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NONLINEAR VIBRATIONS OF PROFILE PRESS MANDREL OF TUBE-PRESS MACHINE

Анотація. Вирішена задача про нелінійні коливання технологічного інструмента в процесі пресування труб. Встановлені динамічні переміщення різних точок голки в умовах неперервного обтікання потоком метала для обраного спектра параметрів процесу пресування.

The processes of extrusion at different technological schemes of tube production, alongside with positive aspects, have some characteristic disadvantages which limits the area of their usage.

Among them, mainly, high variations in wall thickness of obtained shells are shown, caused by vibrations of basic technological tool (mandrel) in deformation zone and outside of it, specified by characteristic dynamic conditions of slip flow by metal. Formation of non-stable deformation zone, mainly, caused by imperfection both of extrusion conditions and by main parameters of deformation zone.

Elimination of pointed disadvantages is possible by choosing of optimal parameters of vibration system which provide rational conditions of extrusion process of tubes [1,2].

Finding of concrete recommendations according to choosing of optimal parameters of tube extrusion process stipulated by technological modes, in the conditions of functioning of mechanic system in some non traditional statement, mainly, connected with forming of demanded dynamic model of the problem stated.

Consider some the most characteristic moments of technological process of extrusion of tubes. The process of tubes extrusion, at the most of horizontal presses, is performed by the following way: preliminary heated tube billet (shell) *6* enters into the container *3*, which have the temperature 380-420 єC. Mandrel *4* is forcibly entered into the tube shell 6 by hydraulic actuator of press. Then press ram 1 with pressure disk *2* press tightly billet 6 into the container.

Mandrel *4*, at the same time, takes the place in annular gap of die *5*, with some projection along axis of piercing. Therefore, at further movement of press ram 1, in limited volume of container *3*, metal is pressed out into gap between mandrel *4* and die *5* is being formed to the tube *6* of given geometrical sizes [3,4,5]. It is necessary to take into consideration, that at realization of some pressing conditions, the process of slip flow of mandrel by metal is accompanied by large dynamic loads at technological tools. It stipulates considerable vibrations of mandrel in deformation zone, and as a result, high nonuniform pipe wall thickness (fig.1).

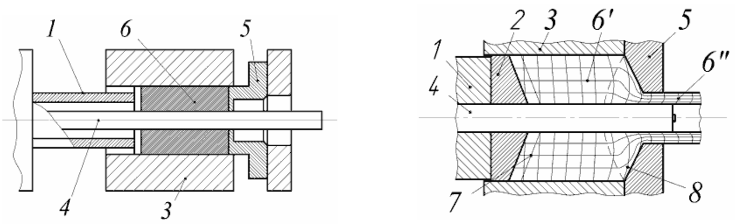

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Figure 1– Diagram and process of extrusion of tube:
1 – press ram, 2 – pressure disk, 3 – container, 4 – mandrel,
5 – die, 6 – tube billet, 7 – remainder of billet 8 – lubricant plate

Consider dynamic processes of slip flow of mandrel by stream flow of hot metal and conditioned its nonlinear vibrations, on the basis of offered loading diagram at the figure 2.

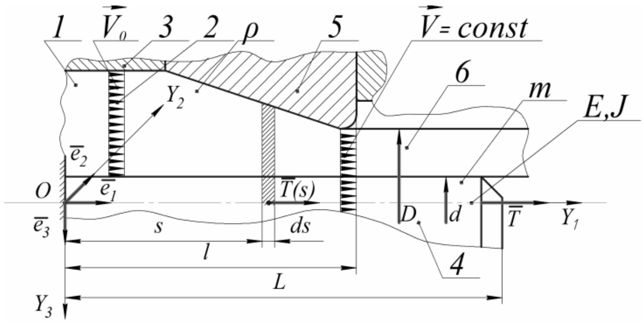

Figure 2 – Loading diagram to nonlinear vibrations of needle (mandrel) at tube extrusion: 1 – press ram; 2 –shell; 3 – container; 4 – needle (mandrel); 5 – die; 6 – tube

For research of vibration processes in deformation zone and dynamic of cantileverly fixed mandrel in nonlinear statement, consider its movements in uniform slip flow of metal being pressed.

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It is necessary to note that for accepted quasi-stationary process of tube extrusion ($\vec{V}$=const) and loading diagram of nonlinear dynamic model according to [6, 7], differential equation of movement of mandrel in vector form is as follows:

$$m\frac{\partial^2\vec{R}}{\partial t^2}+M\frac{\partial\vec{R}}{\partial s}\times\left\{\left[\left(\frac{\partial}{\partial t}+V_\tau\frac{\partial}{\partial s}\right)^2\vec{R}\right]\times\frac{\partial\vec{R}}{\partial s}\right\}=$$
$$=W\vec{e}_3+\frac{\partial}{\partial s}\left(T\frac{\partial\vec{R}}{\partial s}\right)+EI\frac{\partial}{\partial s}\left\{\frac{\partial\vec{R}}{\partial s}\times\left[\frac{\partial\vec{R}}{\partial s}\times\frac{\partial^3\vec{R}}{\partial s^3}\right]\right\}+\vec{f}_\upsilon+$$
$$+\frac{K_n\rho d}{2}\left|\frac{\partial\vec{R}}{\partial s}\times\left[\left(\vec{V}-\frac{\partial\vec{R}}{\partial t}\right)\times\frac{\partial\vec{R}}{\partial s}\right]\right|\frac{\partial\vec{R}}{\partial s}\times\left[\left(\vec{V}-\frac{\partial\vec{R}}{\partial t}\right)\times\frac{\partial\vec{R}}{\partial s}\right]+$$
$$+\frac{\pi K_f\rho d}{2}\left|\vec{V}-\frac{\partial\vec{R}}{\partial t}\right|\left(\vec{V}-\frac{\partial\vec{R}}{\partial t}\right) \quad (1)$$

$$V_\tau=\frac{\partial\vec{R}}{\partial s}\left(\vec{V}-\frac{\partial\vec{R}}{\partial t}\right);\quad\left(\frac{\partial\vec{R}}{\partial s}\right)^2\approx 1 \quad (2)$$

Here t – time; s – present-position coordinate of mandrel; $\vec{R}\equiv(Y_1;Y_2;Y_3)$ – radius vector of chosen coordinates of the system; T – tension of mandrel in Y_1-direction; ρ – density of pressed metal; m – linear mass of mandrel; M – addad mass of metal flow; $\vec{W}$ – lifting force, acting on unit of length of mandrel; d – mandrel diameter; K_n – effective coefficient of resistanse of mandel (shape); K_f – sliding friction factor of metal at mandrel; E – coefficient of elasticity of mandrel material; I – moment of inercia of mandrel; $\vec{e}_3$ – unit vector along direction of gravity force; $\vec{f}_\upsilon$ – distributed force, conditioned by flow separation of metal from surface of mandrel in the process of tube extrusion.

Inertial forces of added mass of pressed metal can be presented as particular generalizations of analytical expressions, pointed in [6, 7, 8]. Formula for elastic forces has been obtained taking into account geometrical nonlinearity of stem deformation of mandrel. At the same time, inertial summunds in equation have been neglected according to conditions given in this research paper [6]. It this statement of problem of dynamic model it has been taken into account that the moment of elastic force of mandrel is proportional to its curvature and is directed at binormal to its elastic line. It is necessary to note that concretization of formula for force $\vec{f}_v$ in each separate case will be lead in accordance with [7]. Though lifting force acting on mandrel is relatively small and flow of metal, in pursuance of requirements of technological process, is directed strictly along axis of extrusion Y_1

$$\vec{V} = V_0 \, \vec{e}_1 \qquad (3)$$

Here $\vec{e}_1$ is unit vector along axis Y_1. Obviousely, that mandrel in position of equilibrium is located along axis of extrusion Y_1. Take into account that under limited deformations of mandrel at exit from equilibrium the angles of gradient of its ais to axis Y_1remains small

$$\vec{R} \cong s\,\vec{e}_1 + y\,\vec{e}_3\,, \ \left(\frac{\partial y}{\partial s}\right)^2 << 1 \qquad (4)$$

Taking into account correlation (3) and (4), further it will be supposed, that in this problem statement, can neglect the force that stipulated breakaway of metal flow from surface of mandrel. Therefore, substituting formula (4) for $\vec{R}$ into equation (2), can be convinced that at neglecting of dimensions, which are quadratic to angle between axis of mandrel and axis of extrusion Y_1, it satisfies to this equation. Substitute formula (3) and (4) to the first component of equation (1). Neglecting values, quadratic to shift of mandrel stem along axis Y_1, after making appropriate operation of integration, have the following:

$$T = T_* - q_f (L - s), \quad q_f = \frac{\pi K_f \rho \, d \, V_0^2}{2} \qquad (5)$$

Here T_* is tension at the end of technological tool (at $L = s$).

Put correlation (3), (4) and (5) to the equation (1). Therefore, neglect the summunds in obtained expression, by summunds which are quadratic to the displacement of mandrel Y_1-direction, except summuns which is proportional to coefficient of mandrel shape K_n, taking into account, that the latest one is large in comparison with coefficient of friction of metal on mandrel. In the result of necessary substitutions and some conversions for y get the following diferential equation:

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$$m\frac{\partial^2 y}{\partial t^2}+M\left(\frac{\partial}{\partial t}+V_0\frac{\partial}{\partial s}\right)^2 y+q_f\frac{1}{V_0}\frac{\partial y}{\partial t}-\frac{\partial}{\partial s}\left\{\left[T_*-q_f(L-s)\right]\frac{\partial y}{\partial s}\right\}+$$

$$EI\frac{\partial^4 y}{\partial s^2}+q_n\frac{1}{V_0^{\,2}}\left|\left(\frac{\partial}{\partial t}+V_0\frac{\partial}{\partial s}\right)y\right|\left(\frac{\partial}{\partial t}+V_0\frac{\partial}{\partial s}\right)y=0, \qquad (6)$$

$$q_n\equiv\frac{K_n d\rho V_0^{\,2}}{2}$$

Compare differential equation (6) with equation (5) of the [8] for case of relatively low amplituds of mandrel vibrations, when can neglect (q_n=0) particular nonlinear summunds in equation (6). If suppose that $C_n=C_T$ in equation (5) of the [8], and make then the following substitution

$$x\to s; u\to V_0;\ \frac{C_T M}{2D}\to q_f;\ \frac{C_n M u^2}{2}\to T_* \qquad (7)$$

in the result obtaint the following differential substitution:

$$m\frac{\partial^2 y}{\partial t^2}+M\left(\frac{\partial}{\partial t}+V_0\frac{\partial}{\partial s}\right)^2 y+q_f\frac{1}{V_0}\frac{\partial y}{\partial t}\left(\frac{\partial}{\partial t}+V_0\frac{\partial}{\partial s}\right)y-$$

$$-\frac{\partial}{\partial s}\left\{\left[T_*-q_f(L-s)\right]\frac{\partial y}{\partial s}\right\}+EI\frac{\partial^4 y}{\partial s^2}=0 \qquad (8)$$

Comparing the expressions (8) and (6) at q_n=0 see that they do not coincide. It can be explained by that the equilibrium equations of streamline body (stem) in transverse direction equated not correctly. Note that in equation (1) of the [8] value F_n there is projection of distributed force to resistance slip flow on normal to axis of stem, at the time when other summunds of equation of equilibrium correspond projections of appropriate forces on axis Y_1.

Incorrectness of close origin is in mathematical model (equation of dynamic equilibrium) of vibration of stem in slip flow of working medium ([6], equation 16). It relates to such circumstance that friction resistance in slip flow of metal was included in deformation force of elastic line axis of stem and was not included in tensile force (tensile force of stem is accepted as constant).

For accepted dynamic model of extrusion process consider some characteristic boundary conditions of the problem under study of nonlinear vibrations of mandrel. On the basis of conditions of realization of stable technological exrusion process, shift and orientation of mandrel in point of mounting to the body of press must be given in the problem [2, 5] in the following form:

$$y\Big|_{s=0} = f(t);\ \frac{\partial y}{\partial s}\Big|_{s=0} = \alpha(t). \qquad (9)$$

Here $f(t)$ and $\alpha(t)$ – proper time functions which are given in conditions of realization of tbe extrusion process.

Let place of mounting of mandrel to the body of mandrel holder of press remains perpendicular to axis Y_1. Therefore, on the basis of equilibrium condition of forces made to mandrel, make factorization for shifting of its relative sections along axis Y_1. In the result in zero and first approximization for shifting of mandrel obtain the following:

$$T_* = \frac{K_* S_* \rho V_0^2}{2}; \qquad (10)$$

$$\left[M_* \frac{\partial^2 y}{\partial t^2} + \frac{T_*}{V_0}\left(\frac{\partial y}{\partial t} + V_0 \frac{\partial y}{\partial s} \right) - EI \frac{\partial^3 y}{\partial s^3} - Q_* \right]\Big|_{s=L} = 0. \qquad (11)$$

Here M_* – mass f stem with mandrel; K_* – effective coefficient resistance of mandrel; S_* – area of front part of mandrel; Q_* – force, applied to mandrel from the side of pressed. Force Q_* can be conditioned, for example, by movement of metal along surface of mandrel. If end of mandrel in the extrusion process is free, then according to [6; 8] obtain necessary and enough condition

$$\left[EI \frac{\partial^3 y}{\partial s^3} + f_2 M V_0 \left(\frac{\partial}{\partial t} + V_0 \frac{\partial}{\partial s} \right) y - (m + f_2 M)\Delta L \frac{\partial^2 y}{\partial t^2} \right]\Big|_{s=L} = 0,$$

$$\Delta L = \int\limits_{L-\ell}^{L} S(s)ds,\ \frac{\partial^2 y}{\partial s^2}\Big|_{s=L} = 0,\quad EI \to 0 \qquad (12)$$

Here ℓ – lengh of mandrel at the sector between die and mounting to the body of mandrel holder; S– area of cross-section of main part of mandrel; $S(s)$ – current area of cross-section of mandrel; f_2– dimensionless parameters of problem $f_2 \le 1$.

Consider that bending moment at the end of mandrel equals to zero, write the condition $\frac{\partial^2 y}{\partial s^2}\Big|_{s=L} = 0$. Obviosely, that this condition and condition (9) can be neglected, if suppose that mandrel in slip flow of metal is flexible enough.

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As boundary conditions of problem accept first demanded condition (9) and necessary and enough condition (12), using

$$f(t) = y_0 \cos(\Omega_0 t), Q_* = G_* \sin(\Omega_* t) \qquad (13)$$

As initial conditions of the problem we accept

$$y\Big|_{t=0} = y_0 \cos(\frac{\pi x}{L}), \ \frac{\partial y}{\partial t}\Big|_{t=0} = 0 \qquad (14)$$

In correlations (13) and (14) dimensions $y_0, \Omega_0, G_*, \Omega_*$ are definite constants, physical meaning of which is obvious from basic conditions of realization of extrusion process.

For convenient imagination and analysis of the problem, supply some non-dimensional parameters of the system

$$\eta \equiv \frac{y}{d}, \sigma \equiv \frac{s}{L}, \tau \equiv \frac{V_0 t}{L}, \gamma_* \equiv \frac{2K_* S_*}{\pi d^2},$$
$$\gamma_f \equiv \frac{2K_f L}{d}, \gamma_n \equiv \frac{2K_n}{\pi}, \eta_0 \equiv \frac{y_0}{d}, \nu_* \equiv \frac{\Omega_* L}{V_0}, \qquad (15)$$
$$\mu_* \equiv \frac{M_*}{ML}, \chi_* \equiv \frac{G_* L}{dMV_0^2}, \nu_* \equiv \frac{\Omega_* L}{V_0}$$

In the result, differential equation (6), and also accepted initial and boundary conditions of the problem imagine in the following form:

$$\frac{\partial^2 \eta}{\partial \tau^2} + \left(\frac{\partial}{\partial \tau} + \frac{\partial}{\partial \sigma}\right)^2 \eta + \gamma_f \frac{\partial \eta}{\partial \tau} - \frac{\partial}{\partial \sigma}\left\{(\gamma_* + \gamma_f (1-\sigma))\frac{\partial \eta}{\partial \sigma}\right\} +$$
$$+\gamma_n \left|\left(\frac{\partial}{\partial \tau} + \frac{\partial}{\partial \sigma}\right)\eta\right| \left(\frac{\partial}{\partial \tau} + \frac{\partial}{\partial \sigma}\right)\eta = 0 \qquad (16)$$

$$\eta\Big|_{\sigma=0} = \eta_0 \cos(\nu_0 \tau); \left[\mu_* \frac{\partial^2 \eta}{\partial \tau^2} + \gamma_* \left(\frac{\partial}{\partial \tau} + \frac{\partial}{\partial \sigma}\right)\eta\right]\Big|_{\sigma=1} = \chi_* \sin(\nu_* \tau) \qquad (17)$$

$$\eta\Big|_{\tau=0} = \eta_0 \cos(\frac{\pi \sigma}{2}); \frac{\partial \eta}{\partial \tau}\Big|_{\tau=0} = 0 \qquad (18)$$

To solve differential equation (16) with chosen boundary and initial conditions (17) and (18) apply method of finite differences according [8] with further use of modern computer technologies. Hence, in order to receive reliable pattern of dynamic processes and spectrum of nonlinear vibrations of mandrel, modify non-dimensional parameters of the system within the bounds, stipulated by technological process of tube extrusion.

Behavior of mathematical model of nonlinear vibrations of mandrel in slip flow of metal, in the extrusion process, has been checked by breaking of computational mesh at further iterations for chosen method of finite differences. Numerical solution of the problem allows to determine instantaneous configurations of lines of mandrel axis and also time dependences (dynamic predictions) of its different sections. Analysis of dependencies of dynamic shifts of different image points of mandrel in time shows distinctly interaction of disturbances attached to mandrel in the process of tubes extruson. External disturbances of mandrel are caused by given periodical shift of basic point of mandrel and periodic force attached to the end of mandrel mounting. This interaction appears in form of mutual modulating of vibration amplitudes of dynamic model of mechanical system under consideration.

Character of dynamic state of mandrel, in established mode of vibrations of system is determined by change on its working length of disturbances amplitudes y_0 and frequencies which correspond to shifts of basic and end points of technological tool (mandrel) in the conditions of flow of stream of metal in the process of extrusion. Attenuation of disturbances caused by periodical shifts of basic point of mandrel and point of mandrel mounting in the direction of metal flow, is to be weaker in comparison with values of disturbances caused by periodical force attached to the end of technological tool in opposite direction. Increase of ratio (V_0 / L) leads to decrease of attenuation of disturbances of technological tool caused by peridic disturbances (shifts) of basic point of mandrel in the direction of movement of metal flow. At the same time, conditions, in opposite direction caused by force applied to end part of mandrel mounting to body of holder by periodical force, promote stronger suppresion of disturbances of the system.

Dependencies of dynamic shifts of different points in time, in the mode of established vibrations of mandrel for selected spektrum of dimensionless parameters, taking into account the most characteristic mode of extrusion process are indicated at the figure 3 and 4.

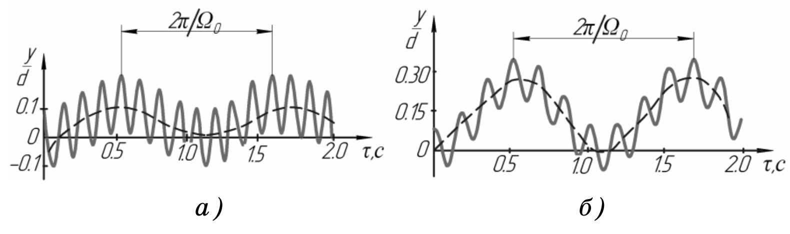

Figure 3 – Dynamic of mandrel of horizontal hydraulic profile 31,5 MH at extrusion of stainless steel tubes 12X18H10T, diameter 168Ч14: а – pressing speed $V_0 = 0,2$ m/s; б – pressing speed $V_0 = 0,35$ m/s

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Transient processes of forming of nonlinear vibrations of mandrel at the figure 3 have not been shown. Average values of amplitudes of nonlinear mandrel vibrations ($2\pi/\Omega_0$) on periodic time in the extrusion process are indicated by a dotted line. Note that for curve line (figure. 3, a) ratio y_0/d twice time more than for curve line (figure 3, б).

Some peculiarities of decay of mandrel vibrations in the extrusion process and changing on length of mandrel of amplitude of disturbances y_0, are indicated at the figure 4.

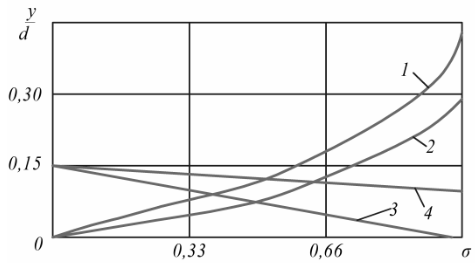

Figure 4 – Attenuation of vibrations on length of mandrel stem in the process of tube extrusion:
1, 2 – caused by vibrations of mandrel stem end;
3, 4 – caused by vibrations of basic point of mandrel stem

Note that nonstable dynamic processes are caused by periodic shifts of basic point and periodic force applied to mandrel. It is typical exceptionally for particular parameters of the system and for wide distributed modes of tube extrusion.

Results of industrial test of horizontal hydraulic press of tube-press machine 31,5 MH in conditions of realization of rational technological process, for example, during extrusion of seamless tubes of diameter 168x14 from stainless steel 12X18H10T, confirms appropriateness of theoretical hypotheses and adequacyи of chosen mathematical model. At the same time, with help of selecting of rational modes of tubes extrusion and of selection of dynamic characteristics of the system, considerable increase of quality of produces seamless tubes (reduction of lengthwise and crosswise nonuniform shell wall thickness equals to approximately 12 %) has been achieved. Reliability of acheived results and correctness of functioning of the system at nonlinear mandrel vibrations has been checked with help of test calculations for cases when solving of the problem in analytical kind for elementary model of mechanic system is known. [9].

CONCLUSIONS

1. Differential equation of nonlinear vibrations of mandrel in uniform slip flow of metal for accepted loading diagram and dynamic model of quasistationary process of tubes extrusion has been obtained.

2. Decision of differential equation of nonlinear vibrations of mandrel, with chosen boundary and initial conditions by method of finite differences with usage of modern computer technologies, has been offered.

3. With help of numerical analysis of mathematical model of nonlinear vibrations of mandrel in the process of tube extrusion, instant configuratios of its elastic line exis and also time dependence (dynamic predictions) of its different sections have been determined.

4. Amplitudes of disturbances on lengh of mandrel caused by periodic shifts of basic point, and applied to the mandrel forces have been determined taking into account particular parameters of dynamic system and modes of tubes extrusion.

5. It has been found that increase raion of extrusion speed to length of mandrel resulted in decrease of atenuation of mandrel disturbance caused by periodic disturbances (shifts) of basic point in the direction of metal flow and stronger attenuation of disturbances caused by periodic force attached to end part of mandrel mounting.

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