IVAN KOMAR, M.Sc.
E-mail: ivan.komar@pfst.hr
University of Split, Faculty of Maritime Studies
Zrinsko-Frankopanska 38, HR-21000 Split,
Republic of Croatia
NENAD VULIĆ, Ph.D.
E-mail: Nenad.Vulic@fesb.hr
Croatian Register of Shipping
Marasovićeva 67, HR-21000 Split, Republic of Croatia
RADOVAN ANTONIĆ, Ph.D.
E-mail: radovan.antonic@pfst.hr
University of Split, Faculty of Maritime Studies
Zrinsko-Frankopanska 38, HR-21000 Split,
Republic of Croatia

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SPECIFICS OF SHAFTING ALIGNMENT FOR SHIPS IN SERVICE

ABSTRACT

Modern ships are means of transport which, during their entire operational lifespan, need to convey cargo and/or passengers in a safe and reliable way, without jeopardising their safety, and with least possible adverse impacts on the marine environment. The ship's safety and functionality directly depend on the reliability of her propulsion system, the shafting being the essential unit of the system. The functionality of the ship's shafting considerably depends on its correct installation. Installation of the ship propulsion shafting is an integral part of the overall positioning (alignment) procedure. Shafting alignment is performed in several stages, starting with the shaft line design, and includes calculating the elastic line and bearing loads, installation of shafting parts onboard ship in compliance with the calculation results, and verifying the alignment results. Procedures are different for ships in service and newly built ships. This paper deals with specific features of the propulsion shafting alignment that is carried out while a ship in service is being converted for a general reason. Unlike a newly built ship, an existing ship imposes additional constraints that should be dealt with in the calculation stage of the process as well as during shafting installation and alignment verification. A calculation approach for ships in service is always different, having specific features from case to case, depending on what is changed and what remains unchanged during the conversion of the ship. The same goes for the implementation and verification of the achieved results. The purpose of this paper is to underline the difference, its contribution being in suggesting the procedure to be followed in case of conversion of an existing vessel.

KEY WORDS

ship in service, shafting, alignment, GAP, SAG

1. INTRODUCTION

The present world merchant fleet exceeds 96,000 units and 770m GT (*Source: Lloyd's Register/Fairplay – World Fleet Statistics/ 2006*). The fleet is an essential factor in long distance international transportation of goods and passengers, in particular with regard to the return on investment and the environment preservation. The primary task of the merchant fleet is conveying huge amounts of cargo, whether general or in bulk, across oceans, and this directly generates the requirements of high reliability of the ship propulsion plant. From a functional point of view, the ship propulsion shafting is a very important system which, in adverse sailing conditions, may have features of a system essential for the ship's safety. Its reliability depends, inter alia, on its correct positioning onboard ship. The shafting alignment includes the elastic line calculation, onboard installation and assembling of its parts (i. e. individual shafts) in compliance with the calculation results and, finally, the verification of the achieved condition, followed by re-alignment if necessary [1-2]. The calculation determines the position of the stern tube bearings and intermediate bearings, as well as the propulsion engine bearings in transverse and vertical position relative to the shafting axis. These positions must ensure an acceptable elastic line, as well as proper distribution of bearing reactions and internal forces that the shafting transfers to the propulsion reduction gearbox or to the directly coupled prime mover [3-4-5]. Calculations are used to model the shafting with a line system of girders of varying cross sections at a number of supports [6-7]. Bearings can be modelled with solid supports, linear elastic supports, or using the non-linear model of radial bearings. As the application of the latter two models is rather complex, today's calculations regularly use the solid support model [8]. It is common practice to present the calculation results in the following way: the computer program evaluates the influence coefficients for the designed (solid support) bearing offsets (i. e. bearing load change for a unit offset of this or some other bearing), bearing reactions, displacements (deflections and slopes of the elastic line), internal forces (bending moments and axial forces), and stresses (due to bending, or equivalent stresses) [9-10]. The shafting alignment verification is performed by measurements which define the deviation of the condition achieved upon the onboard installation from the design condition. The following steps are taken when verifying the shafting alignment on board: measuring GAP and SAG values at the open shaft flange connections, jack-up measurement of bearing reactions, and strain gages measurement [6, 4, 11].

When dealing with the existing vessels, it frequently occurs that the documentation related to the elastic line or shafting alignment criteria are not available. It is therefore recommended, prior the ship's docking, i. e. while she is afloat, to de-couple flanges of shafting sections, measure GAP and SAG, and take these values as reference condition [12]. If the above mentioned measurement is repeated or performed on the ship on dock, considerable differences will be observed, as alignment is to be carried out afloat. During the construction of this very ship, the alignment was performed by measuring GAP and SAG values at the open flange connections; upon the installation, alignment was verified and adjusted by measuring bearing reactions. After an overhaul or inspection, shaft line sections are coupled again. The once measured SAG and GAP values at flanges are no more in accordance with the values defined in the technical documentation (if the latter exists altogether) or considerably differ from the values initially measured before docking. The question is whether this new condition, which we either cannot change or do not want to change, except for some minor adjustments, meets the criteria defining the acceptable limits for bearing loads, deflections, and internal forces [6, 13].

This paper presents the calculation of the initial bearing offsets related to the measured GAP and SAG at the open flange connections. The alignment verification, based on computational bearing offsets that are calculated from SAG/GAP values, will show whether the existing condition is acceptable or not. If the measured condition is proved unacceptable, a minimum of modifications (subsequent adjustments and works on board) required in order to change any value which may have a favourable impact on the condition acceptability are to be searched for.

2. CALCULATION TERMINOLOGY AND ASSUMPTIONS

The propulsion shaft line, ready for GAP and SAG measurement at the open flange connections, is shown in a general way in Figure 1.

Shafting parts, i. e. separate shafts (propeller shaft, intermediate shafts, and the like) will be called elements. Places where flanges meet will be called nodes. The following assumptions are made:

1. Each shaft with de-coupled flanges represents a statically determined system (Figure 2) which moves and makes angular turn as a solid body. The position of each shaft is determined by two supports.
2. For each shaft, offsets at the ends of the coordinate system passing through the bearings, i. e. in the local coordinate system $\bar{x}$, $\bar{y}$, $\bar{z}$, are calculated beforehand.
3. The deflections are small in relation to the distance between supports. Slopes are also small, so we may take that: $\sin\alpha \approx \alpha$, $\cos\alpha \approx 1$.
4. Differences in diameters of flanges that are coupled together may be ignored.
5. If any of the shafts after disassembling (de-coupling of flanges) is not a statically determined system (e. g. a propeller shaft with three bearings), it is assumed that the shaft, as a solid body, has already moved in relation to its previous position. This means that the positions of two bearings en-

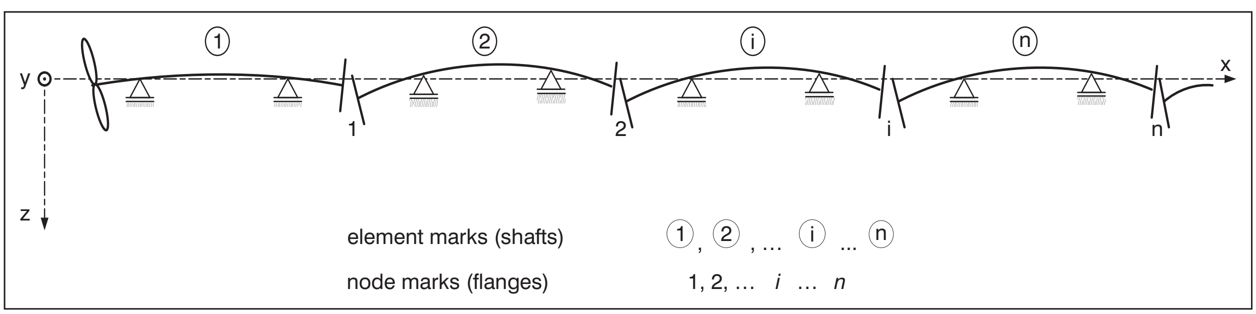

Figure 1 - Shaft line with de-coupled flanges

tirely determine the position of other shaft parts [14].

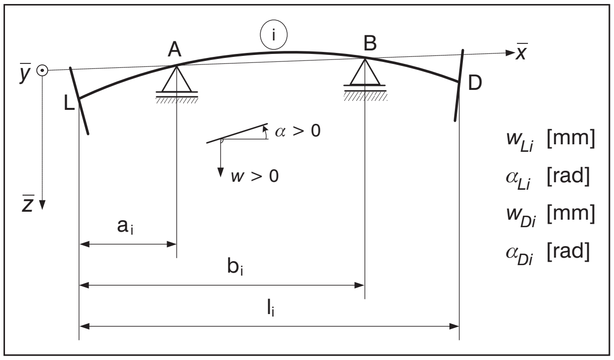

Figure 2 - Part of a shaft line as a statically determined system

The assumption (1) is usually met. Calculation in (2) may be performed with the aid of a computer program, as described in [6]. The assumptions (3) and (4) are regularly met, whereas caution is needed when using the assumption (5); if it is not met, a major mistake may develop. The calculation is feasible from the ship propeller to the main engine (in Figure 1 from left to right, common practice in new built ships) or vice-versa (more frequent practice in service ships) [15].

As a rule, an assembled shafting is a statically non-determined system, whether the ship is under construction or in service. In case of new built ships, the common alignment calculation approach is choosing (defining) offsets of all bearings, aiming at an unambiguous calculation of bearing reactions and all other values. Then these values are checked to make sure that they meet the criteria. In case of a ship in service, we shall start either from the measured SAG/GAP values at flanges, or from the measured bearing reactions within an assembled shafting, in order to determine bearing offsets necessary for the subsequent calculation. It should be always borne in mind that neither the measured SAG/GAP values nor the measured bearing force values can determine, in an unambiguous way, the position of the integral shafting as a solid body, e. g. the coordinates of the centre of the aft flange (in Figures 1-2: left) and its angular turn without deformation around the centre. The difficulty can be overcome by freely choosing the above displacement of the system as a solid body.

3. FLANGE OFFSETS EXPRESSED BY GAP AND SAG AT FLANGES FOR AN INDIVIDUAL NODE

For an observed node i (Figure 3) the values of SAG_i and GAP_i for the defined flange diameters $d_i = d_{D,i} = d_{L,i+1}$ are calculated according to the expressions (2.1) and (2.2).

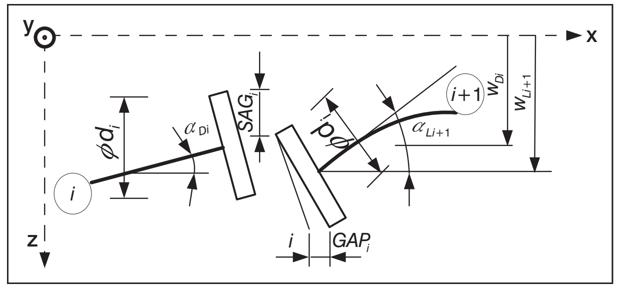

Figure 3 - GAP and SAG in node "i"

$$SAG_i = w_{L,i+1} - w_{D,i} \tag{2.1}$$

$$GAP_i = d_i \cdot (\alpha_{L,i+1} - \alpha_{D,i}) \tag{2.2}$$

where:

$\left.\begin{matrix} w_{Di} \\ \alpha_{Di} \end{matrix}\right\}$ *or* $\left\{\begin{matrix} w_{Li+1}\ \text{[mm]} \\ \alpha_{Li+1}\ \text{[rad]} \end{matrix}\right.$ are displacements of one of the two flanges in the global system.

The following signs are adopted: $SAG_i > 0$ if the left flange is closer to the axis x (i. e. higher), and $GAP_i > 0$ if the rims are closer to the axis x (i. e. if the opening is greater from the bottom side).

3.1 Transition from element i to element $i+1$ (i. e. from left to right):

$$\begin{aligned} w_{L,i+1} &= w_{D,i} + SAG_i \\ \alpha_{L,i+1} &= \alpha_{D,i} + \frac{GAP_i}{d_i} \end{aligned} \tag{2.3}$$

3.2 Transition from element $i+1$ to element i (i.e. from right to left):

$$\begin{aligned} w_{D,i} &= w_{L,i+1} - SAG_i \\ \alpha_{D,i} &= \alpha_{L,i+1} - \frac{GAP_i}{d_i} \end{aligned} \tag{2.4}$$

4. BEARING OFFSETS EXPRESSED BY FLANGE OFFSETS FOR AN INDIVIDUAL ELEMENT

For individual statically determined shafting elements in de-coupled condition, we now present the calculation procedure for determining bearing displacements, as well as the deflection and slope of the other flange, if the deflection and slope are known for one of the flanges. As we deal here with a statically determined system, the procedure is simple and easy to understand, not requiring too much explanation.

For an observed element i of the shafting (Figure 4) the following items are calculated: deflection and slope of the shaft as a solid body around the points L

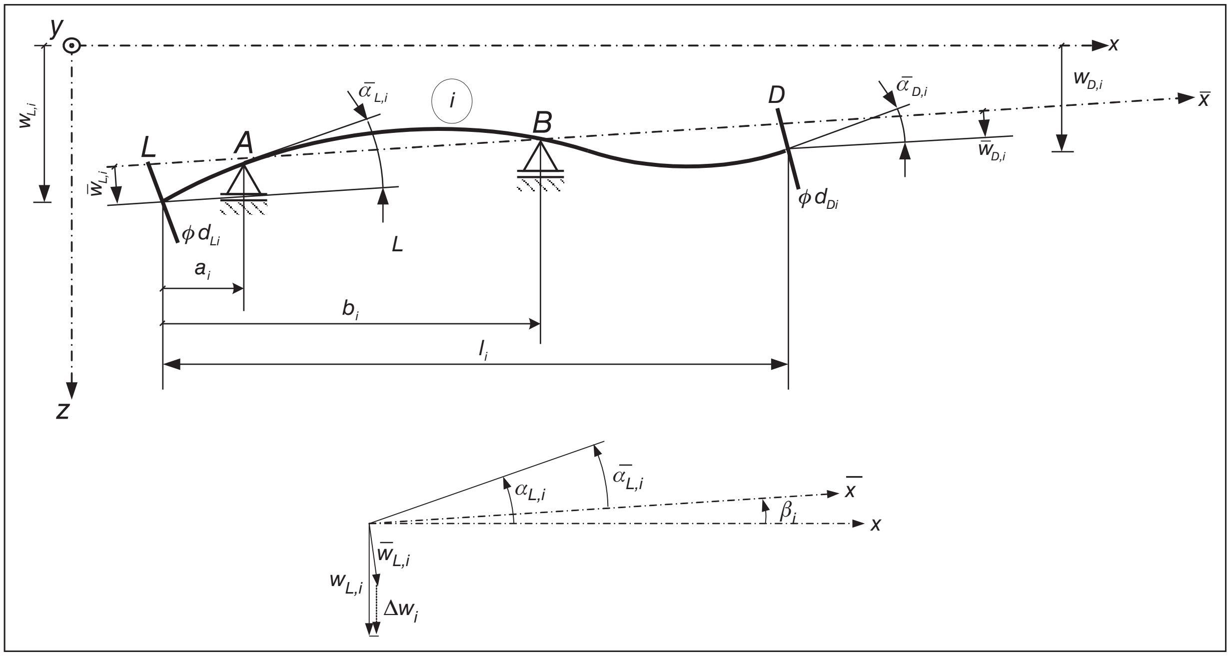

Figure 4 - Displacements and angular offsets of element i

and D, all bearing displacements (in the global coordinate system), as well as displacements of the ultimate right and left (foremost and aftermost) flange in the global system, starting with the following known (directly measured) values:

a) bearing position: a_i, b_i [mm]
b) shaft length (flanges distance): l_i [mm]
c) flange diameters: d_{Li}, d_{Di} [mm]
d) flange displacements in the local coordinate system through bearings: $\bar{x}$, $\bar{y}$, $\bar{z}$:

$$\bar{w}_{L,i}; \bar{w}_{D,i} \text{ [mm]}$$
$$\bar{\alpha}_{L,i}; \bar{\alpha}_{D,i} \text{ [mm]}$$

e) flange displacements in the global coordinate system:

$$\left.\begin{matrix} w_{L,i} \text{ [mm]} \\ \alpha_{L,i} \text{ [rad]} \end{matrix}\right\} \text{or} \left\{\begin{matrix} w_{D,i} \text{ [mm]} \\ \alpha_{D,i} \text{ [rad]} \end{matrix}\right.$$

On the assumption that the displacements are significantly smaller than the distance between the bearings, it is considered that:

$$\sin\angle(x,\bar{x}) \approx \angle(x,\bar{x})$$
$$\cos\angle(x,\bar{x}) \approx 1$$

i.e. the angle βi between the axes x and $\bar{x}$ is small enough to meet the assumption.

4.1 Transition from left to right (from flange L, to flange D)

It is defined:

$$w_{L,i} \text{ [mm]} ; \alpha_{L,i} \text{ [mm]}$$

It is to be determined:

$$w_{A,i} \text{ [mm]} ; w_{B,i} \text{ [mm]} ; w_{D,i} \text{ [mm]} ; \alpha_{D,i} \text{ [rad]}$$

Deflection and slope of the shaft around the point L as a solid body

$$\Delta wi = w_{L,i} - \bar{w}_{L,i} \text{ [mm]} \tag{3.1}$$
$$\beta i = \alpha_{L,i} - \bar{\alpha}_{L,i} \text{ [rad]} \tag{3.2}$$

Bearing displacements (in the global system)

$$w_{A,i} = \Delta w_i - \alpha_i \cdot \beta_i \text{ [mm]} \tag{3.3}$$
$$w_{B,i} = \Delta w_i - b_i \cdot \beta_i \text{ [mm]} \tag{3.4}$$

Displacements of the right flange D (in the global system)

$$w_{D,i} = \bar{w}_{D,i} + \Delta w_i - l_i \cdot \beta_i \text{ [mm]} \tag{3.5}$$
$$\alpha_{D,i} = \bar{\alpha}_{D,i} + \beta_i \text{ [rad]} \tag{3.6}$$

4.2 Transition from right to left (from flange D, to flange L):

It is defined:

$$w_{D,i} \text{ [mm]} ; \alpha_{D,i} \text{ [rad]}$$

It is to be determined:

$$w_{A,i} \text{ [mm]} ; w_{B,i} \text{ [mm]} ; w_{L,i} \text{ [mm]} ; \alpha_{L,i} \text{ [rad]}$$

Deflection and slope of the shaft around the point D as a solid body

$$\Delta wi = w_{D,i} - \bar{w}_{D,i} \text{ [mm]} \tag{3.7}$$
$$\beta i = \alpha_{D,i} - \bar{\alpha}_{D,i} \text{ [rad]} \tag{3.8}$$

Bearing displacements (in the global system)

$$w_{A,i} = \Delta w_i + (l_i - b_i) \cdot \beta_i \text{ [mm]} \tag{3.9}$$
$$w_{B,i} = \Delta w_i + (l_i - a_i) \cdot \beta_i \text{ [mm]} \tag{3.10}$$

Displacements of the left flange L (in the global system)

$$w_{L,i} = \bar{w}_{L,i} + \Delta w_i + l_i \cdot \beta_i \text{ [mm]} \tag{3.11}$$
$$\alpha_{L,i} = \bar{\alpha}_{L,i} + \beta_i \text{ [rad]} \tag{3.12}$$

5. DESCRIPTION OF VALUES NEEDED FOR THE ENTIRE CALCULATION

The previously calculated bearing displacements and the obtained deflection and slope of the flange where these values were unknown, represent the starting data for further calculation. In this way it is possible to connect gradually the front and the end part of the entire shaft line. We should always bear in mind that flange deflection and slope may represent inaccurate values. Yet, except for measuring these values, we usually do not have any other possibilities.

The values needed for the entire calculation can be sorted in groups, as follows:

5.1 Individual shaft dimensions

For each element (shaft) within the system, we need to know:

a) distance between bearing A and left end a_i [mm]
b) distance between bearing B and left end b_i [mm]
c) length of the element l_i [mm]

5.2 Displacements of the shaft ends in the local coordinate system

For each element (shaft) in the local coordinate system $\bar{x}$, $\bar{y}$, $\bar{z}$, whose axis $\bar{x}$ passes through the bearings A and B, the following needs to be calculated:

a) deflection of the element left end $\overline{w}_{L,i}$ [mm]
b) slope turn of the element left end $\overline{\alpha}_{L,i}$ [rad]
c) deflection of the element right end $\overline{w}_{D,i}$ [mm]
d) slope of the element right end $\overline{\alpha}_{D,i}$ [rad]

5.3 Diameter, GAP and SAG at the open flange connections

For each node (place where two flanges meet), we need to know the flange diameters. It is assumed that the difference between diameters of the two connecting flanges is negligible. It is also assumed that GAP and SAG measurements at flanges have been carried out onboard ship (Figure 5):

a) flange diameter d_i [mm]
b) SAG SAG_i [mm]
c) GAP GAP_i [mm]

The positive direction of displacements and angular turn is determined by the global right rectangular system x, z, y. Positive GAP and SAG values are shown in Figure 5 [4, 11].

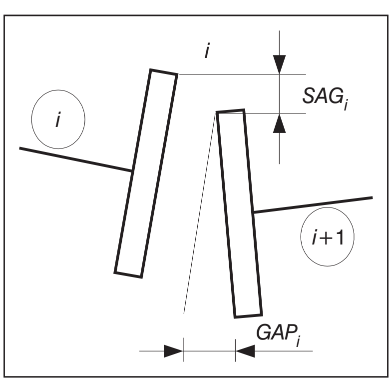

Figure 5 - GAP and SAG at open flange connections

6. SELECTION OF A GLOBAL COORDINATE SYSTEM AND THE CALCULATION OF THE RELATED BEARING OFFSETS

The purpose of this section is to choose the position of the global coordinate system and determine the bearing positions and offsets within the system, which allows the application of the calculation procedure for a ship in service to the new built one. If the calculation is performed from left to right, the global axis x is initially set in the local axis $\bar{x}$ of the element № 1. Node and bearing offsets of all the elements are calculated within the global coordinate system, concluding with the right end of the element № 1. If the calculation is performed from right to left, the global axis x is initially set in the local axis $\bar{x}$ of the element № n. The node and bearing offsets of all the elements are calculated within the global coordinate system, concluding with the left end of the element № 1.

In order to show the final results (in reference to bearing displacement and, if need be, flange displacements), we can retain the above mentioned global system or introduce a new system, by selecting two bearings L_1 and L_2 through which a new global axis x passes, as follows: may bearing displacements be calculated for each element: $w_{A,i}$ [mm] ; $w_{B,i}$ [mm], along with deflections $w_{L,i}$ [mm], $w_{D,i}$ [mm], and slopes $\alpha_{L,i}$ [rad] and $\alpha_{D,i}$ [rad] at the ends in the old (initially selected) global coordinated system. The selected bearing displacements in the old global system, where the bearing L_1 lies to the right of the bearing L_2, are: w_{L1} [mm] and w_{L2} [mm].

For each bearing, the axial position (abscissa) is calculated in the old global system. The abscissa is valid in the new system as well:

$$x_{Ai} = a_i + \sum_{j=1}^{i=1} l_j \text{ [mm]} \tag{5.1}$$

$$x_{Bi} = b_i + \sum_{j=1}^{i=1} l_j \text{ [mm]} \tag{5.2}$$

The bearing displacements in the new global coordinate system x' y' z' (Figure 6) are:

$$w'_{Ai} = w_{Ai} - w_{L1} + (x_{Ai} - x_{L1}) \cdot \beta' \tag{5.3}$$

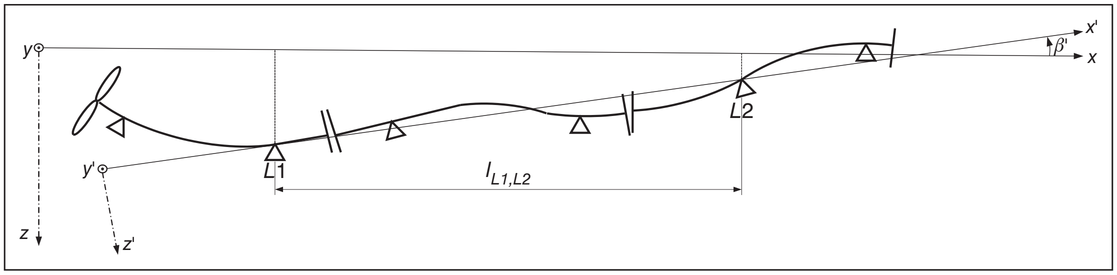

Figure 6 - Bearing displacements in the new global coordinate system *x' y' z'*

$$w'_{Bi} = w_{Bi} - w_{L1} + (x_{Bi} - x_{L1}) \cdot \beta' \tag{5.4}$$

where: $\beta' = (w_{L1} - w_{L2}) / l_{L1,L2}$ is a positive direction according to Figure 6; $l_{L1,L2} = x_{L2} - x_{L1} > 0$

Using this simple method, expressions (5.3) and (5.4) are used for calculating the displacements of all bearings of the completely assembled shafting, on the basis of SAG/GAP measurements at the open flange connections. The above displacements are used in further calculation by suitable programs, e. g. those in [6-8], designed for calculating values related to bearing reactions, deformations, and internal forces, which can be compared to the criteria of acceptability.

7. EXAMPLE OF APPLICATION TO A SIMPLE SHAFTING

A simple shafting consists of a propeller shaft and a gear shaft, with a total of five bearings, as shown in Figure 7.

The following values are known in this case:

w_L, α_L – deflection and slope of the propeller shaft flange,

SAG, *GAP* – sagging and opening at de-coupled flanges.

Values w_L, α_L are determined by a separate calculation for a de-coupled propeller shaft on three supports (in its bearings), performed by a suitable program according to [6-8]. *SAG* and *GAP* values are either measured onboard before dry-docking, or specified by design documentation.

We shall present the procedure for calculating bearing offsets w_4 and w_5, to meet the needs of the calculation of a fully assembled shaft line, and the comparison with the criteria of acceptability.

From the expressions of *SAG* and *GAP* at flanges:

$$SAG = w_D - w_L \tag{6.1}$$

$$GAP = D \cdot (\alpha_D - \alpha_L) \tag{6.2}$$

the deflection and slope of the right (forward) flange, i. e. propulsion gearbox shaft flange are determined:

$$w_D = w_L + SAG \tag{6.3}$$

$$\alpha_D = \alpha_L + \frac{GAP}{D} \tag{6.4}$$

The calculation has to determine bearing displacements w_4 and w_5. For this purpose we should consider the output gearbox shaft being moved to the position of the bearing displacements w_4, and its subsequent rotation by angle β around bearing 4 in order to achieve value w_5 in bearing 5. The displacements w_4 and w_5 are measured in the reference coordinate system, selected for the left part of the shafting.

When the bearing displacements are $w_4 = w_5 = 0$, the deflection at flange D is w_{D0} and its slope is α_{D0}. These are the known values, obtained by calculating the statically determined system of the output gearbox shaft with two bearings. The displacement values w_4 and w_5 are unknown.

The geometric relations shown in Figure 8 clearly show that the following applies to the displacements that are small in relation to the distance between the bearings:

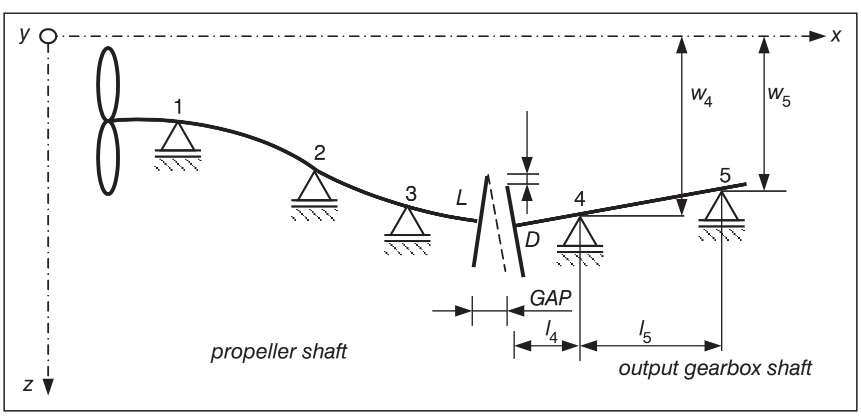

Figure 7 - Example of shafting in order to present the calculation procedure

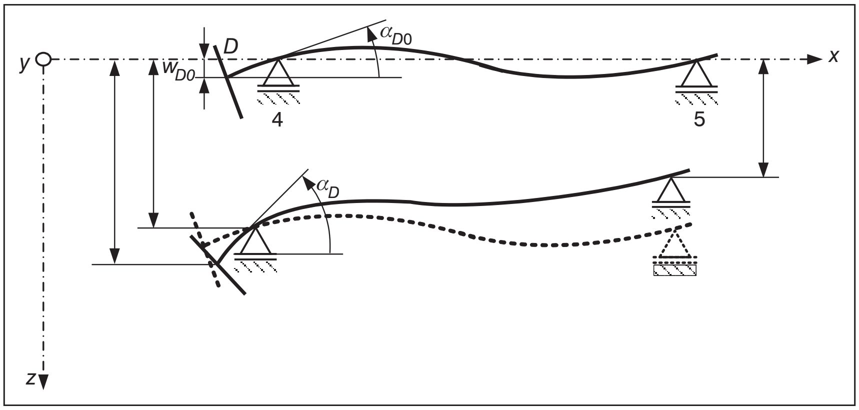

Figure 8 - Displacement and angular turn of the output gearbox shaft

$$\tan\beta \approx \beta = \frac{w_4 - w_5}{\lambda_5} \tag{6.5}$$

Furthermore:

$$w_D - w_{D0} = w_4 + \lambda_4 \tan\beta = w_4 + \frac{\lambda_4}{\lambda_5} \cdot (w_4 - w_5) \tag{6.6}$$

$$\alpha_D - \alpha_{D0} = \frac{1}{\lambda_5} w_4 + \left(-\frac{1}{\lambda_5}\right) \tag{6.7}$$

The unknown bearing displacements w_4 and w_5 are determined by a 2-equation system:

$$\begin{Bmatrix} w_4 \\ w_5 \end{Bmatrix} = \begin{bmatrix} 1+\frac{\lambda_4}{\lambda_5} & -\frac{\lambda_4}{\lambda_5} \\ \frac{1}{\lambda_5} & -\frac{1}{\lambda_5} \end{bmatrix} \cdot \begin{Bmatrix} w_D - w_{D0} \\ \alpha_D - \alpha_{D0} \end{Bmatrix} \tag{6.8}$$

Solutions of the equation system (6.8) are:

$$w_4 = w_D - w_{D0} - \lambda_4 \cdot (\alpha_D - \alpha_{D0}) \tag{6.9}$$

$$w_5 = w_D - w_{D0} - (\lambda_4 + \lambda_5) \cdot (\alpha_D - \alpha_{D0}) \tag{6.10}$$

Table 1 - Presentation of the real-case results

outset values	calculation results
SAG = -0.1 mm	
GAP = -0.05 mm	
w_L = 0.9796 mm	
α_L = -0.3988 mm/m	
D = 320 mm	
	w_D = 0.8796 mm
	α_D = -0.5551 mm/m
w_{D0} = 0.192·10^{-4} mm	
α_{D0} = 0.805·10^{-3} mm/m	
l_3 = 241 mm	
l_4 = 359 mm	
	w_3 = 1.014 mm
	w_4 = 1.213 mm

Owing to the above procedure, we have calculated the previously unknown values of the displacements w_4 and w_5. These are to be used for further calculation of the fully assembled shafting as a statically non-determined system with 5 supports, aided by a suitable computer program, e. g. the one described in [6-8], with the purpose of verifying whether the criteria of acceptability have been met.

The specific values obtained for a real-life calculation case, shown in a general way in Figure 7 are presented more appropriately in Table 1.

It should be noted that very small values of deflection w_{D0} and slope β_{D0} for the output shaft indicate its relatively great stiffness, which is common in practice. The final displacement and angular turn values are indeed obtained by moving and rotating the output shaft as a solid body.

8. DISCUSSION

The procedure of aligning the propulsion shaft line for ships in service differs considerably from the procedure performed on a new built ship, in all stages: calculation, assembling, and verification. The only common feature is that in both cases the final verification is to be carried out afloat. Designing the elastic line of the propulsion shafting of a new built ship is subject only to the constraints resulting from the physics of the very procedure, described in detail in the available literature [1, 3, 4, 6, 7, 8, 12, 13, 15]. For instance, all bearings must have reactions directed upwards; they must not be overloaded; the shafting must not transfer excessive internal forces (transverse forces and bending moment onto gearbox flange or directly-coupled engine); the greatest acceptable bearing offsets are limited by their clearance, etc. Varying and selection of certain calculation values aimed at meeting the criteria and constraints, are simple and, as a rule, feasible without difficulties, because the real ship has not been constructed yet: it exists only in its technical documentation (drawings). The conversion (overhaul) of an actually existing service ship propulsion shafting is always subject to additional constraints, resulting from the decisions regarding what, how, and why a ship part is to be changed (bearings and/or shafting, and/or gearbox/engine position due to installation of a new gearbox/engine), and what is to be left unchanged. This paper proposes the procedure for gradual de-coupling of shaft line flanges, and measurement of SAG and GAP values as references for the calculated condition after overhauling, prior to any other works onboard when afloat and prior to dry-docking. If need be, even during the stage when the ship is afloat, before overhauling, we can measure the values of the accessible bearing reactions, which may be as well useful for the forthcoming calculation, as SAG and GAP may be insufficiently accurate. Generally speaking, the basic idea is to de-couple the shafting into statically determined elements, take the position of the foremost or aftermost end as a reference and, using the measured SAG and GAP values, determine the bearing positions of all other elements in relation to the initially selected (fore or aft) end of the system. The obtained bearing displacements are to be entered into the suitable computer program for calculating the shafting alignment (computer program not being the subject of this paper as it is described in other papers listed below). Then we are to find out whether the obtained condition, and the respective values that have been measured, meet the calculation criteria. After that, using the calculation, we need to adjust the values of bearing displacement of other de-coupled statically determined system elements, so that the calculation of the fully-assembled condition could meet all the requirements of the criteria of acceptability.

Then the assembling (connecting) of individual elements must be carried out in compliance with the calculated (not initially measured) SAG/GAP values.

A likely objection that the presented procedure is not accurate enough, as it is based on *SAG* and *GAP* values, can be repudiated, given the fact that de-coupling of the shafting and measurement at open flange connections is often the only feasible procedure in onboard practice. Namely, it regularly occurs that some of the bearings are not accessible for direct measurement of their reactions. Upon the completion of conversion works, it is possible to check reactions at the *accessible* shafting bearings, and adjust their values in compliance with the calculation, by lifting/lowering as described in [6], prior to the final setting of the very bearing supports (customised metal supports, or supports cast in resin such as Epocast). Such an approach makes sense as the elastic line is determined along with all the respective values.

It is essential that the final verification and adjustment of the obtained bearing reactions are conducted afloat after all overhaul work is done, with the fully assembled shafting, and the still adjustable height of bearings where the reactions will be measured.

9. CONCLUSION

The reliability of shafting, hence the reliability of the very ship as a means of transport and as a complete system, depends considerably on the correct installation of the shafting.

This paper proposes the procedure for gradual de-coupling of shaft line flanges, and measurement of SAG and GAP values as references for the calculated condition after overhauling, prior to any other works onboard when afloat and prior to dry-docking.

Given the fact that SAG/GAP measurements are usually not sufficiently accurate, the final assessment of the obtained elastic line is to be performed by direct measurement of bearing reactions at accessible shafting bearings, their comparison with the calculated values, and their adjustment by lifting and lowering certain bearings, in order to achieve the calculated values.

Future efforts should address in more detail the approaches to likely specific real-life cases (replacement of worn-out bearings, replacement of a shafting when cracks are identified, replacement of a propulsion engine/gearbox by the one having different dimensions and features, etc.). Due to the need for generality in the present paper and the intention of remaining focused on a principled approach to all the above cases, the specific cases and approaches have not been discussed here.

Mr. sc. **IVAN KOMAR**
E-mail: ivan.komar@pfst.hr
Sveučilište u Splitu, Pomorski fakultet
Zrinsko-Frankopanska 38, 21000 Split, Republika Hrvatska
Dr. sc. **NENAD VULIĆ**
E-mail: Nenad.Vulic@fesb.hr
Hrvatski registar brodova
Marasovićeva 67, 21000 Split, Republika Hrvatska
Dr. sc. **RADOVAN ANTONIĆ**
E-mail: radovan.antonic@pfst.hr
Sveučilište u Splitu, Pomorski fakultet
Zrinsko-Frankopanska 38, 21000 Split, Republika Hrvatska

SAŽETAK

POSEBNOSTI CENTRACIJE VODA VRATILA ZA BRODOVE U SLUŽBI

Suvremeni brodovi su prometna sredstva koja tijekom cijeloga svog uporabnog vijeka moraju sigurno i pouzdano obavljati svoju temeljnu zadaću prijevoza tereta i/ili putnika, ne ugrožavajući pri tome njihovu sigurnost, uz najmanji mogući nepovoljan utjecaj na pomorski okoliš. Sigurnost i funkcionalnost broda izravno ovisi o pouzdanosti njegovoga porivnog sus-

tava, kojega je temeljni sklop vod vratila. Funkcionalnost brodskoga voda vratila značajno ovisi o njegovu pravilnom polaganju na brodu. Polaganje voda vratila brodskoga porivnog sustava obavlja se slijedom cjelovitoga postupka postrojavanja (centracije). Centracija voda vratila obavlja se u nekoliko koraka polazeći od projektiranoga voda vratila: proračun elastične linije s opterećenjem le ajeva, ugradnja dijelova voda vratila na brodu slijedom rezultata proračuna, te provjera postignutog stanja. Postupak je različit za postojeći brod u slu bi od onoga za novogradnju. Ovaj se rad bavi posebnostima postupka centracije porivnog voda vratila za brod u slu bi, koji se provodi tijekom njegove preinake. Za razliku od novogradnje, na brodu u slu bi postoje dopunska ograničenja koja često treba zadovoljiti, kako u proračunskoj fazi postupka, tako i tijekom njegove provjere i provedbe na brodu. Pristup je proračunu drugačiji na brodu u slu bi, sa svojim posebnostima od slučaja do slučaja, ovisno o tome što se tijekom preinake mijenja, a što ostaje. Isto vrijedi za provedbu i za provjeru postignutoga stanja. Svrha je rada ukazati na ovu razliku, a njegov doprinos u prijedlogu postupka kojega valja slijediti u općem slučaju preinake postojećega broda.

KLJUČNE RIJEČI

brod u službi, vod vratila, centriranje, GAP, SAG

LITERATURE

[1] **Kozousek W. M., Davies P. G.**: *Analysis and Survey Procedures of Propulsion Systems: Shafting, Alignment*, LR Technical Association, Paper No. 5, Session 1999 - 2000, London, 2000

[2] **Ozretić V.:** *Brodski pomoćni strojevi i uređaji*, Split Ship Management, Split, 2004

[3] **Piotrowski J.:** *Shaft Alignment Handbook (Third Edition)*, CRC Press, Boca Raton, 2007

[4] *Guidance Notes on Propulsion Shafting Alignment*, American Bureau of Shipping, Houston, 2004

[5] **Kovač A.:** *Postrojavanje voda vratila* (Diploma thesis), Faculty of Electrical and Mechanical Engineering and Naval Architecture, University of Split, Split, 2008

[6] **Vulić N.:** *Shaft Alignment Computer Calculation* (in Croatian), Jugoregistar Bulletin, No. 1, 1988, pp. 1-13

[7] **Vulić N. Šestan A., Cvitanić V.**: *Modelling of Propulsion Shaft Line and Basic Procedure of Shafting Alignment Calculation*, Brodogradnja 59 (223-227), Zagreb, 2008

[8] **N. Vulić**, *Advanced Shafting Alignment: Behaviour of Shafting in Operation*, Brodogradnja 52 (203-212), Zagreb, 2004

[9] **Alfirević I.:** *Linearna analiza konstrukcija*, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Zagreb, 1999

[10] **Jelaska D.:** *Elementi strojeva I dio*, Faculty of Electrical and Mechanical Engineering and Naval Architecture, University of Split, Split, 2007

[11] *Guidelines on Shafting Alignment*, Nippon Kaiji Kyokai, Tokyo, 2006

[12] **Pressicaud J. P.**: *Technical assistance for line-shafting alignment*, Technique du Bureau Veritas Bulletin, Special report: *Line shafting alignment and vibrations* - (1986) 11-12, pp. 423-438

[13] **Murawski L.:** *Analysis of measurement methods and influence of propulsion plant working, parameters on ship shafting alignment* - Part II, Polish Maritime Research, 4 (1997)

[14] **Pavazza R.**: *Tehnička mehanika – statika,* Faculty of Electrical and Mechanical Engineering and Naval Architecture, University of Split, Split, 2007

[15] **Schiffer W.:** *Advanced methods for static and dynamic shafting calculations*, Brodogradnja, 58, Zagreb, 2007