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THE RATIONAL ALIGNMENT OF SHAFT LINE
WHY-HOW TO DO

PAPER N° 14

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THE RATIONAL ALIGNMENT OF SHAFT LINE

WHY - HOW TO DO

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ABSTRACT

This Paper deals with general problems encountered on line shafts and more particularly behaviour of propeller shaft.

Two technologies will be approached :

. practical application of propeller shaft in sea water with materials such as :

- lignum vitae,
- synthetic material as tufnol or celoron,
- rubber,

on the form of staves or monobloc bushes ;

. practical application of propeller shaft in oil, with materials such as :

- white metal bushes,
- synthetic bushes (Raïlko).

First one is widely used for military and fish vessels but the second one, more recent, is used for merchant ships.

According to the two technologies, contact real pressure problems will be compared with specific pressure used for basic calculations of bushing width.

Rational alignment notions will be presented, such as :

. quick scuffing or damage processus explanation,

. justification, necessity of the realisation of rational alignment (theoretical studies and practical realisation).

External influences will be stated, such as :

. moments and forces due to the screw,

. structure deformations modifying line shafting conditions.

The aim of this Paper is to deal with specific problems due to line shafting operations in order to specify the importance of the quality of the project and of line shafting mounting for which Shipowners, Shipyards, Project and Production Departments are all concerned from point of view of ship operation reliability.

ACKNOWLEDGMENTS

The Authors wish to express their gratitude to Mr Hervé DILHAN BOISIER General Manager of BUREAU VERITAS - Chili who has insisted from four years for the necessity of a technical paper on the present subject.

The Authors express also their keen thanks to all colleagues of the Research and Development Centre (CRD) who, through their experience in modern methods of Calculations and Experimentations of highly complex phenomena, too long disregarded, have thus facilitated the explanation of many damages and the discovery of appropriate remedies.

I N T R O D U C T I O N

Twenty eight years ago, BUREAU VERITAS created a Research Team specialized in problems of vibrations and alignment of shafting for ships'proulsive plants.

Through its numerous articles, published since 1960 and regarding the problem of shaftings and related issues, BUREAU VERITAS has contributed to the generalization of alignment technology in French and foreign shipbuilding.

This department now called Research and Development Centre and located in Levallois near Paris has gradually become specialized in this field. Its personnel has acquired both a practical and theoretical experience in studying the behaviour of propulsive installations of all kinds.

The department's aim and role were not only to examine the theoretical aspect of alignment or realignment but also to offer assistance to shipyards and shipowners in producing rational alignments, precalculated and recommended by the department.

Requests for this kind of technical assistance were brought about by damages, such as :

- destruction or abnormal wear of the stern bearings of the shafting or of reduction gear bearings or of main engine bearings ;
- destruction of the bronze liner of the propeller shaft ;
- cracking or rupture of the propeller shaft or of the crankshaft ;
- pitting on the reduction gear ;
- natural vibrations of the shafting or of its supports ;
- vibrations of structures surrounding the shafting or the propulsion plant ;
- vibrations of the aft structure or superstructures ;
- cracking in steelworks supporting the engine or in the frame of the engine.

As this experimental and practical assistance was given, for a variety of ships, to many French and foreign shipyards, the various means for checks and measurements, necessary to insure the quality of assistance, gradually improved.

1 - WHY A STUDY OF ALIGNMENT

1 - Study of line shafting alignment conditions during outfitting or ship's operations.

The experience acquired in respect to the correct running of line shaftings and their bearings have proved that it is absolutely necessary to **assure correct and permanent contact conditions** between these two elements which are :

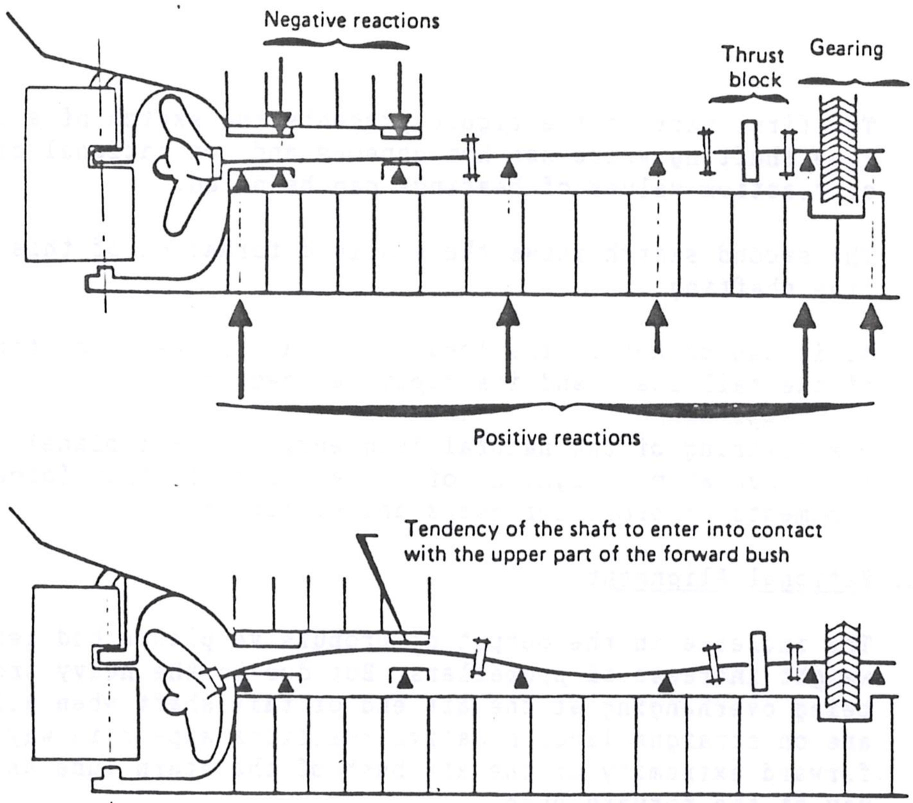
- the shaft with its natural deflection
- the support with its own characteristics (material stiffness).

1.1. Straight or light line alignment

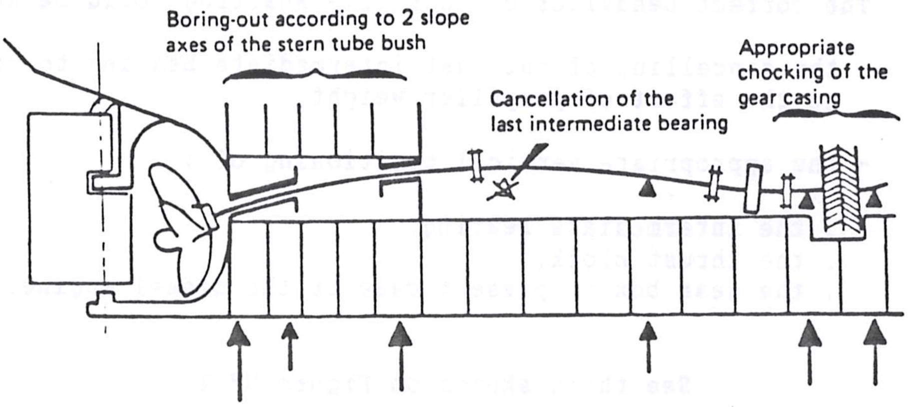
This type of alignment carried out previously has its origin in the technology of line shafting mounting for propulsive plants of old ships.

The light line being drawn before the launching of the ship and passing through the sighting marks does not longer exist, once the ship is afloat and even more after its completion (installation of the propulsive apparatus and the remaining equipment). Moreover this alignment during outfitting was then modified by the loading conditions of the ship and the corresponding deformations of the steel work. These facts have stimulated the researches related to the interaction between the hull girder and the line shafting which have led to give up the straight alignment and to introduce the curved alignment called rational alignment.

See Figure N° 1



- Non homogeneous and non rational distribution of the reactions of the bearings supports of a conventional line shafting



- Rational curved realignment of the conventional line shafting

Figure 1. The rational alignment. Why it is justified.

The first part of the figure presents the sketch of a classical line shafting where non homogeneous and non rational distribution of reaction values of bearings can be noted.

The second sketch shows the static deformation of this considered line shafting.

As it can be noted, the loss of contact between the forward part of the tail shaft and its supports leads to :

- a lowering of the natural frequency (lateral plane),
- an angular misalignment of propeller shaft from forces and moments of propeller means and harmonics.

1.2. Rational Alignment

The increase in the output of propulsive plants had led to the weight increase of propellers. But due to the heavy propeller being overhanging at the aft end of tail shaft when all bearings are on straight line, negative reactions appear in way of the forward extremity of the aft bush of the stern tube as well as in way of the forward bush.

These negative reactions together with the presence of radial clearance lead to a loss of contact between the journals and their respective supports.

The correct behaviour of this line shafting could be achieved by :

- the cancelling of the last intermediate bearing to counterbalance the effect of propeller weight,

- the appropriate vertical positioning of :

  . the intermediate bearing,
  . the thrust block,
  . the gear box in present case or the diesel engine.

See third sketch on Figure N° 1

1.3. Contact conditions between the journals of propeller shaft and bushing material of stern tube

See Figure N° 2

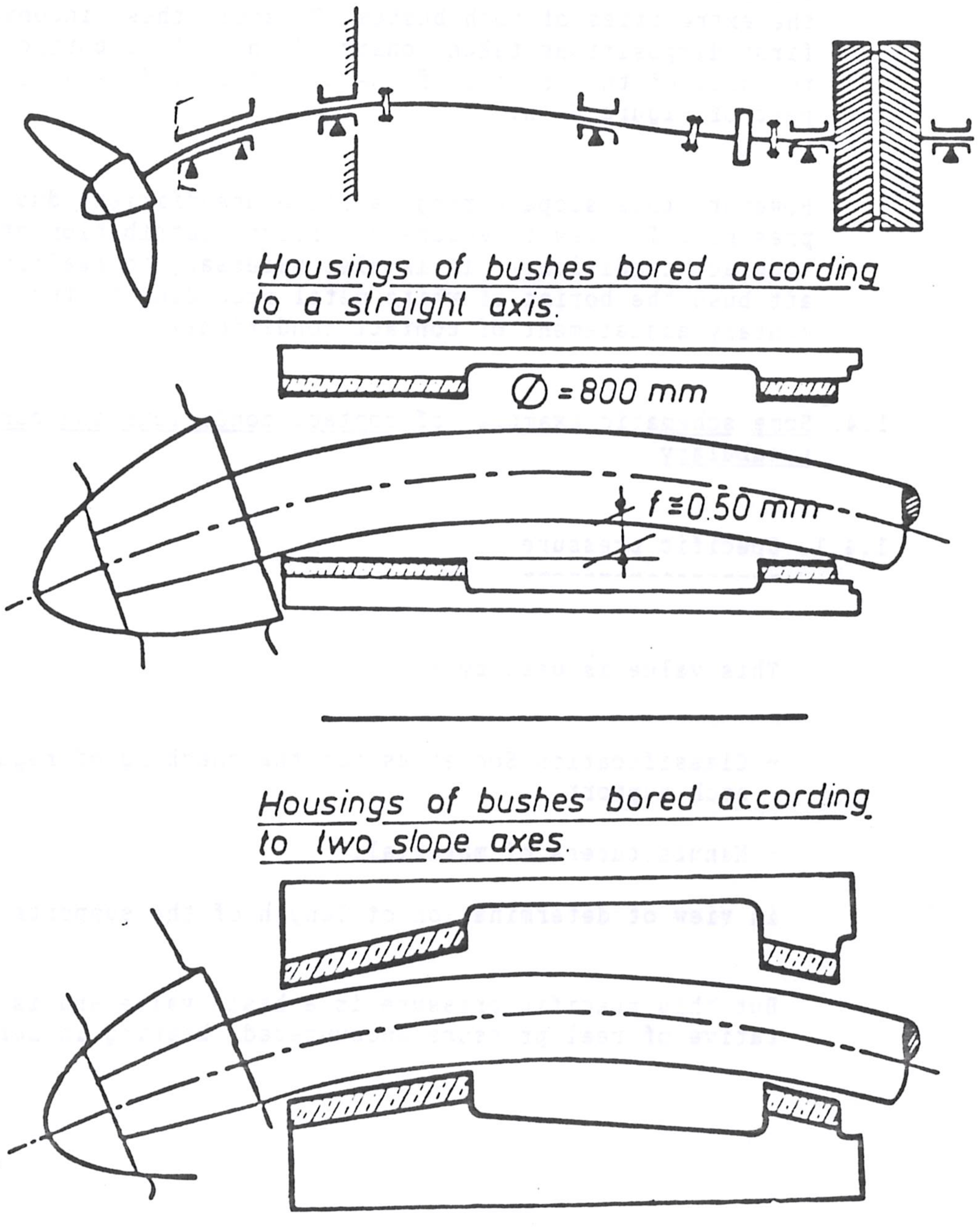


Figure 2 - Contact conditions between the tail shaft journals and two stern tube bushes

This figure presents a concrete example (shaft diameter : 800 mm) with two stern tube bushes.
Its natural deformation can be noted, leading to a hard contact at the extremities of both bushes. To avoid these inconveniences, the first dispositions taken consisted in a slope boring, according to two axes of the housing of the bushes as indicated on the lower part of Figure N° 2.

However, this slope boring is often unsufficient due to weights in presence. In view to ensure a correct distribution of the load (contact conditions), it is also necessary to realize in way of aft bush the boring of white metal according to two axes (supplementary adjustement of contact conditions).

1.4. Some schematic examples of contact conditions and corresponding vocabulary

1.4.1. Specific pressure

This value is used by :

- Classification Societies for the checking of regular length of each support,

- Manufacturers of material,

in view of determination of length of the supports.

But this specific pressure is a basic value and is not representative of real pressure encountered, bearing in service.

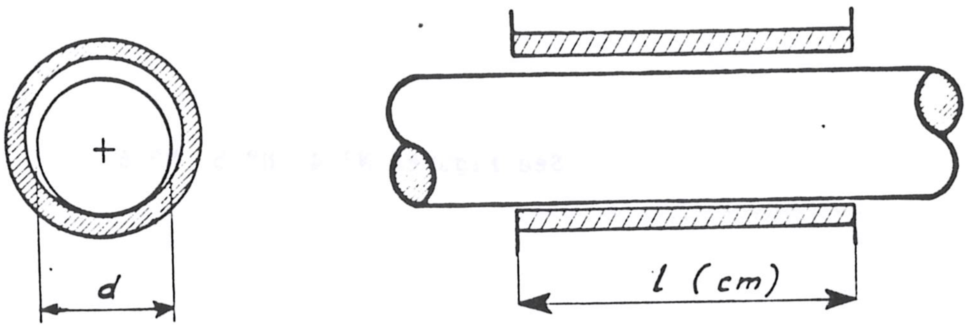
See Figure N° 3

Specific pressure $P_{sp} = \frac{load}{d \times l}$

P_{sp} in bars

load in Newton x 10.

in cm.



Same values of specific pressure used for supports of the line shafting.

- Lignum vitae, Rubber, Celoron (staves), in sea water:
  - Lignum vitae: 2 bars
  - Rubber: 2,5 to 3 bars
  - Celoron: 2,5 to 3 bars

- Synthetic material. — 7 to 9 bars
- White metal — 6 bars for stern tube; 9 bars for intermediate or crankshaft bearing

Figure 3. Specific pressure.

1.4.2. Real static pressure in the support

In order to explain the fundamental difference between the two vocabularies of pressure :

- specific and real,

the figures N° 4, N° 5, and N° 6 show several cases of alignment conditions (contact conditions) from extreme case of angular misalignment (Figure N° 4) to rational distribution of pressure (Figure N° 6).

See Figures N° 4, N° 5, N° 6

It is necessary to compare :

- the values of specific pressure situated between 2.5 and 9.5 bars with values of pressure encountered in concrete cases of line shaft from 100 bars till 200 bars (extreme case) in spite of good and regular specific pressure.

Example 1:

Extreme case of angular misalignment.

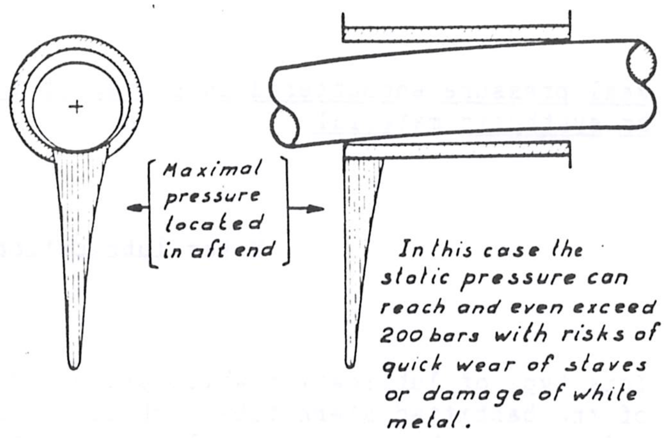
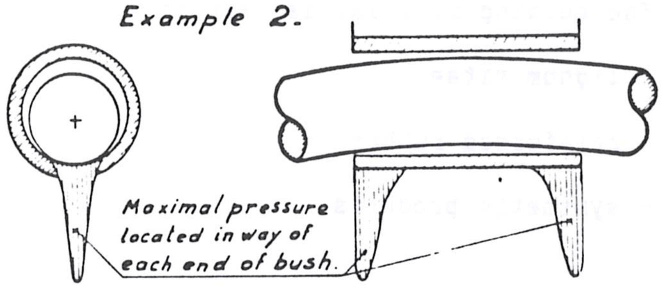


Figure 4. Extreme case of angular misalignment.

Example 2.

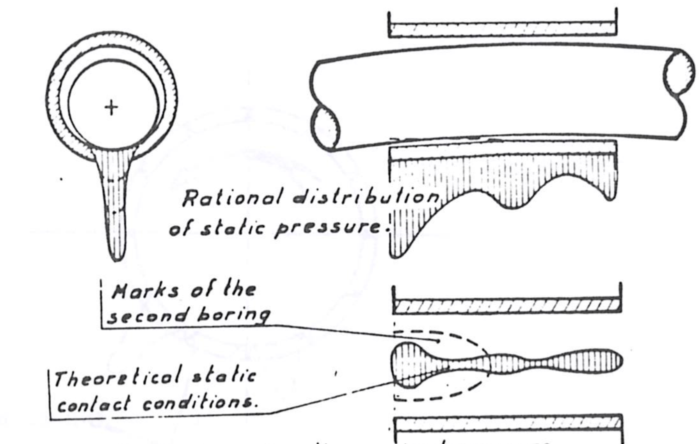


Typical distribution of static pressure (no rational) with aft bush bored according to a straight axis only.

Figure 5. Contact conditions in bush with straight profil of white metal.

Example 3.

Rational distribution of static load with bush bored according to two slope axes.



Nota: In this configuration, the maximal pressure is situated betwen 80 and 120 bars.

Figure 6. Optimal alignment conditions.

1.4.3. Real pressure encountered in staves of lignum vitae, rubber or synthetic material

Water lubrication

This type of lubrication which prevailed before the appearance of the babbitted stern tube bush is still often encountered on medium size ships and generally on military ships of all powers and fishing ships of all sizes.

The bushing material is made of :

- lignum vitae
- reinforced rubber
- synthetic products.

The grooves resulting of staves technology act unfavourably on pressure distribution.

In order to reduce the wear of staves, it could be recommended to foresee (navigation in sandy waters), at the project stage, a water circuit ensuring the forced entry of clean water.

Due to small viscosity of water, there is no formation of hydrodynamic film and consequently the wear occurs. Due to the difficulties in obtaining the optimal contact conditions, the real pressure reaches quickly 150 to 200 bars.

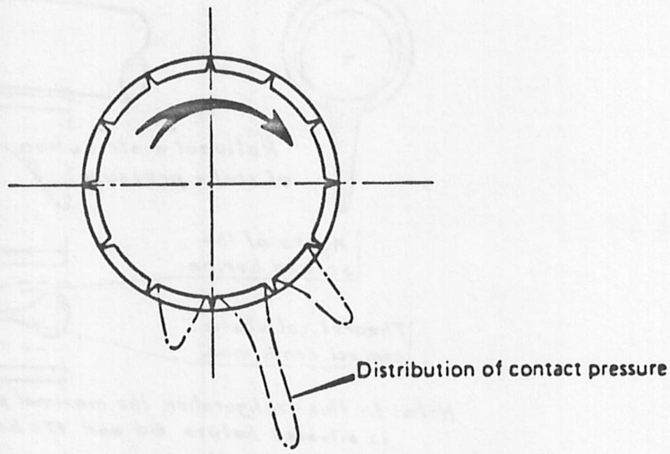


Figure 7. - Bushes with lignum vitae or rubber for water lubrication

1.4.4. Oil lubrication technology

The introduction of babbitted bushes lubricated by oil in the stern tube has the following essential advantages :

- elimination of white metal wear,

- elimination at normal speed of direct contact between the journal and the bushing material,

- improvement in damping characteristics of lubricated oil favoured by the reduction of the diametral clearances.

General Remakrs

Whatever the type of technology may be :

- water lubrication
  or :

- oil lubrication

the realization of correct and much more precised alignment conditions is requested (rational load distribution in way of each support of line shaft and optimal contact conditions in way of stern tube bushes).

1.5. Enumeration of essential phenomena which can act on the initial alignment conditions

1.5.1. Quick wear of staves

Progressive action of the wear on load distribution for other supports

See Figure N° 8

1.5.2. Effects of hydroelastic coupling between propeller and line shafting

See Figure N° 9 and N° 10

1.5.3. Tilting of thrust block acting on forward part of line shaft (gear box)

See Figure N° 11

1.5.4. Deformation of structure of doube bottom in way of engine room

See Figure N° 12

1.5.5. Forces and torque reactions from pressures acting on the wheel shaft of gear

See Figure N° 13

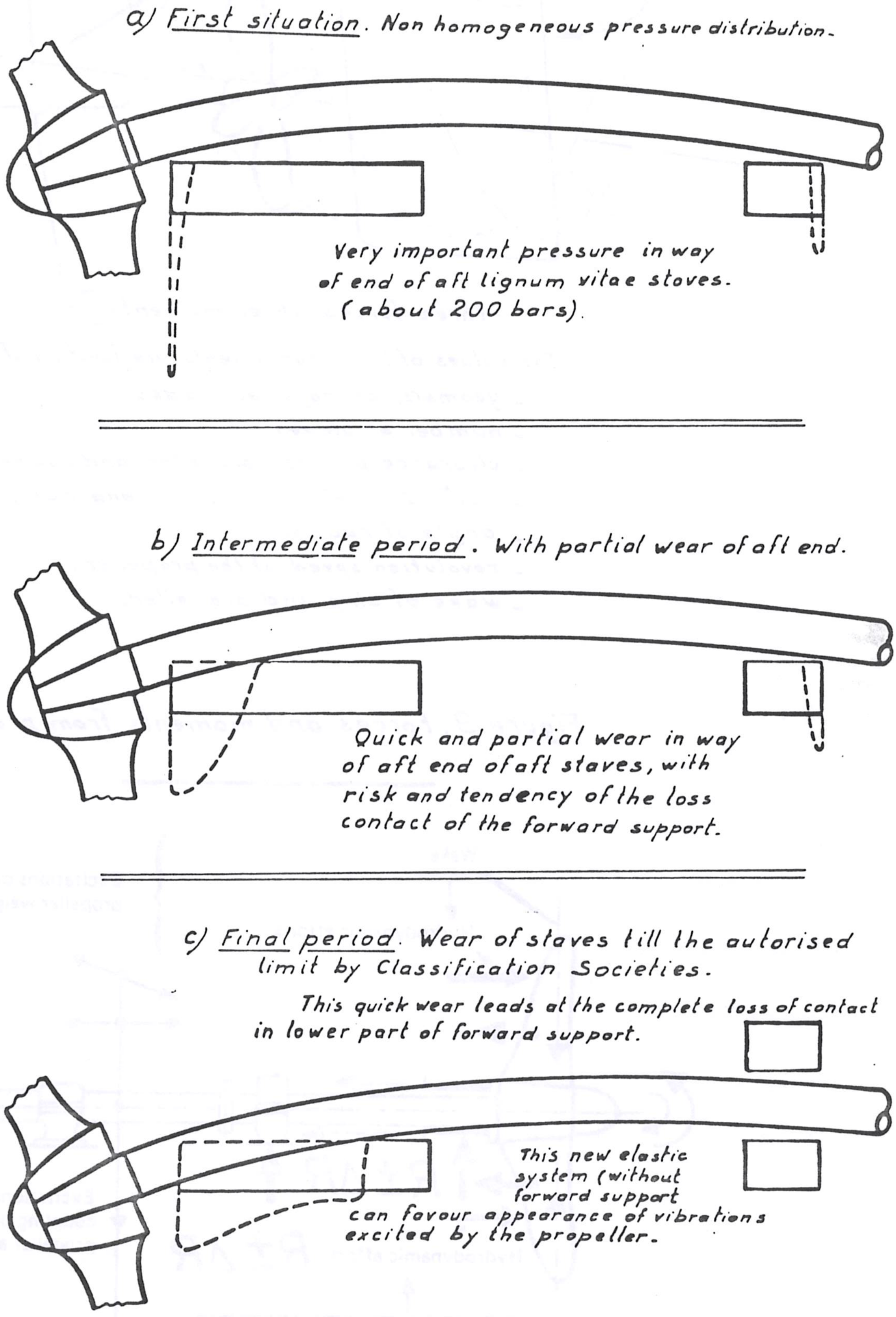
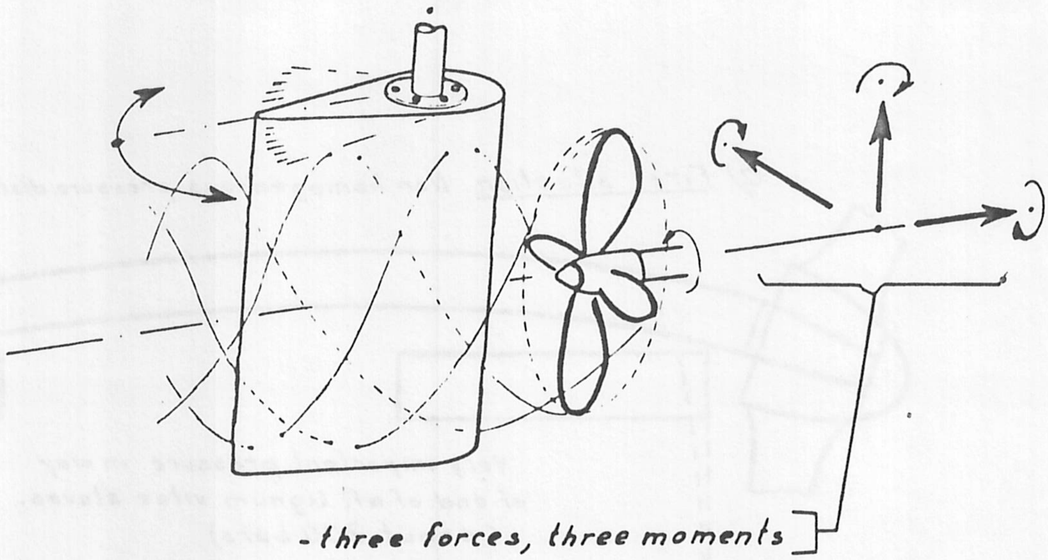


Figure 8. Film/process of wear on the original alignment conditions with staves of stern tube.



The values of these components are fonction of:

- geometry of propeller blades,
- number of blades,
- clearance between propeller and rudder,
- _ " _" d° " _ "_ and hull,
- angle of rudder,
- revolution speed of the propeller,
- wake of ship and propeller.

Figure 9. Forces and moments from propeller.

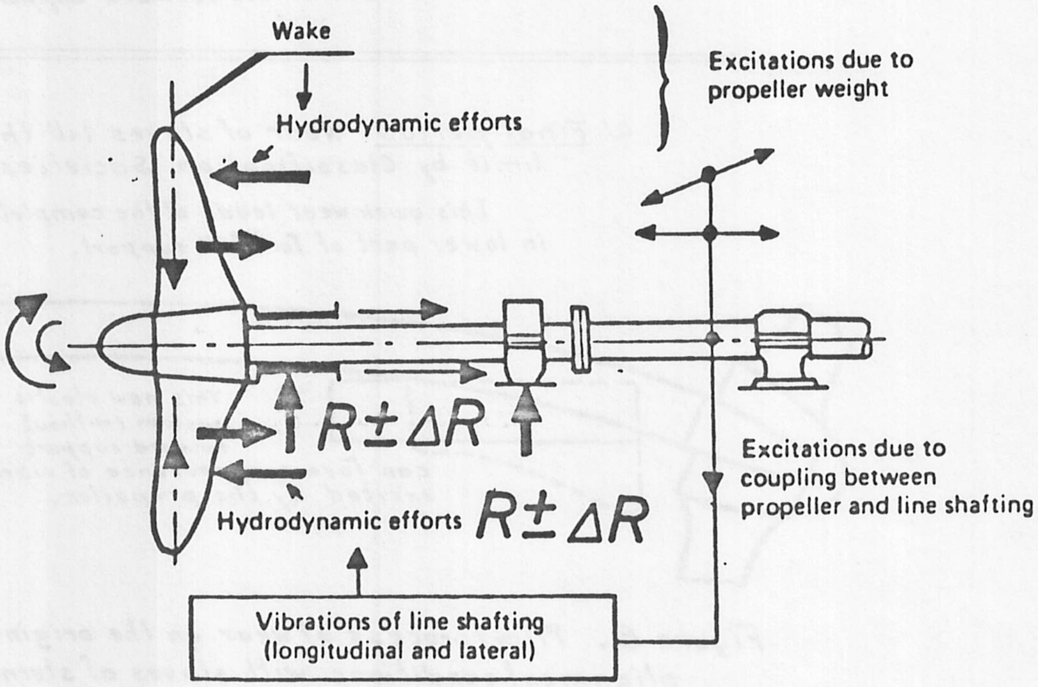
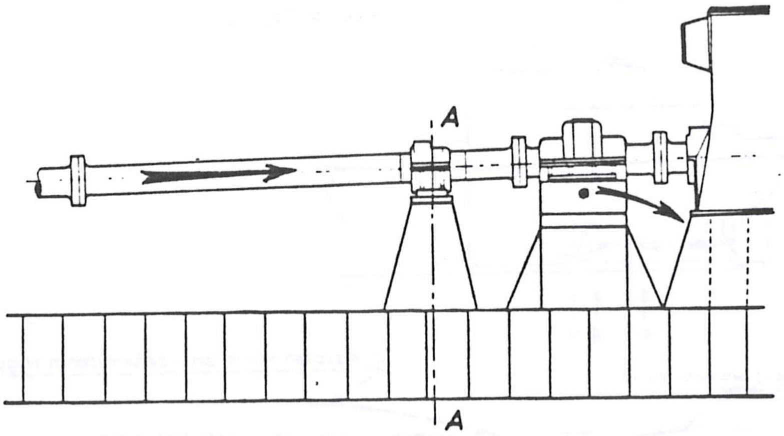
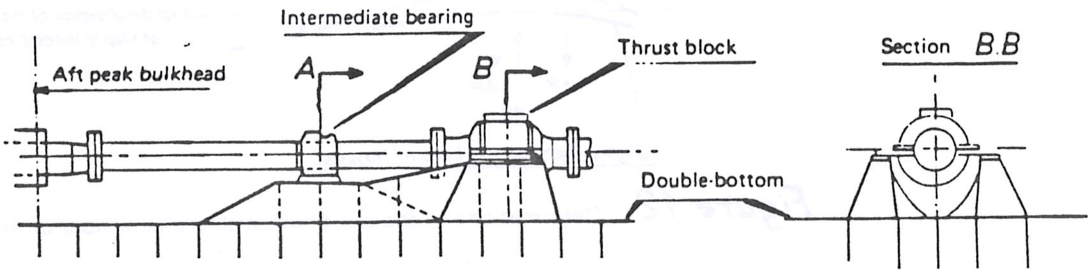


Figure 10 - Effects of hydroelastic coupling between propeller and line shafting



Independant cantilever type thrust block (not advised) with risk of pinions/wheel misalignment due to the tilting of thrust block (excessive bending moment in the shaft.



Improved design of the thrust block (height of the double - bottom increased)

Figure 11. Evolution of architecture of thrust block foundation.

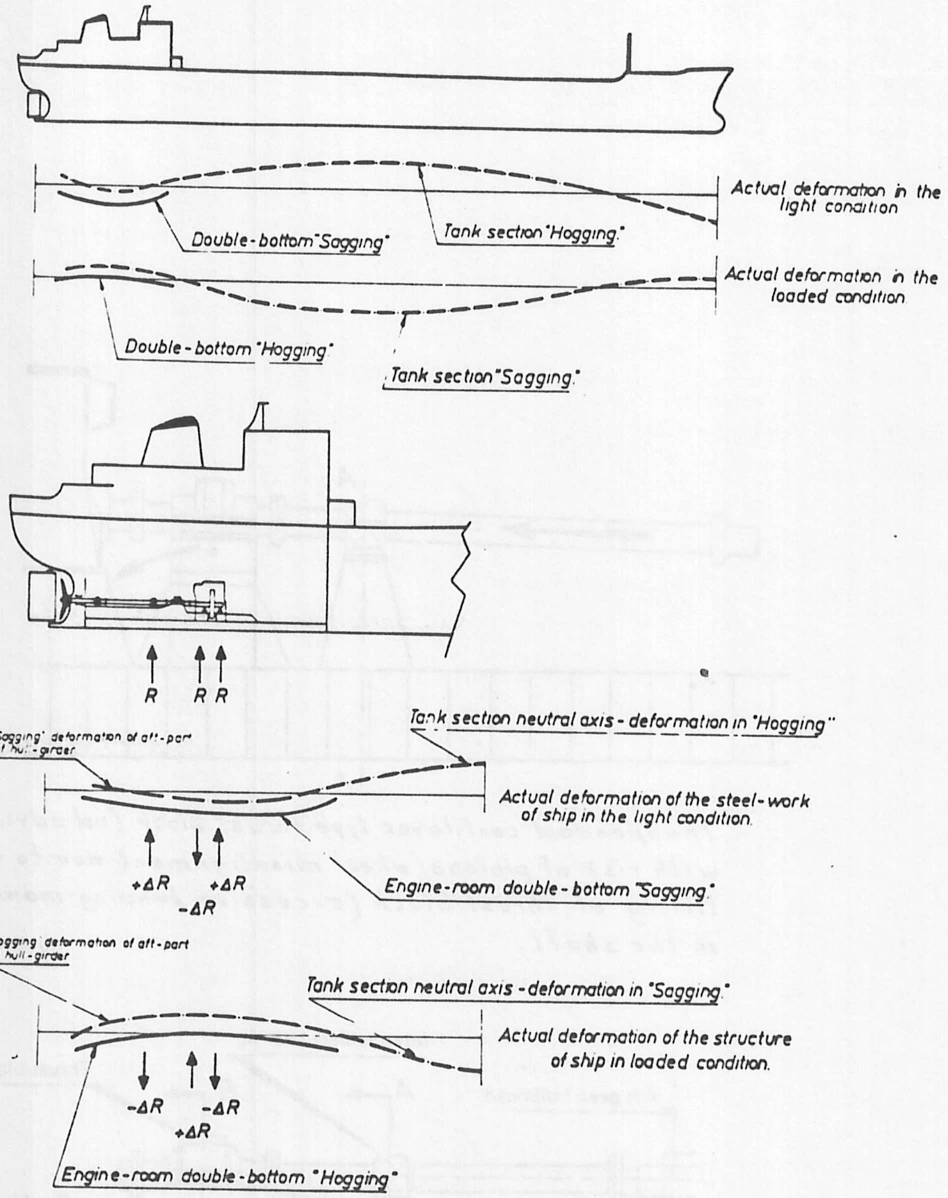


Figure 12. Deformations of the hull girder with the behaviour of the engine room located aft

LOOKING FORWARD

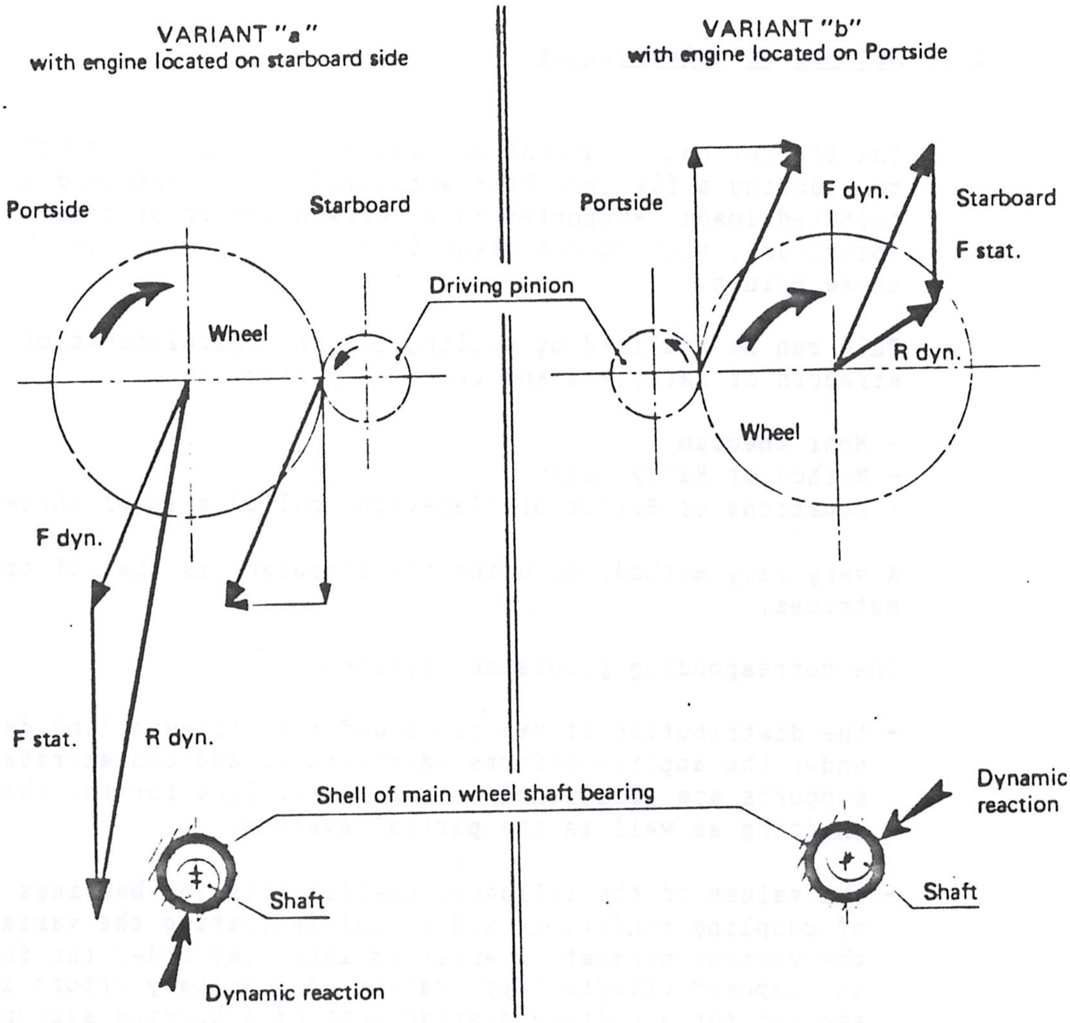


Figure 13. Polygon of forces and torque reactions of the gearing - Two variants of pinion position.

2 - HOW TO DO

2.1. Methods of calculations

The theoretical treatment of alignment conditions consists in considering a flexible beam submitted to concentrated and distributed loads, supported in a certain number of points (bearings), with forces (reactions) or displacements imposed at these points.

This can be realized by calling for the calculations of the strength of materials and using in particular :

- Mohr theorem,
- Method of Hardy-Cross,
- Equations of Bertot or Clapeyron, called aslo of three moments.

A very easy method, by using the computer, is that of transfer matrices.

The corresponding programme provides :

- the distribution of reactions and the corresponding deformations under the applied efforts (distributed and concentrated) if the supports are positioned on a straight line for the whole line shafting as well as the partial systems,

- the values of the influence coefficients (of bearings as well as of coupling conditions and so on) indicating the variation of the various parameters entering into play under the influence of the imposed efforts (application of a unitary effort in way of a section for a unitary displacement of a bearing/support, and so on...)

Using these basic calculations, it is then proceeded to the calculations concerning the judicious and rational distribution of reactions according to the inherent criteria of the various parts or types of propulsion plants which will be dealt with later. Once having realized this rational distribution, it is proceeded to the calculations concerning the practical realization of the precalculated rational alignment.

Parameters necessary for rational alignment calculations

- Weight and stiffness ($\frac{I}{\ell^3}$) of the line shafting

- Weight of : propeller (and its density), helmet, and so on.
  various accessories of the line shafting (servo-motor, flywheel).
  main gearings (wheel, pinions, and so on).
  crankshaft, piston assemblies, and so on.

- Position of the equivalent point(s) of support (preferably of the contact conditions mainly in way of the stern tube bush(es) of the supports or the bearings of the line shafting as well as the permissible mean and maximum pressures of each shell of the line shafting supports.

- Stiffness (infinite or not) of the steel work on which rest the supports/bearings of the line shafting.

- Stiffness of the bushing material of supports and/or bearings.

- Eventually conditions of building-up of oil film (temperature, minimum pressure, attitude angle).

- Values of thermal expansion of :

  . all supports/bearings

  . gearing casing

  . bed plate of the main engine(s)

  . steel work supporting the above mentioned elements.

- Displacement of the mobile(s) of the main gearing(s) as function of the polygon of forces (and eventually of the oil film).

- Maximum permissible values of desequilibrium of reactions between the bearings of the main wheel shaft during normal operation.

- Values of maximum bending moments and shearing forces which can be introduced in the thrust shaft and the crankshaft when coupling, during outfitting alignment conditions.

- Values of vertical and transverse deformations of the steel work (eventually) due to :

  . loading conditions

  . sea state

  . action of the thrust on the thrust block

- Mean values of the four components of the efforts (forces Z, Y and moments M, N) appearing on the propeller.

See paragraph 1.5.

2.2. Practical realization of the rational alignment

Before passing to the practical realization of the alignment, it is indispensable :

- to have the results of a certain number of auxiliary calculations necessary for preparing this practical realization,

- to carry out the calculations of the judicious and rational distribution of reactions to be realized in way of the bearings/supports of the line shafting,

- to have the data issued from previous calculations and related to :

  . the boring out of stern tube(s)
  . as well as the positioning of all line shafting bearings, those of the propulsion apparatus included.

The practical operations of alignment are carried out : (* see remark)

- starting by the positioning of the tail shaft,

- continuing by the positioning of the various sections of the intermediate shaft(s) and the thrust shaft in respect to the tail shaft,

- ending by the positioning of the shafts of the propulsion apparatus :

  . the main wheel shaft
  . or the crankshaft.

Important remark : It is strongly recommended to follow this chronology of practical operations.

2.2.1. Boring-out of stern tube(s)

Once having realized the rational distribution of reaction of all bearings and being in possession of the data concerning the relative position of the propulsion apparatus in respect to the stern tube, it can be proceeded to the boring-out of the last one. This boring-out can be carried out in two different ways :

- either straight
- or sloped.

But it must be carried out when all weldings of the neighbouring steel work of the aftbody of the ship are completed.

See Figure N° 2

a) Straight boring-out according to light line

The rational alignment consisting in the realization of a precalculated deformation of the line shafting is obtained by the positioning in space of different supports/bearings in relation one to the other, according to precalculated values. In case of straight boring-out of the stern tube, determined by a straight line drawn from the propulsion apparatus (i.e. parallel to the basic line for instance), the positioning of the propulsion apparatus will probably require its chocking in respect to the inclined line. This leads to foresee the execution of inclined chocks of variable thickness. In view to simplifying the chocking operation, it could be foreseen a sloped machining of the surface of the basis of the foundations of the propulsion apparatus, in order to allow the use of chocks having the same thickness.

b) Slope boring-out

From the straight line drawn from the propulsion apparatus, it is necessary to foresee in way of the stern tube bush(es) a slope boring of the housing of the bush(es). Once the tail shaft is installed in the bush(es), it will be then possible to realize the desired deformation of the line shafting so that during the mounting and alignment of the shaft of the propulsion apparatus, it can be parallel to the basic line and the machined surface of the foundations being also parallel to the basic line and the machined surface of the foundations being also parallel to this basic line.

These two techniques are quite equivalent, their choice depends on the habits and experience of the shipyard.

2.2.2. Checking of boring-out

Once the boring-out has been realized according to one of the described techniques, the stern tube manufactured and bored-out in workshop being installed and definitively fixed, it is very important and even indispensable (mainly for the stern tube with two bushes) to check as accurately as possible the exact size of the boring for the definitive axes of the bushes and their relative positions.

The experience proves that for different reasons it happens that these values do not correspond to the precalculated ones and this can lead to incidents during operations, even during trials at quay. If such a difference is noted in time, it can be corrected, generally easily, by acting on the profile of the white metal of the bush(es).

This checking can be carried out by means of :

- optical device,

- piano wires,

- or even from the coupling conditions (for the realignment) with checking of the contact conditions by blue marker.

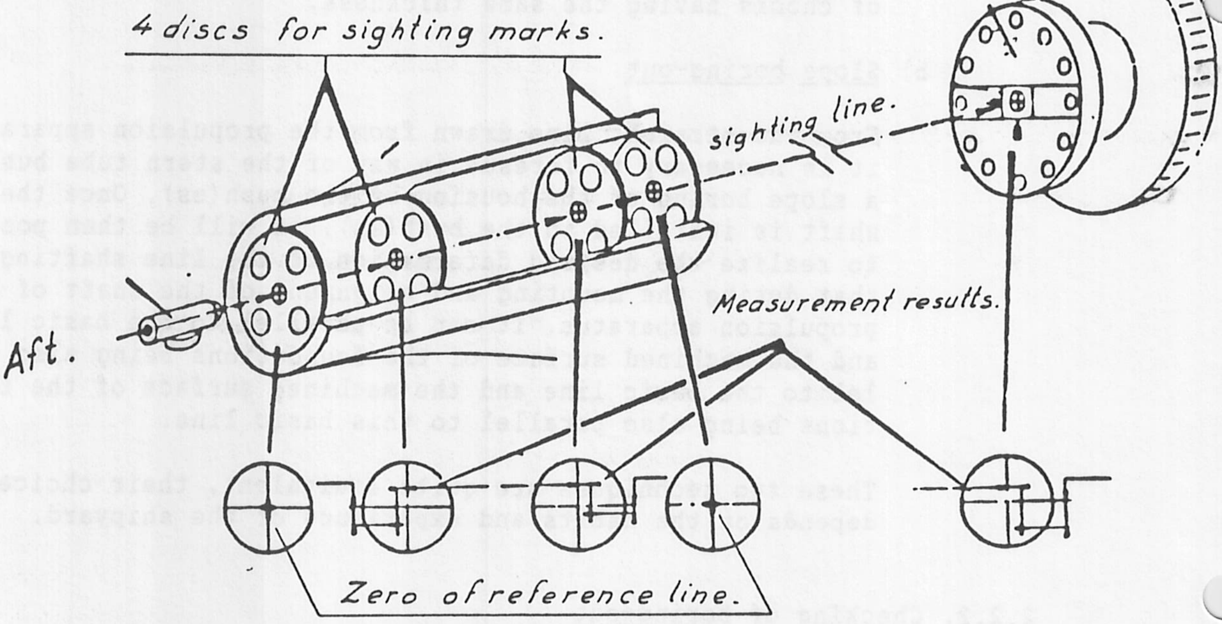


Figure 14. Example of complete optical check of stern tube.

2.2.3. Positioning of bearings/supports

a) Alignment (or re-alignment) conditions

Once the tail shaft introduced in the bush(es) of the stern tube (or in a bush and the last intermediate bearing) and once the propeller as well as the oiltight devices are mounted, the ship can be put afloat. In fact, it is highly recommended to realize the definitive positioning of the bearings of the whole line shafting afloat, with a maximum aft draft (the filling of the aft peak is highly recommended) in order to come as near as possible to the normal running conditions of the line shaft. Moreover, it is not recommended to proceed to the definitive alignment, the ship being on building blocks, either in drydock or in floating dock.

b) Method of the straight or light line and sighting marks

The positioning of bearings to obtain the precalculated deformation of the line shafting can be realized in putting the bearing axes according to the sighting marks and determined from the straight line drawn from the propulsion apparatus.

c) Method of sag and gap (values of eccentricity and opening of couplings)

This method is at present the most used due to its flexibility of application and the good results obtained in its correct application.

In fact, it consists in realizing the precalculated coupling conditions between the different partial isostatic systems of the line shafting assembly. When these conditions are realized, this means that the bearings supporting the line shafting are located on precalculated positions which, once the couplings being bolted, will impose the desired reactions to the line shafting bearings.
On Figure N° 15, is shown the line shafting, called short, of a propulsion plant where it can be noted its division in four partial systems. The attention is drawn on the introduction of three provisional supports enabling the realization of the coupling conditions A, B, and C as described above.

See Figure N° 15

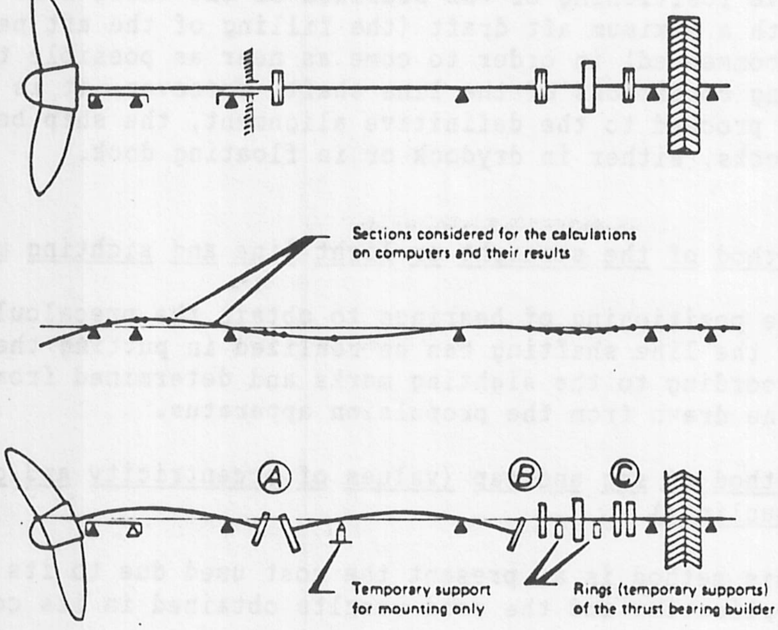


Figure 15. Rational alignment calculation.
Transformation in isostatic systems in view of theoretical coupling conditions.

2.2.4. <u>Checking of the alignment during outfitting</u>

The method of alignment according to the values of sag and gap is already a checking of the alignment conditions. However, some additional checkings can be either recommended or used in case of need :

a) checking by blue marker

b) checking of contact by means of fillers

c) checking of reaction values.

- Jack-up tests

This method is based on the principle that, for a beam of a given span, the deflection under the influence of a force is a linear function $f_\ell = f(\Delta R)$.

It consists in determining experimentally this function by lifting or lowering a bearing. Once in possession of the curves representing the influence coefficient of the considered bearing, it is deducted its reaction value. This principle is shown graphically on the Figure N° 16 :

- by strain gauges and measurements of bending moments.

To apply this method, it is necessary to have a programme of calculations on computer enabling to calculate the reactions of the supports from the measurements of bending moments and to install, along the line shafting to be studied, strain gauge bridges sticked on the line shafting.

See Figure N° 16

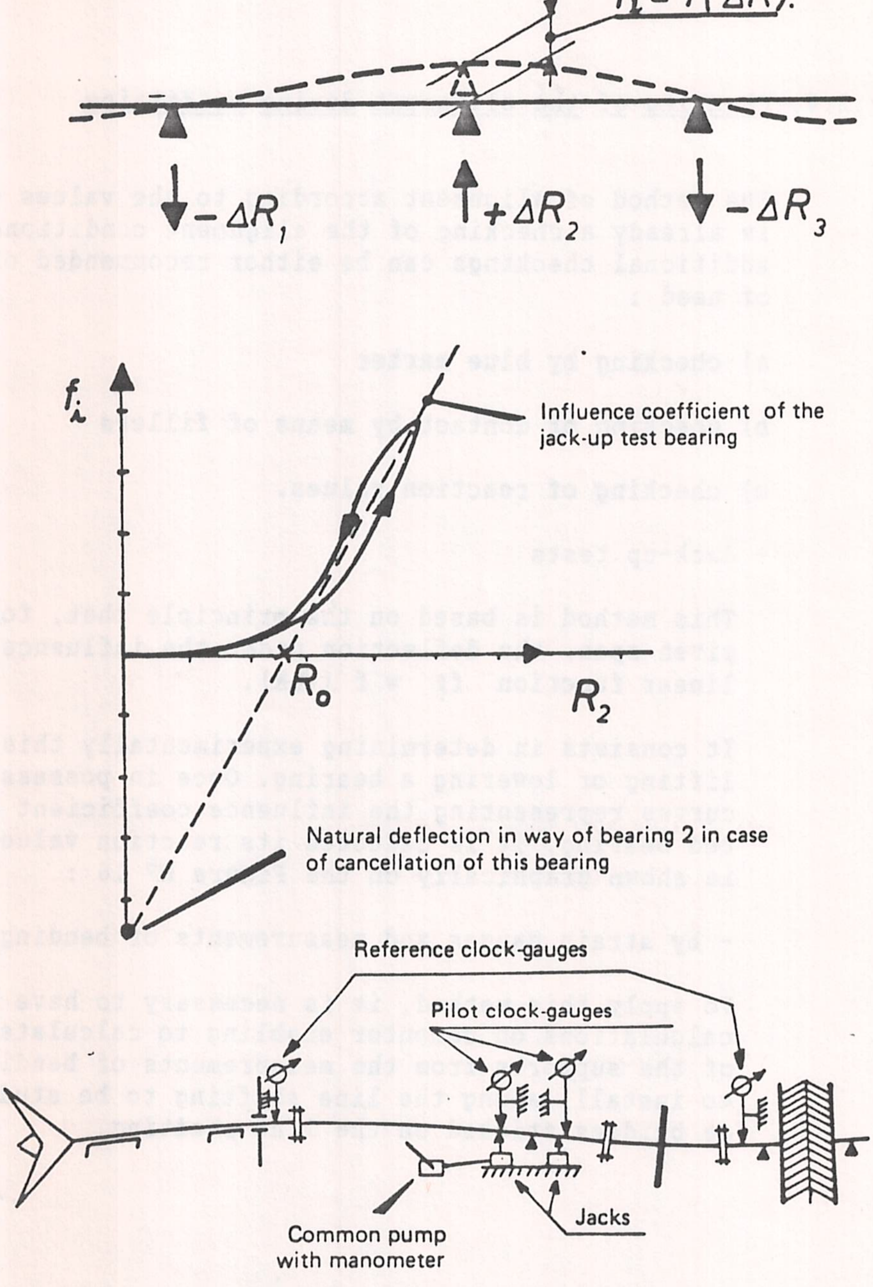


Figure 16. Principle of jack-up tests of bearing reactions

d) **Tolerances of specific pressure and reaction values**

As regards the tolerances of reaction values, the following comments can be presented.

The experience proved that generally the tolerances on the intrinsic values of bearing reactions are relatively great provided that :

. the line shafting is flexible,

. the deformations of the steel work are not too important,

. there is no concentration of hard contact on the journal shells,

. the possibility of cooling of the lubricant are compatible with the heat created by the friction in the bearing,

. there are no abnormal external influences affecting the correct beha-viour of the line shafting.

e) **Checking of the alignment in service**

The experience has shown that the conditions of alignment during outfitting are modified during operation. For this reason, certain dispositions could be taken in order to check the correct behaviour of the bearings/supports and the journals of the various parts of the line shafting. The following checkings may be recommended :

- measurements of temperature and pressure,

- measurements of the displacements of the journals,

- measurements of bearing reactions after a period of relaxation,

- measurements of the deformations of the double-bottom steel work.