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Correlation method for calculation of weight coefficients of artificial neural-like networkin hydraulic units' diagnostic systems

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ABSTRACT

The paper proposes a new method for calculating the weight coefficients of an artificial neural network in the systems of technical diagnostics of hydro aggregates, in which it is proposed to use the coefficients of correlation between vibration signals in spatially distributed points of a hydro aggregate. A mathematical model and algorithm for calculation of weight coefficients of an artificial neural network are developed. The expediency of use of wavelet transformation of time realizations of a vibration signal is shown, as a result of which the received vibration signal is divided into ampli-tude-frequency-time spectrum, which leads to increase its informativeness. Experimentally confirmed the presence of strong inter-correlation links between spatially distributed points of the hydro aggregate and their dependence on the na-ture and place of application of disturbing forces. The dependence of the correlation coefficients on the load of the hydro aggregate and the water pressure in the reservoir is established. The obtained results can be considered as an experi-mental confirmation of the expediency of using the proposed method for calculating the weight coefficients of an artifi-cial neural network.

Keywords: artificial neural network, amplitude-frequency-time spectrum, frequency band, vibration factor, probability index, correlation coefficient, weight coefficient

1. INTRODUCTION

The system of automatic diagnostics and forecastingof hydraulic units' defects development (SADF-HUDD)[1] is based on a modified frequencytechnology ofvibration diagnostics,being ahardware and software complexcomposed ofvibration measurement channels, a sub-system for routine monitoring ofvibrationand a sub-system fordiagnostics and forecasting. Commercial operation of vibration measurement channels and sub-system for routine monitoring commenced atNyzhnyodnistrovs'kaHPP (Ukraine), with thetest operation of diagnostics and forecastingsub-system being com-menced in a stage-by-stage manner[2-9].

The diagnostic sub-systemis based on athree-layerartificial neural-like network (ANLN). Eachvibroacoustic signal re-ceived from the routine monitoring sub-systemby way ofdiscretewavelettransformation (DWT) is decomposed in theamplitude-frequency-timespectrum (AFTS). Further on, allAFTSarrive atthe entry point of ANLN[10-11].

The mathematical model ofANLNis shown in detail in[1-2],that is why we will turn our attention to the results of its opera-tion – by determining the probability of the fact that certain vibration factor may cause excessive vibration displacement.

The informative probability indicator of $PV_{k\tau}$ factor thatcorresponds to k^{th}neuron, as of the time point τ ,is determined as follows^

$$\forall k = 1,6 \forall i = 1,4 \forall j \in \Psi_k \left(PV_{k\tau} = \sum_{i,j} w_{kij} d_{kij\tau}^{norm} \right), \tag{1}$$

where w_{kij} – weight coefficientsthat define the significance ofaccounting forwaveletcoefficients of AFTS's j^{th}frequency bandof the i^{th}vibration signalat theprobability level ofthe k^{th} neuron; $d_{kij\tau}^{norm}$ – standardized valuesof wavelet coeffi-cients of AFTS's j^{th} frequency band of the i^{th} vibration signal at the probability level of the k^{th} neuron as of the time

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point τ ; Ψ_k – the multitudeof frequency bands' numbers, where the influence of vibration factor exists, which corresponds to the k^{th}neuron[12,13].

The task of this research paper lies in development of thecorrelationmethodfor determination of weight coefficients w_{kij} asthe coefficientsof cross-correlation;it presents the analysis of their dependence on thehydrogenerator's loadand water pressure headinwater reservoir.

2. THEORETICAL RESEARCH RESULTS AND ANALYSIS THEREOF

The mathematical modelfor determinationof cross-correlation coefficientsis shown in detail in[3-6]. Let us recall its main provisions.

The hydraulic unitis shown as a relativelystationary distributed quasilinearized inseparable elastic systemwithspace-variantstiffness coefficients[7]. Another specificity ofa controlled unit (CU) lies in its exposure to k spatially distributeduncompensated forcesof differentphysical nature, amplitude and vector direction that vary randomly with time function. Generalized structure of suchCUmay be shown as follows (fig. 1).

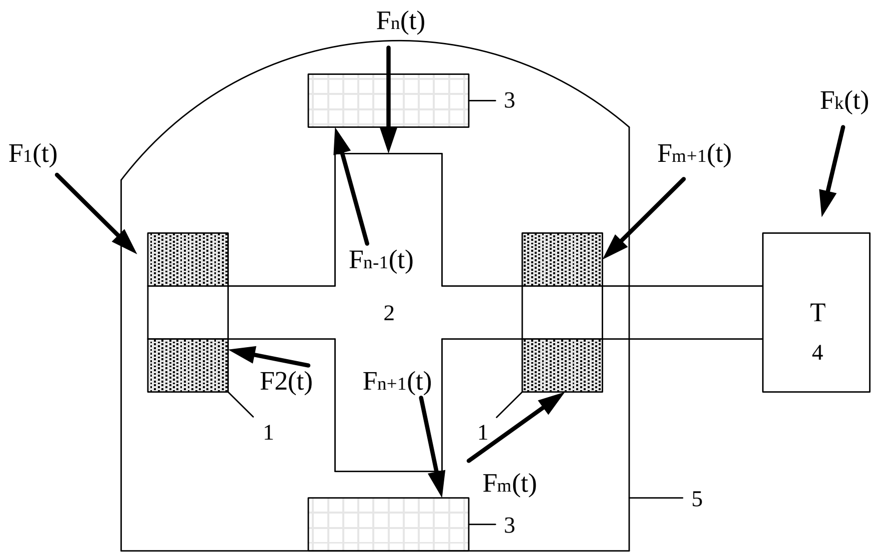

Fig. 1 Generalizedstructural diagramof hydraulic unit (1 – bearings; 2 – rotor; 3 – stator; 4 – turbine; 5 – housing)

In view ofsuch system's inseparability, any ofkexternaluncompensateddisturbing forceswill evokein the system'srandomly chosen point (assembly) the occurrence ofkthcomponent ofvibration signal (response), the amplitude of which will different than zero. This being the case, in view of the system's quasilinearity, the vector-similar force, the resultant of which is applied to one and the same point of electrical machine with time delay Δtwill cause the occurrence of the system'sidenticalresponse with the same time delay in anyrandomly selected unit assembly. Hence, for arandomly selected controlled assemblyin relation to eachofkpossibledisturbing forces, one can obtain a link function. For arandomly selected assembly A being a part of CU, the following equation system will be true:

$$\begin{cases} \psi_{A1}(t) = F_1(t) \cdot H_{A1}(t), \\ \psi_{A2}(t) = F_2(t) \cdot H_{A2}(t), \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ \psi_{Ak}(t) = F_k(t) \cdot H_{Ak}(t), \end{cases} \qquad (2)$$

where F1(t) – Fk(t) – uncompensatedforce affecting anelectricalmachine; HA1(t) – HAk(t) – link functions in relation todisturbing forcesF1(t) – Fk(t), respectively; ψA1(t) –ψAk(t) – system's responseat point A to thedisturbing actionin the form ofF1(t) – Fk(t)force, respectively.

Such being the case,the resultingvibration signalto be observed at point Amay be obtained on the basis of superposition principle $\psi_A(t)=\sum_{i=1}^{k}\psi_{Ai}(t)=\sum_{i=1}^{k}F_i(t)\cdot H_{Ai}(t)$.

On similar groundsfor point B,the dependence betweenvibration signal responseanddisturbing forceswill be written in the following form $\psi_B(t)=\sum_{i=1}^{k}\psi_{Bi}(t)=\sum_{i=1}^{k}F_i(t)\cdot H_{Bi}(t)$, and the dependencebetween eachsystem responseat point B andsystem responseat point A will appear as: $\psi_{Bi}(t)=\frac{H_{Bi}(t)}{H_{Ai}(t)}\psi_{Ai}(t)$.

Hence, generalsystem responseat point B is defined as

$$\psi_B(t)=\sum_{i=1}^{k}\frac{H_{Bi}(t)}{H_{Ai}(t)}\psi_{Ai}(t). \tag{3}$$

In a similar way,other points belonging to the CU may be interconnected.

Sincein view of astochasticnature of disturbinguncompensatedforcesF1(t) – Fk(t)the analyzedCUmay be considered a stochasticsystem, presented expressions serve thetheoretical substantiation for presence ofcross-correlationconnections between vibration signal responses at various points of the electrical machine under research.

A considerable challenge in the use of proposed approach lies in obtaining of cross-correlation coefficients' instantaneousvalues. Sincevibrationprocesses inelectrical machines' controlled assemblesare of occasional nature, precise evaluation of linear relationship between two valuesψA(t) and ψB(t)would requirethe use of the following expression[8].

$$K_\psi(t_1,t_2)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}(\psi_1-m_A(t_1))(\psi_2-m_B(t_2))\cdot f(\psi_1,\psi_2,t_1,t_2)\,d\psi_1 d\psi_2, \tag{4}$$

wheremA(t1), mB(t2) – mathematicalexpectations of functionsψA(t) and ψB(t)at time pointst1 and t2., respectively; $f(\psi_1,\psi_2,t_1,t_2)$ – two-dimensionalprobabilityof occasional process ψ(t), which preconditions the occurrence of vibration signalsin A and B assemblies.

In its turn, $f(\psi_1,\psi_2,t_1,t_2)=\frac{\partial^2 F(\psi_1,\psi_2,t_1,t_2)}{\partial\psi_1\partial\psi_2}$, where $F(\psi_1,\psi_2,t_1,t_2)$ is atwo-dimensionalfunctionof occasional process probability distribution ψ(t), which assigns the value of probability of the fact thatat time pointt1inequalityψA≤ ψ1is implemented, with inequality ψB≤ ψ2 being implemented at time pointt2, that is

$$F(\psi_1,\psi_2,t_1,t_2)=P(\psi_A(t_1)\le\psi_1,\psi_B(t_2)\le\psi_2). \tag{5}$$

Considering the particularity ofCU, the coefficientof auto-correlation betweensignalsψA(t) and ψB(t) would be advisable tobe determinedfor one and the same time point $t_1=t_2$, that is $K_\psi(t_1,t_2)=K_\psi(t_1)$.

GivenstationaryexternaldisturbancesF1(t) – Fk(t)signalsψA(t) and ψB(t) may be consideredergodic, that is why, following the chain of transformations, the required quasiinstantaneouscross-correlation coefficient can be obtained as $K^*_\psi(t_1)=\frac{1}{T}\int_0^T(\psi^*_A(t_1))(\psi^*_B(t_1))dt_1$, and fordiscretetime implementations, with due regard toknownPearson's equation, one can write the following correlation:

$$K^*_\psi(t_1)=\frac{\sum_{i=1}^{n}\psi^*_{Ai}\psi^*_{Bi}}{\sqrt{\sum_{i=1}^{n}\psi^{*2}_{Ai}\cdot\sum_{i=1}^{n}\psi^{*2}_{Bi}}}, \tag{6}$$

whereψ^*_{Ai} and ψ^*_{Bi} – i^{th}valuesof time implementations of$\psi_A(t)$ and $\psi_B(t)$functions.

3. METHODFOR CALCULATION OFCROSS-CORRELATION COEFFICIENTS

Based on the foregoingmathematical model, the calculation methodwas developed, the algorithm for which implementation is shown below:

1. Selection ofsynchronizedtime implementations ofvibration signalsof the support ψ_A and tested assemblies $\psi_B$with the length of n and starting at time moment t.
2. Calculation of amplitude-frequency-time spectra of supporting assembly's vibration signal.
3. Calculation of amplitude-frequency-time spectra of tested assembly's vibration signal.
4. Assignment of the initial value (j=1) to the control mark.
5. Calculation of neuron's j^{th}weight coefficientresponsible for the tested assembly using formula (6).
6. Recording the calculated j^{th}weight coefficientinANLN.
7. Raising thecontrol mark by one (j=j+1) and in the case when the value obtained does not exceed the number of tested harmonics, going on to item 5, otherwise – termination of the calculation.

This algorithm was implemented by the example of real archived values ofvibration signalsobtained from the sensors installed atjournal-and-thrust bearing and turbinebearingof the otherhydraulic unitof Nyzhnyodnistrovs'ka HPP (Ukraine) in the process of its commercial operation[14,15].

4. RESULTS OFEXPERIMENTAL INVESTIGATION AND ANALYSIS THEREOF

Experimental investigations were carried out in two stages. Matrices ofAFTS waveletcoefficients weredesigned, using discretewavelettransformation[9],for archival values ofvibration signalsinequal time periods for each of thevibration sensors installed atturbine and journal-and-thrust bearingsalong the horizontal and the vertical axes. At the first stage of the experimental investigation, required stacks of archival data were selectedforhydrogenerator load parameters of 6.1 MW and 3.7 MWwith thepressure head values that differed from each other by no more than 20%.

An example of such a matrix is shown infig.2.

0,00058	0,01155	0,01438	0,01576	0,01212	-0,00096	0,00346	0,00287	-0,0078	-0,00846	-0,00734	-0,0045	0,0
0,03872	0,00872	-0,0115	-0,03566	-0,04232	-0,03	-0,00131	0,05437	0,05372	0,05523	-0,00306	-0,03252	-0,0
0,15454	-0,16133	0,0555	0,04689	-0,05505	0,13334	-0,04775	0,07545	-0,19004	0,24963	-0,12663	0,18934	-0
-0,72517	0,73477	-1,05508	0,97104	-0,03406	0,97215	0,03884	0,87108	-3,94973	0,66259	-0,78816	0,78332	
-7,78715	13,04255	4,62815	-3,72211	-1,1116	5,23574	3,05388	-10,54587	2,24375	6,12588	-1,75158	0,41051	
-2,21957	-3,53178	-3,16962	-3,55569	-3,21698	-2,80924	-2,85577	0,47871	0,65359	-1,20723	-0,96873	0,16932	
1,28836	0,67028	0,38083	1,1104	2,32887	1,49697	-0,74232	-1,60403	0,99532	-0,71171	1,34484	-0,09773	1,1
1,5978	-1,66826	3,41903	-1,30703	-0,19206	-1,09668	2,10297	-0,0658	-1,43045	-0,73242	-0,67391	0,06276	-
-1,96601	0,10126	0,7241	-1,8216	0,34918	-1,18097	2,15002	-0,08153	-1,42263	-0,73579	-0,67224	0,06198	-0
-1,96604	0,10127	0,72411	-1,82159	0,34918	-1,18097	2,15002	-0,08153	-1,42263	-0,73579	-0,67224	0,06198	
-1,96604	0,10127	0,72411	-1,82159	0,34918	-1,18097	2,15002	-0,08153					
-1,96604	0,10127	0,72411	-1,82159									
-1,96604	0,10127											
-1,96604												

Fig.2Example ofAFTS wavelet-coefficients' matrix for the journal-and-thrust bearing (axis Y, load – 4.1MW, water pressure head 4.85 m)

Further on (according to the calculation algorithm proposed),cross-correlationcoefficients were determined forthe third through the fourteenth frequencybands. Moreover, to generate time implementationsof the thirdfrequencyband, 4 consecutive values were used, with eight ones used for the fourth band and ten ones for the remainder. Coefficients determined on the basis of experimental data are summarized in tables 1 and 2.

Table 1 – Computer simulation results (load – 6.1 MW)

Place of receipt and input signal axis	Frequency band No.											
	3	4	5	6	7	8	9	10	11	12	13	14
Support bearing, axis Y – turbine bearing, axis Y	0,821	0,707	0,73	0,953	0,703	0,879	0,693	0,527	0,64	0,754	0,53	0,699
Support bearing, axis Y – support bearing, axis X	0,851	0,83	0,862	0,864	0,846	0,794	0,683	0,699	0,763	0,849	0,64	0,68
Support bearing, axis X – turbine bearing, axis X	0,642	0,658	0,612	0,688	0,606	0,846	0,753	0,688	0,585	0,816	0,668	0,57
Turbine bearing, axis X – turbine bearing, axis Y	0,625	0,524	0,691	0,877	0,905	0,741	0,831	0,765	0,781	0,641	0,634	0,29

Table 2 – Computer simulation results (load – 3.7 MW)

Place of receipt and input signal axis	Frequency band No.											
	3	4	5	6	7	8	9	10	11	12	13	14
Support bearing, axis Y – turbine bearing, axis Y	0,908	0,6939	0,767	0,75	0,565	0,68	0,485	0,46	0,75	0,908	0,526	0,755
Support bearing, axis Y – support bearing, axis X	0,611	0,614	0,765	0,744	0,626	0,637	0,791	0,598	0,774	0,646	0,698	0,62
Support bearing, axis X – turbine bearing, axis X	0,891	0,588	0,517	0,288	0,475	0,68	0,728	0,684	0,63	0,381	0,882	0,389
Turbine bearing, axis X – turbine bearing, axis Y	0,815	0,73	0,636	0,703	0,696	0,511	0,758	0,83	0,678	0,536	0,722	0,177

At the second stage of experimental investigation, stacks of archival data required for thesame-type hydraulic unitwere selectedfor the time periods corresponding to hydrogenerator load of 4.1 MWwith water pressure headof 4.85 m and the load of 4.7 MWwith water pressure headof6.35 m.Coefficients determined on the basis of experimental data are summarized in tables3 and 4.

Table3– Results of cross-correlation coefficients' calculation (load – 4.1 MW, pressure head 4.85 m)

Place of receipt and input signal axis	Frequency band No.											
	3	4	5	6	7	8	9	10	11	12	13	14
Support bearing, axisY – turbine bearing, axis Y	0,57	0,677	0,678	0,678	0,706	0,523	0,65	0,871	0,548	0,864	0,659	0,808
Support bearing, axisY – support bearing, axis X	0,479	0,539	0,537	0,537	0,528	0,629	0,622	0,664	0,555	0,7	0,648	0,77
Support bearing, axisX– turbine bearing, axis X	0,534	0,512	0,511	0,511	0,641	0,801	0,677	0,791	0,646	0,722	0,527	0,931
Turbine bearing, axis X – turbine bearing, axis Y	0,654	0,742	0,757	0,757	0,794	0,556	0,633	0,893	0,603	0,79	0,47	0,819

Table4 – Results of cross-correlation coefficients' calculation (load – 4,7 MW, pressure head 6.35 m)

Place of receipt and input signal axis	Frequency band No.											
	3	4	5	6	7	8	9	10	11	12	13	14
Support bearing, axis Y – turbine bearing, axis Y	0,679	0,796	0,732	0,732	0,809	0,697	0,71	0,949	0,673	0,619	0,778	0,789
Support bearing, axis Y – support bearing, axis X	0,636	0,703	0,662	0,662	0,882	0,78	0,765	0,704	0,69	0,687	0,915	0,931
Support bearing, axis X – turbine bearing, axis X	0,854	0,803	0,772	0,772	0,667	0,884	0,75	0,702	0,544	0,632	0,608	0,627
Turbine bearing, axis X – turbine bearing, axis Y	0,833	0,861	0,836	0,836	0,801	0,716	0,722	0,425	0,459	0,648	0,736	0,877

5. ANALYZING THE RESULTS OF EXPERIMENTAL INVESTIGATIONS

It was demonstrated in research papers[1] and [9] that each line of AFTS waveletcoefficients' matrix corresponds to certain frequency band of thespectrum.

The upper limit of thespectrum, according toKotelnikov-Shannon theorem, equals to a half of vibration measurement channels' sampling frequency. Sincesampling frequency forvibration measurement channels at Nyzhnyodnistrovs'ka HPP (Ukraine), as used during experimental investigation,equals to 913.92 Hz, the upper limit of spectrumis 456.96 Hz.

The contraction coefficientof discretewavelettransformation, which was used in the course of the above-mentioned investigation, equaled to 2, that is why each subsequent frequency band was twice as wide as the preceding oneand, according to the algorithm ofdiscretewavelettransformation, the number of calculatedfrequency bands inAFTSequals to 14.

Calculation of AFTS frequency bands was performed in Excel environment (see [1], [9]) with the calculation results shown infig.3.

	A	B	C	D	E
1	*Fd*	*Frequency band*	*Band width*	*Band start*	*Band end*
2	*913,9*	*1*	*0,027892327*	*0*	*0,027892327*
3	*dF*	*2*	*0,055784655*	*0,027892327*	*0,083676982*
4	*k*	*3*	*0,11156913*	*0,083676982*	*0,195246112*
5	*2*	*4*	*0,223138619*	*0,195246112*	*0,418384731*
6	*M*	*5*	*0,446277239*	*0,418384731*	*0,86466197*
7	*14*	*6*	*0,892554477*	*0,86466197*	*1,757216447*
8		*7*	*1,785108954*	*1,757216447*	*3,542325401*
9		*8*	*3,570217909*	*3,542325401*	*7,11254331*
10		*9*	*7,140435818*	*7,11254331*	*14,25297913*
11		*10*	*14,28087164*	*14,25297913*	*28,53385077*
12		*11*	*28,56174327*	*28,53385077*	*57,09559404*
13		*12*	*57,12348654*	*57,09559404*	*114,2190806*
14		*13*	*114,2469731*	*114,2190806*	*228,4660537*
15		*14*	*228,4939462*	*228,4660537*	*456,9599999*

Fig.3 AFTS frequency bandof vibration signalat Dnistrovs'ka HPP -2hydraulic unitwith contraction coefficient of 2

It is known that rotor speed fr (generator speed) of hydraulic units atNyzhnyodnistrovs'ka HPP (Ukraine) equals to 1.785Hz. As shown in[1], electrodynamic components ofvibrationare directly proportional tohydrogenerator load, and theirmaineffects arefocusedon the generator speed (f_r) and on the nearest harmonic ($2f_r$) and sub-harmonic($f_r/2$).

It follows fromfig. 4 thatgenerator speed is confined to the beginning of the seventhfrequency band, with the nearest harmonic respectively being in the eighth band and the nearest sub-harmonic – in the sixth one.

It also follows fromtables 1 and 2 that these very frequency bands are the place where, with the increase inhydrogeneratorload, cross-correlation coefficients grow significantly. This confirms the hypothesis set forth in research papers[5] and [6] that coefficients of cross-correlationbetweenvibration signalsin the assemblies investigated will growwith the approach of external disturbance's significantcomponentapplication point to theconditional point ofthe mechanical center between them, being alsoproportional to the this disturbing force's relative contribution toformation of general vibration signal [14,15].

Let us analyze the results of experimental investigation's stage two.

Considering that,during the above-mentionedexperimental investigation, thehydraulic unit's capacity differed byno more than 15% and thepressure headby more than 30 %, and given thatthe investigations were performed in the course of one dayaccording to hydraulic unit's standard operating procedure, which disablesany considerable influence on the results of changes in the system's mechanical stiffnessorother considerablemechanical changes, these are the hydrodynamic factors that can be considered the primary drivers of change invibrationcharacteristics[16,17].

It was demonstrated in research papers [1] and [9] that hydrodynamic vibrations are characterized byrotor speed $f_r = 1.785\text{Hz}$ (which is confined to the beginning of the seventhfrequency band), and itsharmonics and sub-harmonics, which corresponds to thefrequency bands 3 (minimum frequency 0.08 Hz) through 9 (maximum frequency 14.25 Hz), as well as higher frequencies in the case when vibration originates from pressure pulsationsor cavitational phenomena. These papers also prove that hydrodynamic vibrationsare occasional, characterized by poor autocorrelation and poor cross-correlation between their axial projections, and they also grow with reduction in flow laminarity, which is typical for pressure head reduction.On the other side,paper [5] contains theoretical and computer-simulated proofs of the fact that, with considerable disturbing force's estrangement from a conventionalpoint of mechanical center between them (the said effect occurswithzooming of hydrodynamicvibration signal, since hydrodynamic forces' application points are located atthe hydroturbine),their cross-correlationcoefficients will decrease[18-21].

When analyzing the results ofexperimentalinvestigations set forth in tables 1 and 2, one can observe adistinct trend to reduction ofcross-correlation coefficientswith pressure head decrease atfrequencybands 3 through 9 and 13, which entirely corresponds to the theoretical assumptions set forth in papers[1], [5] and [9]. However, as already mentioned, the change inload was also significant during the experiment, which was inevitably reflected in hydraulic unit's overallvibration.

When analyzing the data obtained at stage one ofexperimentalinvestigations, one can note that, given almost unchangedpressure head ofhydraulic unit ofexamined type,with reductionof its loadobserved was the reduction in cross-correlation coefficientsbetween investigated assemblies atfrequencybands 6 through 8. Given that,concurrently with pressure head reduction, hydraulic unit's load also decreased, one can assume thatreduction ofcross-correlation coefficientsatfrequencybands 6 through 8 was conditioned bothhydrodynamically and electromagnetically, with both factors acting in the same direction and magnifying the effect revealed during the experiment.

Based on the above, it would be advisable to state that cross-correlationcoefficients may be used not only as ANLN weight coefficients, but also as an additional diagnosticattribute of one or another vibration components' presence in particularfrequency bands.

6. CONCLUSIONS

1. It was experimentally proven that there are powerfulcorrelationrelationships betweenvibration signal's time implementations (vibration acceleration) atspaced points and in hydraulic unit's differentcoordinate axesin stationary operating conditions.
2. It was proven advisable to determine ANLN weight coefficientsforvibration diagnosticsofhydraulic units' defectsusing the correlationmethod, i.e. considering them as cross-correlation coefficients. This procedure's input data are represented bynumerical values ofwaveletcoefficientsof particular AFTS frequency bands.
3. It was found that, in the frequency bands, where electrodynamic components ofvibration are concentrated, with the increase ofhydrogenerator load,cross-correlation coefficients of vibration signals grow significantlyat hydraulic unit's spaced quasisymmetricpoints. This enables us to considercross-correlationcoefficients as an additional signof electrodynamic vibration component's presenceinparticular frequency band.
4. It was experimentally proven that, with pressure head reduction, observed is the decrease ofcross-correlation coefficientsbetweenvibration signals at support and turbinebearingswithinfrequencybands, where hydrodynamic disturbing forces are concentrated.

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