6th IAHR International Meeting of the Workgroup on Cavitation and Dynamic Problems in Hydraulic Machinery and Systems, September 9-11, 2015, Ljubljana, Slovenia

MUTUAL EFFECTS OF CAVITATION AND ELECTROMAGNETIC FIELD

S. Fialová[1] 🖂, F. Pochylý[2]

Abstract

The effect of cavitation intensity on the value of electromagnetic field is investigated within this work using theoretical and experimental approaches.
This effect is examined in a cavitation tube made of organic glass.
The motivation is based on the Rayleigh-Plesset equation which describes the collapse of cavitation bubbles over time. The degradation of cavitation bubbles is solved using the non-linear shape of the Rayleigh-Plesset equation.
The effect of the electromagnetic field depends on the flow rate of electrical charge that is carried by the conductive liquid.
The interaction of the conductive fluid and the electromagnetic field is expressed by the Lorentz force. The effect of the Lorentz force creates an electromagnetic force (emf), which can be determined by solving the Navier-Stokes equations in accordance with Maxwell's equations.
The definition of emf is introduced in the paper. Hence, the cavitation tube under the effect of the magnetic field can be considered as an electricity microsource.
Given that the change in the emf is stepwise, it is possible to identify the onset of cavitation by measuring the emf.
The intensity of the cavitation bubbles is studied by measuring the rate of the cavitation bubbles collapse. For this evaluation, an indirect method is used of measuring the acceleration frequency of the oscillating wall of the cavitation tube in the cavitation zone.
It turns out that the frequency depends strongly on the liquid flow through the cavitation tube. The frequency of the collapse of cavitation bubbles is reaching up to the value of 24 kHz.
It was demonstrated on the basis of the performed experiments that the frequency of cavitation bubbles collapse creates unfavorable conditions for the life of microorganisms, e.g. cyanobacteria.
From here it is possible to hypothesize that cavitation may be one of the methods of mechanical destruction of unwanted microorganisms.

Keywords: electromagnetic field, cavitation, Navier-Stokes equation, Rayleigh-Plesset equation, Maxwell's equations

1. Introduction

The motivation for addressing the interaction between an electromagnetic field and a cavitating fluid is the nonlinear Rayleigh-Plesset equation and the Lorentz force.
From Maxwell's equations [4], it can be deduced that the intensity of the electromagnetic field depends on the flow rate of the conductive fluid. This is consistent with the definition of the Lorentz force, which is dependent on the flow rate of the electrical charge carried by the conductive liquid.
From these consequences it can be deduced that with an increased fluid velocity even higher value of magnetic induction can be expected.
From the Rayleigh-Plesset equation [5], it is implied that the collapse of cavitation bubbles is accompanied by high velocities, which are the source of the impulse for the motion of cavitation caverns. Thus, due to cavitation the motion state of fluid changes fundamentally to higher velocities. The

[1]Assistent professor, Brno University of Technology, Technická 2896/2, Brno, 616 69, CZ
[2]Professor, Brno University of Technology, CZ
🖂 fialova@fme.vutbr.cz

disadvantage of this state is the random direction of motion of individual cavitation caverns. An increase in the intensity of magnetic induction is achieved only by those particles whose direction of movement is not parallel to the direction of the magnetic induction. The particles with maximal effect are those whose motion is perpendicular to the direction of the basic magnetic induction induced with a permanent magnet or an electromagnet. Therefore, the intensity of magnetic induction and thus the emf depends on the shape of the cavitation area, respectively the cavitation tube. Most preferred are tubes of a non-circular, rectangular cross section.

2. The basic equation

The interrelation magnetic induction and velocity of a fluid is given by equations (1) and (2). Equation for the Lorentz force:

$$\mathbf{F} = Q \cdot (\mathbf{v} \times \mathbf{B}) \tag{1}$$

The equation of motion for a conductive incompressible liquid:

$$\rho \cdot \frac{d\mathbf{v}}{dt} - \eta \cdot \Delta\mathbf{v} + gradp = rot\mathbf{B} \times \mathbf{B} \tag{2}$$

Magnetic induction equation:

$$\frac{d\mathbf{B}}{dt} + \frac{1}{\delta \cdot \mu} rot\, rot\mathbf{B} - rot(\mathbf{v} \times \mathbf{B}) \tag{3}$$

Continuity equation:

$$div\mathbf{v} = 0 \tag{4}$$

On the basis of known magnetic induction, a relationship for emf can be derived:

$$U = -\frac{d}{dt}\int_S \ \mathbf{B} \cdot \mathbf{n}\, dS = -\frac{d}{dt}\int_V \ div\mathbf{B}\, dV \tag{5}$$

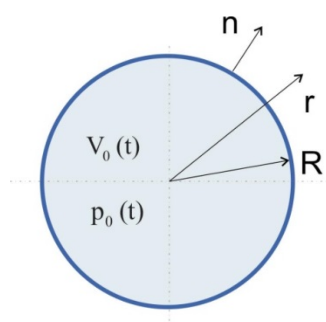

Fig. 1 Cavitation cavern

Collapse of a solitary cavitation bubble, as shown in Fig. 1, is described by Rayleigh-Plesset equation [5] in the form:

$$\frac{3}{2}R^{\circ 2} + RR^{\circ\circ} + \frac{2\sigma}{\rho R} - \frac{1}{\rho}\left[p_0(0) + \frac{2\sigma}{R_0}\right] \cdot \left[\frac{R_0^3}{R^3}\right]^{\kappa} + 4\eta\frac{R^{\circ}}{R} = -\frac{1}{\rho}[p_0(0) - p_N(t)] \tag{6}$$

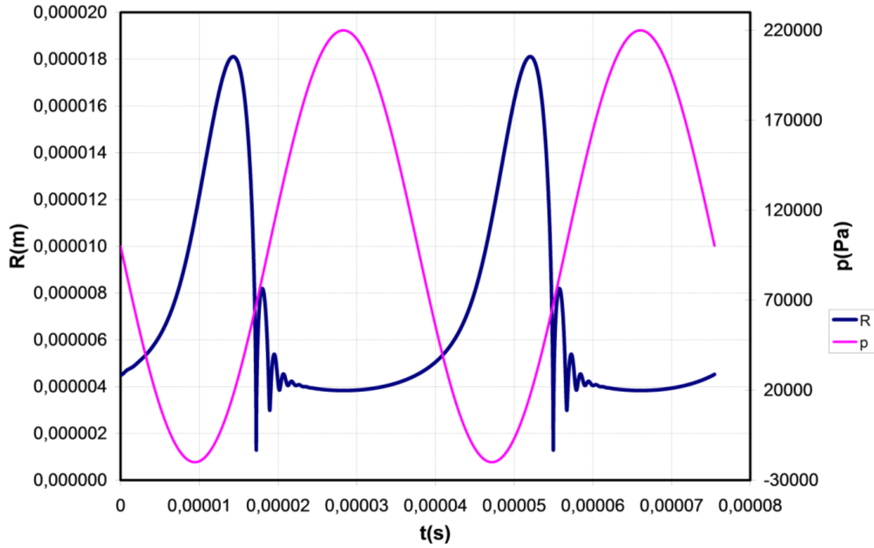

Fig. 2 Cavitation cavern collapse

Equation (6) is derived assuming symmetry, using Navier-Stokes equations without the influence of magnetic field, continuity equation and Laplace equation applicable to the boundary of a sphere and showing the effect of surface tension. Fig. 2 shows the collapse of cavitation bubbles (caverns) by changing their radius and pressure over time.

We note that in commercial software the nonlinear terms of the equations are neglected. From Fig. 2 it is still apparent that there will be large and frequent changes in velocity during the collapse of the cavitation bubbles. And these changes will affect the value of the magnetic induction *B* and hence the value of the emf according to equation (5).

3. Electromotive force due to cavitation

First let's assume that the liquid flows through the tube without causing a cavitation. The tube is connected to a permanent magnet or an electromagnet. The situation is shown in Fig. 3

The relationship for emf (5) can be adjusted to the form:

$$U = -\int_S \frac{d\mathbf{B}}{dt}\mathbf{n}\, dS + \int_S rot(\mathbf{v} \times \mathbf{B})\mathbf{n}\ dS \tag{7}$$

If the flow is steady, based on the mathematical model (2), (3), (4), the relation (7) can be written in a simplified form:

$$U = \int_S rot(\mathbf{v} \times \mathbf{B})\mathbf{n}\ dS \tag{8}$$

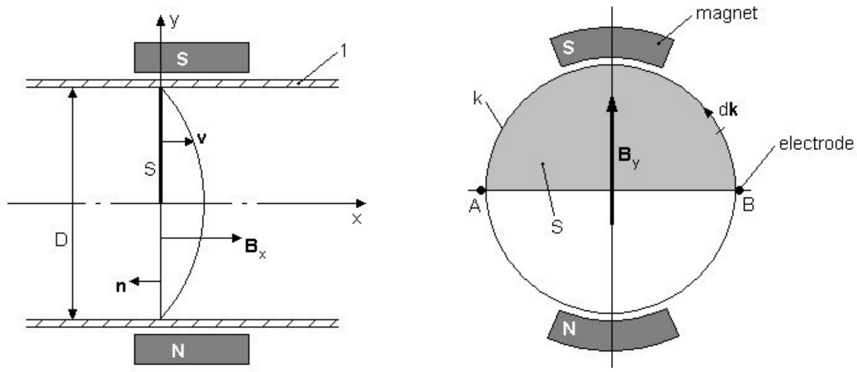

Fig. 3 Fluid in a magnetic field

Considering now the half-section of the tube S, bounded by the curve k, the expression (8) can be written in the form:

$$U = \oint_k (\mathbf{v} \times \mathbf{B})\; d\mathbf{k} = \int_A^B |\mathbf{v}| \cdot |\mathbf{B}_\gamma|\; dk \tag{9}$$

The expression (9) applies only on condition that the liquid adheres to the surface S, namely in the event of $v = 0$ on S. Expressing the integral (9) in terms of the mean value of the integral calculus or provided that $B = const.$, expression (9) can be simplified to:

$$\boldsymbol{U} = |\mathbf{B}_\gamma| \int_{\boldsymbol{A}}^{\boldsymbol{B}} |\mathbf{v}|\; \boldsymbol{dk} = D|\mathbf{B}_\gamma| v_s \tag{10}$$

where v_s is medium velocity defined by:

$$v_s = \int_{\boldsymbol{A}}^{\boldsymbol{B}} |\mathbf{v}|\; \boldsymbol{dk} \tag{11}$$

The condition (10) is valid only when assuming that the tube surface is hydrophilic so that the fluid velocity at the surface is equal to zero. Another case occurs when we consider the tube surface to be hydrophobic - when slip occurs at the surface of the liquid.
Under this assumption, expression (10) changes as follows:

$$\boldsymbol{U} = \oint_k (\mathbf{v} \times \mathbf{B})\; d\mathbf{k} = D|\mathbf{B}_\gamma| v_s + \mathrm{R}\int_0^\pi |\mathbf{v}_k||\mathbf{B}_\gamma| \boldsymbol{d\varphi} \tag{12}$$

where $\mathbf{v}_k$ is velocity on the curve k

It is known that induction flow meters are based on principle (10). Emf can be recorded for example using point electrodes at points A, B in the same way as it was configured in the case of our experiment. Now consider a more complex case where only one cavitation cavern exists in the examined domain. The situation is shown in *Fig. 4*
In such case, when considering the movement and collapse of the cavitation cavern, it is necessary to take into account the general expression for emf calculation (7).

From there one can deduce:

$$U = -\int_S \frac{d\mathbf{B}}{dt}\mathbf{n}\, dS + D\left|\mathbf{B}_\gamma\right| v_s + \oint_{k_1} (\mathbf{v} \times \mathbf{B})\ d\mathbf{k_1} \tag{13}$$

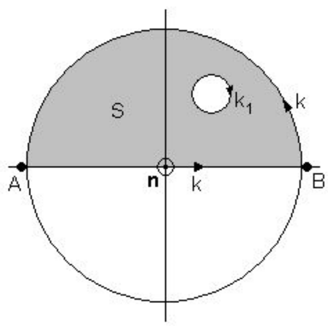

Fig. 4 Flowing liquid with a cavitation cavern

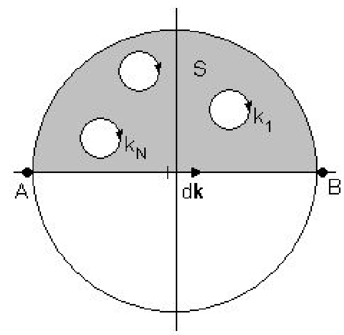

Fig. 5 Flowing liquid with cavitation caverns

From (13) it is apparent that emf will be significantly affected by the cavitation cavern. The velocity $\boldsymbol{v}$ on the boundary of the cavitation cavern is necessary to be determined from two components. From the actual velocity and the velocity of the cavern $\overset{\circ}{R}$, giving impulse to the surrounding liquid. Based on this impulse, the value of velocity v_s will also be influenced. In the case of *N* cavitation caverns being within the cross-section *S* , see Fig. 5, the term for an emf will be written in form:

$$U = -\int_S \frac{d\mathbf{B}}{dt}\mathbf{n}\, dS + D\left|\mathbf{B}_\gamma\right| v_s + \sum_{l=1}^{N} (\mathbf{v} \times \mathbf{B})\ d\mathbf{k}_l \tag{14}$$

4. Experiment

To verify the interaction of liquid and magnetic field, a simple experiment was proposed [2], [3]. The experiment is based on the flow of a liquid through the cavitation tube, as shown in *Fig. 6*.
The tube is fitted with two point electrodes at points *A* and *B*, see *Fig. 6*, where the emf *U* changes. The electrodes are positioned outside the cavitation zone (*U1*) and in the cavitation zone (*U2*).
The tube is narrowed at a specific place so that the pressure decreases below the saturated vapor and cavitation occurs. The cavitation intensity was controlled by changing the flow rate Q in the cavitation tube.
The original version of the cavitation tube was made of glass and after one hour of operation a rupture occurred due to the effect of the impact pressure on the tube wall. The frequency of the collapse of cavitation caverns near the wall of the tube could be up to *24 kHz,* as we shall see further.
The structure of the cavitation caverns after the rupture of the tube is shown in *Fig. 7*. After this experience, different material was chosen for the cavitation tube - organic glass (plexiglass).
Before the experiment, the electrical conductivity of water was measured. The measurement of emf was obtained both out of the cavitation zone (*U1*) as well as in the cavitation zone (*U2*). The results are shown in *Fig. 8* for $\sigma = 6{,}86 \cdot 10^3\ S \cdot m^{-1}$.

Fig. 6 The cavitation tube with point electrodes

Fig. 7 Structure of the cavitation caverns

In *Fig. 8*, it is visible that a stepwise change in emf occurs in the cavitation zone caused by both the movement of cavitation caverns, but also by the influence of their dynamics as is qualitatively assumed by expression (14). *U* is time dependent and the mean value *U* is shown in *Fig. 8* .
The frequency of cavitation caverns collapsing was scanned at the surface of the cavitation tube by an acceleration sensor. The structure of these frequencies, depending on the flow rate can be observed in *Fig. 9* - *Fig. 13*.

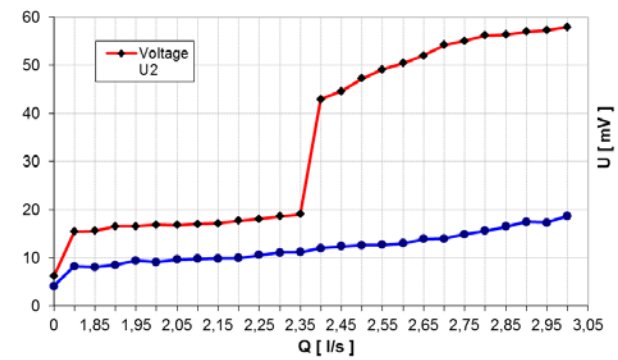

Fig. 8 Emf outside and inside the cavitation zone

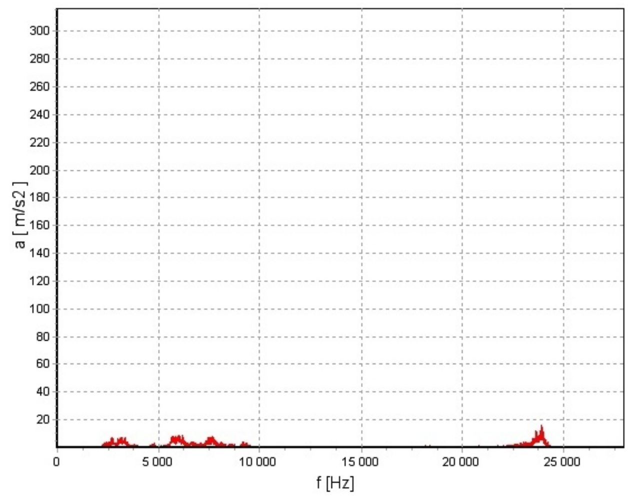

Fig. 9 The beginning of an audible cavitation $Q = 1{,}9\ l \cdot s^{-1}$

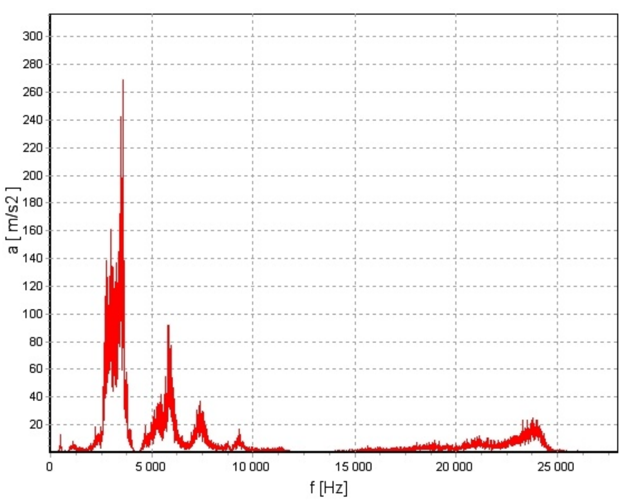

Fig. 10 Cavitation along the entire length of the tube, $Q = 2{,}35\ l \cdot s^{-1}$

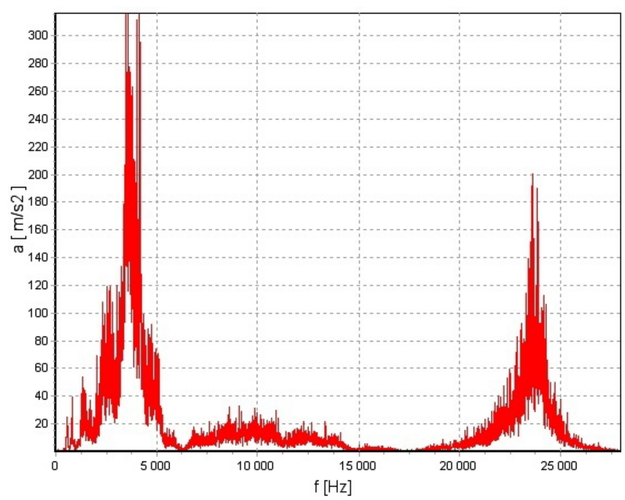

Fig. 11 Cavitation along the entire length of the tube, $Q = 2{,}5\ l \cdot s^{-1}$

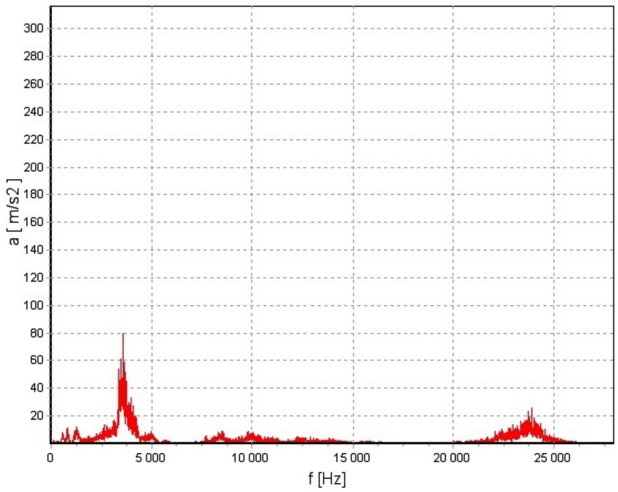

Fig. 12 Reduction of vibrations, $Q = 2{,}6\ l \cdot s^{-1}$

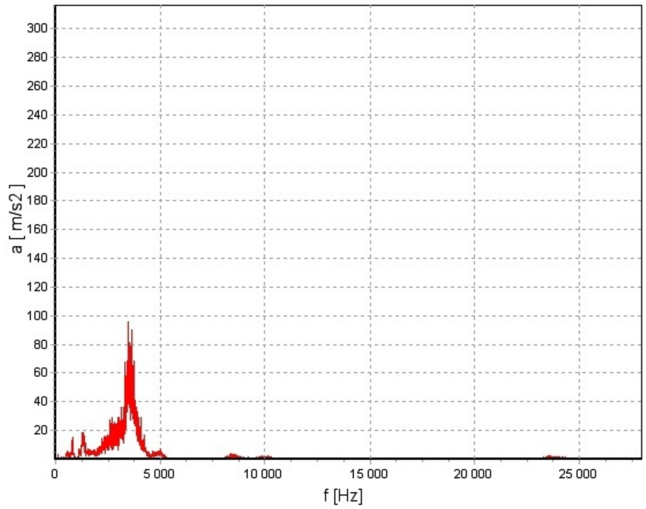

Fig. 13 Supercavitation along the whole cavitation zone, $Q = 3\ l \cdot s^{-1}$

From *Fig. 9* - *Fig. 13* it is apparent that the frequency of cavitation bubbles collapsing on the wall of the cavitation tube strongly depends on the flow rate.

It was shown in the experiments that a specific flow rate exists at which high values of impact pressures occur at ultrasonic frequencies, up to *24 kHz*, see. *Fig. 11*. When increasing the flow rate, the cross section of the cavitation tube is gradually filled with saturated steam at a rapid reduction in the frequencies of the impact pressure, acting on the wall of the tube due to the collapse of the cavitation bubbles. When the flow rate reaches $Q = 3\ l \cdot s^{-1}$ it will cancel out frequencies above the value of *4 kHz* and significantly reduce the impact pressure on all frequencies.

The creation and collapse of the cavitation caverns were captured by high-speed camera scanning [1]. In the article [1] the situation is shown, where the motion of the cavitation cavern is apparent as well as the growth and collapse of its volume at a point just before enlargement of the cavitation tube.

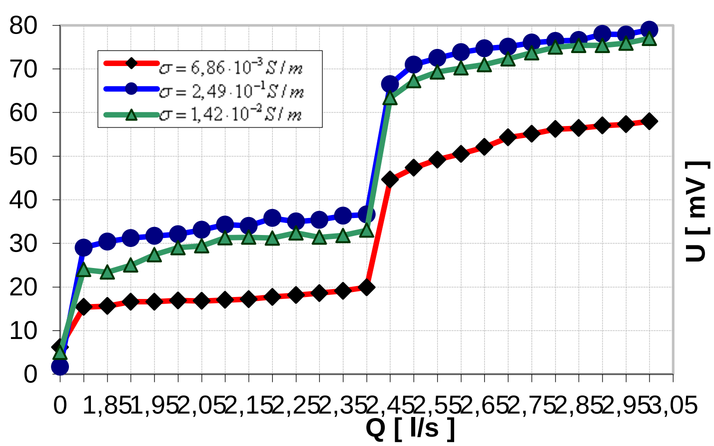

Fig. 14 Emf on the electrodes in dependence on electrical conductivity

All these phenomena will naturally affect the value of emf, taking into account the expression (14).

Emf is however also dependent on the electrical conductivity of water, which is very small. So we decided to increase it by adding a saline solution, see *Fig. 14*. From *Fig. 14* it is clear that by increasing the electrical conductivity of the liquid higher values of emf can be achieved as expected, even in the cavitation zone, but the increase has limitations apparent from *Fig. 14*.

5. Conclusion

From the above experiments it is possible to make the following conclusions:

- Dependence of emf U1 outside the cavitation zone, in accordance with the expression (10) has a linear dependence on the flow rate, see. *Fig. 8*. Mild nonlinearity is caused by the electrode 1 (U1), see *Fig. 6*, being placed near the cavitation zone.
- From *Fig. 8* and *Fig. 15* it is apparent that the flow in the cavitation zone causes a stepwise change in the emf. Taking into account *Fig. 9 - Fig. 13* in correlation with *Fig. 8* and *Fig. 15* it is evident that the value of emf at the point of its greatest changes corresponds to a frequency of approximately 4 kHz. Higher collapse frequency of the cavitation caverns, ie. 24 kHz does not significantly affect the value of the emf. The situation is evident from *Fig. 15*, where it is clear that due to the effect of cavitation caverns collapsing at a frequency of 24 kHz no significant increase in the emf has occured. Starting from the flow rate $2{,}45\ l \cdot s^{-1}$, the dependence of the emf is already linear. These results are strongly influenced by the placing of the electrode (U2) deep into the cavitation zone, as is apparent from *Fig. 6*. Here, 24Khz frequencies have been significantly dampened, and therefore only the collapse of cavitation caverns at 4 kHz frequency makes a significant impact. Much higher gradients $\frac{\partial \mathrm{U}_2}{\partial \mathrm{Q}}$ would be achieved by placing the electrodes into the tube constriction, or with an electrode of greater areal content (electrode strips). In that sense, further experiments will be set out.
- From *Fig. 9*- *Fig. 13* is apparent a significant impact of the flow rate on cavitation bubbles collapse. The maximum amplitude at the frequency of 24 kHz is obtained at a flow of $2{,}5\ l \cdot s^{-1}$, but already at values of $2{,}35\ l \cdot s^{-1}$and $2{,}6\ l \cdot s^{-1}$ *it* is already unsubstantial. Thus, there is only a small range of flow rates where the collapse of cavitation caverns at a frequency of 24 kHz can be achieved. The frequency of approximately 4 kHz is high for the entire interval of the flows $\mathrm{Q} = \langle 2{,}3; 3\rangle l \cdot s^{-1}$.
- On the basis of the experiment, it is demonstrated that the onset of cavitation is characterized by a stepwise change in emf. This fact can be practically used for the identification of the beginning of the cavitation formation.

Acknowledgment

Grant Agency of Czech Republic within projects GA101/13-20031S and GA101/15-06621S is gratefully acknowledged for support of this work.

Regerences

[1] Pochylý F., Fialová S.: The cavitation effect on the electromagnetic field, Recent Advances in Mechatronics, ISBN 978-3-642-05021-3, DOI 10.1007/978-3-642-05022-0, 2009
[2] Kantor D.: Diploma thesis. BUT Brno, 2007
[3] Veverka A.: Diploma thesis. BUT Brno, 2007
[4] Bo Fidé: Electromagnetic field theory, ISBN 978-0-486-4773-2, 2012
[5] Prosperetti A.: A generalization of the Rayleigh–Plesset equation of bubble dynamics, AIP Phys. Fluids **25**, 409, 1982