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# The use of the wavelet-analysis for the research of the unsteady processes in the pipeline network of a pumping complex

***Abstract**. The authors propose the use of the wavelet-analysis to research the wave processes in the unsteady modes of the pumping complex operation. We demonstrate that the use of the wavelet analysis enables the determination of both the fact of the presence of the emergency mode and the time of the beginning of the unsteady process. We determined that the frequency-time dependences of wavelet coefficients are to underlie the quantitative assessment of the unsteady modes in the pipeline network. We obtained the frequency ranges and the boundaries of the wavelet-coefficients variation for each of the analyzed unsteady processes.*

***Streszczenie.** Autorzy proponują wykorzystanie analizy falkowej do badania procesów falowych w niestabilnych trybach pracy zespołu pompowego. Pokazujemy, że wykorzystanie analizy falkowej umożliwia określenie zarówno faktu wystąpienia trybu awaryjnego, jak i momentu początku stanu niestabilnego. Ustaliliśmy, że zależności częstotliwościowo-czasowe współczynników falkowych mają leżeć u podstaw ilościowej oceny trybów niestabilnych w sieci wodociągowej. Uzyskaliśmy zakresy częstotliwości i granice zmienności współczynników falek dla każdego z analizowanych procesów nieustalonych. (**Wykorzystanie analizy falkowej do badania procesów nieustalonych w sieci rurociągowej zespołu pompowego**)*

**Keywords:** pumping complex, wave processes, unsteady mode, wavelet-analysis, wavelet-spectrum.
**Słowa kluczowe:** zespół pompowy, procesy falowe, tryb nieustalony, analiza falkowa, widmo falowe

## Introduction

Unsteady processes sometimes occur during the operation of pumping complexes (PC) because of frequent switching on/off of the pump units, alteration of the consumer's operation mode, non-observance of the tempo of shutting the pipeline valves in the hydraulic network. Such unsteady processes include head pulsation, water hammer, leakage, cavitational self-oscillations, etc. Complex wave processes of different amplitude and frequency accompany their appearance and in some cases may result in the damage of the pumping and pipeline equipment.

To identify PC unsteady modes there are a number of methods based on the continuous or periodical monitoring of the parameters of liquid pumping, the frequency analysis of the signals of the head or discharge, etc. [1]. Recently, engineers have often been using wavelet analysis for the diagnostics of various unsteady processes, which proved to be successful in the problems of diagnosis of damages in electric machines and gas turbine engines, the study of the properties of turbulent fields, etc [2]. In comparison with the Fourier transform, the wavelet analysis makes it possible to assess the unsteady processes by the analysis coefficients more accurately and to follow the alteration of the signal frequency properties in the time domain. In this case both a periodic and a non-periodic time function can be considered an analyzed signal. That is why the problem of the research of the wave processes in the pipeline network in unsteady operation modes of a pumping complex with the use of wavelet analysis is of interest.

## Research method

Taking into account the above said, we propose a PC mathematical model including a frequency converter (FC); an induction motor (IM) in u,v,0-coordinates; a centrifugal pump; a block generating a moment of resistance created by the pump; a pipeline network represented by n-number of sections in the form of *RLC*-circuits; a consumer model with input hydraulic resistance equivalent to the current water consumption; a block of modeling the emergency modes which allow forming a disturbance in the pipeline network that results in occurrence of a leakage, water hammer or cavitation.

Paper [3] contains a mathematical description of the model elements. For the analysis of the wave processes in the pipeline network we consider the signals of head $H(t)$, discharge $Q(t)$ and hydraulic power $p_h(t) = \rho g H(t) Q(t)$, where $\rho$ – the density of the pumped liquid, kg/m$^3$; $g = 9.81$ m/s$^2$ – gravity.

As an example, for an object with the following parameters: motor $P_n = 7500$ W, $U_n = 220$ V, $\omega_n = 303.7$ s$^{-1}$, $I_n = 15$ A, $M_n = 24.7$ Nm; pump $Q_n = 0.012691$ m$^3$/s, $H_p = 22.4$ m; pipeline network $d = 0.1$ m, $L = 1000$ m, $n = 20$, $S = \pi d^2/4 = 0.00785$ m$^2$, $R_0 = 0.0183$ s/m$^2$, $C_0 = 2038.7$ m$^2$, $L_0 = 0.1962$ s$^2$/m$^2$, $R_{con} = 9.855$ s/m$^2$ we obtain the transient processes curves when cavitation develops (Fig. 1), when a leakage (Fig. 2) and a water hammer (Fig. 3) occur in the pipeline network at the time moment $t = 90$ s, respectively.

A sharp alteration of the flow velocity cause cavitation processes due to the change of the cross section of the pipeline or the growth of liquid discharge in the consumer network, which result in the pressure decrease in the pumping main below the pressure of saturated steam [4]. During cavitation the cavitation caverns – cavities filled with gas or air – form and collapse. It results in periodic variation of the head in the hydronetwork. One can see from the analysis of the curves (Fig. 4) that, when cavitation oscillations appear, the head $H(t)$ in the pipeline network reduces and discharge $Q(t)$ grows.

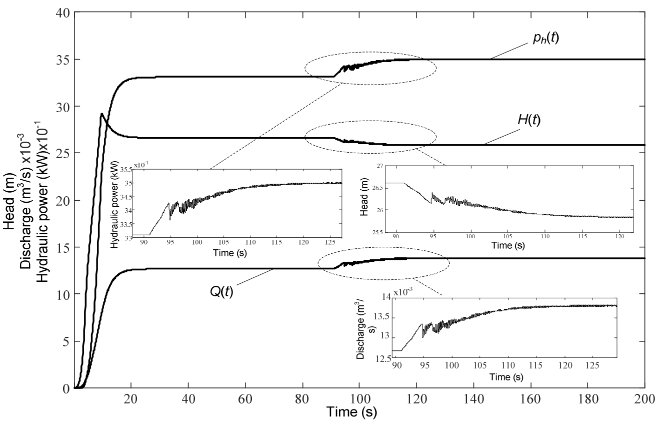



Fig.1. The curves representing the transient processes in the pipeline during cavitation

When modeling a leakage, we additionally included hydraulic resistance $R_{leak}$, equivalent to the leaking liquid volume $Q_{leak}$, into the mathematical model. The analysis of the obtained curves (Fig. 2) reveals that the occurrence of the leakage results in the drop of the head along the whole pipeline network length due to the discharge decrease at the consumer. In this case the value of the discharge at the pump unit output increases, which results in the growth of hydraulic power $p_h(t)$ at the pump output. We determined that the closer the leakage is to the point of measurement the more explicit the character of the wave process in the PC pipeline network is.

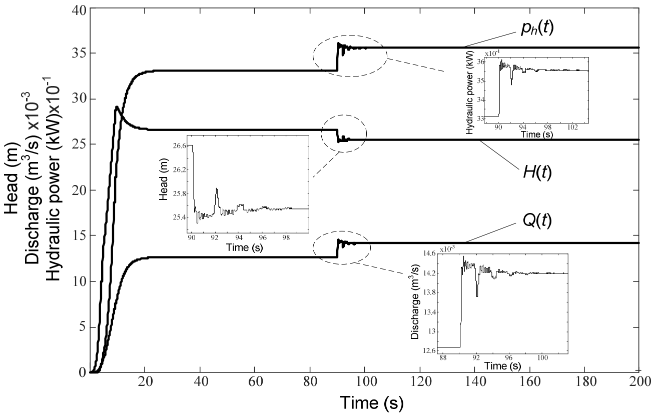


Fig.2. The curves representing the transient processes in the pipeline network with a leakage

We simulated a water hammer by closing the stopcock at the end of the pipeline, accompanied by a sharp drop of the value of the discharge and the propagation of the attenuating oscillations of high-amplitude head along the pipeline length (Fig. 3).

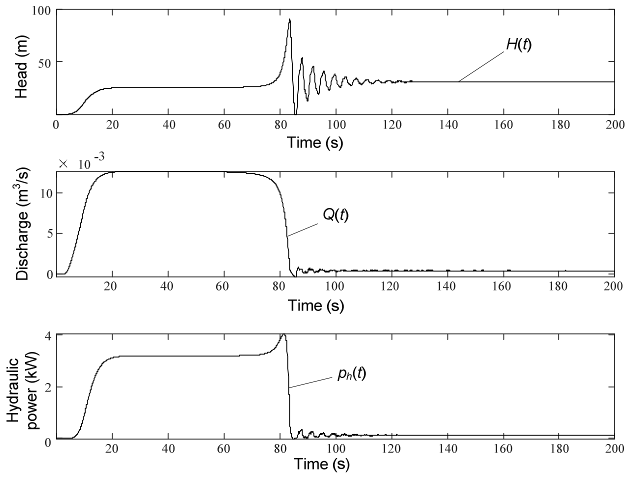


Fig.3. The curves representing the transient processes in the pipeline network at the occurrence of a water hammer

The use of the continuous wavelet transform (CWT) underlies the research of unsteady processes. It allows carrying out the frequency-time analysis aiming at the localization of the transient processes in non-stationary signals [5].

In our work we regarded hydraulic power $p_h(t)$, equal to the product of the head $H(t)$ and discharge $Q(t)$ signals as an initial signal. It enables taking into account all the informational signs typical of particular unsteady modes [6]. To process the researched signal out of the CWT analytical signals group we chose the Morlet wavelet distinguished for the maximal spatial and spectral resolution.

Figs. 4–6, contain the wavelet-spectra of the hydraulic power signals with the use of the Morlet wavelet at the development of cavitation, occurrence of a leakage and a water hammer in the PC pipeline network, respectively. The analysis revealed that the highest values of the wavelet-coefficients correspond to the unsteady process taking place in the pipeline. It allows determining the time when the emergency mode starts to develop in the hydraulic network and the harmonic components characterizing the unsteady process. For the quantitative assessment of the development of the emergency modes in the pipeline network we obtained curves representing the alteration of the average values of the wavelet coefficients $A_{mk}$ in the time domain (Figs. 7) of the hydraulic power signals for each of the considered unsteady modes.

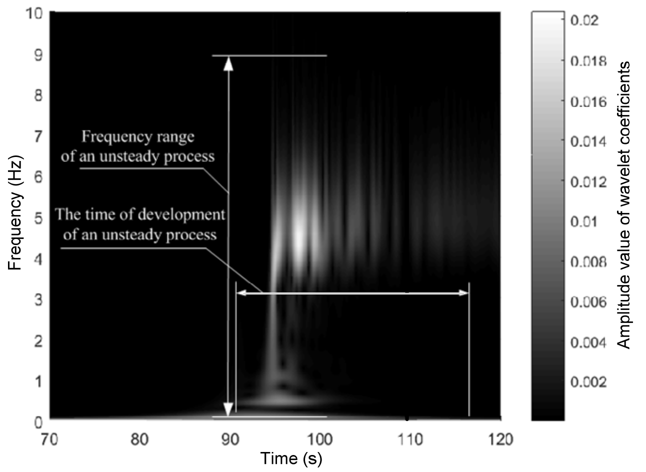


Fig. 4. The wavelet-spectrum of the hydraulic power signal at the development of cavitation

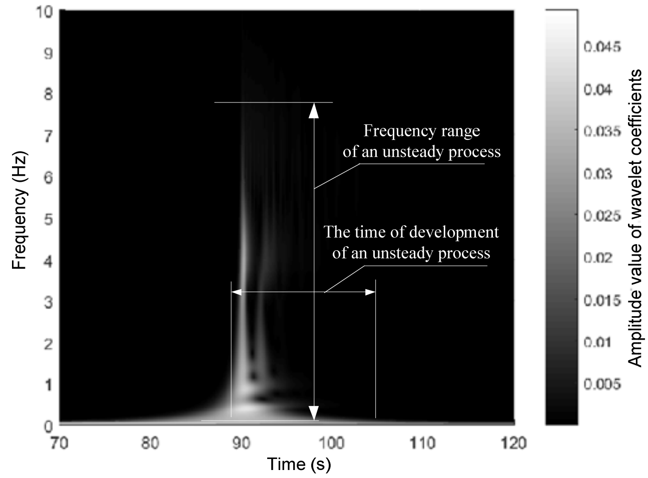


Fig. 5. The wavelet-spectrum of the hydraulic power signal at the occurrence of leakage

The analysis of the obtained results revealed that the wavelet-spectrum of the hydraulic power signal (Fig. 4) at the development of cavitation is distinguished by an oscillating character and presence in curve $A_{mk}(t)$ of insignificant breaks (Fig. 7) and periodic harmonics surges in the frequencies interval from 0 ÷ 0.5 Hz and 1.5 ÷ 7 Hz (Fig. 4). At leakage the wavelet-spectrum (Fig. 5) has the values of wavelet-coefficient of lower amplitude, the oscillations are attenuating, and the frequency spectrum (Fig. 5) is characterized by the highest density of harmonics distribution in the domain up to 1 Hz in comparison with all the other emergency modes. At the water hammer the wavelet-spectrum (Fig. 6) has an explicit peak of wavelet-coefficients variation in the frequency range from 0.1 to 0.5 Hz (Fig. 6).

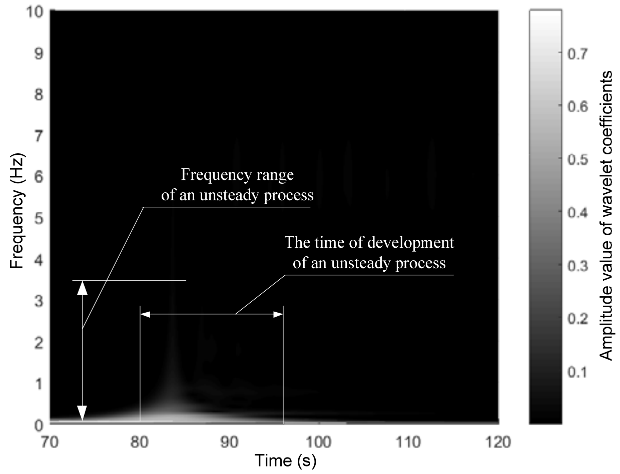



Fig. 6. The wavelet-spectrum of the hydraulic power signal at the occurrence of a water hammer

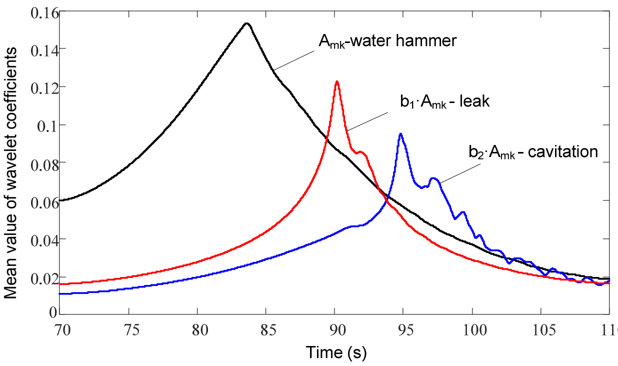



Fig. 7. Curves representing the alteration of the average values of the wavelet-coefficients in the time domain of the hydraulic power signal during unsteady modes development

## Experimental verification

We confirmed the obtained results of the mathematical modeling by the experimental research based on the PC laboratory plant. Paper [7] contains the description of the laboratory stand and the used equipment. Table 1 contains the engineering performance of the pump unit.

Table 1. The engineering performance of the electric equipment

| Parameter name | Parameter value |
|---|---|
| Electric motor rated power, W | 830 |
| Rated voltage, V | 380 |
| Rated current, A | 1.7 |
| Network frequency, Hz | 50 |
| Rotation frequency, rev/min | 2900 |
| Pump maximal capacity, m³/h | 8 |
| Maximal head, m | 22 |
| Pump rated power, W | 550 |

The laboratory plant includes: the sensors of current, voltage operating by Hall's effect; OWEN and JUMO pressure sensors; a discharge sensor (we used a two-channel ultrasonic counter Ergomera 125); a velocity sensor (a tachogenerator installed on the motor shaft). An analog-to-digital converter connects the sensors measuring the PC technological and mechanical parameters with a personal computer.

As an example, we analyzed the transient processes in the pipeline network at the pump shutting-off and a sharp shutting of the stopcock at its output imitating the operation of the check valve. The analysis of the hydraulic power curve (Fig. 8) revealed that the initial drop of the value of the power $p_h(t)$ at time moment *t = 3* s is due to the pump shut-off, and the following occurrence of oscillations in signal $p_h(t)$ at time moment *t = 13.8* s results from the occurrence of a water hammer in the pipeline due to the stopcock shut-off.

Fig. 9 a, b contains a wavelet-spectrum and a curve representing the alteration of the average values of wavelet-coefficients $A_{mk}(t)$ during the time of the transient process of the hydraulic power signal, respectively.

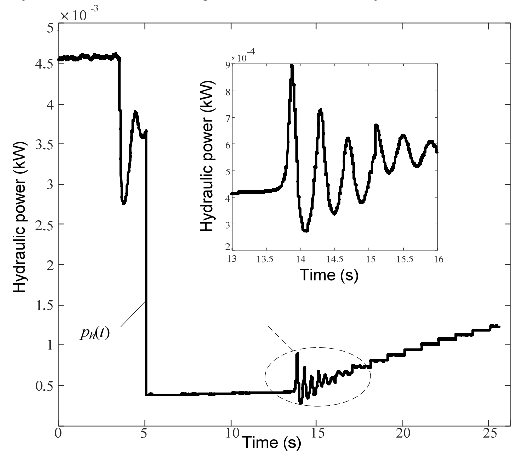
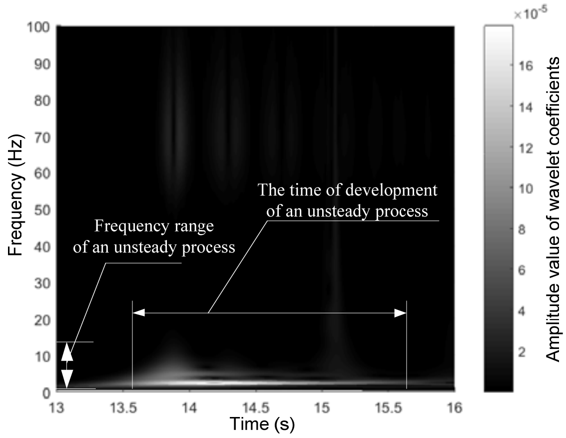
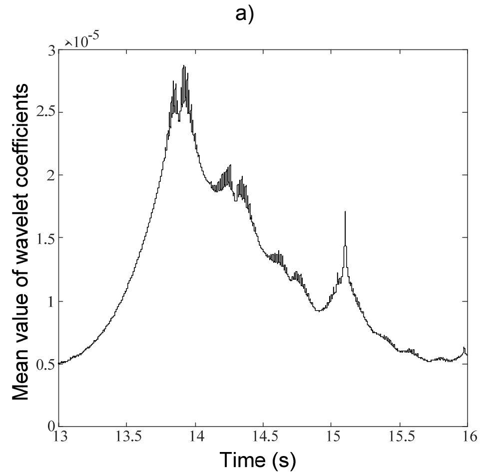



Fig. 8. The curve representing the alteration of hydraulic power at a water hammer in the pipeline network of the laboratory plant




a)




b)

Fig. 9. The wavelet-spectrum (a), the curve representing the alteration of the average values of the wavelet-coefficients in the time domain (b) of the hydraulic power signal at the occurrence of a water hammer

The analysis of the obtained dependences reveals that in curve $A_{mk}(t)$ there is an explicit peak with the following insignificant surges of the values of wavelet-coefficients, caused by the specific features of the used sensors measuring technological parameters (in particular, the discharge sensor). This is also the reason for certain widening of the frequency composition of the hydraulic power signal $p_h(t)$ – the highest amplitude values correspond to the frequency range up to 10 Hz.

**Conclusions**

We have demonstrated that the use of the wavelet analysis makes it possible to determine not only the fact of the presence of an unsteady mode in the pipeline network of the pumping complex but also the exact time of the start of the transient process.

We have determined that the frequency-time dependences of the wavelet-coefficients are to underlie the quantitative assessment of the unsteady modes in the hydrodynamic network. We have obtained that the highest values of the wavelet-coefficients correspond to the unsteady process taking place in the pipeline. In this case the most gently sloping form of the increase of the wavelet-coefficients is typical of the wave processes occurring in the pipeline network at cavitation, a faster rate of the wavelet-coefficients increase is observed at leakage and an explicit peak of the wavelet-coefficients alteration takes place at a water hammer. A low-frequency spectrum of harmonic components distribution characterizes all the considered unsteady processes.

The above said deserves special attention in the problems of the diagnostics of the unsteady modes of the pumping complex for the timely response to the development of emergency situations in the pipeline networks and warning the maintenance staff.

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