EARLY DIAGNOSTICS OF REAL TIME TECHNICAL CONDITION OF STEEL SHAFTS

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Abstract. Testing of mechanical stresses in steel shafts by means of the magnetic method is proposed in the article. This method is referred to nondestructive methods. The growth and concentration of mechanical stresses result in micro-cracks and their enlargement. Further growth of micro-cracks can lead to a severe accident - damage to the shaft. Replacing of the shaft is a very expensive operation. The authors propose a testing and monitoring method based on the dependence of the ferromagnetic material magnetic properties on mechanical stresses.

Keywords: mechanical stress, micro-cracks, magnetic permeability, electro-motive force, magnetisation, coercive force, hysteresis loop, bending, torsion, compression.

Introduction

A method of monitoring of the steel shafts condition is suggested in the paper. The method is related to a kind of non-destructive methods of control. It is based on the dependence of magnetic properties of the material on mechanical stresses and elastic deformations. The concentration of the mechanical stresses results in micro-cracks and their further enlargement that in its turn leads to an accident. The early technical diagnostics allows estimating the residual life of the equipment. Shaft is an expensive product, manufactured at special industrial enterprises with an extremely high accuracy. Its replacement requires a vessel to be installed at a dock, attracting highly qualified personnel and considerable time of work. Due to the considerable length the shaft is made of multiple intermediate shafts. Particularly topical is the early diagnostics of the shaft technical condition at the vessels of early construction being in operation for 15-25 years. A continuous usage of modern monitoring and diagnostics equipment to determine the current state of the shaft to detect defects at an early stage of their development is economically feasible. This paper proposes such system of early diagnostics with stationary fixed coils placed in the bearings of the shaft.

Regular detailed examination is made only with the negative results of the measurements of the conventional means of early diagnostics. The expenses of ship-owners for the propeller (intermediate) shaft replacement in the case of sudden failure are about 6 times higher than those for the planned replacement of the shaft resulted from early diagnostics [1]. The main places of the crack possible origin in the shafts [2] are shown in Fig.1.

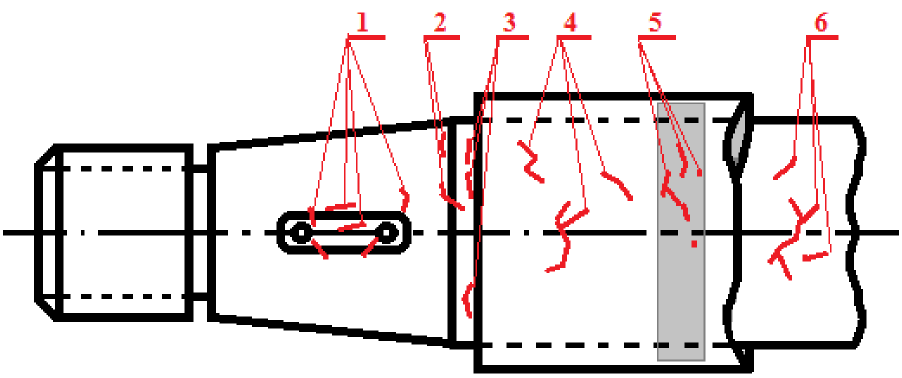
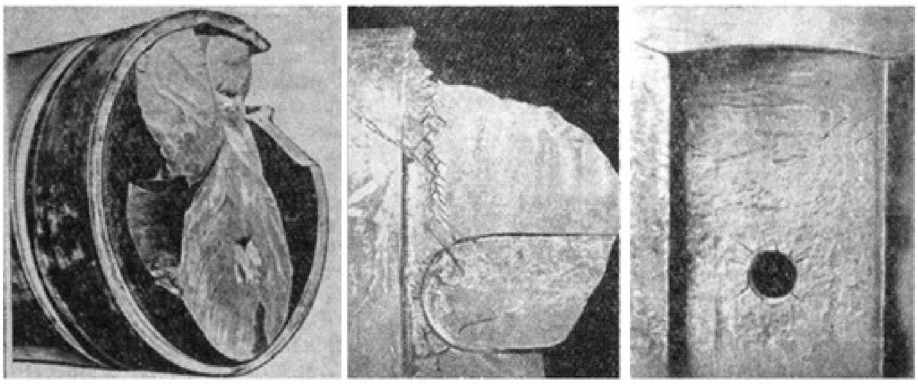


Fig. 1. **Main locations of the crack possible origin in the shaft:** 1 – in the slot, close to it with the progress of cracks deep into the shaft body in the fastening holes; 2 – in the places of transition of the cone into a cylindrical form shaft; 3 – at the front and edges of the shaft sides; 4 – cracks in the walls of the shaft; 5 – in the welding and heat affected zones; 6 – directly in the body of the shaft

The most dangerous damages of the shafts are the fatigue cracks. Fatigue crack arises in the surface layers and then it is developed deeper into the shaft, forming an incision of sharp form. Such cracks strongly concentrate the stresses, which result in the destruction of the shaft with cyclic loads [1]. The formation of cracks in the area of slots (Fig. 2 a and b) and holes for fixing the key in the slot is typical for shafts and takes place due to the fact that the slots and holes concentrate the stresses in the shaft. The presence of cracks in large diameter of the cone (Fig. 1, Nr. 2) of the screw shaft is resulted from the maximum loads in this section of the shaft.



a) b) c)

Fig. 2. **Destruction of the shaft in the area of the slot**

The diameter of the shaft is form 400 mm to 600 mm and even more. The total length of the shaft can be within the range from 6 m to 15-18 m, and the shaft in this case is made of several intermediate countershafts [3]. The use of early diagnostics of the technical condition is also very important for the shafts of turbines and generators at hydro and thermal power plants, large gas-pumping units, etc.

Materials and methods

A lot of methods are proposed to control the mechanical stresses in steel elements – among them there are the visual, optical, strain gauge, fluoroscopic, ultrasound, magnetic (using metal magnetic memory effect, eddy current, etc.), acoustic emission, capillary, etc. [4-7].

The methods of control of the steel shaft technical condition are divided into 3 groups: 1.Vibration methods; 2. Analytical or numerical methods; 3. Methods of magnetic control of metal condition.

In the first group the problem is focused on monitoring and diagnostics of the shaft on the basis of experimental investigations [8; 9]. The examining is based on the vibration method. In [9] a shaft is experimentally investigated on the basis of the analysis of the spectrum of vibration-frequency signals. In papersthe equipment for research and investigations in various directions of the shaft cross-section is considered [10; 11]. The second group represents the problem in the form of mathematical models and functional analytical dependencies [12], as well as the investigations of the shaft condition monitoring on the basis of the finite element method.

The third group includes the works devoted to magneto-electric monitoring of the metal shaft. Influence of mechanical stresses on the magnetic properties of steel materials is known for a relatively long time. There is a whole class of magnetically an isotropic sensors of mechanical stresses [15-17], the devices using the magneto-striction effect, etc. The use of magneto - electric methods does not require special preparation of the surface of a steel element.

The electromagnetic control methods are based on the measuring of the magnetic parameters (magnetic noise (Barkhausen jumps), oercive force [18; 19], magnetic permeability, change of the hysteresis loop form, residual magnetization), which are associated with mechanical stresses.

The papers [18; 19] show the dependence of the mechanical stresses of metal on its magnetic permeability in mutually perpendicular directions. The converter signal proportional to the changing in the magnetic permeability of metal linearly depends on the value of the mechanical stress:

$$\Delta\mu = K\sigma, \tag{1}$$

where $\Delta\mu$ – increasing of relative magnetic permeability of metal,
K – constant factor depending on the physical properties of metal.

In general terms, the magnetic induction in the core can be written as a function of two variables: magnetic field strength H and the value of stress σ.

$$B = f(H, \sigma). \tag{2}$$

As H and σ are the functions of time, the full differential of magnetic induction B is:

$$dB = \frac{dB}{dH}dH + \frac{\partial B}{\partial \sigma}d\sigma, \tag{3}$$

where first component on the right side of the equation is induction of stationary state $B_{st.}$;
the second component is the induction of non-stationary state (compression – tension, bending, torsion) B_{mv}. , i.e. $B = B_{st} + B_{mv}$;
σ – mechanic stress, $N \cdot mm^{-2}$;
B_{st} – induction with absence of mechanic stress, T;
B_{mv} – induction with presence of mechanic stresses (compression – tension, bending, torsion), T.

In its simplest approach the principle of continuous monitoring of mechanical stresses requires a fixed magnetization coil fed with alternating current, and placed on one side of a steel shaft; a fixed receiving coil on the other side of the shaft. The magnetic circuit is a steel shaft itself. Both coils are around the shaft with a minimum air gap. The proposed scheme is a type of transformer magnetoelastic sensor of mechanical stresses.

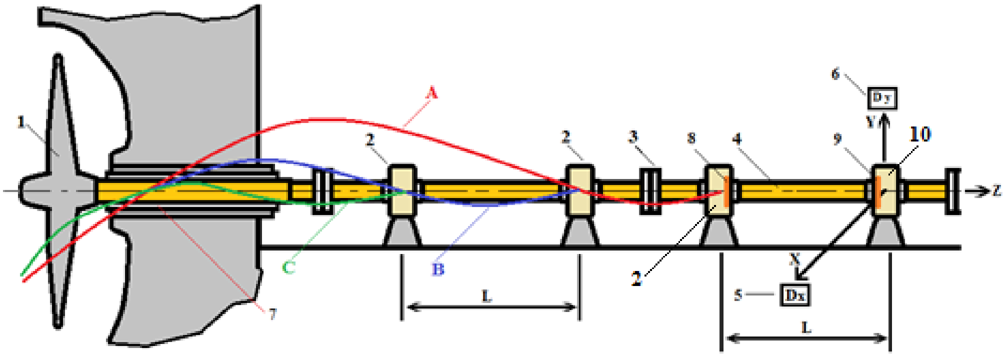


Fig. 3. **Location of magnetizing and receiving coils, curves of the shaft line in the case of transversal vibration:** A – curve in the case of unloaded bearings; B – curve with loaded deadwood bearing; C – curve with loaded deadwood and aft bearings; 1 – propeller; 2 – bearings; 3 – clutches; 4 – section of the propeller shaft; 5 – vibro-sensor in the horizontal surface along the X-axis; 6 – vibration sensor in the vertical sensor along the Y-axis; 7 – deadwood; 8 – magnetization coil; 9 – receiving coil. 10 – thrust bearing

The propeller shaft while operating experiences alternating torsional (due to non-uniform water flow around the propeller), mechanical loads (flexures of the shaft – curves A, B,C- Fig. 3),- from the deformation of the hull on waves, manoeuvres, etc. The propeller also experiences a considerable compression-tension stresses from the lock propeller while the ship is moving forward and back. The forces of compression-tension are transmitted to the thrust bearing, rigidly connected to the hull of the vessel. Vibrations, mechanical stresses form deformation of the hull on waves, maneuvers, etc.

In the first approximation, the shaft can be represented as a long rod with a ratio l/d We can assume that the rod experiences mechanical stresses of compression, tension, stretching, bending, torsion.

a) **Mechanical stresses in compression – tension** are described with Euler formula [21]:

$$\sigma = \frac{N}{A}, \ (N \cdot mm^{-2} = MPa) \tag{4}$$

where N – longitudinal force, N;
A – area of the rod, mm^2.

b) **Mechanical stresses in a simple case of flat bending** of the rod are described with the formula [21] – with the Z-axis directed along the axis of the rod; -axis lies in the plane of bending; point O coincides with the center of gravity of the rod (Fig. 4):

$$\sigma = -\frac{M_X}{W_x}, \ (\mathrm{N \cdot mm^{-2} = MPa}) \tag{5}$$

where M_X – bending torque, Nm;
W_x – resistive torque at bending, for a bar of round cross-section it is equal to

$$W_x = \frac{\pi d^3}{32}.$$

Fig. 4. **Flat bending of the rod in the area of Y-axis**

Some types of the stress of the shaft are given in Fig. 3. Curved A, B, C.

c) **Mechanical stresses in case of torsion rod**. While being influenced with torsional torque M_κ the cross-section areas of the rod remain plane (Bernoulli's hypothesis) and are not deformed, but turned around the Z-axis for angle φ, [20].

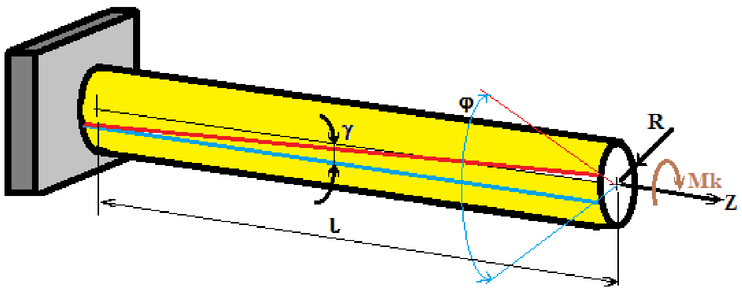


Fig. 5. **Torsion of the circular rod**

The shear stresses are:

$$\tau = \frac{M_k}{J_p} R, \tag{6}$$

where M_κ – rotating torque, Nm;
J_p – pole moment of inertia,

$$J_p = 2\pi \int_0^R r^3 dr = \frac{\pi R^4}{2} = \frac{\pi d^4}{32};$$

R – radius of the rod;
r – present radius of the circular layer of the rod.

If the turn angle of the end cross-section of the rod is φ, then the angle of the shifting γ along radius R:

$$\gamma = \frac{\varphi(l) R}{l}. \tag{7}$$

Value

$$\frac{\varphi(l)}{l} = \Theta \quad (8)$$

is an angle of the angle of twist per unit of the length of the rod.

In accordance with Hooke's law the share stresses are:

$$\tau = G\gamma = G\Theta r, \quad (9)$$

where Θ – module of the shift.

While the torsion of the round rod the shear stresses are linearly distributed along the radius. The angle of rotation of the end section of the rod is:

$$\varphi(l) = \frac{M_k l}{GJ_p}. \quad (10)$$

For experimental verification of dependencies and searching for optimal parameters of electromagnetic elements the experimental prototype was created – on the basis of the turning lathe 1K62 Fig.6.

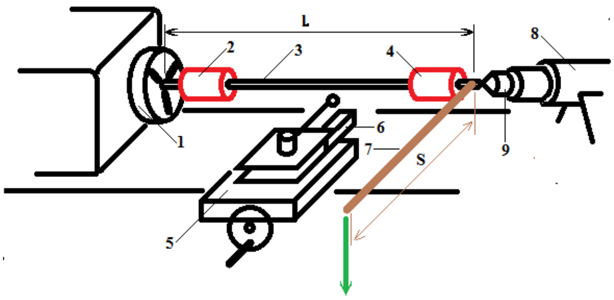


Fig. 6. **Scheme of the experiment:** 1 – spindle; 2 – magnetization coil; 3 – rod; 4 – receiving coil; 5 – direction of traverse; 6 – stop; 7 – lever; 8 – end head; 9 – rotating center

Coils 2 and 4 are placed on the bar 3 (fig. 6). If necessary, the two coils can be moved along the rod. The front end of the rod is clamped in the patron 1. The patron 1 is locked without rotation. The patron 1 is stopped – not rotating. This end of the bar can be assumed stationary and rigidly fixed. The opposite end of the rod is urged with the rotating center 9 of the end head 8. In this part the bar can rotate under the influence of forces. The rotating torque is created by the lever 7 of S length. The bending torque is created by stop 6. The compression force is created by extension of the end head 8, 9. The movement of stop 6 and the end head is measured by the relevant limbs of the bench. Material of the rod is steel 10, diameter- 18 mm, length – 1100 mm. The active length of the bar is 830 mm. Ratio l/d = 41.1.

Electromagnetic diagram of the experiment is given in Fig. 7. Numeration of the elements continues that of Fig. 6.

Computer 11 amplifies EMF of the receiving coil 4,providing comparison in the frequency from amplitude and phase with the reference (magnetizing) signal supplied to the magnetisation coil 2. The hysteresis loop area is calculated, its basic points are determined. The operating principle of the magneto-anisotropic converter is based on the effect of rotation of the magnetic induction vector B, produced by the primary winding in the measurement area. EMF induced in the measuring coil 4 can be described by the following formula [2]:

$$E = KB_{midl} S_0 f \sin \beta\omega , \quad (11)$$

where B_{midl} – average value of induction, T;
S_o – area of the winding, mm^2;
K – proportional factor;
β – angle between the surface of the measuring winding and the vector of magnetic induction, B;
f – frequency of the supply voltage, Hz;
ω – number of turns.

The formula is obtained for similar direction of vectors δ and β.

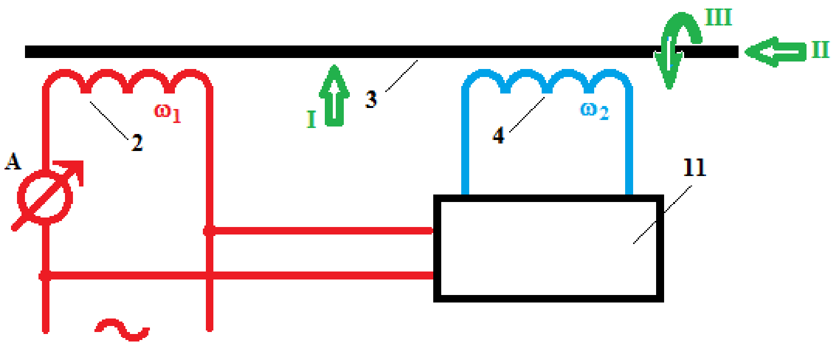


Fig. 7. **Electromagnetic elements:** 11 – computer; I – bending torque; II – compressing torque; III – rotating torque. Ammeter A is used to determine the value of the magnetizing current

Fig. 8 represents calculations and measurements of EMF, experimental measurements of EMF, in the measurement coil 4 at the flexural shaft and under the influence of a torque.

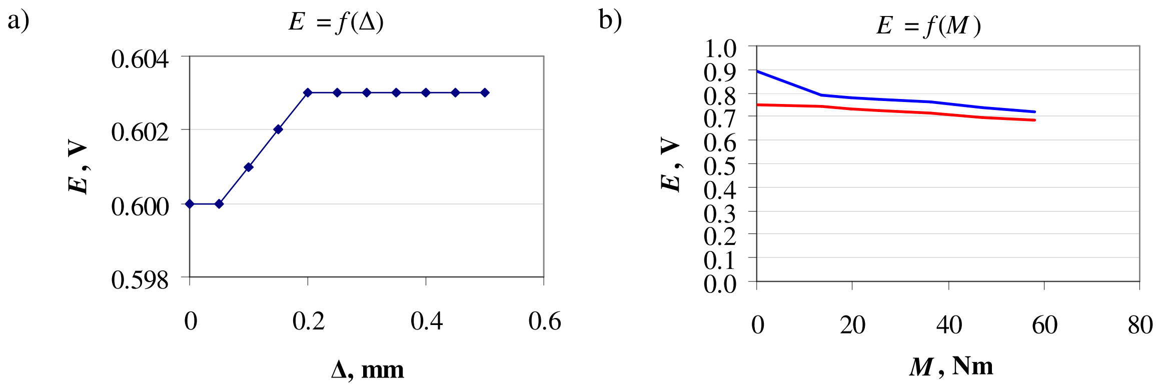


Fig. 8. **Dependence of EMF E:** a – on flexure value Δ; b – on torque M (red curve – for the case of torque increasing, blue – for the case of torque decreasing)

Ferromagnetic materials have different dependences on the magnetic permeability μ on mechanical stress σ: so the magnetic elasticity of permalloy decreases with the increasing of the tensile force, so permalloy has a positive magnetic striction. But that of nickel – increases, i.e. it has a negative magnetic striction. Some ferromagnetic materials (e.g., iron) have the sign of magnetic striction depending on the direction of the magnetic flux in relation to the crystallographic direction of the material.

The initial measurements are made with a stationary shaft. These data are stored and serve as initial points. Then similar measurements are repeated with a rotating shaft. Thus, it is desirable to change the direction of rotation in both directions. The data are also stored. Further, these data are processed and analysed. The analysed data are stored and, if necessary, can be compared with the previous measurements. This system of early general diagnostics does not define the exact place of the forming mechanical stresses. It evaluates the technical condition of the shaft as a whole from one bearing unit to another. When exceeding the specified level of the magnetic properties changing (stresses concentration) of the shaft a detailed examining of the shaft by means of other portable devices is required. If the shaft is long and consists of several intermediate shafts then the receiving and magnetising coils are placed in each supporting bearing. Computer 10 (Fig. 7) in this case is supplemented with the coils selector and addresses to them one by one with a predetermined time interval.

Conclusions

1. A system of early diagnostics of stationary steel shafts is proposed. A special attention in the article is turned to the electromagnetic method of measurement and control of mechanical stresses in the steel shaft.
2. The method for determination of excess stresses is based on registration of the changing of the steel shaft magnetic properties.
3. Changes in the magnetic properties are made at the beginning on the stationary shaft. These measurements are taken as the initial data. Further, the measurements are made with a rotating shaft. The obtained data are stored and used to analyze the changes depending on the specified time.
4. Comparison of the results of the measurements is made previously with the current results to determine the dynamic of the mechanical stresses growth and to predict the remaining service life. For example, Fig.8a demonstrates that bending of the shaft can be determined by means of EMF induced in the measuring coil. When bending the shaft is 0.2 mm EMF reaches its limit of 0.603 V.

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