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Measurement uncertainty of acoustic emission spectra in cavitating mineral insulating oil

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Abstract

The paper presents the research results on acoustic emission signal observed during acoustic cavitation in fresh insulating oil sample. The paper introduces a method of evaluation of measurement uncertainty of acoustic emission spectra by the statistical analysis of series of observations. The drawn probability density functions of used cavitation intensity factor values at different generated source signal parameters show the differences of its uncertainty.

Keywords: spectral analysis, acoustic cavitation, mineral insulating oil, acoustic emission.

Niepewność pomiaru widm emisji akustycznej podczas kawitacji w mineralnym oleju izolacyjnym

Streszczenie

W artykule przedstawiono wyniki pomiarów sygnału emisji akustycznej obserwowanej podczas kawitacji akustycznej w próbce czystego oleju izolacyjnego. Artykuł przybliża przede wszystkim metodę wyznaczania niepewności pomiaru widm emisji akustycznej poprzez analizę statystyczną serii pomiarów. Badania emisji akustycznej dokonano przy wzajemnych kombinacjach następujących wartości skutecznych sygnału: 200 V, 400 V, 600 V, 800 V, 1000 V, 1100 V; oraz jego częstotliwości: 100 kHz, 105 kHz, 110 kHz, 115 kHz. Wykreślone funkcje gęstości prawdopodobieństwa proponowanego wskaźnika intensywności kawitacji przy różnych parametrach źródłowego sygnału pokazują zaobserwowane różnice niepewności pomiaru. Wybór odpowiedniego punktu pracy układu do generacji kawitacji akustycznej pozwala na znaczne ograniczenie niepewności wyznaczania wartości przyjętego wskaźnika intensywności kawitacji poprzez minimalizację wpływu rezonansu naczynia kawitacyjnego.

Słowa kluczowe: analiza widmowa, kawitacja akustyczna, mineralny olej izolacyjnym, emisja akustyczna.

1. Introduction

Acoustic Cavitation

Acoustic cavitation known as the formation, growth and rapid collapse of gas-vapor bubbles in surrounding liquid during acoustic irradiation has been investigated theoretically and experimentally many times since the first time ultrasonics were used for cavitation excitation. The cavitation bubbles dynamics according to the Rayleigh-Plesset equation and its modified versions proposed by another researchers in the last decades depends mainly on two factors [1, 2, 6]:

- the parameters of a source for generation of acoustic field i.e. its intensity and frequency;
- the properties of used liquid medium and the content of dissolved gases. The various physical properties of the media are represented by its density, surface tension, vapor pressure, polytropic constant, thermal diffusivity and other parameters of the medium.

The acoustic emission accompanying the cavitation phenomena is often used as a cavitation intensity indicator [9, 10].

Aging of Insulation Liquids

Aging of transformer in service is due to the combination of different stresses like electrical, magnetic, mechanical and thermal. Decomposition of the oil is a consequence of these stresses. During oil degradation process gases will evolve as the hydrocarbon chains break down leaving large free radicals in the liquid phase. The most significant gases appearing during degradation of transformer mineral oils are O_2, N_2, H_2, CH_4, CO, CO_2, C_2H_6, C_2H_4, C_2H_2, C_3H_8 and other liquid hydrocarbons [3, 4, 5]. Them main aim of our research is to check out the influence of some of the oil aging stresses on the properties of acoustic cavitation [7, 8].

Investigation of Measurement Uncertainty

The paper introduces a method for evaluating the measurement uncertainty of acoustic emission spectra by the statistical analysis of series of observations. Because of using a high voltage sine signal for generation of acoustic cavitation, the measurement uncertainty value is an important parameter of the obtained measurement results. The drawn probability density functions of used cavitation intensity factor values for different parameters of the generated source signal show the differences of its uncertainty. The paper presents the behavior of ultrasound induced cavitation voids and bubbles in a fresh mineral insulating oil sample. The main objective of this work is to point out the possibility of using acoustic emission signal of cavitation induced by a high energy acoustic field as a diagnostic tool for power transformer life-time prediction.

2. Experimental Set-up

This paper presents an experimental study dealing with the measurement uncertainty of the cavitation intensity in mineral oil, carried out with a vessel fitted with piezoelectric transducers to induce acoustic-excited cavitation. A round bottomed glass flask was used as a cavitation vessel. The used transducers created a high energy acoustic field in the prepared insulating oil sample.

The used experimental set-up consist of four main units (Fig. 1):

- Acoustic cavitation generation unit
- Acoustic emission measurement unit
- Microcontroller based central control system communicating with other units
- MATLAB based communication and data analysis application

More details about used experimental set up can be found in previous papers [7, 8, 9, 10].

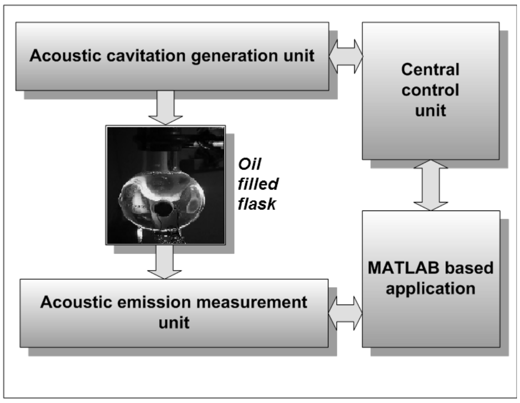

Fig. 1. Schematic diagram of the used acoustic cavitation measurement system
Rys. 1. Schemat blokowy wykorzystywanego systemu pomiarowego kawitacji akustycznej

3. Acoustic Emission Data Analysis Method

Acoustic emission during ultrasound cavitation

The acoustic cavitation phenomenon was observed at different signal frequencies and rms voltage value supplied to two piezoelectric transducers. An imploding gas-vapor bubble during cavitation is a source of the broadband acoustic emission signal and consist of the fundamental frequency component produced by the direct driving acoustic field and its harmonic, subharmonic and ultraharmonic components. The acoustic emission signal also contains a broadband noise generated by shock waves of collapsing bubbles of a wide range of sizes [2]. The bubbles created during cavitation were easily visible only in fresh mineral oils.

Acoustic emission signal descriptors of ultrasound cavitation

The paper presents an analysis of acoustic emission signal observed during acoustic cavitation in insulating oils in time and frequency domain. In preview research works several efficiently descriptors of cavitation intensity in frequency domain have been proposed. Power spectral density estimation of a discrete-time signal vector using Welch's averaged, modified periodogram method was used as a data analysis tool in frequency domain. Then a proposed cavitation intensity factor P_{CAV} (1) was calculated from power spectral density using the following formula:

$$P_{CAV} = \frac{1}{N_f}\sum_{n=1}^{N_f} PSD(f_n) \qquad (1)$$

where: P_{CAV} – cavitation intensity factor; $PSD(f_n)$ – power density of acoustic emission signal at n-th frequency component (f_n); N_f – the size of used estimated output frequency vector during the estimation of *PSD*

The round bottomed 250 ml cavitation vessel was filled with fresh mineral oil with 0.022 mgKOH/g acidicity, 0.88 kg/dm^3 density at 20 ºC and 9.48 mm^2/s viscosity at 40 ºC. The cavitation was excited using the following source signal frequency-rms voltage combinations depicted in Table 1.

Tab. 1. Source Signal Parameter Values Used for Generation of Acoustic Cavitation in Insulating Oil
Tab. 1. Wartości parametrów sygnału źródłowego wykorzystywanego do generacji kawitacji akustycznej w oleju izolacyjnym

Rms voltage U_S	Source signal frequency f_S
200 V	100 kHz
400 V	105 kHz
600 V	110 kHz
800 V	115 kHz
1000 V	-
1100 V	-

The spectral analysis of the acoustic emission signal is presented in Fig. 2. For every source signal parameter combination the power spectral density was estimated and the value of cavitation intensity factor P_{CAV} was calculated.

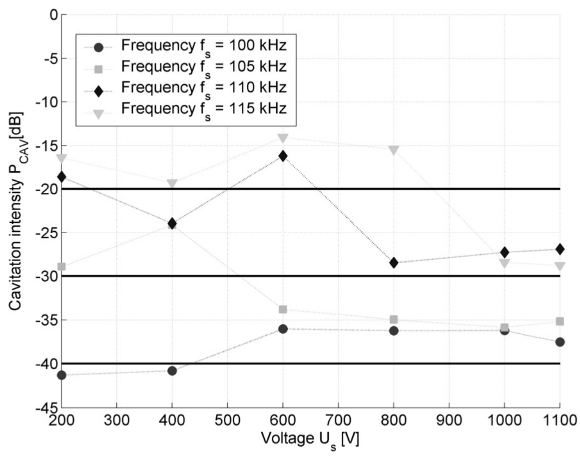

Fig. 2. The results of frequency domain acoustic emission signal analysis observed at acoustic cavitation in insulating oil
Rys. 2. Wyniki analizy częstotliwościowej sygnału emisji akustycznej obserwowanej podczas kawitacji akustycznej w mineralnym oleju izolacyjnym

Tab. 2. Cavitation Intensity Levels in Fresh Insulating Oil
Tab. 2. Poziomy natężenia kawitacji w czystym oleju izolaycjnym

Cavitation intensity range of P_{CAV}	Cavitation intensity level description
> -20 dB	High intensity cavitation (broadband noise present)
-30 ... -20 dB	Medium intensity cavitation (high intensity interharmonics of the source frequency present)
-40 ... -30 dB	Low intensity cavitation (low intensity interharmonics of the source frequency present)
< -40 dB	No cavitation present (the acoustic emission contains only the source sine signal component and its harmonics)

In this study the highest values of P_{CAV} indicator were observed for frequencies of 115 kHz and 110 kHz. It should be noted that for these frequencies the variance σ_x^2 values were the smallest.

Finally, we can came to a conclusion that the higher the amplitude of the noise components in the observed acoustic emission signal of cavitating gas bubbles, the higher the value of the proposed cavitation intensity factor P_{CAV}. According to the measurement results depicted in Fig. 2 four cavitation intensity levels can be pointed out. Table 2 contains the cavitation intensity level description and the corresponding P_{CAV} value range.

4. Investigation of Measurement Uncertainty

This study presents the measurement results of Type A method of evaluating the uncertainty by a statistical analysis of series of observations. Acoustic cavitation was excited for several source signal parameter combinations given in Table 1. In every step 1000 repetitions of acoustic emission measurements were carried out and the value of P_{CAV} was estimated. The sample results at U_S=200V are presented in Fig. 3. The value of P_{CAV} can be acknowledged as stable independently of the cavitation intensity level.

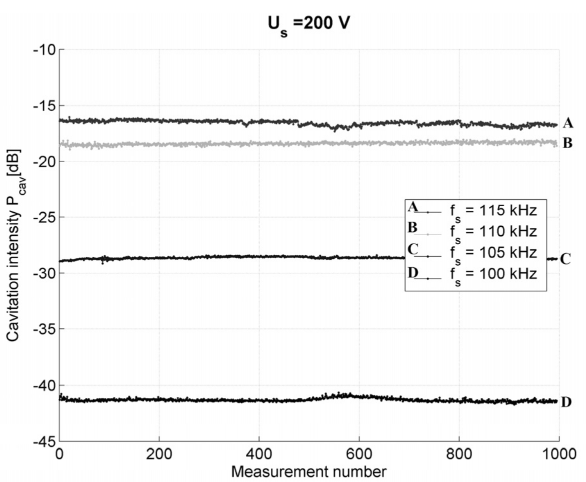

Fig. 3. Time changes of cavitation intensity factor values (P_{CAV}) for the generated signal rms value equal to 200 V

Rys. 3. Zmiany czasowe wskaźnika intensywności kawitacji (P_{CAV}) przy wartości skutecznej sygnału generowanego o wartości 200 V

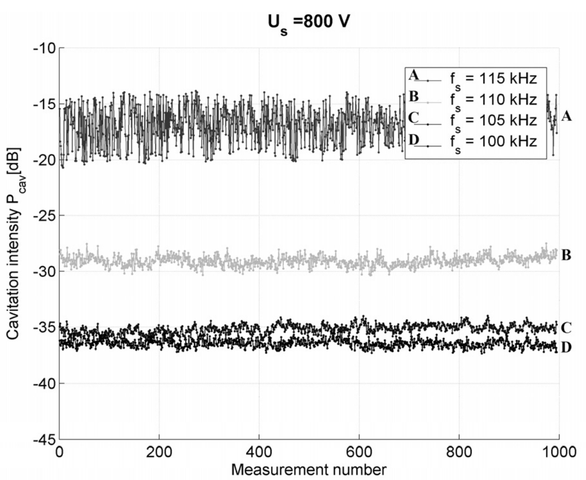

Fig. 4. Time changes of cavitation intensity factor values (P_{CAV}) for the generated signal rms value equal to 800 V

Rys. 4. Zmiany czasowe wskaźnika intensywności kawitacji (P_{CAV}) przy wartości skutecznej sygnału generowanego o wartości 800 V

Unlike the preview example, for U_S=800V (Fig. 4) the value of P_{CAV} is characterized by changes of almost 6dB, especially at the source signal frequency f_S=115kHz. The changes in time of estimated P_{CAV} value for frequencies 105kHz, 110kHz, 115kHz are much smaller and reach the maximum value of about 2dB.

An uncertainty component obtained by a Type A evaluation is represented by a statistically estimated standard deviation s. At every source signal parameter combination the mean value μ and standard deviation of the normally distributed cavitation intensity factor P_{CAV} was estimated. All of the calculated values are presented in Table 3.

Tab. 3. Normal Distribution Parameters of Acoustic Cavitation Intensity Factor Measurements in Insulating Oil

Tab. 3. Parametry rozkładu normalnego pomiarów wskaźnika intensywności kawitacji akustycznej w oleju izolacyjnym

Source signal rms voltage U_S	Source signal frequency f_S			
	100 kHz	105 kHz	110 kHz	115 kHz
200 V	μ = -41.33 dB s = 0.16 dB	μ = -28.63 dB s = 0.09 dB	μ = -18.41 dB s = 0.13 dB	μ = -16.56 dB s = 0.21 dB
400 V	μ = -40.58 dB s = 0.19 dB	μ = -25.51 dB s = 0.60 dB	μ = -24.50 dB s = 0.34 dB	μ = -16.11 dB s = 1.53 dB
600 V	μ = -36.84 dB s = 0.72 dB	μ = -34.12 dB s = 0.54 dB	μ = -15.97 dB s = 0.95 dB	μ = -13.79 dB s = 0.17 dB
800 V	μ = -36.46 dB s = 0.35 dB	μ = -35.19 dB s = 0.40 dB	μ = -29.04 dB s = 0.78 dB	μ = -16.78 dB s = 1.64 dB
1000 V	μ = -36.16 dB s = 0.38 dB	μ = -36.12 dB s = 0.42 dB	μ = -27.35 dB s = 0.43 dB	μ = -28.67 dB s = 0.42 dB
1100 V	μ = -36.92 dB s = 0.45 dB	μ = -35.04 dB s = 0.38 dB	μ = -27.20 dB s = 0.66 dB	μ = -28.86 dB s = 0.36 dB

Legenda: μ – wartość średnia, s – odchylenie standardowe eksperymentalne
Legend: μ – the mean value, s – standard deviation

The obtained standard deviation of P_{CAV} was in the range between 0.06 dB and 1.64 dB. For acoustic cavitation generation in insulating oil using signal rms value of 800 V and frequency of 115 kHz, the highest uncertainty of P_{CAV} measurements was observed. The probability density function of P_{CAV} in this case is depicted in Fig. 5. Meanwhile, the lowest uncertainty was detected for the source signal U_S=200 V and f_S=105 kHz. Tin this case the standard deviation value equals 0.09 dB. The corresponding probability density functions of P_{CAV} are shown in Fig. 6.

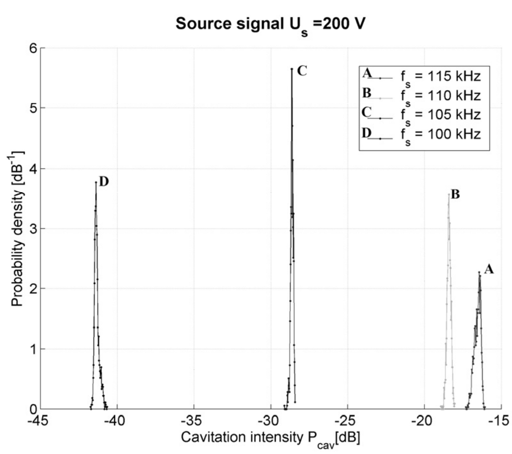

Fig. 5. Probability density functions of cavitation intensity factor values (P_{CAV}) for the generated signal rms value equal to 200 V

Rys. 5. Funkcje gęstości prawdopodobieństwa wskaźnika intensywności kawitacji (P_{CAV}) przy wartości skutecznej sygnału generowanego o wartości 200 V

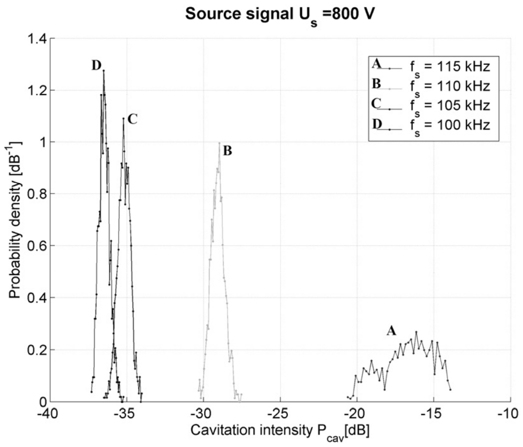

Fig. 6. Probability density functions of cavitation intensity factor values (P_{CAV}) for the generated signal rms value equal to 800 V
Rys. 6. Funkcje gęstości prawdopodobieństwa wskaźnika intensywności kawitacji (P_{CAV}) przy wartości skutecznej sygnału generowanego o wartości 800 V

5. Conclusion

The paper presents an experimental study dealing with the measurement of cavitation intensity in mineral oil. The main application expected from this system is to develop a diagnostic tool for the aging of oil, based on the hypothesis that the measured cavitation intensity and spectrum could be affected by aging. The previous published measurements showed some relationships between the insulating oil aging process and changes of acoustic emission of cavitation [11].

The paper introduces a method for evaluating the measurement uncertainty of acoustic emission spectra by the statistical analysis of series of observations. The drawn probability density functions of the used cavitation intensity factor values for different generated source signal parameters show the differences of its uncertainty. These results of measurements allowed the authors to determine the most favorable frequency and voltage range to induce the cavitation in their setup.

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