Identification of Cavitation by Noise

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Abstract. The identification of cavitation is very important in technical practice for operational and especially economic reasons. The article deals with the use of another way to measure noise during cavitation. The current approach of measuring noise with an intensity probe is used in practice for identification, but it does not immediately address the position of the cavitation source for a given frequency range. Measurement by an acoustic camera is not entirely common in practice, but it allows to determine the location of the noise source for a given frequency range. To test the acoustic camera, the authors focused on the cavitating flow in a hydraulic circuit with three previously tested nozzles. Noise was measured for these nozzles using an acoustic intensity probe with two microphones. The results were evaluated by statistical methods and compared with measurements using an acoustic camera. The aim of the article is to point out the advantages of using this approach for accurate area identification of the problem.

Research background: The work is focused on the issue of cavitation and its identification in the hydraulic circuit. For cavitation research, a variant of cavitation identification by noise was chosen. However, this measurement brings problems that are only revealed through more sophisticated and accurate measurements.
Purpose of the article: The purpose of the article is to point out other possibilities of measuring cavitation noise using modern technologies and subsequently verify the results.
Methods: Metody: A common way of measuring noise is to measure it with a suitably located acoustic intensity probe. A more modern approach is area noise measurement. Measurement methodology and benefits are described.
Findings & Value added: The commonly used way of measuring noise using an acoustic intensity probe has proved to be insufficient, as it is not possible to distinguish the location of sources in the case of complex measurements. When using an acoustic camera, there are more sources of noise in a given circuit and they are detected according to the required frequencies in different places than expected. The article points out the specific identification of noise sources using the frequency spectrum of noise for selected elements.
Keywords: *cavitation, noise, acoustic camera, acoustic intensity probe.*

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1 Cavitation and noise measurement

Cavitation is a long-term problem in technical practice. With increasing demands on the performance of hydraulic equipment (pumps, turbines, valves, cooling systems, etc.), it occurs in almost all hydraulic elements. The critical places for the formation of cavitation from the point of view of hydraulic systems are especially the places where the velocity increases, resp. the pressure of the working fluid reduces. Cavitation occurs mainly in the narrowing of the flow cross-section, when closing or opening valves, in the impeller, in the inlet part of the hydrodynamic pump, etc. [1, 3] Cavitation is distinguished as vapor and gaseous. [4, 5]

Vapor cavitation is described as the content of bubbles is mostly vapor (water). Gaseous cavitation is defined if the bubble content is formed from a non-condensed gas such as air. [4, 5]

If at some point in the hydraulic area the pressure drops to the value of the cavitation pressure p_W (saturated vapor pressure) for the given liquid, the connection of the liquid is broken, and a cavitation bubble is formed. This is then considered to be the place of cavitation (vapor) and the creation of the cavitation area. If the pressure value decreases or remains the same, the vapor bubble will increase. In the flowing liquid, the vapor bubble moves to a region of higher pressure (than the saturated vapor pressure p_W), the vapors contained in it condense violently and the bubble will shrink quickly - it disappears, i.e., it implodes. The gases partially diffuse into the liquid. The liquid thus enters the space thus freed and the rest of the gases is compressed. [1, 2, 9] The formation and development of cavitation can be affected by temperature.

The real liquid may contain bubbles of undissolved gas (air), so-called cavitation nuclei. Cavitation bubbles arise from cavitation nuclei. [1, 2, 9] Under certain fluid conditions (pressure and temperature), the cavitation nuclei reach a critical size, after which it becomes visible to the naked eye like a cavitation bubble. When the cavitation pressure decreases, the air bubbles in the liquid increase, and therefore the expansion of the bubbles can occur even at a higher pressure (critical pressure p_{cri}) than the cavitation pressure p_W. This facilitates the formation of gas cavitation. Assuming that the cavitation nuclei have a spherical shape, the equilibrium condition is valid for the pressure inside the bubble p_B:

$$p_B = p_K + \frac{2\sigma}{R} \tag{1}$$

where p_K [Pa] is the fluid pressure around the bubble, σ [N·m^{-1}] is the surface tension and R [m] is the radius of the bubble. [1, 6, 7] Water has a relatively high surface tension, so it can be a very effective cavitation medium. [3] The residual air in the bubble is the reason why the bubble disappears in an oscillating way (the air acts as a spring when compressed). Similarly, the gases dissolved in the liquid reduce its strength and promote cavitation.

According to the Rayleigh-Plesset theory, the change in the bubble radius can be expressed, assuming that the temperature of the flowing liquid is constant, and the liquid is incompressible, by the equation for bubble dynamics as

$$\frac{p_B(t) - p_\infty(t)}{\rho_L} = R\frac{d^2R}{dt^2} + \frac{3}{2}\left(\frac{dR}{dt}\right)^2 + \frac{4\nu_L}{R}\frac{dR}{dt} + \frac{2\sigma}{\rho_L R} \tag{2}$$

where ρ_L [kg·m^{-3}] is density of liquid (water), ν_L [m^2·s^{-1}] is kinematic viscosity of liquid, [1, 6, 7]

Cavitation noise is created by the formation, growth, pulsations of cavitation bubbles, and especially by their extinction. The pressure waves propagate from the centre of the bubble to the surrounding fluid and interact with each other. Noise can be transmitted by liquid or piping to the system. [3] Thus, noise is related to turbulent flow and the existence of cavitation and can be used as a tool to identify them.

Turbulence is generally evaluated by statistical methods that give exactly defined results only for random processes in the space of homogeneous turbulence. The energy spectrum is used for evaluation (basically power spectral density of velocity fluctuations), so PSD is a basic statistical characteristic of random nature signals, which contain information about the size of structures flow. [12] It should be noted that the turbulent scale is dependent on the dissipation rate at turbulent flow for high Re numbers, and it is not dependent on viscosity. This area is called the inertial subregion and it is characterized by its slope (-5/3) (in the logarithmic coordinate system). In the case of turbulent flow with cavitation, it is necessary to use a milder requirement, i.e., the stationarity of the process in terms of statistical quantities.

Separate microphones are used to measure dynamic changes in acoustic pressure levels. These changes are evaluated using frequency spectra. To locate a noise source in an environment where it is difficult to locate individual noise sources, it is advantageous to use a microphone array, thanks to which a unit called Pressure Contribution can be evaluated for a selected point in space. This value indicates how the location affects the measured sound pressure level. [18, 19]

1.1 Circuit description and measurement

To investigate the properties of cavitation (especially noise), three similar hydraulic elements typical for the formation of hydraulic cavitation were chosen:

I - converging - diverging nozzle of circular cross section [14],
II - converging - diverging nozzle of rectangular cross-section [15]
III - Venturi tube [16]

All elements are transparent and have the same inlet flow area corresponding to an inlet diameter of 50 mm, resp. rectangular cross section (50 x 12) mm. The width at the narrowest cross-section is 14.8 mm. The length of the narrow part of the Venturi tube is 30 mm. All geometries are placed vertically in the hydraulic circuit. The authors also use a similar geometry for cavitation research [8, 10, 11].

Hydraulic parameters (pressures, flow), physical properties of water (temperature, amount of oxygen in the water tank) and noise were measured during the flow through the elements. The size of the cavitation area was evaluated visually. The measuring range is chosen so that the cavitation development is the same for all variants, i.e.

A - flow without cavitation,
B - flow with initial cavitation,
C - fully developed cavitation.

The measurement scheme is shown in fig. 1. The liquid (water) is sucked from the tank by a five-stage Grundfos pump, which is controlled by the frequency inverter YASKAWA VS mini J7. The volume flow [$l \cdot s^{-1}$] is measured by the electromagnetic flow meter ELIS PLZEŇ. The measured element is located behind the flow meter in the vertical position (see fig. 1). Hydrotechnik pressure sensors [Pa] are connected in front of and behind the measured element and records are stored in the Hydrotechnical analyser. The dissolved oxygen transmitter ENDRESS + HAUSER LIQUISYS-M is placed in the tank.

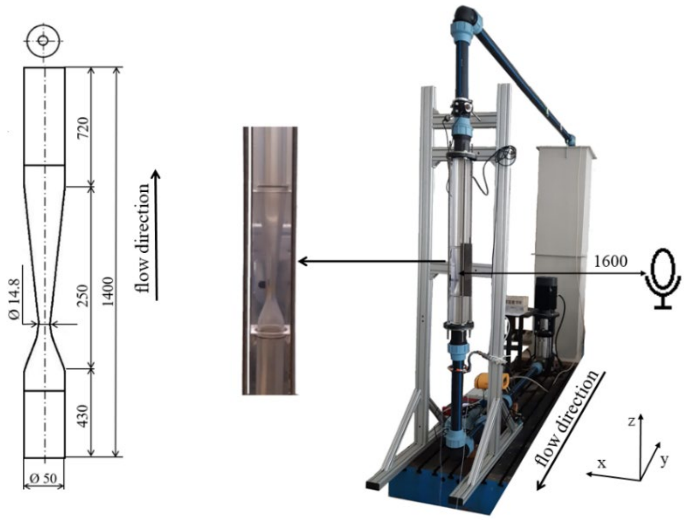

Fig. 1. Measuring circuit, location and orientation of sensors. Dimensions are in mm.

The acoustic camera Bruel & Kjaer WA1764-W-001 was used for experimental noise measurements, it is located 1.6 m in front of the examined element. If known noise sources are measured, a sound pressure level spectrum with suppressed ambient sources can be obtained. Often, this pressure contribution is calculated not for a point, but for M x N points on an area that corresponds to the area of the visual recording from the camera. A graphical representation of the noise sources can be obtained by combining these two visualizations, where the places with the highest pressure contribution are shown in colour. [17] The frequency range and quality of the localization is strongly dependent on the distribution of the microphones and the angle between the different noise sources and the microphone array.

The converging - diverging nozzle (CDN) of circular cross section was chosen for area noise measurement. The onset of cavitation was detected visually and by noise.

1.2 Evaluation of basic hydraulic parameters

Measurements that have been published in the literature [13, 14, 15, 16] are used for evaluation. For each measurement variant, pressures and volume flow rates were recorded with a time step of 0.001 s and subsequently the average values were evaluated. At the same time, the noise intensity was recorded with a given sampling frequency 32.768 kHz.

The dependence of the pressure drop on the volume flow rate is shown in fig. 2 (a). The evaluation of the dependence of the cavitation number on the Reynolds number at the measured element inlet is in fig. 2 (b). The Reynolds number is determined as

$$Re = \frac{v_{in} d_h}{\nu_L} \tag{3}$$

where v_{in} [m·s^{-1}] is the velocity at the measured element inlet, d_h [m] is the hydraulic diameter, ν_L [m^2·s^{-1}] is kinematic viscosity of liquid (water).

The cavitation number is determined as

$$Ca = \frac{2(p_{out} - p_w)}{\rho_L v_{max}^2} \tag{4}$$

where p_{out} [Pa] is the mean value of the pressure at the outlet of the measured element, p_w [Pa] je saturated pressure at given conditions, ρ_L [kg·m^{-3}] is density of water, v_{max} [m·s^{-1}] is the maximum velocity of water flow i.e., the velocity at the narrowest cross-section.

Figure 2 (a) shows that with increasing volume flow rate the pressure drop increases for all variants. The characteristic of element II is different due to the larger flow area in the narrowest cross-section, therefore the cavitation in this element was created arose at the latest. The flow was turbulent in all cases, see fig. 2 (b). Cavitation for various geometries originated at different cavitation numbers. The critical cavitation number was around 1 for the Venturi tube, for other geometries it was less than 1. The initial cavitation number also increases with air content.

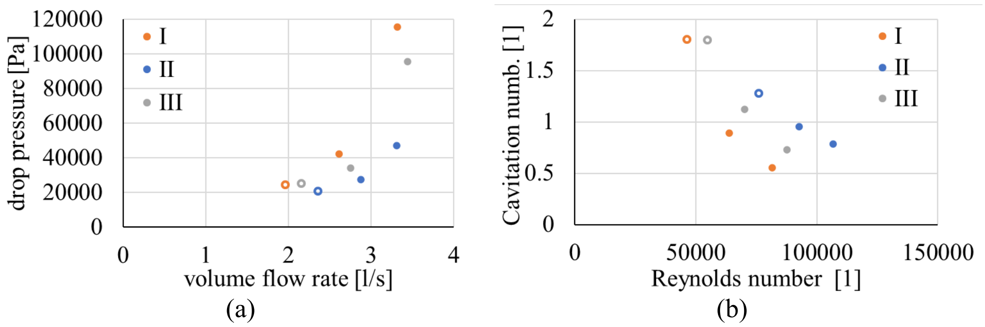

Fig. 2. Dependence of pressure drop on volume flow rate (a), dependence of cavitation number on Reynolds number (b) Unfilled points represent flow without cavitation, filled points represent flow with cavitation.

2 Evaluation by noise intensity probe

Noise measurement by a noise intensity probe with two microphones was performed using the above geometries (see chapter 1.1). The MiniSPL probe was placed 0.4 m in front of the measured element. Other noise sources have been partially shielded.

The acoustic intensity probe evaluates the acoustic intensity I [W·m^{-2}], which can be converted to the acoustic intensity level *La* [dB] as

$$La = 10\, log_{10}\left(\frac{I}{I_0}\right) \tag{5}$$

where *I* [W·m^{-2}] is acoustic intensity, $I_0 = 1 \cdot 10^{-12}$ W·m^{-2} is reference values of acoustic intensity.

Figure 3 shows the frequency spectra obtained from the noise measurements. For all three nozzles, it is possible to evaluate the same spectrum trend for flow without cavitation. Spectrum slope (-5/3) for frequency <1000; 10,000> is typical for turbulent flow. In cases with initial and developed cavitation, the character changes significantly. For all variants, it is clear that the noise frequencies are significant in the range of 2000 Hz to 8000 Hz.

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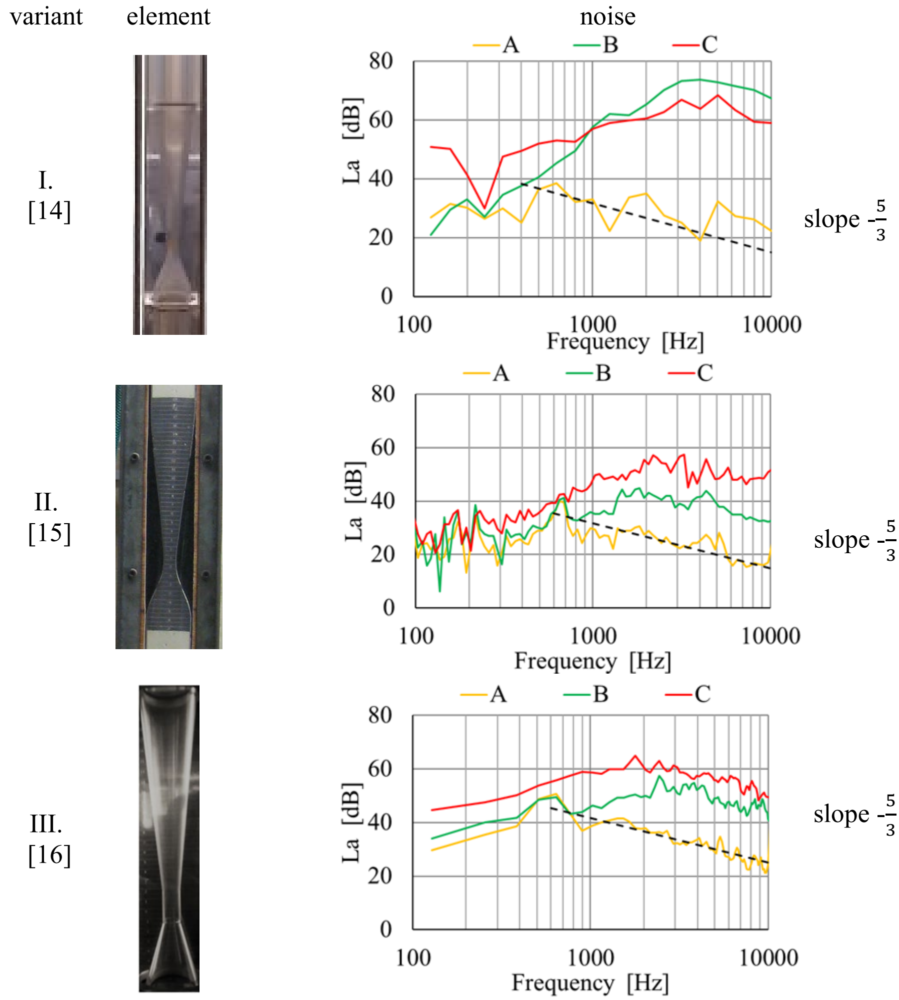

Fig. 3. Evaluation of noise measurements for defined geometries.

3 Evaluation by acoustic camera (microphone array)

Noise measurement using an acoustic camera allows you to evaluate the total noise and also the noise on the element. In this noise measurement, it is not appropriate to evaluate frequencies less than 1500 Hz, which is related to the microphone distribution of the camera used. By evaluating the measurement, it is possible to determine the total noise and subsequently the noise of selected sources.

From the frequency spectrum of the noise for the measured element it is evident that a significant increase of the acoustic noise level for the flow with cavitation (B, C) in the frequency range 2000 Hz to 10000 in comparison with the flow without cavitation (A), see fig. 4. The same was confirmed by measurement with an acoustic intensity probe, see fig. 3.

In the case of converging - diverging nozzle of circular cross section, the noise measurement by the intensity probe and the acoustic camera confirmed that the initial cavitation is noisier than the developed cavitation. Curve B is in the range of expected cavitation frequencies above curve C. The literature [3] describes that the onset of cavitation is often accompanied by a distinct hissing sound.

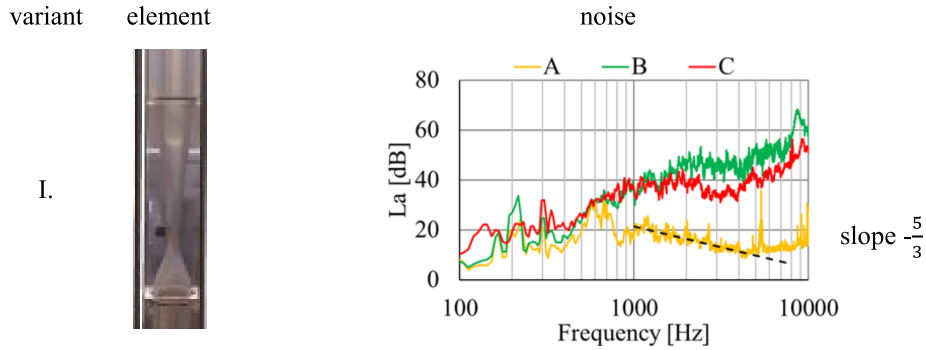

Fig. 4. Evaluation of noise measurements by area noise for variant I.

When measuring noise in the entire monitored area, the place of its occurrence can be evaluated for a given significant frequency. Figure 5 shows the frequency spectrum of the total noise for converging - diverging nozzle of circular cross section (I) and variant C, i.e., fully developed cavitation. An increase in the PSD value can be observed in the frequency range from 5000 Hz to 6000 Hz and from 9000 Hz to 10000 Hz, which is caused by cavitation in the circuit. The PSD increase around the 8000 Hz frequency value is due to the operation of the pump's electric motor, i.e., it is not caused by cavitation.

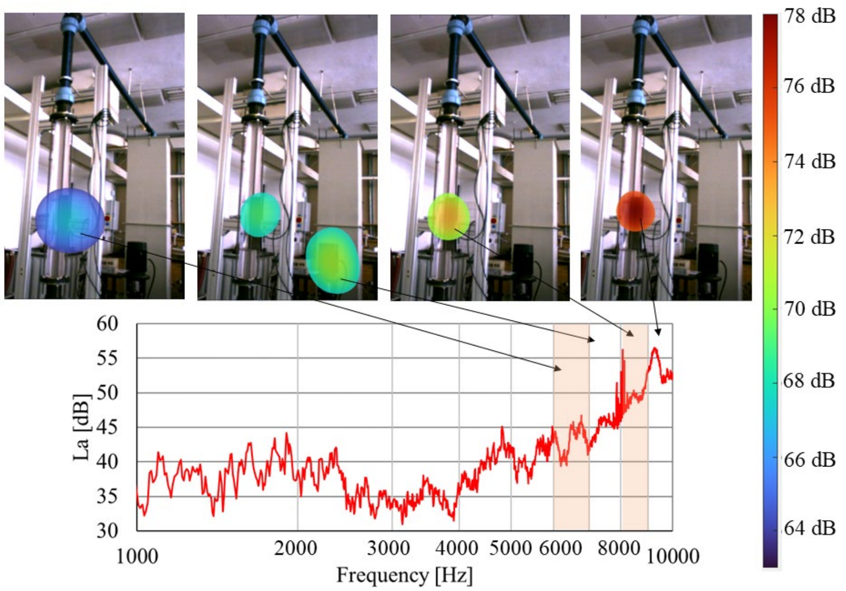

Fig. 5. Evaluation of the frequency spectrum of noise and definition of the problem in the circuit for converging - diverging nozzle of circular cross section, variant C - fully developed cavitation.

4 Conclusion

Cavitation in hydraulic systems results in noise that alerts you to possible circuit problems during normal operation. Cavitation noise may not be dominant in a given area, so better identification methods must be used.

The classic method is the measurement of noise by a noise intensity probe, where the evaluated spectrum shows an increase in intensity at frequencies in the order of <1000;

10000> Hz. A more accurate variant is the use of area noise measurement, where it is also possible to identify the location of noise sources in the room. It can be concluded that the frequency spectrum of the noise measured by the intensity probe (Fig. 3, variant I) and the acoustic camera (Fig. 4) gives identical results. However, when using an acoustic camera, it is possible to precisely define the location of the noise (Fig. 5) and the corresponding frequency. Therefore, acoustic camera recordings better identify noise sources. It is obvious that another significant source of noise is the electric motor of the hydrodynamic pump.

In the case of non-cavitating flow (variant A), it can be seen that the slope of the frequency spectrum curves in Fig. 3 and Fig. 4 corresponds to the slope at turbulent flow. The frequency spectrum of noise obtained during flow with initial or developed cavitation deviates significantly from this curve, which is a signal to identify cavitation. In addition, with increasing flow, the noise of the system increases, but in the case of converging - diverging nozzle of circular cross section, the initial cavitation (formation) is noisier than the developed cavitation.

Cavitation detection using area noise measurement helps in practice to identify the place in the circuit where cavitation with lower noise occurs. Subsequently, the problematic element or circuit can be optimized in terms of cavitation suppression using numerical simulation.

The aim of the authors in the future is to apply the numerical method of multiphase cavitation flow consisting of liquid, steam and air for water and especially for oil, where air is a major component and steam cavitation is essentially non-existent. The frequency response of cavitation noise is obtained by applying the acoustics model in the ANSYS Fluent software and the mathematical model is verified with experimental noise measurements. Numerically, it will then be possible to optimize the hydraulic element in terms of suppressing cavitation and reducing the noise of the hydraulic equipment.

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