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Diagnostic Simulation Model of the Needle Assembly in a Needle Punching Machine

Abstract
An attempt has been made to formulate a simulation diagnostic model of the driving unit of a needle bench in a needle punching machine. The journal of the main shaft was indicated as the node which receives the diagnostic signals in the form of its relative trajectory. The ambiguity of this symptom, together with the necessity of introducing other stricter diagnoses, have been demonstrated.

Key words: *needle punching machine, journal bearings, symptom, diagnosis, relative trajectory.*

Introduction

Non-woven needling textiles are widely applied in the clothing industry, medicine, and civil engineering. This field of textile production has generated not only new manufacturing methods, but also new, previously unknown, manufacturing machinery alongside new types of traditional machinery. These machines are increasingly complicated, with high operating parameters and consequently high susceptibility to exploitation errors.

At present, the concept of exploitation covers the set of deliberate techno-organisational and economic actions of people with technical devices, as well as mutual relations between them from the moment of receiving the device for its intended application to utilisation after its disposal.

In the system of machine exploitation, the subsystem of application, alongside the bound subsystem of servicing (including diagnostic issues) is considered most important. The core of diagnostic knowledge founded on experiments is limited, for various reasons. The technical diagnostic should be considered from two viewpoints:

- as a means of improving the design and operation of the machine (design diagnostic),
- as a means of enhancing the exploitation of a machine, in particular the servicing subsystem .

The process of machine and device servicing should (according to [1]) result from the physical need to service them. Fulfilling this condition requires the establishment of the machine's state at any given moment, as well as the speed of state changes, by means of technical diagnostic methods.

Modern diagnostic methods consists in the (non-invasive) investigation of the residual processes that in accompany the functioning of the machine in an unintentional but unavoidable way. The variability of the machine's state can be identified on the basis of measuring the values of selected features such as external interactions, the so-called diagnostic symptoms. A diagnostic symptom is defined as a measurable physical quantity which is proportional to the non-observable variable describing the state of the machine.

The diagnostic task consists in searching for the links between the state of the object and the states of the signals (symptoms). The STATE - relation - SYMPTOM models, which are recognised as traditional, are the basis of the diagnostic conclusion. Diagnosing is the process of mapping diagnostic signal features onto the features of the machine's state, together with defining the probable causal conjunction.

Diagnosis of the Needle Assembly in the Needle Punching Machine

The mathematical model of a needle-punching machine which was presented in paper [2] forms the basis of the design diagnostics. This model allows the behaviour of the designed needle machine to be predicted, even at the stage of design concept. It can also provide grounds for the prototype investigation and information series, as well as the exploitation diagnostic, after allowing for the time-dependent values of some structure parameters.

The diagnostic issue of needle-punching machines requires separate consideration because of the specific character of the motion of the operating unit, and thus the different mechanism of force interactions among the machine elements. Most needle-punching machines have a needle bench drive (operating unit) by the crank-slider mechanism. Electric motors are used as the source of drive, which through the belt drive, gear and clutch transmit the drive to the main shaft (crank or eccentric). The main bearings of the shaft are the journal bearings. The motion from the crank shaft through the cranks is transmitted to the slides connected with the needle bench.

The main failures occurring in the process of exploiting the needle-punching unit generally result from the wear of main shaft bearings, crank bearings, bearings of node crank-slide, guiding brushes of slides, etc. These main failures of needle module elements cause vibro-acoustic effects in the form of impact elimination clearances, as well as causing an increase in dynamic forces.

Diagnostic Model

The task involves gaining diagnostic knowledge with regard to the selected problems of the dynamics of the crankshaft-slider assembly of the needle bench, consisting of the needle punching machine module.

The basic functional nodes of this system are the journal bearings of the main shaft, and the crank-shaft system which acts on the main shaft through the crank bearing. This decomposition into functional nodes makes it easier to determine the inefficiency arising in these nodes, and allows us to establish the dynamic forces which are generated by the crankshaft system and act on the main journal bearings.

According to the author, the system of dependencies transforming the operational parameters and the parameters of the technical state of the nodes under consideration in the needle-punching machine, in the trajectory of journal motion with regard to the bearing, provides an adequate model which represents the diagnostic relations between the features of the needle-punching machine's state and the features of the diagnostic signals.

Methods of analysing the dynamic phenomena occurring in the 'journal-oil film-bearing-external restraint' system, which have been recognised in science, have been applied for the elaboration of a model describing the motion of the journal in the oil film pressure field. This model takes into consideration the variation in the design parameters of the bearing (bearing clearance, geometric parameters) and exploitation, e.g. changes in the values and character of load, overload of bearings, variation of oil supply conditions.

Dynamic models of the 'journal-bearing-support' system, which are known in literature, generally concern the bearing systems of turbogenerators in power- or combined heat-and-power-plants, or the dynamically loaded bearings of internal-combustion engines.

A diagnostic model of needle assembly is depicted in Figure 1.

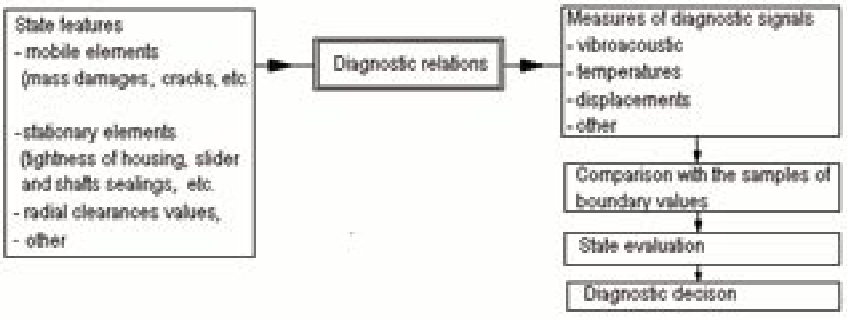

***Figure 1.** Diagnostic model of needle assembly.*

$$W = m \cdot r \cdot \omega^2 \sqrt{\beta^2 + (1-2\beta)\cos^2\varphi + 2(1-\beta)\lambda\cos\varphi\cos 2\varphi + \lambda^2\cos^2 2\varphi} \qquad 1)$$

$$\frac{\partial}{\partial\varphi}\left[\frac{H^3}{\eta}\frac{\partial p}{\partial\varphi}\right] + \left(\frac{D}{L}\right)^2 \frac{\partial}{\partial z}\left[\frac{H^3}{\eta}\frac{\partial p}{\partial z}\right] = 6 \cdot \frac{\partial H}{\partial\varphi} + 12\frac{\partial H}{\partial\phi} \qquad 5)$$

Equations 1 and 5.

The diagnostic symptom in the assumed relation model consists of the values of trajectory features of the relative motion of the journal. The system of links which allows the journal centre trajectory to be determined is the relation that transforms the values of the features of the needle assembly elements' technical state into the values of diagnostic signal features (journal trajectory).

The resultant inertia force of the masses in rotational movement and the masses in the plane-back motion acts on the main bearings. The value of this resultant is determined [3] by the following equation (1), where:

m - the mass in plane-back motion,
r - the crank radius,
ω - the angular velocity of the shaft,
β - the balance coefficient of the masses in the plane-back motion,
φ - the angle of shaft rotation,
l - the length of the connecting rod.

$$\lambda = \frac{r}{l}$$

Equation (1) gives the total inertia force of the first and second order. The direction of non-balanced inertia force is determined from equation (2):

$$tg\psi = \frac{-\beta\sin\varphi}{(1-\beta)\cos\varphi + \lambda\cos 2\varphi} \qquad (2)$$

The vector of force W rotates with variable angular velocity in the direction opposite to the velocity ω of the driving shaft.

The operation of the dynamically-loaded journal bearing is investigated by comparing the hydrodynamic forces generated at an assumed position and at an assumed velocity of the journal's centre to the external load at the considered time.

Comparing the hydrodynamic force F to the applied load W, the equation (3) can be obtained.

$$F = W(L/D, \varepsilon, \alpha, \dot{\varepsilon}, \dot{\alpha}) \qquad (3)$$

where:
L/D - the bearing-length to diameter ratio,
ε - the relative eccentricity of the bearing,
α - the attitude angle,
$\dot{\varepsilon}, \dot{\alpha}$ - derivatives of the eccentricity and attitude angle with respect to time.

The geometry of the lubricating gap can be obtained from equation (4).

$$H_e = 1 - \varepsilon \cdot \cos(\varphi - \alpha) \qquad (4)$$

where:
φ - the peripheral co-ordinate.

The journal centre trajectory in the journal bearing under consideration was determined by the numerical solution of Reynolds, energy, viscosity and the geometry of the oil film equations. Partial derivatives of these equations were replaced by finite differences. The method applied for the solution of Reynolds, energy, viscosity equations [4-7] and for determining the journal centre trajectory is characterised by the assumption required for describing the phenomena of lubrication and the dynamic of the 'journal-lubricant-bearing brush' system, i.e.:

- the assumption of a stiff journal and bush,

Table 1. *Model of transforming the state features C into the symptom S for the elements of the needle-punching unit. The set of equation (C) must be solved for each trajectory point.*

State features	Relation	Symptom
Values of state features (and their changes) of nodes of the needle-punching unit, which are particularly important in diagnostic investigation: **C⇒** bearing clearances, geometric dimensions of bearings, values and character of loads, type of lubricant, number of revolutions.	Set of equations from (1), (2), (3), (4) to (5)	**⇒S** (6) Values of features of journal centre trajectory

- an isothermal or adiabatic model with the temperature determined from the heat balance,
- the boundary conditions of the oil film - the regions of negative oil film pressures are neglected.

A Reynolds equation applied for the oil film pressure field, with the assumption that the pressure and viscosity are constant on the oil film thickness, takes the form presented in equation (5), where:
H - the dimensionless oil film thickness,
p - the dimensionless oil film pressure,
z - the dimensionless axial co-ordinate,
η - the dimensionless oil viscosity,
ϕ - dimensionless time.

For the calculation, an isothermal model of oil film was assumed [5], which makes the numerical calculation process faster. This is important in the case of dynamically loaded journal bearings, where for each point of the journal trajectory the set of equations must be solved. The model of transforming the state features C of the needle-punching unit elements into the symptom S is presented in Table 1.

Results of Calculation

The basic function of simulation investigation according to the diagnostic model is to obtain the relations of type defect to symptom, i.e., obtaining a simulation of diagnostic relations which forms the basis for the diagnostic of the needle-punching system. An identical mathematical model can also be applied for optimising the properties of analysed system. Simulation calculations have been carried out for the following parameters:

- bearing diameter D=85 mm
- bearing length L=69 mm
- relative bearing clearance: ψ=1.5‰ , ψ=2.0‰ , ψ =3.0‰
- journal rotational velocity n=1500 rpm
- mass in the reciprocating motion m_p=34.66 kg
- length of crank r=0.03 m
- length of connecting link l=0.27 m
- coefficient of balancing of masses in the reciprocating motion β=0.5.

The run of dynamic loads is shown in Figure 2.

The example results of simulation calculations are shown in Figures 3 to 7 as charts of the relative trajectory of the journal centre. As a result of transformation based on the system (6), the set of (some tens of) journal centre trajectories was obtained, and the exact values of the state features, which are the cause of this form of symptom, were determined.

The journal centre trajectory is affected by the values of features of the journal bearings of the main shaft and the values of features of the crank system, which influence the character and values of dynamic forces. The symptom determined is the result of a conjunctive interaction of state feature values. However, an effect of clearance changes can be distinguished, and in this case the trajectories of different parameters are obtained.

As a result of the simulation investigation, the set of trajectories representing the base of diagnostic knowledge is obtained. This diagnostic method based on the 'trajectory of motion of spindle end' symptoms was applied by the author [8] with positive results.

In the relation transforming state C into symptom S, many different parameters such as stiffness and damping of oil film, stiffness of bearing supports, shaft deflection, etc. were not taken into account. This is an initial version of the relation model which lays the groundwork for a development of the pilot version of the basis of knowledge.

Analysis of Results

For all the calculated cases, and at both the assumed load character and the assumed bearing clearances in the main bearing, the journal centre trajectory has the shape close to a deformed ellipse.

From the runs shown in Figure 3, the relative eccentricity increases with the increase in the bearing clearance in the main journal bearing. The analysis of the runs on Figures 4 to 7 makes it obvious that the value and character of load have a small effect on the relative journal centre's trajectory. On the other hand, the shape of the relative journal centre's trajectory depends on the effect of the relative clearance of the main bearing.

In addition, it is necessary to analyse another state symptom, which allows the run of linear accelerations of the needle

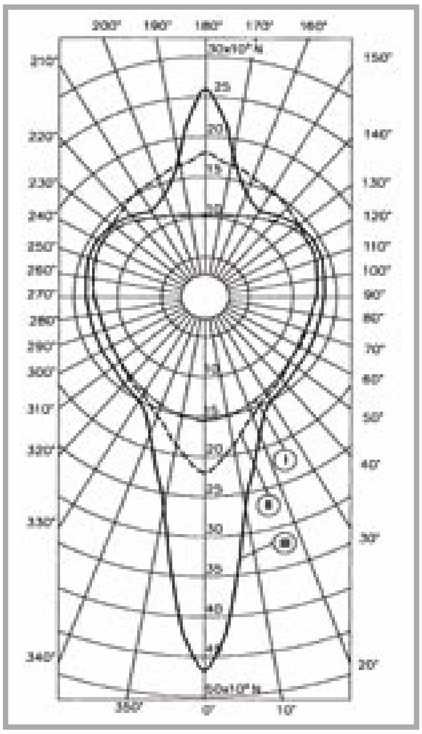

Figure 2. *The run of dynamic loads of main bearing: I - nominal load, II - mean load (permissible clearances), III - impact load (with given clearances).*

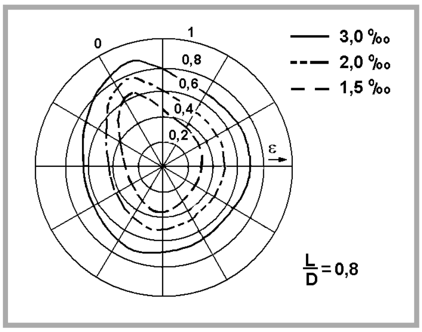

Figure 3. *Relative journal centre trajectory: I - load, ψ=1.5‰.*

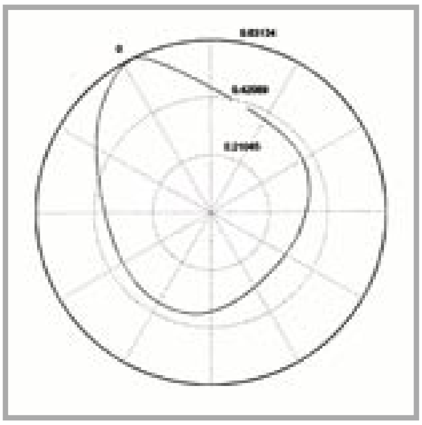

Figure 4. Relative journal centre trajectory: II - load, ψ=1.5‰.

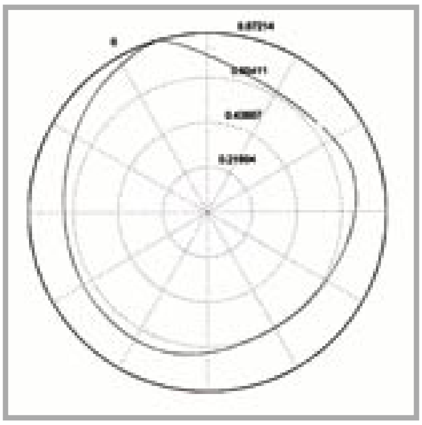

Figure 5. Relative journal centre trajectory: II - load, ψ=3.0‰.

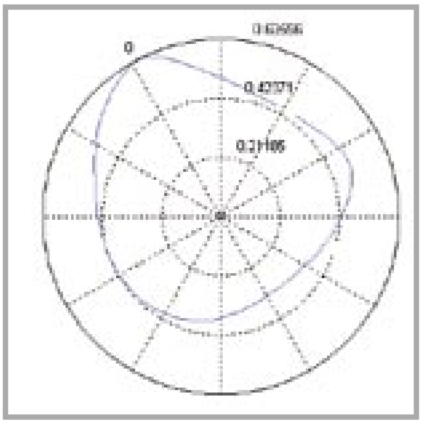

Figure 6. Relative journal centre trajectory: III - load, ψ=1.5‰.

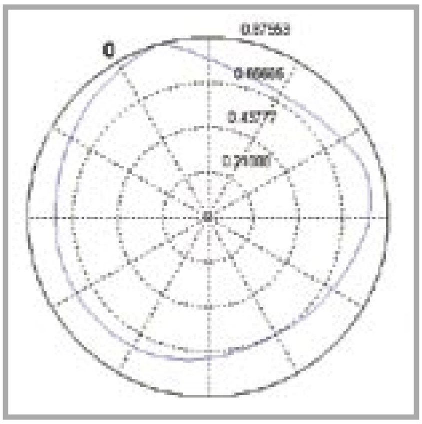

Figure 7. Relative journal centre trajectory: III - load, ψ=3.0‰.

bench to be determined. The values and character of the dynamic forces can be determined on the basis of these measurements.

The measurement of the proposed symptoms and their analysis do not present any difficulties. The measurement of journal vibration is carried out in two perpendicular directions. Many measuring systems which allow periodic overseeing and fast analysis are known. Fast analysis allows us to undertake the diagnostic decisions after previously determining the threshold values. It is necessary to underline that the physical processes, the symptoms of single damage, often screen each other, and on the other hand conclusions based on the features of the symptom about the features of the state.

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