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SIMULATION MODELING IN THE RESEARCH OF METALLURGICAL EQUIPMENT OPERATION

Annotation. Rolling production refers to the final link of the metallurgical cycle, the quality of products shipped to the consumer depends on the consistency of the work of all units. The wear and tear of the main production facilities of enterprises of the metallurgical complex requires not only updating, but also constant modernization of dated equipment in the conditions of active production. The main equipment of the production lines of wide scale rolling mills in cludes coilers, the quality of which depends not only on the rhythm of the rolling equipment, but also on the quality of the material shipped to the consumer. Simulation modeling of the winding process of hot rolled billot made it possible to establish the possibility of torsional oscillations in the coiler drum drive. Further analysis of the form of the resulting oscillations made it possible to establish that the elastic deformations from the resistance forces of the electric motor and the rotating parts of the coiler drum are in antiphase. The performed calculations create prerequisites for the study of forced oscillations occurring in the coiler drum drive.

Key words: simulation modeling, coiler, strip, torsional oscillations, elastic deformations, free oscillations

Statement of the problem

Modern production lines of rolling shops have a lot of additional and basic equipment, such as scissors, plate straightening machines, coilers, uncoilers, turnover devices, manipulators, conveyors [1-3]. Not only the rhythmicity of the work of the entire workshop depends on how well and efficiently each unit from the rolling mill performs its functions, but also the timeliness of the shipment of the final product to the consumer.

The main equipment of the rolling mill includes coilers of hot-rolled billot, the quality of the billot's winding depends on rolling mill's operation, which affects not only the next sheet cutting operation, but also the shipment of a high-quality, tightly wound roll according to the requests.

Today, coilers are precisely the vulnerable technological equipment that prevents the further improvement of the productivity of the rolling line. They are often the reason for the lack of rolling. The creation of new high-speed models or

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the improvement of the design of existing ones require thorough studies of the loads on their units in the form of a full-scale experiment [4].

Analysis of recent research and publications

Modernization of existing equipment poses the task of mechanical designers to develop a sufficiently reliable design that can provide quick and easy adjustment during the flow of the technological process. Correctly determined technological loads and coefficients of the durability reserve allow not only to extend the life cycle of the equipment, but also to significantly reduce its metal content [5].

Work [6] considered in detail the issue of the impact of dynamic loads on the interaction of mechanical rolling equipment, while the impact of changing the technological modes of operation of coilers on the dynamics of the staff winding process was not covered.

Any calculation related to technological equipment is a prediction of its performance. There are calculations designed to ensure the functioning of mechanical systems and the possibility of performing the technological operations entrusted to them (1st group), as well as calculations for strength and reliability, designed to confirm the resource and quality of works due to the equipment (2nd group). The first group of calculations includes calculations of operating parameters of processes and structures for their implementation (productivity, speed, technological supports, power). The second group includes calculations that determine the load on individual structural elements and their stress-strained state, limit state equations, durability reserves, and the probability of failure-free operation [7].

Due to uncertainty during the martial law in the country, it is quite difficult to conduct full-scale experiments that would allow to confirm or disprove certain aspects of the technological process, therefore the problem of using simulation modeling and experiment in the design of metallurgical equipment becomes urgent [8].

Simulation modeling allows to replace the researched model with a mathematical one and conduct experiments on it by means of statistical modeling using numerical methods in specialized programs of computational experiments [9].

Purpose of the study

Taking into account the importance of the technological process of winding hot-rolled billot, the purpose of the study was to develop a simulation model of winding billot into a roll depending on the change in technological parameters, for its further use in the conditions of current production in order to optimize not only the technological cycle, but also when modernizing the structural elements of technological equipment.

Statement of the main research material

The nature of the movement of the coiler drum when winding the hot-rolled billot is rotational, that is, all dynamic processes in this case will be characterized by the moment of inertia. If we accept the case when the staff is tightly wound and all structural gaps have already been selected, then the drum together with the wound coiler can be considered as a rotating cylinder for which the moment of inertia [10]:

$$J_{б} = \frac{m_{т} \cdot D_{б}^{2}}{8}, \text{ kg·m}^2 \qquad (1)$$

where $m_{т}$ – technological load taking into account the weight of the drum;
$D_{б}$ – coiler's diameter;

Under the condition of a constant linear speed of winding the billot, the instantaneous weight of the roll can be calculated by the formula:

$$m_{р} = V \cdot t \cdot m_{м.п.}, \text{ kg} \qquad (2)$$

where V – winding's speed (linear);
t – time of the technological winding operation;
$m_{м.п.}$ – the mass of one meter of winding billot:

$$m_{lm.} = \rho \cdot t \cdot b, \text{ kg/m} \qquad (3)$$

where ρ – density of the material of the winding billot;
t – thickness of the winding material;
b – width of the winding material.

Taking it as the technological load in the expression (1) – roll's mass, drum's diameter – instantaneous roll's diameter, expression (1) will be:

$$J_{б} = \frac{(m_{б} + m_{р}) \cdot D_{р}^{2}}{8}, \text{ kg·m}^2 \qquad (4)$$

where $m_{б}$ – directly the mass of the drum;
m_r – instantaneous roll's mass calculated by (2);
D_r – instantaneous roll's diameter, m;

During the flow of the technological process of winding hot-rolled stock, the diameter of the roll is a variable value over time. The technological process should be considered for a different assortment of billot, wound in the thickness range t=1.5÷4 mm with a roll width of 1250 mm, for the most complex technological mode, when the mass of the product roll reaches a maximum, i.e. 16 tons.

At the start of winding, the diameter of the roll will be equal to the diameter of the drum. The results of the calculation according to formulas (1)-(4) are entered in table 1 and we plot the dependence of the mass and diameter of the roll as a function of time (Fig. 1-2).

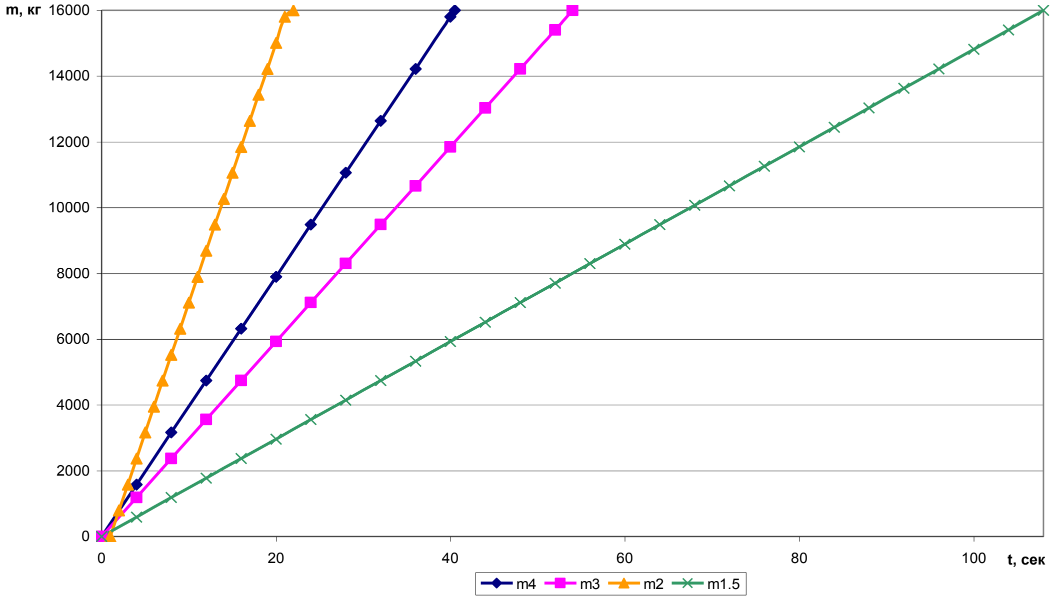

Figure 1 – Graph of the dependence of the mass of the roll in a function of time

Table 1

The results of determining the moment of inertia of the coiler drum or different conditions of flow of the technological process

The time of the technical operation of roll formation t, sec	Billot's thickness											
	4 mm			3 mm			2 mm			1,5		
	m_p kg	D_p m	$J_б$ $kg\cdot m^2$	m_p, kg	D_p m	$J_б$ $kg\cdot m^2$	m_p kg	D_p, m	$J_б$ $kg\cdot m^2$	m_p kg	D_p m	$J_б$ $kg\cdot m^2$
0	0	0,75	1177	0	0,75	1177	0	0,75	1177	0	0,75	1177
4	1580	0,90	1871	1185	0,87	1688	790	0,83	1511	593	0,81	1425
8	3160	1,04	2666	2370	0,97	2256	1580	0,90	1871	1185	0,87	1688
12	4740	1,15	3562	3555	1,07	2881	2370	0,97	2256	1778	0,92	1965
16	6320	1,26	4558	4740	1,15	3562	3160	1,04	2666	2370	0,97	2256
20	7900	1,36	5655	5925	1,23	4299	3950	1,10	3101	2963	1,02	2561
24	9480	1,45	6853	7110	1,31	5094	4740	1,15	3562	3555	1,07	2881
28	11060	1,53	8151	8295	1,38	5945	5530	1,21	4047	4148	1,11	3214

32	12640	1,61	9550	9480	1,45	6853	6320	1,26	4558	4740	1,15	3562
36	14220	1,69	11049	10665	1,51	7817	7110	1,31	5094	5333	1,19	3924
40	15800	1,76	12649	11850	1,57	8838	7900	1,36	5655	5925	1,23	4300
40,5	15998	1,77	12857	11998	1,58	9570	7999	1,36	5727	5999	1,24	4348
44				13035	1,63	9915	8690	1,40	6241	6518	1,27	4690
48				14220	1,69	11049	9480	1,45	6853	7110	1,31	5094
52				15405	1,75	12240	10270	1,49	7489	7703	1,34	5513
54				15998	1,77	12857	10665	1,51	7817	7999	1,36	5727
56							11060	1,53	8151	8295	1,38	5945
60							11850	1,57	8838	8888	1,41	6392
64							12640	1,61	9550	9480	1,45	6853
68							13430	1,65	10287	10073	1,48	7328
72							14220	1,69	11049	10665	1,51	7817
76							15010	1,73	11837	11258	1,54	8320
80							15800	1,76	12649	11850	1,57	8838
81							15998	1,77	12857	119988	1,58	8969
84										12443	1,60	9369
88										13035	1,63	9915
92										13628	1,66	10475
96										14220	1,69	11049
100										14813	1,72	11638
104										15405	1,75	12240
108										15998	1,77	12857

By analyzing the graphs obtained in fig. 1-2, it can be concluded that the mass of the winding roll is directly proportional to the winding time, and the diameter of the roll does not change linearly, which can cause oscillations in the coiler's drive; to study the nature of these oscillations, it is worth studying their shape.

Concentrated masses, which during rotational movement at different moments of time either lead or lag behind each other, create torsional oscillations. From the point of view of the strength of the machine nodes, this can be very dangerous, because with this phenomenon moments of elastic forces can significantly exceed the calculated loads, especially if cyclical technological loads are added. Therefore, there is an important issue of taking into account and controlling changes in the nature and magnitude of elastic forces during the flow of the technological process [11].

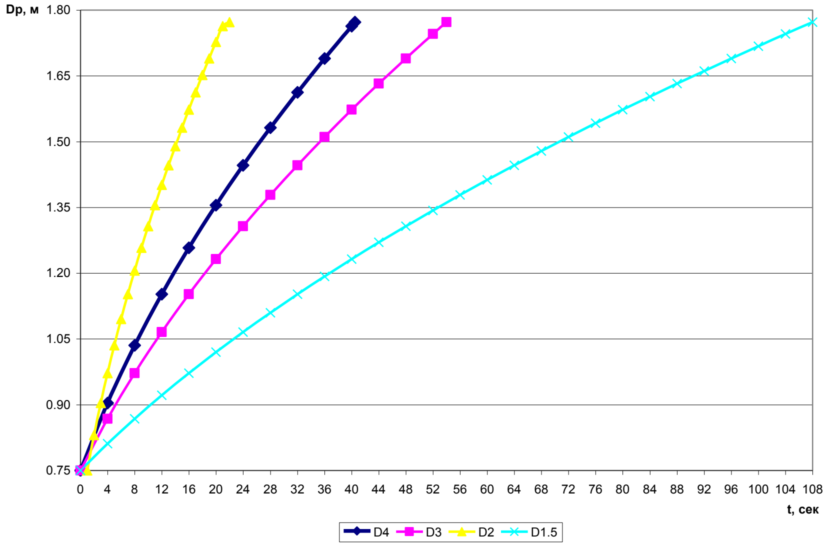

Figure 2 – Graph of dependence of roll diameter in a function of time

When calculating the oscillations of a multi-mass system, the most important stage is the compilation of the calculation scheme [10], while it is worth considering that the more elements in the system, the more complicated the calculation, therefore it is worth moving from multi-mass to two-mass calculation schemes (Figure 3).

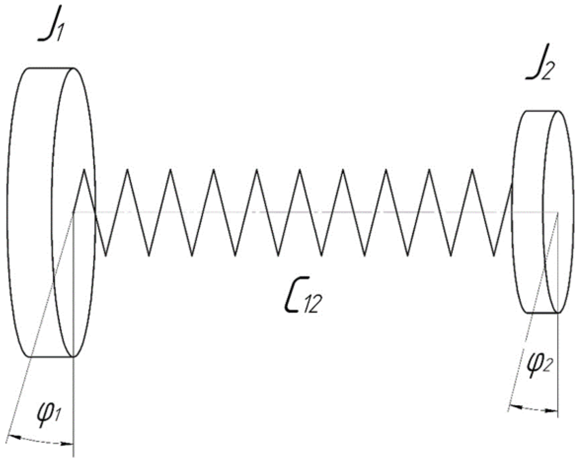

Figure 3 – Scheme for calculating free oscillations occurring in the coiler's drive of hot-rolled staff: J_1 – moment of inertia of the roll with the coiler drum, J_2 – moment of inertia of the armature electric motor of the drive, C_{12} – the stiffness of the intermediate shaft

The task of calculations on oscillations is to find, first of all, the spectrum of natural frequencies and the shape of oscillations.

When studying the oscillations of mechanical systems with a limited number of degrees of freedom, Lagrangian equation of motion of the second kind is used [10].

For the case of free oscillations without taking into account resistance forces, the Lagrange equation has the form [12]:

$$\frac{d}{dt}\cdot\left(\frac{\partial E}{\partial \dot{q}_i}\right)-\frac{\partial E}{\partial q_i}+\frac{\partial E_{П}}{\partial q_i}=0 \qquad (5)$$

For a two-mass system, the Lagrange equation can be written in the form [13]:

$$\frac{d}{dt}\cdot\left(\frac{\partial E}{\partial \dot{q}_2}\right)-\frac{\partial E}{\partial q_2}+\frac{\partial E_{П}}{\partial q_2}=0\ ;\frac{d}{dt}\cdot\left(\frac{\partial E}{\partial \dot{q}_1}\right)-\frac{\partial E}{\partial q_1}+\frac{\partial E_{П}}{\partial q_1}=0 \qquad (6)$$

After the necessary transformations of equations (5)-(6), we obtain the formulas for determining, respectively, the spectrum of natural frequencies and the form of oscillations for the calculation scheme of Fig. 3:

$$p^2=\frac{C_0(j_1+j_2)}{j_1 j_2} \quad \text{or} \quad p=\sqrt{\frac{C_0(j_1+j_2)}{j_1\cdot j_2}} \qquad (7)$$

$$\mu=\frac{C_0-j_1p^2}{C_0}. \qquad (8)$$

where $C_0=C_{12}$ – stiffness of the intermediate shaft:

$$C_{12}=\frac{\pi\cdot G\cdot d^4}{64\cdot g\cdot l}\text{, kg·m} \qquad (9)$$

where l – length of the intermediate shaft;
G – modulus of rigidity;
d – diameter oft he shaft;
g – gravitational acceleration.

Next, we find the amplitude of oscillations:

$$A_1=\frac{\omega}{p(1-\mu)} \qquad (10)$$

where ω – angular velocity of the drum;

Now that the frequency, amplitude and form of oscillations are known, it is possible to determine the elastic deformations that occur during the winding of the billot in a function of time using the formulas:

$$\varphi_1=A_1\sin(pt+\beta);\qquad \varphi_2=\mu A_1\sin(pt+\beta), \qquad (11)$$

where β – initial phase of oscillations (the angular displacement of the beginning of oscillations relative to the coordinate reference point is β=0);

p – own circular frequency of oscillations;

μ – shape coefficient of oscillations;

A_1 – amplitude of oscillations.

Using the known parameters of the technological process of winding billot and formulas (7)-(11), we obtain the necessary data (table 2-3) for constructing a graph of free oscillations occurring in the drive of the hot billot coiler (Fig. 4).

Table 2

Results of calculating the circular frequency of oscillations, shape factor and amplitude of oscillations

The time of the technical operation of roll formation t, sec	Billot's thickness											
	4 mm			3 mm			2 mm			1,5		
	p	μ	A	p	μ	A	p	μ	A	p	μ	A
0	162	-0,02150	0,16137	162	-0,02150	0,16137	162	-0,02150	0,16137	162	-0,02150	0,16137
4	161	-0,01352	0,13546	161	-0,01499	0,14076	161	-0,01674	0,14674	161	-0,01775	0,15002
8	161	-0,00949	0,11898	161	-0,01121	0,12643	161	-0,01352	0,13546	161	-0,01499	0,14076
12	161	-0,00710	0,10733	161	-0,00878	0,11572	161	-0,01121	0,12643	161	-0,01288	0,13302
16	161	-0,00555	0,09854	161	-0,00710	0,10733	161	-0,00949	0,11898	161	-0,01121	0,12643
20	160	-0,00447	0,09159	161	-0,00588	0,10053	161	-0,00816	0,11271	161	-0,00988	0,12072
24	160	-0,00369	0,08593	160	-0,00497	0,09487	161	-0,00710	0,10733	161	-0,00878	0,11572
28	160	-0,00310	0,08120	160	-0,00426	0,09007	161	-0,00625	0,10265	161	-0,00787	0,11129
32	160	-0,00265	0,07718	160	-0,00369	0,08593	161	-0,00555	0,09854	161	-0,00710	0,10733
36	160	-0,00229	0,07369	160	-0,00324	0,08231	160	-0,00497	0,09487	161	-0,00645	0,10377

40	160	-0,00200	0,07064	160	-0,00286	0,07911	160	-0,00447	0,09159	161	-0,00588	0,10053
40,5	160	-0,00197	0,07028	160	-0,00282	0,07874	160	-0,00442	0,09121	161	-0,00582	0,10015
44				160	-0,00255	0,07626	160	-0,00405	0,08863	160	-0,00539	0,09758
48				160	-0,00229	0,07369	160	-0,00369	0,08593	160	-0,00497	0,09487
52				160	-0,00207	0,07137	160	-0,00338	0,08347	160	-0,00459	0,09238
54				160	-0,00197	0,07028	160	-0,00324	0,08231	160	-0,00442	0,09121
56							160	-0,00310	0,08120	160	-0,00426	0,09007
60							160	-0,00286	0,07911	160	-0,00396	0,08793
64							160	-0,00265	0,07718	160	-0,00369	0,08593
68							160	-0,00246	0,07537	160	-0,00345	0,08406
72							160	-0,00229	0,07369	160	-0,00324	0,08231
76							160	-0,00214	0,07212	160	-0,00304	0,08066
80							160	-0,00200	0,07064	160	-0,00286	0,07911
81							160	-0,00197	0,07028	160	-0,00282	0,07874
84										160	-0,00270	0,07765
88										160	-0,00255	0,07626
92										160	-0,00242	0,07494
96										160	-0,00229	0,07369
100										160	-0,00217	0,07250

104										160	-0,00207	0,07137
108										160	-0,00197	0,07028

Table 3

Calculation results of elastic deformations resulting from free oscillations and moments of elastic forces

The time of the technical operation of roll formation t, sec	Billot's thickness							
	4 mm		3 mm		2 mm		1,5	
	φ_1	φ_2	φ_1	φ_2	φ_1	φ_2	φ_1	φ_2
0	0	0	0	0	0	0	0	0
4	-0,131	0,00177	-0,136	0,00204	-0,141	0,00237	-0,144	0,00256
8	-0,053	0,00050	-0,059	0,00066	-0,066	0,00089	-0,070	0,00106
12	0,085	-0,00060	0,090	-0,00079	0,095	-0,00106	0,097	-0,00125
16	0,073	-0,00041	0,082	-0,00058	0,095	-0,00090	0,104	-0,00117
20	-0,048	0,00022	-0,049	0,00029	-0,049	0,00040	-0,047	0,00047
24	-0,080	0,00030	-0,090	0,00045	-0,104	0,00074	-0,113	0,00100
28	0,016	-0,00005	0,014	-0,00006	0,008	-0,00005	0,001	-0,00001
32	0,077	-0,00020	0,086	-0,00032	0,098	-0,00054	0,106	-0,00075
36	0,011	-0,00003	0,016	-0,00005	0,027	-0,00013	0,037	-0,00024
40	-0,067	0,00013	-0,074	0,00021	-0,082	0,00037	-0,086	0,00051
40,5	0,011	-0,00002	0,016	-0,00004	0,026	-0,00012	0,036	-0,00021
44			-0,040	0,00010	-0,053	0,00022	-0,065	0,00035
48			0,055	-0,00013	0,059	-0,00022	0,059	-0,00029
52			0,056	-0,00012	0,070	-0,00024	0,082	-0,00038
54			0,014	-0,00003	0,024	-0,00008	0,035	-0,00015
56					-0,031	0,00010	-0,027	0,00012
60					-0,077	0,00022	-0,087	0,00035
64					0,004	-0,00001	-0,004	0,00002
68					0,075	-0,00018	0,082	-0,00028
72					0,022	-0,00005	0,032	-0,00010
76					-0,064	0,00014	-0,068	0,00021
80					-0,043	0,00009	-0,054	0,00015
81					0,021	-0,00004	0,031	-0,00009

84							0,047	-0,00013
88							0,068	-0,00017
92							-0,022	0,00005
96							-0,073	0,00017
100							-0,004	0,00001
104							0,069	-0,00014
108							0,028	-0,00006

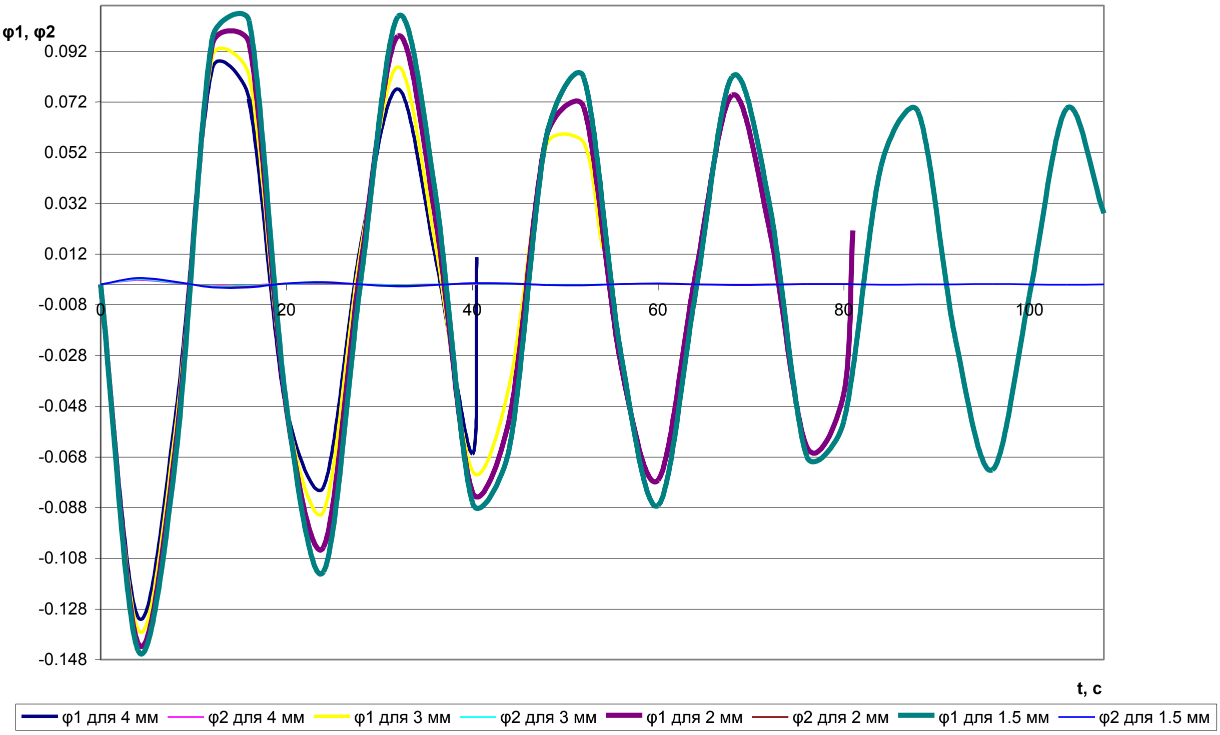

Figure 4 – The graph of free oscillations occurring in the drive of the winding of the hot billot

Conclusions Simulation modeling of the technological process of winding hot-rolled billot indicates that the mass of the winding roll is directly proportional to the winding time, and the diameter of the roll does not change lineary, which causes the need to study the form of possible oscillations in the coiler drum drive. According to the obtained schedule of free oscillations that occur in the coiler drive during the technological process of winding the billot, it can be concluded that the elastic deformations from the resistance forces of the electric motor and the rotating parts of the coiler drum are in antiphase, therefore the breakdowns associated with resonant oscillations can be disregarded. The obtained results create prerequisites for the study of forced oscillations occurring in the coiler drum drive and will allow to determine the most unfavorable technological mode from the point of view of dynamic component loads.

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Імітаційне моделювання при дослідженні роботи металургійного обладнання

Сучасні потокові лінії прокатних цехів в своєму складі мають багато допоміжного та основного обладнання. Від того на скільки безвідмовно та якісно виконує свої функції кожен агрегат зі складу прокатного стану залежить не тільки ритмічність роботи всього цеху, а й своєчасність відвантаження кінцевого продукту споживачеві. До основного обладнання прокатного стана можна віднести моталки, що намотують основну продукцію широкоштабових станів – штабу, у рулон. Від роботи моталок залежить якість намотки штаби, що впливає не тільки на наступну операцію різання листа, а й відвантаження якісного, щільно-намотаного рулону згідно заявок.

На сьогодні моталки є саме тим вразливим технологічним устаткуванням, що перешкоджає подальшому підвищенню продуктивності потокової лінії прокатки. Вони нерідко є причиною браку прокату. Створення нових моделей, або удосконалення конструкції діючих, вимагають прискіпливих досліджень навантажень на їхні вузли у формі натурного експерименту.

В умовах воєнного стану в країні досить важко провести натурні експерименти, які б дозволили підтвердити або спростувати ті чи інші аспекти технологічного процесу, тому актуальним постає питання використання імітаційного моделювання при конструюванні металургійного обладнання. Імітаційне моделювання дозволяє досліджувану модель замінювати математичною і над нею вже проводити досліди шляхом статистичного моделювання чисельними методами в спеціалізованих програмах обчислювальних експериментів.

Характер руху барабана моталки при намотуванні штаби – обертальний, тому всі динамічні процеси при цьому процесі характеризуються моментом інерції.

При імітації процесу намотування штаби різного типорозміру встановлено, що маса намотуємого рулону прямо пропорційна часу намотки, а діаметр рулону має не прямолінійну зміну, що може викликати у приводі моталки коливання, для дослідження природи цих коливань в першу чергу необхідно встановити спектр власних частот та форму коливань. Визначені частота, амплітуда і форма коли-

вань, дозволили дослідити пружні деформації, що виникають в процесі намотування штаби, у функції часу.

Графічний аналіз форми виникаючих коливань дозволив встановити, що пружні деформації від сил опору електродвигуна та обертових частин барабана моталки знаходяться в протифазі. Виконані розрахунки створюють передумови для дослідження вимушених коливань, що виникають в приводі барабана моталки.

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