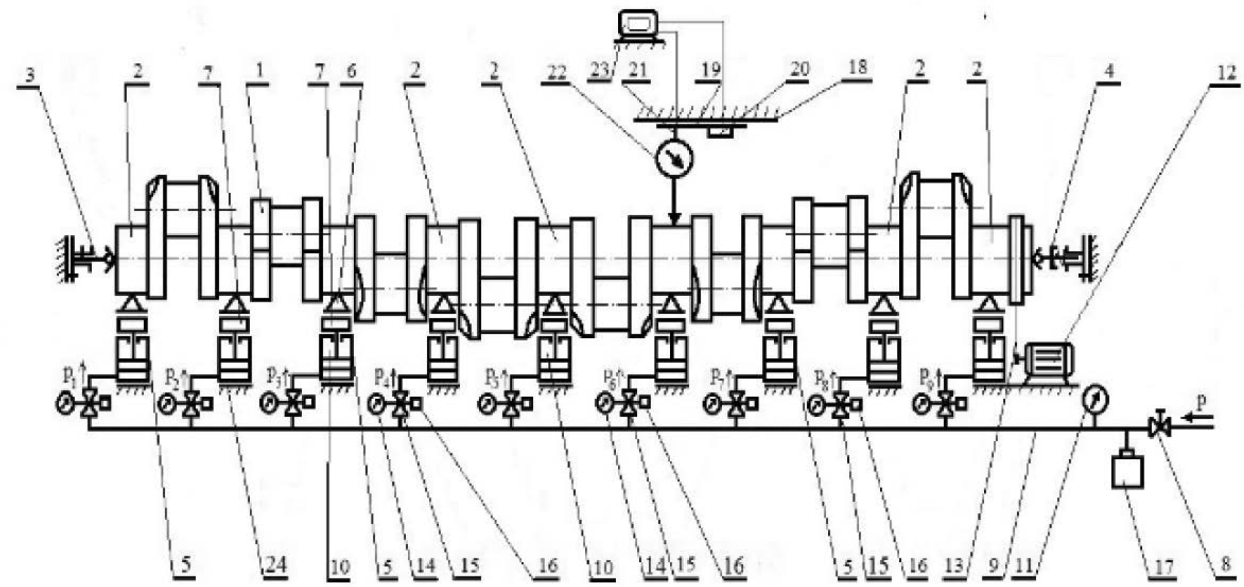


Fig. 2. Main components of the measurement system; the crankshaft is locked in locking pins

(powered by a certain medium), provide all degrees of freedom. The flexible supports provide passive forces that eliminate the elastic deflection of the measured object and simultaniously compensate for any movement (displacement) caused by its geometric irregularities. The values of pressure variables p_i and the corresponding forces provided by the actuators (10) of the flexible load distribution supports (5) are adjusted on an continuous basis by means of ARA-PNEUMATIK Tecno-basic PRE-I1-06-20-15 proportionate current-controlled reduction valves (15). The settings (manometer-controlled (16)) are adjusted individually, depending on the crankshaft design, so that elastic strain measured on the main journals is eliminated, and the spherical tip pins (3) and (4), which constitute the measurement base (used for further determination of geometric errors), do not carry vertical or horizontal loads. Values of force variables (depending on the crankshaft turn angle) provided at each of the flexible supports can be determined with the use of software for the calculation of the strength of machine parts (e.g., modelled by the finite element method), assuming that deflection on each of the main journals equals zero or is not larger than a certain predefined value [9, 10].

Tests performed with the use of the Nastran 2010 strength calculation software showed that, in order to obtain zero-value deflection on the main journals, the values of load distribution forces applied to every main journal must change, not only across the crankshaft's length, but also in coordination with the change of its turn angle on the supports [9]. Figure 3 presents the distribution of forces for four typical angle positions of the crankshaft which ensure zero-value deflection on the main journals, as determined by the Nastran 2010 strength calculation software for the crankshaft of the medium speed main engine of the Buckau Wolf R8DV 136 ship.

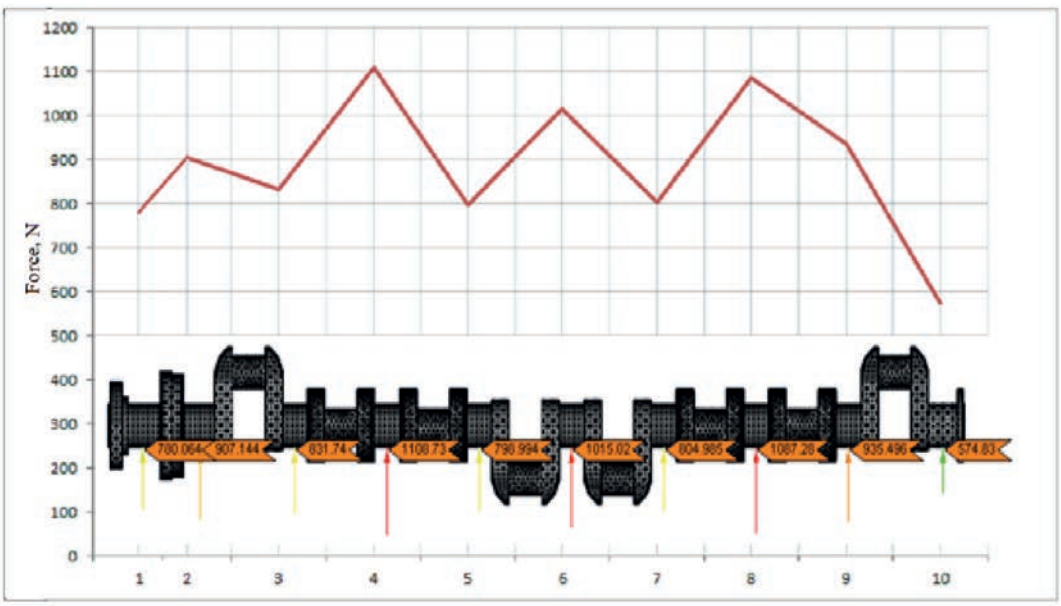
Changes of force values, obtained through changes of in the pressure of the medium powering the actuators of the load distribution supports, do not guarantee precise and unequivocal adjustment of the required load distribution forces. Real values of forces provided by the pressure-controlled supports depend on a number of properties of the actuator, such as frictional resistance, the type of powering medium, the shape of its components, materials, or design. This solution additionally utilizes SPAIS FT 5367-4 |IP68| (7) strain gauge force transducers with electrical ambient temperature compensation, placed between the heads (6) and actuators (10) of the flexible supports (5). Thus, the required force is the parameter that controls the pressure of the control valves (15). The pressure in the actuators (10) of the flexible supports (5) is force-controlled and corresponds to the required value of the load distribution force. A diagram of the flexible support control system is presented in Fig. 4.

The crankshaft is locked in the axial direction by means of pins (3) and (4), of which one is rigid and the other one provides the axial pressure force, which guarantees continuous contact of the crankshaft with the locking pins.

Once the crankshaft is placed on the supports and the defined values of pressure provided by the supports is set by means of the control valves (15), the position of the locking pins is adjusted. The last action in the crankshaft locking process is placing the locking pins in the punch marks on the face surfaces of the crankshaft. Next, the pins are locked in the position. The locking pins (3) and (4) provide a permanent and fixed measurement base, which is further used for the determination of geometric errors.

The measurement system, composed of a truck (19) with a tripod (21), a measurement sensor (22), and a laser distance meter (20) mounted on it, moves along the crankshaft on precise and stiff guide bars (18). The tripod with the sensor are mounted pivotally on the truck plate; thus, the sensor's height and angle can be adjusted relative to the measured outline of roundness in the assumed dimensional system of the measurement system (Fig. 2). The sensor is interfaced with a PC (23). The PC has a connection with a crankshaft rotation control system (not shown in Fig. 3).

a)



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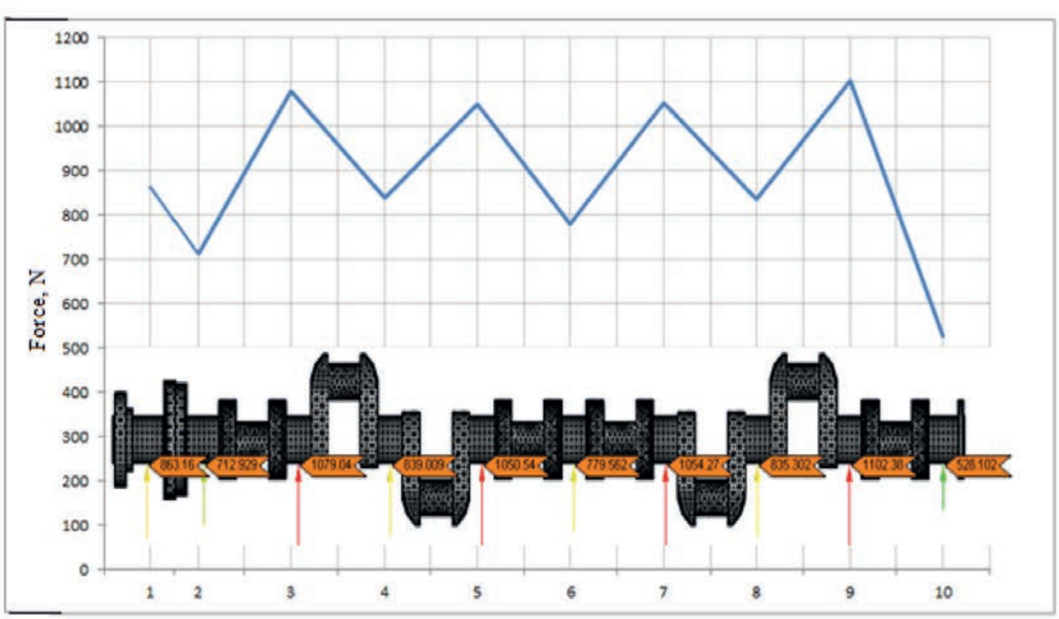

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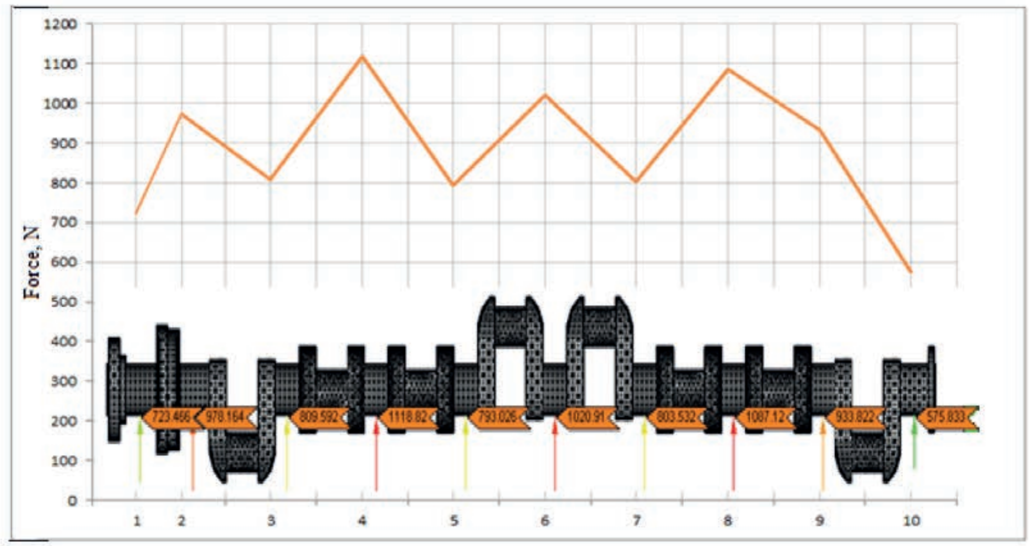

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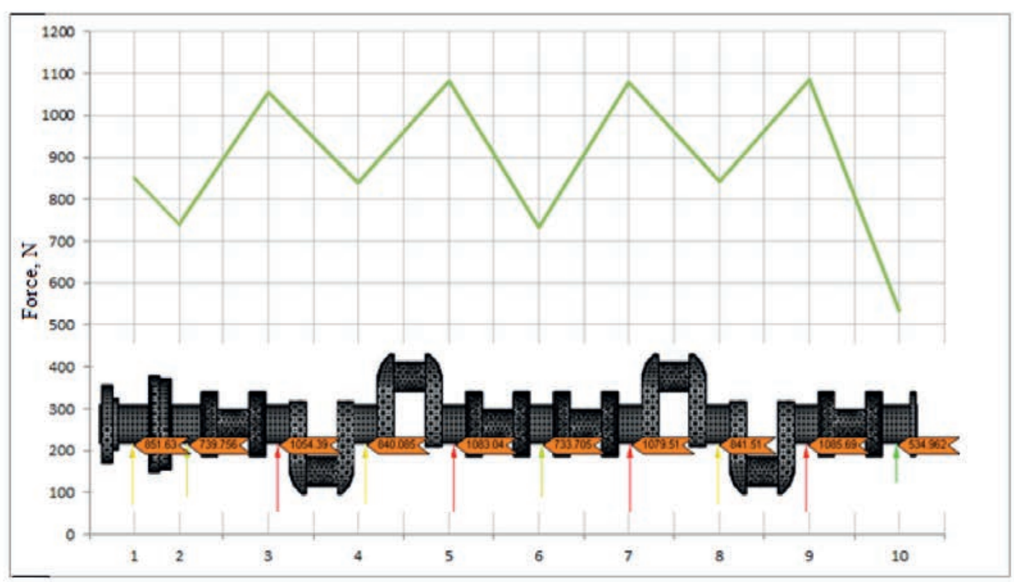

Fig. 3. Distribution of forces for selected angle positions of the crankshaft which ensure zero-value deflection on main journals (engine of the Buckau Wolf R8DV 136): (a) 0° turn angle; (b) 90° turn angle; (c) 180° turn angle; (d) 270° turn angle

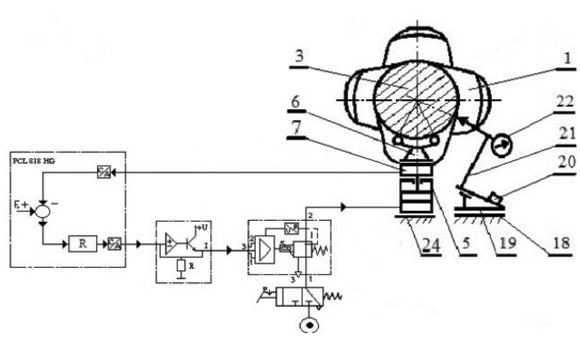

Fig. 4. Flexible support control system

The engine (12), controlled by a frequency converter, drives the shaft by means of a flexible connector (13) equipped with a crankshaft-load distribution mechanism.

The main pneumatic supply system includes a valve (8), a manometer (11), and a balancing tank (17). The pressure p in the supply cord (9) is higher than the pressure pi in the pneumatic actuators (10) of the flexible load distribution supports (5).

If the outer face surfaces of the crankshaft are not punch-marked, the crankshaft must be based with its end journals on the supports (25) with permanently fixed V-block heads (26) and supported at mid-section with load distribution supports (5) with V-block heads (6) (Fig. 5). The heads (6) of these supports can also provide all degrees of freedom (similarly to the solution presented above).

The end supports provide the measurement base that will be used for the calculation of geometric errors. The values of pressure in the load distribution supports must be adjusted, so that the heads (26) of the locking supports (25) are not excessively loaded. Axial movement of the shaft is limited by means of the spherical tip pins (3) and (4), of which one is rigid and the other one provides axial pressure force, which guarantees continuous contact of the crankshaft with the locking pins.

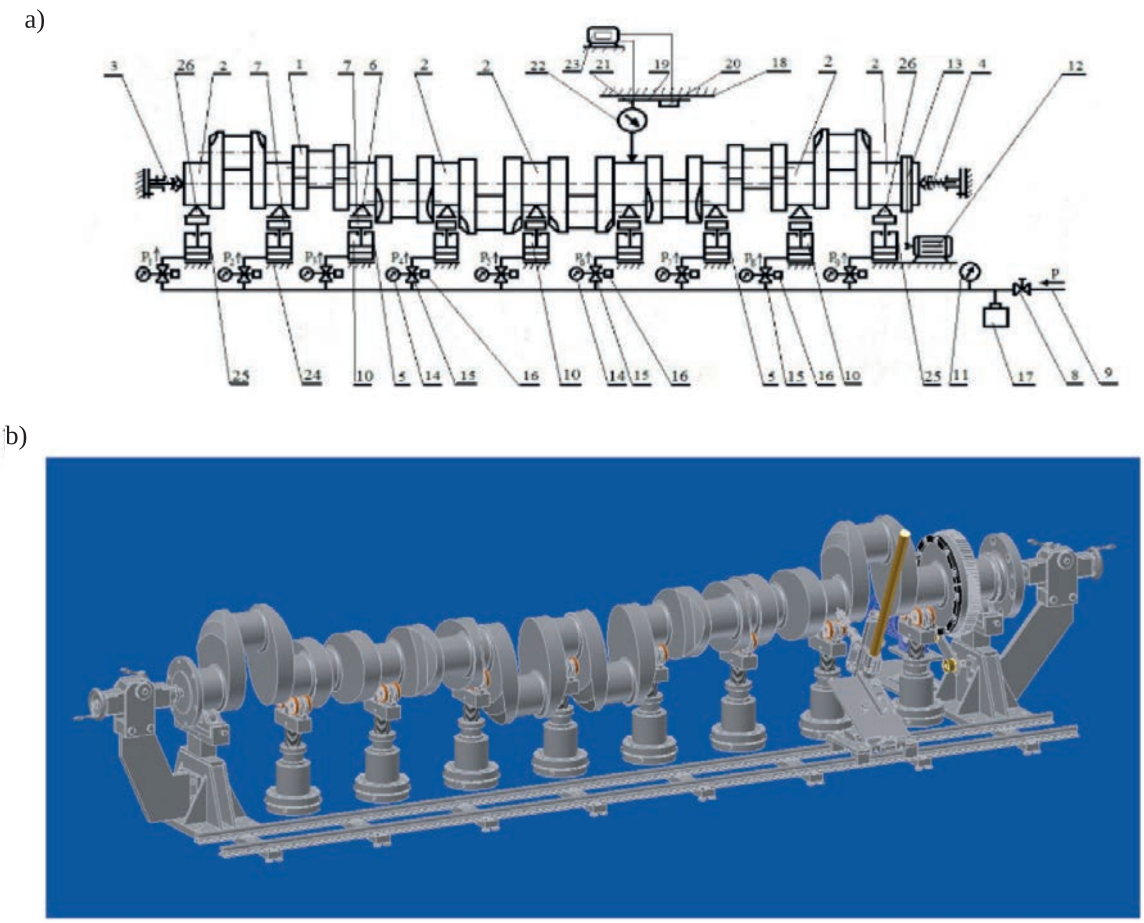

Fig. 5. Diagram (a) and geometric body (b) of the main components of the measurement system for a crankshaft resting on V-blocks

In this case as well, the development of measurement results requires transformation of the measured outline of roundness into the "transformed real outline," which is a procedure developed for the measured object locked in two V-blocks. It results from the fact that, in reference measurements (e.g., measurements in V-blocks), the measured object is subject to movement due to the constant contact of irregular roundness of the main journals with the forming surfaces of the V-blocks during the rotation of the crankshaft.

Figure 6 presents an updated version of a test stand, developed and built at the Maritime University of Szczecin. The crankshaft rests on V-blocks with flexible load distribution supports.

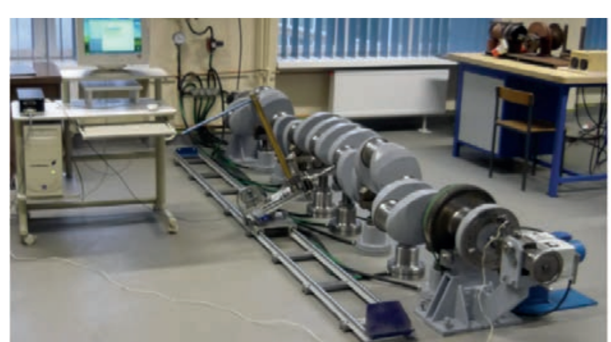

Fig. 6. Test stand for the measurement of geometric deviations of crankshafts, equipped with the flexible crankshaft support system

2. Analysis of forces in the flexible support system

The flexible support system permits the elimination of the elastic deflection of crankshafts during their measurements. The prerequisite for the proper operation of the flexible support system is the correct selection of the number of supports and their distribution as well as the adjustment of the pressure and, in consequence, the forces provided by the supports. As shown in [9, 10], any change to the recommended support conditions results in the occurrence of the deflection of variable values. It results from the fact that the crankshaft is a highly flexible component, and its cranks react with one another.

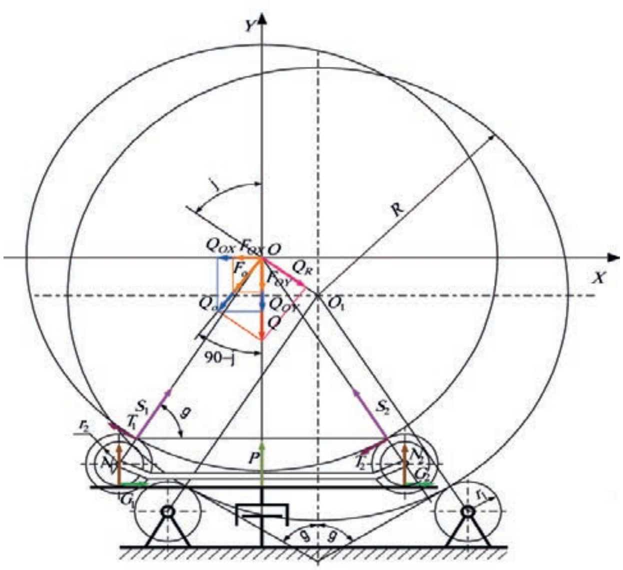

Fig. 7. Determination of the rolling resistance of load distribution support heads

Due to the high flexibility of the crankshaft, its deflection should be considered in both the vertical and horizontal planes. The flexible supports provide a passive force which eliminates deflection. The heads of the supports, designed to provide all degrees of freedom, do not impede any possible movement of the journals locked in them. The movement may be caused by the fact that the centre of the cross section outline measured does not line up with the rotation axis provided by the locking pins or V-blocks. As a result, the centre of the cross section outline measured and the supporting heads move eccentrically relative to the rotation axis. The movement is compensated for in the vertical plane through changing the values of the load distribution forces. In the horizontal plane, the movement of journals is compensated for by the susceptibility to rolling of the load distribution support heads. Considering the loads carried by the flexible supports, variable forces of rolling resistance occur at the contact surface of the support head guide bars, which react with the crankshaft journals. The forces may affect the horizontal deflection of the crankshaft.

The diagram in Fig. 7 presents an analysis of these forces. The analysis takes into consideration the impact of load Q carried by the flexible support heads and circumferential force F_o resulting from the torque provided by the crankshaft driving system on the values of rolling resistance forces G_1 and G_2.

The total force of rolling resistance is a sum of G_1 and G_2. It was assumed for the analysis that the centre of the cross section outline measured O may move eccentrically relative to the rotation axis O_1 provided by the V-blocks of the locking supports. The reaction forces in the contact points of the measured outline with the head rollers $S_1$and S_2, as well as in contact points of the rollers with the guide bars N_1 and N_2, were determined. The reaction force values were expressed depending on the shaft turn angle φ and the opening angle of the roller V-block φ. The resultant of the maximum rolling resistance force acting on the crankshaft in the horizontal plane was calculated for the assumed input data with the use of the following formula:

$$T_{c\max} = \frac{N_{c\max} \cdot f_t}{r_2} \qquad (1)$$

where:

- $N_{c\,max}$ – maximum reaction force at the contact point of the rollers with the guide bars,
- f_t – rolling friction coefficient,
- r_2 – radius of the roll of the load distribution support head.

In the case under analysis, considering the measurement conditions, the following values were assumed: N_{cmax} = 1234.4 N, f_t = 0,012 mm, and r_2 = 30 mm.

The calculation produced the maximum value of the force under analysis less than 0.5 N. An assumption may be made that, in this case, the impact of rolling resistance on horizontal deflection of the measured object is insignificantly small. The assumption is confirmed by simulation calculations of the deformation of the crankshaft loaded with a horizontal force of 5 N (i.e. 10-fold higher than the calculated rolling resistance force) acting on main journal (No. 7) counting from the gear train. The values of horizontal deflection for the crankshaft loaded in this way are smaller than 1.5 μm (Fig. 8).

Certainly, the values of resistance forces largely depend on the dimensions of roller V-blocks, the heads of the flexible supports, and measurement conditions. The impact of these forces should be analysed on a case-by-case basis and taken into consideration in measurements.

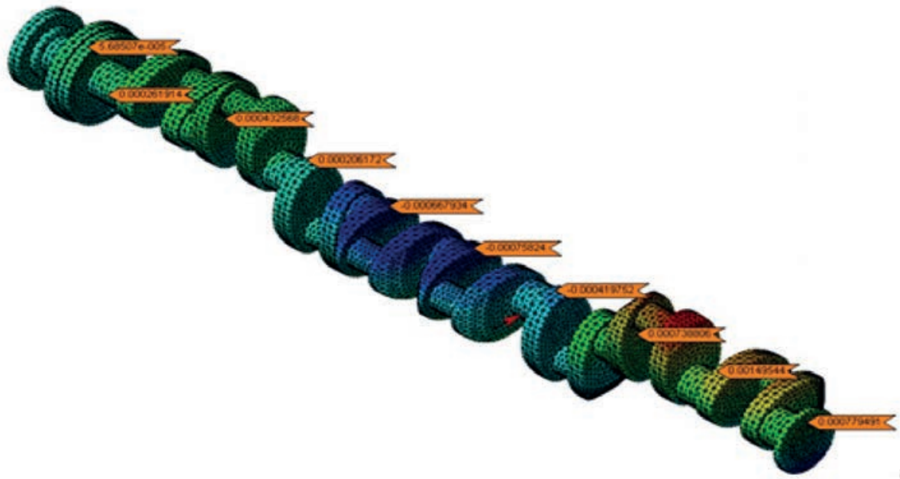

Fig. 8. Horizontal strain of the crankshaft loaded with a horizontal force of 5 N

Summary

The proposed flexible support system permits the elimination of the elastic deflection of the crankshaft caused by its weight. Regardless of whether the crankshaft is locked in locking pins or V-blocks, the elements compensating for elastic strain of the crankshaft are the flexible supports distributed at the mid-section of the crankshaft. This measurement system can be used for measurements taken at crankshaft manufacturing facilities, and engine mounting and engine overhaul facilities.

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