

dynamic model; cylinder case; pulsed pressure; longitudinal and transversal oscillations

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DEVELOPMENT OF GENERALIZED DYNAMIC MODEL OF OSCILLATIONS OF CYLINDER CASE OF DIESEL ENGINE OF LOCOMOTIVE

Summary. An engineering method of design, worked out by the authors, is considered in the paper. It allows to carry out design of amplitude-frequency specter and vibration loading of cylinder cases of the diesel engine of locomotive with account of cavitation-erosion damage. Offered method of design of parameters of cavitation-erosion damage may be used in design of new structures of diesel engines of locomotives and systems of cooling.

РАЗРАБОТКА ОБОБЩЕННОЙ ДИНАМИЧЕСКОЙ МОДЕЛИ КОЛЕБАНИЙ ГИЛЬЗЫ ЦИЛИНДРА ДИЗЕЛЯ ТЕПЛОВОЗА

Аннотация. В статье приведен полученный авторами инженерный метод расчета, позволяющий проводить расчет амплитудно-частотного спектра и вибрационного нагружения цилиндрических гильз дизеля тепловоза с учетом кавитационно-эрозионного разрушения. Предложенный метод расчета параметров кавитационно-эрозионного разрушения можно использовать при проектировании новых конструкций дизелей тепловозов и систем охлаждения.

1. INTRODUCTION

In piston-type engines of internal combustion the bush (case) of cylinder is damaged due to summed up effect of different physical-chemical factors on metals. One of the reasons of damage (roughening of bush metal) is the presence of cavitation in cavities of engine cooling. Calculations of the motors considering effect of cavitation were carried out by many researchers [7, 8, 10].

The main reason of cavitation erosion is the presence of high-frequency vibrations of bushes under the effect of lateral pressure, occurring in the process of operation of diesel piston (as a result of transposition from one wall of cylinder to another while passing the upper dead position when the sign of the forces of lateral pressure N is changing).

2. EVALUATION OF STRESS-STRAIN STATE OF CYLINDER CASE OF AN ENGINE OF LOCOMOTIVE WITH ACCOUNT OF COMBINED EFFECT OF LONGITUDINAL AND TRANSVERSAL OSCILLATIONS ON THE SYSTEM

To evaluate stress-strain state of cylinder case of diesel engine of locomotive and to assess the processes of cavitation-erosion wear under the effect of cooling liquid in the system, we will consider

oscillations of the case of cylinder in the form of finite shell, elastically fixed at the ends, and will turn to equations of elastic shells with account of wave propagation in their material. Option of Kirchhoff-Love linearized theory of shells is taken here, considering flexures of shells U_1, U_2, W_1, W_2 – as small ones comparing with the thickness of a shell [1, 2].

Design scheme to study oscillation of internal and external cylinders of a case in a block of cylinders of diesel engine of locomotive in the form of finite shell, elastically fixed at the ends, under the effect of pulsed pressure in cooling liquid, is given in Fig. 1.

Dynamic model under study presents two co-axially located elastic cylinder shells (shell 1 – external cylinder of a case and shell 2 – internal cylinder of a case, respectively); between these shells there is a cooling liquid with pulsed pressure $P_g(x, t)$.

Circular elastic cylinder shells have external radii R_1, R_2 , thickness of a wall h_1, h_2 , the length - L_1, L_2 , at the ends – elastic fixing.

Between internal shell 2 and piston 3 in points of a contact there acts a force of friction, expressed by:

$$P_{fr}(x, t) = f_{fr} \cdot P_{dyn} \quad (1)$$

Outside there is an external impulse dynamic load

$$P_{dyn}(x, t) = \sum_{n=1}^{N=5} \{P_{an}(x) \cdot \cos n\omega_a t\} \quad (2)$$

Superpose axis OX with longitudinal axis of a case, having two co-axially located cylinder shells (shell 1 – external cylinder of a case and shell 2 – internal cylinder of a case, respectively). Displacements of middle surface of shell 1 in directions of generatrix we will mark as U_1 , and displacements of middle surface of shell 2 - as U_2 , and radial displacements as W_1, W_2 , respectively.

Taking into consideration results of works by Volmir A.C. and Kilchevsky N.A. [1, 2], an equation of oscillation of cylinder case of diesel engine of locomotive may be written in the form of equations of longitudinal-radial oscillations of two elastic thin-wall cylinder shells with cooling liquid between them; it has pulsed pressure in length and time under the effect of external dynamic effects P_{dyn} , in displacements (oscillations are taken as axis-symmetrical ones):

- for the first shell (1- internal cylinder of a case) equation of longitudinal oscillations has the form:

$$\frac{E_1 h_1}{1 - \mu_1^2} \left(\frac{\partial^2 U_1}{\partial x^2} + \frac{\mu_1 \partial W_1}{R_1 \partial x} \right) - \beta_1 \frac{\partial U_1}{\partial t} = \rho_1 h_1 \frac{\partial^2 U_1}{\partial t^2} + f_1 P_{dyn}(x, t) \quad (3)$$

Equation of transversal displacements (along the radius) of the first shell

$$\bar{m}_1 \frac{\partial^2 W_1}{\partial t^2} + D_1 \frac{\partial^4 W_1}{\partial x^4} + \bar{N}_1 \frac{\partial^2 W_1}{\partial x^2} + \frac{1}{R_1} \frac{E_1 h_1}{1 - \mu_1^2} \left(\mu_1 \frac{\partial U_1}{\partial x} + \frac{W_1}{R_1} \right) = F_g(x, t) \quad (4)$$

For the second shell (2- internal cylinder of a case) equation of longitudinal oscillations has the form:

$$\frac{E_2 h_2}{1 - \mu_2^2} \left(\frac{\partial^2 U_2}{\partial x^2} + \frac{\mu_2 \partial W_2}{R_2 \partial x} \right) - \beta_2 \frac{\partial U_2}{\partial t} = \rho_2 h_2 \frac{\partial^2 U_2}{\partial t^2} + f_{fr} P(x, t) + f_2 P_{dyn}(x, t) \quad (5)$$

Equations of transversal displacements (radial oscillations) of the second shell

$$\bar{m}_2 \frac{\partial^2 W_2}{\partial t^2} + D_2 \frac{\partial^4 W_2}{\partial x^4} + \bar{N}_2 \frac{\partial^2 W_2}{\partial x^2} + \frac{1}{R_2} \frac{E_2 h_2}{1 - \mu_2^2} \left(\mu_2 \frac{\partial U_2}{\partial x} + \frac{W_2}{R_2} \right) = -P_g(x, t) \quad (6)$$

So, we get general solution for the study of transversal oscillation of shells of a case under pulsed pressure and velocity in cooling liquid, neglecting the effect of longitudinal displacements of neutral axis of shell on transversal ones (at elastic fixing of ends) in the form:

For the first shell of a case

$$W_1(x,t) = \sum_{k=1}^{\infty} W_{1k}(x) \cdot W_{1k}(t) \quad (7a)$$

For the second shell of a case

$$W_2(x,t) = \sum_{k=1}^{\infty} W_{2k}(x) \cdot W_{2k}(t) \quad (7b)$$

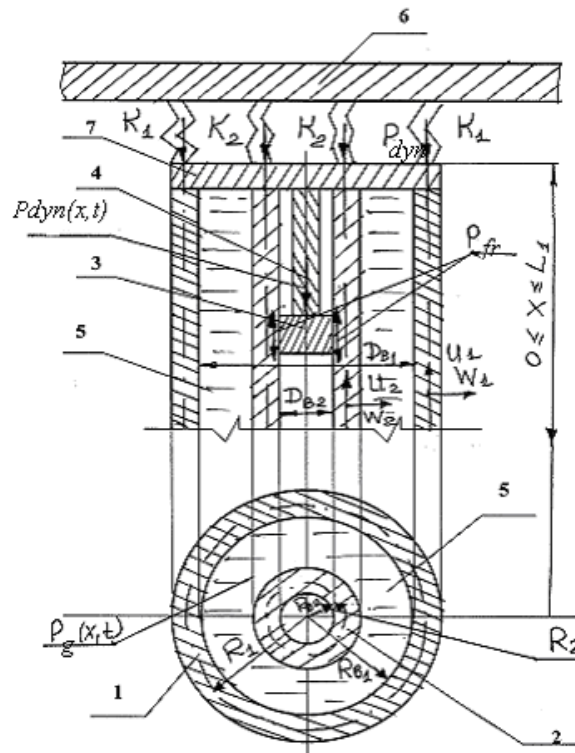


Fig. 1. Design scheme to study oscillations of internal and external cylinder of a case in the block of cylinders of diesel engine of locomotive in the form of finite shell, elastically fixed at the ends under the effect of pulsed pressure in cooling liquid (1 - external cylinder of a case; 2 - internal cylinder of a case; 3 - piston; 4 - rod; 5 - cooling liquid; 6 - block of cylinders of diesel engine of locomotive; 7 - case lid)

Рис. 1. Расчетная схема для исследования колебаний внутреннего и внешнего цилиндров гильзы в блоке цилиндров дизеля тепловоза в виде конечной оболочки, упруго закрепленной по концам, под воздействием пульсирующего давления в охлаждающей жидкости (1 - внешний цилиндр гильзы; 2 - внутренний цилиндр гильзы; 3 - поршень; 4 - шток; 5 - охлаждающая жидкость; 6 - блок цилиндров дизеля тепловоза; 7 - крышка гильзы)

Here $W_{1k}(t)$, $W_{2k}(t)$ - determine dynamic displacements of neutral lines of shells in time and are determined according to formulae (8a)

- for the first shell of a case of diesel engine of locomotive

$$W_{1k}(t) = D_{1k}(x) \cdot \frac{\cos n \omega_g t - \cos \eta_{1k} t}{\eta_{1k}^2 - (n \omega_g)^2} + W_{01} \cos \eta_{1k} t + \frac{\dot{W}_{01}}{\eta_{1k}} \sin \eta_{1k} t \quad (8a)$$

- for the second shell of diesel engine of locomotive

$$W_{2k}(t) = D_{2k}(x) \cdot \frac{\cos n \omega_g t - \cos \eta_{2k} t}{\eta_{2k}^2 - (n \omega_g)^2} + W_{02} \cos \eta_{2k} t + \frac{\dot{W}_{02}}{\eta_{2k}} \sin \eta_{2k} t \quad (8b)$$

and

$$W_{1k}(x) = C_{11}sh\omega_{1k}x + C_{12}ch\omega_{1k}x + C_{13} \sin \omega_{1B}x + C_{14} \cos \omega_{1B}x, \quad (9a)$$

$$W_{2k}(x) = C_{21}sh\omega_{2k}x + C_{22}ch\omega_{2k}x + C_{23} \sin \omega_{2B}x + C_{24} \cos \omega_{2B}x, \quad (9b)$$

where $W_{1k}(x), W_{2k}(x)$ - are own functions for general case of elastic fixing of the ends for the first and second shells of a case of diesel engine of locomotive, and $\omega_{1k}, \omega_{2k}, \omega_{1B}, \omega_{2B}$ - are own frequencies of oscillations of the first and second shells of a case at transversal displacements, which are, respectively:

$$\omega_{1k} = \sqrt{-d_{14} + \sqrt{(d_{14})^2 - \left(d_{12}^4 \frac{1}{R_1} - \lambda_{1k}^2\right)}}; \quad \omega_{2k} = \sqrt{-d_{24} + \sqrt{(d_{24})^2 - \left(d_{22}^4 \frac{1}{R_2} - \lambda_{2k}^2\right)}}$$

$$\omega_{1B} = \sqrt{d_{14} + \sqrt{(d_{14})^2 - \left(d_{12}^4 \frac{1}{R_1} - \lambda_{1k}^2\right)}}; \quad \omega_{2B} = \sqrt{d_{24} + \sqrt{(d_{24})^2 - \left(d_{22}^4 \frac{1}{R_2} - \lambda_{2k}^2\right)}}$$

Consider solution of the system of equations (3)+(6) with account of successive complication: 1st problem. First consider longitudinal oscillations of two co-axial shells (Fig. 1) with assumption of small value of transversal widening (that is $\frac{\partial W_1}{\partial x}$ and $\frac{\partial W_2}{\partial x}$ tend to 0); we will have beam-type forms

of oscillations of shells. With this assumption, equations (3) and (6) will have the form

$$\frac{E_1 h_1}{1 - \mu_1^2} \frac{\partial^2 U_1}{\partial x^2} - \beta_1 \frac{\partial U_1}{\partial t} = \rho_1 h_1 \frac{\partial^2 U_1}{\partial t^2} + f_1 P_{dym}(x, t), \quad (10)$$

$$\frac{E_2 h_2}{1 - \mu_2^2} \frac{\partial^2 U_2}{\partial x^2} - \beta_2 \frac{\partial U_2}{\partial t} = \rho_2 h_2 \frac{\partial^2 U_2}{\partial t^2} + f_{fr} P(x, t) + f_2 P_{dym}(x, t), \quad (11)$$

2nd problem. Oscillations of two co-axial shells (Fig.1) of a case of diesel engine of locomotive with the effect of transversal displacements (on radius) $W_1(x, t)$ and $W_2(x, t)$ on longitudinal ones. Write down the system of differential equations for the 1st and 2nd shells of a case for interconnected longitudinal-transversal oscillations, taking oscillations of thin-wall shells as axis-symmetrical ones.

$$\frac{E_1 h_1}{1 - \mu_1^2} \frac{\partial^2 U_1}{\partial x^2} - \beta_1 \frac{\partial U_1}{\partial t} - \rho_1 h_1 \frac{\partial^2 U_1}{\partial t^2} = f_1 \cdot P_{dym}(x, t) - \frac{E_1 h_1}{1 - \mu_1^2} \frac{\mu_1}{R_1} \frac{\partial W_1}{\partial x}, \quad (12)$$

$$\bar{m}_1 \frac{\partial^2 W_1}{\partial t^2} + D_1 \frac{\partial^4 W_1}{\partial x^4} + \bar{N}_1 \frac{\partial^2 W_1}{\partial x^2} + \frac{1}{R_1} \frac{E_1 h_1}{1 - \mu_1^2} \left(\mu_1 \frac{\partial U_1}{\partial x} + \frac{W_1}{R_1} \right) = P_g(x, t), \quad (13)$$

$$\frac{E_2 h_2}{1 - \mu_2^2} \frac{\partial^2 U_2}{\partial x^2} - \beta_2 \frac{\partial U_2}{\partial t} - \rho_2 h_2 \frac{\partial^2 U_2}{\partial t^2} = f_{fr} \cdot P_{dym}(x, t) + f_2 \cdot P_{dym}(x, t) - \frac{E_2 h_2}{1 - \mu_2^2} \frac{\mu_2}{R_2} \frac{\partial W_{21}}{\partial x}, \quad (14)$$

$$\bar{m}_2 \frac{\partial^2 W_2}{\partial t^2} + D_2 \frac{\partial^4 W_2}{\partial x^4} + \bar{N}_2 \frac{\partial^2 W_2}{\partial x^2} + \frac{1}{R_2} \frac{E_2 h_2}{1 - \mu_2^2} \left(\mu_2 \frac{\partial U_2}{\partial x} + \frac{W_2}{R_2} \right) = P_2 g(x, t), \quad (15)$$

Where pulsed pressure in cooling liquid has the form

$$P_g(x, t) = \sum_{n=1}^{N=5} \{ F_{g^n}(x) \cdot \cos n \omega_g t \} \quad (16)$$

3rd problem. Consideration of the effect of longitudinal oscillations on transversal ones for the first and second shells of a case of diesel engine of locomotive. We will make an attempt to study

discussed effect on example of solution of equation (12) for the first shell of a case for longitudinal oscillations with account of two-way influence of transversal oscillations of shells on longitudinal ones (in the form of additional term $\frac{E_1 h_1}{1 - \mu_1^2} \cdot \frac{\mu_1}{R_1} \cdot \frac{\partial W_{1k}}{\partial x}$, derived in solution of equation (13).

Find out the value for the calculation of the term $\frac{E_1 h_1}{1 - \mu_1^2} \cdot \frac{\mu_1}{R_1} \cdot \frac{\partial W_{1k}}{\partial x}$ from equation (13),

introducing the designation $T_1 = \frac{E_1 h_1}{1 - \mu_1^2} \cdot \frac{\mu_1}{R_1}$.

As a result we get

$$-T_1 \frac{\partial W_{1k}}{\partial x} = -T_1 \cdot (W_{1k}(t) \cdot (C_{11} \omega_{1k} ch \omega_{1k} x + C_{12} \omega_{1k} sh \omega_{1k} x + C_{13} \omega_{1B} \cos \omega_{1B} x - C_{14} \omega_{1B} \sin \omega_{1B} x)) \quad (17)$$

Substituting equation (17) into (12) for longitudinal oscillations of the first and second shells of a case, we get

$$\frac{E_1 h_1}{1 - \mu_1^2} \frac{\partial^2 U_{1k}}{\partial x^2} - \beta_1 \frac{\partial U_{1k}}{\partial t} - \rho_1 h_1 \frac{\partial^2 U_{1k}}{\partial t^2} = f_1^P \frac{\partial}{\partial y_{1n}}(x, t) - T_1 \cdot W_{1k}(t) \cdot \bar{E}_{1k}(x) \quad (18)$$

$$\begin{aligned} \frac{E_2 h_2}{1 - \mu_2^2} \frac{\partial^2 U_{2k}}{\partial x^2} - \beta_2 \frac{\partial U_{2k}}{\partial t} - \rho_2 h_2 \frac{\partial^2 U_{2k}}{\partial t^2} &= f_{fr}^P \frac{\partial}{\partial y_{2n}}(x, t) + f_2^P \frac{\partial}{\partial y_{2n}}(x, t) - \\ &- T_2 \cdot W_{2k}(t) \cdot \bar{E}_{2k}(x) \end{aligned} \quad (19)$$

where designations are introduced

$$\begin{aligned} \bar{E}_{1k}(x) &= ((C_{11} \omega_{1k} ch \omega_{1k} x + C_{12} \omega_{1k} sh \omega_{1k} x + C_{13} \omega_{1B} \cos \omega_{1B} x - C_{14} \omega_{1B} \sin \omega_{1B} x)), \\ \bar{E}_{2k}(x) &= ((C_{21} \omega_{2k} ch \omega_{2k} x + C_{22} \omega_{2k} sh \omega_{2k} x + C_{23} \omega_{2B} \cos \omega_{2B} x - C_{24} \omega_{2B} \sin \omega_{2B} x)) \end{aligned}$$

Further in analogy, applying Laplace transforms in time [3], we will have formulae to calculate $U_1(p)$ and $U_2(p)$ (with account of the effect of transversal oscillations on longitudinal ones) in the form

$$\begin{aligned} U_1(p) &= -\bar{P}_{12n}(x) \cdot \frac{p}{(p^2 + (n\omega_g)^2) \cdot (p^2 + \beta_1 p + \lambda_{1n}^2)} + \frac{pU_{01}}{p^2 + \beta_1 p + \lambda_{1n}^2} + \frac{V_{01} + \bar{\beta}_1 U_{01}}{p^2 + \beta_1 p + \lambda_{1n}^2} + \\ &+ T_1 \bar{E}_{1k}(x) \cdot \left(D_{1k}(x) \frac{p}{(p^2 + (n\omega_g)^2) (p^2 + \eta_{1k}^2)} + \frac{W_{01} p}{p^2 + \eta_{1k}^2} + \frac{\dot{W}_{01}}{p^2 + \eta_{1k}^2} \right) \end{aligned} \quad (20a)$$

$$\begin{aligned} U_2(p) &= -\bar{P}_{22n}(x) \cdot \frac{p}{(p^2 + (n\omega_g)^2) \cdot (p^2 + \beta_2 p + \lambda_{2n}^2)} + \frac{pU_{02}}{p^2 + \beta_2 p + \lambda_{2n}^2} + \frac{V_{02} + \bar{\beta}_2 U_{02}}{p^2 + \beta_2 p + \lambda_{2n}^2} + \\ &+ T_2 \bar{E}_{2k}(x) \cdot \left(D_{2k}(x) \frac{p}{(p^2 + (n\omega_g)^2) (p^2 + \eta_{2k}^2)} + \frac{W_{02} p}{p^2 + \eta_{2k}^2} + \frac{\dot{W}_{02}}{p^2 + \eta_{2k}^2} \right) \end{aligned} \quad (20b)$$

Then using Heavyside theorem [4] to obtain the originals of functions, we will get them in the form - for the first shell of a case of diesel engine of locomotive

$$\begin{aligned} W_{1k}(t) &= D_{1k}(x) \cdot \frac{\cos n\omega_g t - \cos \eta_{1k} t}{\eta_{1k}^2 - (n\omega_g)^2} + W_{01} \cos \eta_{1k} t + \frac{\dot{W}_{01}}{\eta_{1k}} \sin \eta_{1k} t + \\ &+ T_1 \cdot \bar{E}_{1k}(x) \cdot \left(D_{1k}(x) \frac{\cos n\omega_g t - \cos \eta_{1k} t}{\eta_{1k}^2 - (n\omega_g)^2} + W_{01} \cos \eta_{1k} t + \frac{\dot{W}_{01}}{\eta_{1k}} \sin \eta_{1k} t \right) \end{aligned} \quad (21a)$$

- for the second shell of a case of diesel engine of locomotive

$$W_{2k}(t) = D_{2k}(x) \cdot \frac{\cos n\omega_g t - \cos \eta_{2k} t}{\eta_{2k}^2 - (n\omega_g)^2} + W_{02} \cos \eta_{2k} t + \frac{\dot{W}_{02}}{\eta_{2k}} \sin \eta_{2k} t +$$

$$+ T_2 \cdot \bar{E}_{2k}(x) \cdot \left(D_{2k}(x) \frac{\cos n\omega_g t - \cos \eta_{2k} t}{\eta_{2k}^2 - (n\omega_g)^2} + W_{02} \cos \eta_{2k} t + \frac{\dot{W}_{02}}{\eta_{2k}} \sin \eta_{2k} t \right) \quad (21b)$$

So, we have obtained expressions to study stress-strain state of the first and second shells of a case of diesel engine of locomotive under interconnected longitudinal-transversal oscillations of a case in a block of cylinders of diesel engine of locomotive with account of pulses of pressure and velocity in cooling liquid; these expressions were further used in conducting numerical calculations. To build the program and carry out numeric studies MathCad 13 programming was used. Results of calculations are resulted in Fig. 2-5.

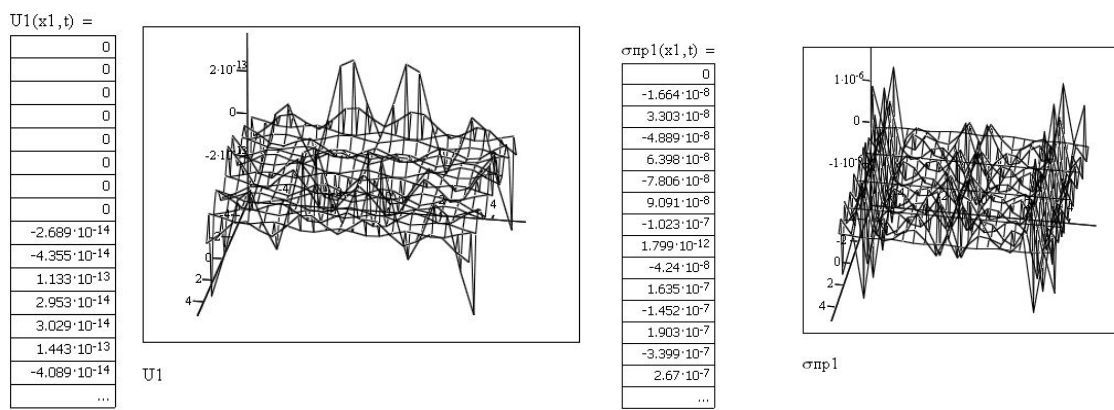


Fig. 2. Volume graphic dependence of longitudinal oscillations and arising pressure in 1 shell (in an external cylinder of a case) at dynamic external loading and with account of pulses of pressure and velocity in cooling liquid (on 5 harmonics)

Рис. 2. Объемная графическая зависимость продольных колебаний и возникающих напряжений в 1 оболочке (во внешней оболочке цилиндрической гильзы) при динамическом внешнем нагружении и влиянии пульсаций в охлаждающей жидкости (по 5-ти гармоникам)

3. CONCLUSION

From the analysis of volume graphic dependences (Fig. 2-5) it is visible that at engine work there is an increase in values of longitudinal deformations and pressure as in the central part of a cylinder of a case, and is closer to fastening places that also corresponds to practical supervision as in installation sites of a cylinder of a case in the block of cylinders on the top landing belts of cylinder of a case under sealing ledge destruction of a surface of metal and a congestion of erosive bowls is observed.

The maximum values of longitudinal pressure and deformations can be observed in the centre of a cylinder of a case that corresponds to practical supervision as in the central part of a cylinder sleeve (approximately in places of a supply of a cooling liquid) and in places corresponding to them on a surface of the block of cylinders the greatest destruction of a surface is observed.

Therefore in the central part (in a place of a supply of a cooling liquid) it is necessary to provide actions for decrease value of the high-frequency fluctuations arising at work of the engine, and on increase in deformation firmness of a surface to influence of cavitations-erosive destruction that has been considered by working out of constructive actions for decrease in cavitations-erosive destruction in diesels [11].

As a result we have developed a new method of prediction of stress-strain state of shells of a case of diesel engine of locomotive at elastic fixing of the ends, with account of pulses of pressure and velocity in cooling liquid and the effect of cavitation-erosion wear.

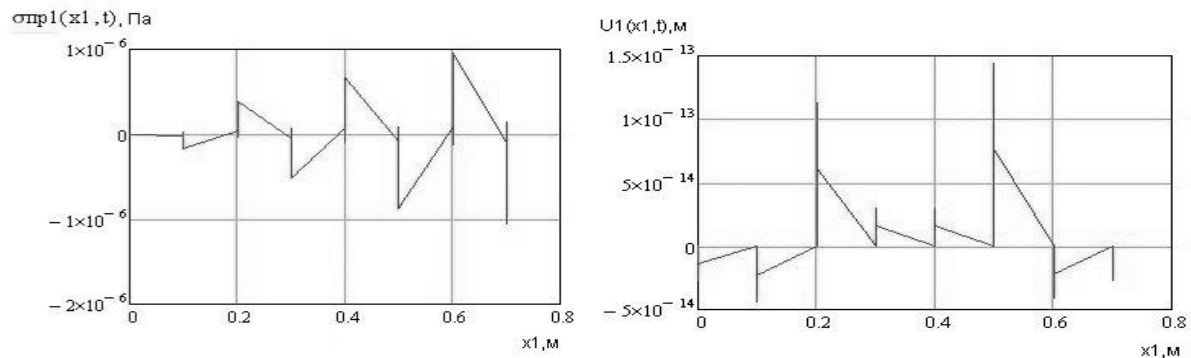


Fig. 3. Graphic dependence of longitudinal oscillations and arising pressure in 1 shell (in an external cylinder of a case) at dynamic external loading and with account of pulses of pressure and velocity in cooling liquid (on 5 harmonics) on cylinder of a case height

Рис. 3. Графическая зависимость продольных колебаний и возникающих напряжений в 1 оболочке (во внешней оболочке цилиндрической гильзы) при динамическом внешнем нагружении и влиянии пульсаций в охлаждающей жидкости (по 5-ти гармоникам) по высоте гильзы

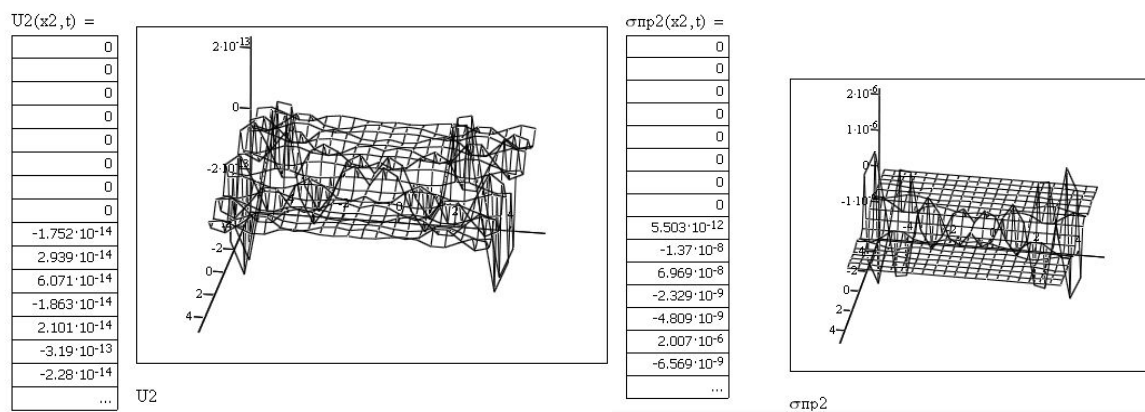


Fig. 4. Volume graphic dependence of longitudinal oscillations and pressure in 2 shell (in internal cylinder of a case) at dynamic external loading and with account of pulses of pressure and velocity in cooling liquid (on 5 harmonics)

Рис. 4. Объемная графическая зависимость продольных колебаний и напряжений во 2 оболочке (во внутренней гильзе цилиндра) при динамическом внешнем нагружении и влиянии пульсаций в охлаждающей жидкости (по 5-ти гармоникам)

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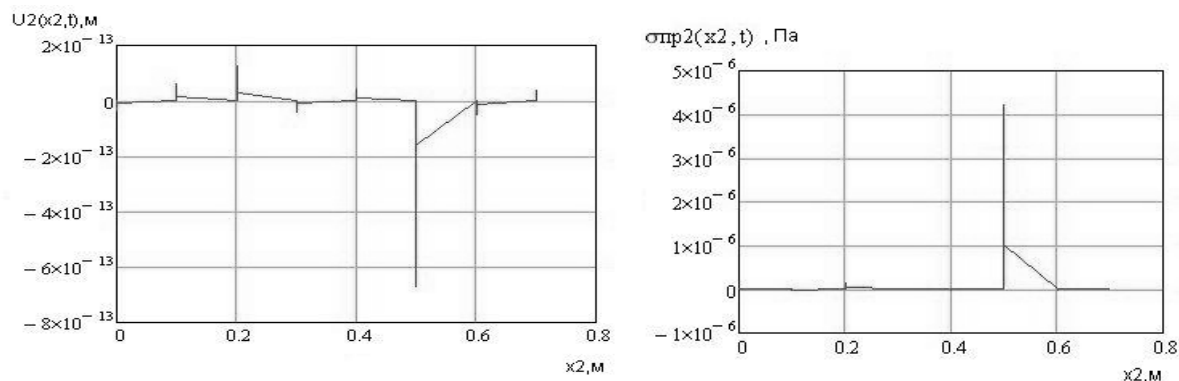


Fig. 5. Graphic dependence of longitudinal oscillations and arising pressure in 2 shell (in internal cylinder of a case) at dynamic external loading and with account of pulses of pressure and velocity in cooling liquid (on 5 harmonics) on cylinder of a case height

Рис. 5. Графическая зависимость продольных колебаний и напряжений во 2 оболочке (во внутренней гильзе цилиндра) при динамическом внешнем нагружении и влиянии пульсаций в охлаждающей жидкости (по 5-ти гармоникам) по высоте гильзы