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Research into ultrasonic and hydrodynamic cavitation phenomena in a hydraulic system

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Abstract. *The article describes the course of the ultrasonic cavitation in a hydraulic tank and the hydrodynamic cavitation in a gear pump. The course of those phenomena was confirmed in experimental tests carried out with the use of a tank and a pump made of transparent plastics. It has been proved that the oscillator-cavitation system made according to the original project is useful to induce the phenomenon of ultrasonic cavitation. It has also been shown that the PIV visualization method, consisting in a special system of illuminating transparent objects and recording the flow through those objects with a fast camera, is useful for the studying of the cavitation phenomena.*

A visible interaction between the ultrasonic and the hydrodynamic cavitation was observed. The induction of ultrasonic cavitation in the tank causes degassing of the oil, and the degassed oil supplying the pump reduces the hydrodynamic cavitation in its internal channels and clearances. This is an example of beneficial effects of the ultrasonic cavitation on the operation of a pump and a hydraulic system.

The presented work is an example of effective co-operation between the communities of Wroclaw University of Science and Technology and Igor Sikorsky Kiyv Politechnic Institute, National Technical University of Ukraine.

Keywords: *ultrasonic cavitation; hydraulic tank; hydrodynamic cavitation; gear pump; plastic; PIV-visualization.*

Introduction

Cavitation is a physical phenomenon involving a rapid release of gas bubbles dissolved in a liquid. It is caused by a local drop in pressure p_O of a liquid below the vapor pressure p_I inside the bubbles, i.e. $p_O < p_I$ [1–3].

In hydraulic systems, cavitation is caused by the flow of a liquid through various obstacles, such as internal channels and clearances, edges, orifices or holes. In those places, there is a local rapid decrease in pressure p_O below the pressure of gases p_I, which results in the occurrence of cavitation. This is called HYDRODYNAMIC CAVITATION as it is caused by the flow of a liquid through obstacles. The hydrodynamic cavitation in the hydraulic system is unfavourable and causes:

– improper functioning of the machines and devices, reducing their technical parameters [4–7],

– improper functioning of hydraulic units such as pumps [8, 9], valves [10] or cylinders [11],

– an increase in the noise levels of pumps and other units of a system [12, 13],

– damage of the internal surface of hydraulic elements [14].

Therefore, cavitation must be eliminated, and this is achieved predominantly by design measures such as:

– selection of appropriate hoses and connections of the hydraulic system in order to ensure minimal flow resistance [14],

– special shaping of internal channels and clearances in hydraulic elements, such as relief grooves in gear pumps [15],

– special shaping of control systems, e.g. the poppet-seat system in hydraulic valves [16],

– application of special anti-cavitation overload valve units in hydraulic systems [14].

The phenomenon of cavitation can also be used to cause positive effects in the hydraulic system. One important example is the induction of cavitation in a hydraulic tank to degas the oil. An effective way to induce such cavitation is the use of ultrasonic waves. The phenome-

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non, called ULTRASONIC CAVITATION, with its theoretical basis is presented in [17–19]. Special devices and technical methods for the implementation of the ultrasonic cavitation are presented in [20–22].

The PIV visualization method can be used to observe and investigate the cavitation phenomena. The essentials of this method are presented in [23], and the appropriate research system and the observation method are shown in [24, 25].

The analysis of various types of cavitation and the determination of their impact on the operation of the hydraulic system resulted in the definition of the work's objectives which are:

– to study the phenomenon of ultrasonic cavitation and the process of degassing the oil in the hydraulic system tank;

– to investigate the phenomenon of hydrodynamic cavitation in a gear pump supplied from a degassed tank,

– to determine the interaction between the ultrasonic and the hydrodynamic cavitation which are observed in a hydraulic system,

– to adapt the PIV visualization method for the study of the cavitation phenomena.

The ultrasonic and the hydrodynamic cavitation

Using [1, 2], the course of the ultrasonic cavitation phenomenon was considered and it is shown in Fig. 1 (on the left from the hydraulic tank). The cavitation is caused by the cavitator (*1*) and its discs (*2*) immersed in the tank with hydraulic oil (*3*). The cavitator body and the discs generate an ultrasonic wave. Vibration of the cavitator alternately increases in the vicinity of the discs, creating arrows of the ultrasonic wave, and between the discs, nodes of that wave. That causes the oil pressure changes in the tank and, consequently, cavitation.

As shown in Fig. 1-zone (*A*), cavitation phenomena begin with the nuclei which are:

– micro-bubbles (*a*) occurring in micro-cracks and on the surfaces of the cavitator, tank or other elements immersed in the oil,

– bubbles of air (*b*) or other gases (*c*) dissolved in the oil,

– micro-bubbles (*d*) adhering to the solid particles (impurities) in the oil.

Those nuclei are contained in the entire volume of the oil.

The cavitator's vibration results in several simultaneously ongoing cavitation phenomena. In the area of the ultrasonic wave node (see Fig. 1 – zone (*B*)), bubbles develop from the cavitation nuclei, and those, consequently, group and grow into larger bubbles. Around the node, this process runs relatively slowly because the vibration is not intensive. Bubbles may be also generated as a result of the diffusion of gases dissolved in the oil into their interior when the external pressure p_O is higher than the internal pressure in the bubble, i.e. $p_O > p_I$. The diffusion is also possible in the opposite direction, i.e. from the gas bubble

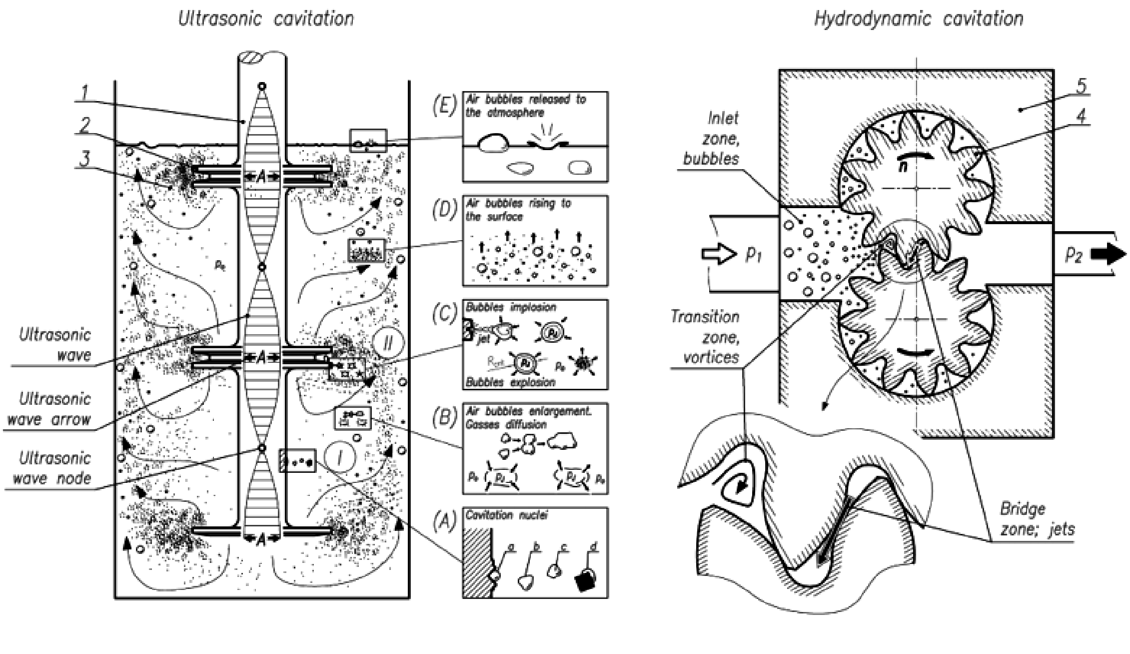

Fig. 1. The course of the ultrasonic and the hydrodynamic cavitation phenomena.
1 – cavitator, *2* – cavitator's disc, *3* – tank, *4* – gear, *5* – body of the pump, *I* – outflow of the bubbles from the area of the ultrasonic wave node, *II* – outflow of the bubbles from the area of the ultrasonic wave arrow,
a – air bubble in the micro-crack of the cavitator surface, *b* – air bubble, *c* – gas bubble, *d* – air bubble with a hard compound (p_O – pressure of the oil in the tank, p_I – pressure of the gas inside the air bubble)

into the oil, when shrinkage of the bubble size is observed. Then, the external pressure p_O is lower than the internal pressure p_I, namely $p_O < p_I$. The process of shaping and growing of the bubbles takes place much more intensively in the zone of the ultrasonic wave arrows, where the cavitator discs are located. The bubbles move towards the nodes and in that area join into larger groups and flow out towards the oil surface (see: Fig. 1, streams I, II).

Parallel to the growth of the bubbles, the phenomena of implosion and explosion of the bubbles may occur, as shown in Fig. 1 – zone (*C*). The implosion may be observed when the bubble remains within the area of the ultrasonic wave arrow and the external pressure is higher than the internal pressure, i.e. $p_O > p_I$. If the imploding bubble is in the immediate vicinity of an obstacle, which may be the cavitator wall or another bubble, then a stream of high pressure liquid, the so called "jet", is formed. A bubble explodes when it breaks down into small bubbles when the internal pressure pI is higher than the external pressure p_O, i.e. $p_I > p_O$. The small bubbles become the cavitation nuclei and the process repeats itself.

Fig. 1 – zone (*D*) shows that large bubbles and groups of bubbles rise to the surface of the oil and there they merge with the atmosphere. It is shown in Fig. 1 – zone (E).

The course of the hydrodynamic cavitation phenomenon is presented on the basis of [15, 25, 26] in Fig. 1, on the right. The phenomenon has been described in reference to the gear pump. Hydrodynamic cavitation occurs in the medium flowing through the internal channels and clearances of the gear pump while the gears (4) are rotating in the body (5) at the pressure difference between the inlet to and the outlet from the pump, which is marked with arrows.

As shown in Fig. 1 – zone (*F*), the cavitation nuclei appear between the teeth of the gears in the so-called closed space. As a result of increasing the volume of this space, the pressure drops below pressure p_I in the gas bubbles, i.e. $p_O < p_I$. As a result, there is a jet that moves towards the inlet zone of the pump.

The next stage of the cavitation phenomenon occurs in the transition zone, as shown in Fig. 1 – zone (*G*). Due to the opening of the closed space, further reduction in the pressure is created and the jets get transformed into vortices and those are pushed by the rotating gears to the entrance zone.

In the entrance zone shown in Fig. 1 – zone (*H*), the vortices dissolve and disappear, leaving only single bubbles or small groups of them.

The cavitation phenomenon occurring in three zones (*F, G, H*) repeats cyclically due to the successively engaging pairs of teeth.

Research objects

The cavitation phenomena were studied on specially prepared objects, i.e. a hydraulic tank (Fig. 2) and a gear pump (Fig. 3).

Fig. 2 *a* depicts the tank with the ultrasonic cavitation induction system. The tank was designed and manufactured at the Department of Fundamentals of Machine Design and Tribology of Wroclaw University of Science and Technology, Poland, while the cavitation induction system was designed and manufactured at Igor Sikorsky Kyiv Polytechnic Institute, National Technical University of Ukraine.

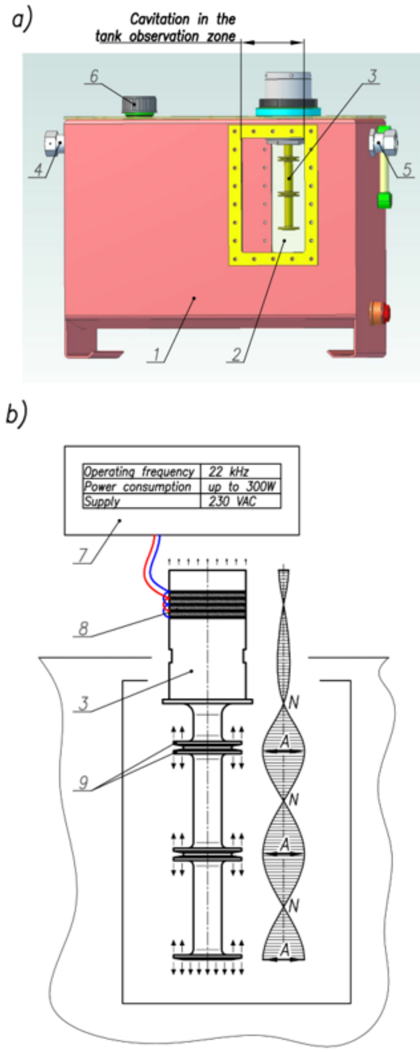

Fig. 2. Hydraulic tank (*a*) with the system of generating the ultrasonic cavitation (*b*)
1 – tank, 2 – windows in the front/back wall of the tank, 3 – vibration inducer, 4, 5 – inlet and outlet, 6 – vent valve, 7 – electronic oscillator, 8 – piezoelectric transducer, 9 – radiating discs

The windows (2) are made of a transparent plastic. Inside the tank, there is a cavitator (3) used to induce the ultrasonic vibration. The inlet (4) and the outlet (5) ports lead to the tank, and the vent valve (6) is located in the cover. As shown in Fig. 2 *b*, the cavitator (3) is placed vertically in the tank between the windows. It is connected to the electronic oscillator (7) which powers the piezoelectric system (8) that generates the vibration of the shaft (3) and the discs (9) of the cavitator. As shown schematically in Fig. 2 *b*, the cavitator produces a standing ultrasonic wave with arrows A and nodes N. This wave causes

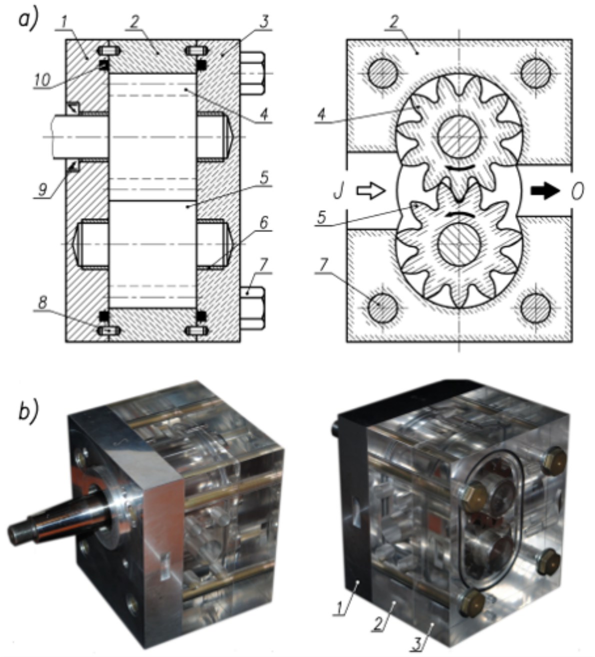

Fig. 3. Gear pump with a plastic body
a) design solution of the pump: *1* – front body (aluminum alloy), 2, 3 – central and back bodies (transparent technical glass), 4, 5 – gears, 6 – bearing, 7 – screw, 8 – pin, 9, 10 – sealing, *b*) experimental pump with the transparent body: 11 – front body (aluminium), 12, 13 – central and back bodies (technical glass)

local rises and falls of the oil pressure and, as a result, the ultrasonic cavitation process (see Chapter 1, Fig. 1).

Fig. 3 *a* shows a design solution of an experimental gear pump for the testing of the hydrodynamic cavitation.

The pump was designed and manufactured by the Department of Fundamentals of Machine Design and Tribology of Wroclaw University of Science and Technology, Poland. It consists of three bodies (1 – 3) in which gears (4, 5) rotate and pump the oil from the inlet zone (J) to the outlet zone (*O*). Fig. 3 *b* shows that the front body is made of an aluminium alloy while the central (2) and the rear (3) bodies are made of the transparent PMMA which enables observation of the flow phenomena in the internal channels and clearances of the pump during its operation. The observation concerns mainly the area of the engaging gears as well as the input channel and the input chamber where the cavitation phenomena occur most intensively. In order to show the phenomena, no relief grooves have been applied in the pump.

Stand for the visualization tests of the cavitation phenomena in the tank and the gear pump

The diagram of the stand which was designed and built at the Department of Fundamentals of Machine Design and Tribology of Wroclaw University of Science and Technology [14, 24] is shown in Fig. 4 *a*.

The oil flows from the tank (1) to the gear pump (2) which is driven by the electric motor (3).The inlet and outlet pressure in the pump is set by throttling valves (4) and measured with pressure transducers (5). The ultrasonic cavitation in the tank is generated by the oscillator (6) and the cavitator (7). The hydrodynamic cavitation is induced by increasing the rotational speed of the motor (3) and by increasing pressure difference Δp between the inlet and outlet of the gear pump (2). The cavitation phenomena visible in the tank (1) and in the pump (2) are illuminated by the lamps (8) and recorded by the fast camera (9) and by the computer (10). This system can be used both for investigating the cavitation in the tank (1) and in the pump (2). The test stand is depicted in Fig. 4 *b*.

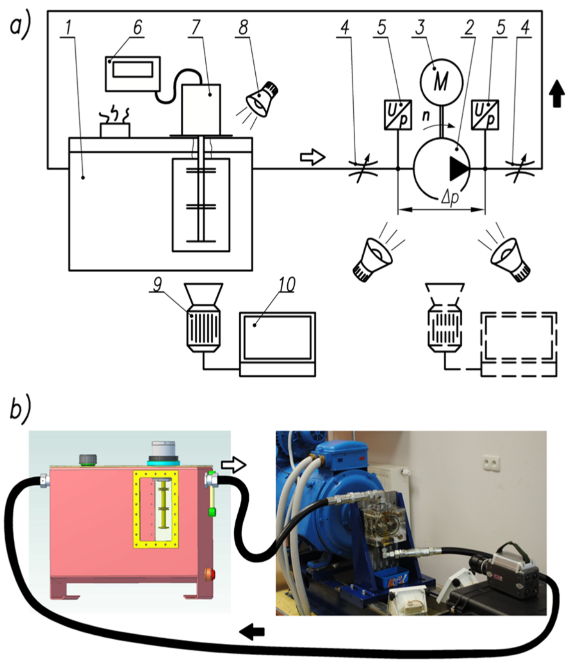

Fig. 4. Stand for the research on the cavitation phenomena in the tank and gear pump
a) diagram of the stand, *b*) view of the stand (*1* – tank, *2* – pump, *3* – electric motor, *4* – throttle valve, *5* – pressure transducer, *6* – oscillator, *7* – vibration inducer, *8* – lamp, *9* – fast camera, *10* – computer (for the recording))

Visualization tests of the cavitation, test results, discussion.

The research was carried out at the Department of Fundamentals of Machine Design and Tribology of Wroclaw University of Science and Technology. Fig. 5 shows the course of the ultrasonic cavitation process in the oil tank.

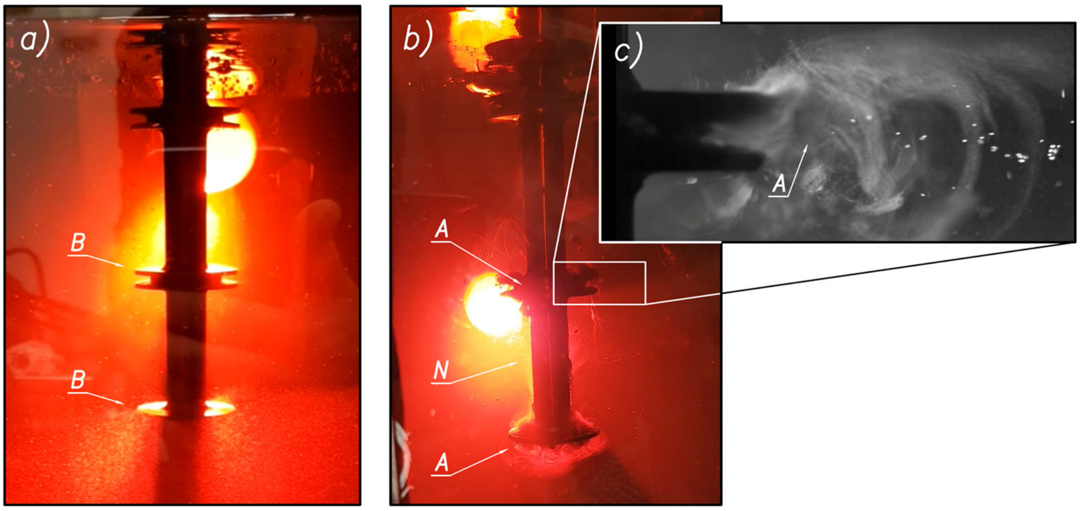

Fig. 5. Findings of the research on the ultrasonic cavitation in a hydraulic tank
a) view of the tank prior to the cavitation process, *b*) view of the tank during the cavitation process,
c) detailed view of the cavitation process in the area of the disc (arrow A of the ultrasonic wave),
A – ultrasonic wave arrow, *N* – ultrasonic wave node

The view of the oil in the tank prior to the beginning of the cavitation process is shown in Fig. 5 *a*. The lamps illuminate the cavitator through the window. In their light, the still oil with air bubbles dissolved in it can be observed. It is particularly visible in the area of the cavitator discs (bubbles B). Fig. 5 *b* shows the course of the ultrasonic cavitation process. Waves of bubbles are generated around the discs where the ultrasonic wave arrow A occurs. Smaller numbers of bubbles are generated around the core where the ultrasonic wave N node is present. Fig. 5 *c* shows the detailed results of the ultrasonic cavitation in the neighbourhood of the disc (arrows A). You can see the ring-shaped waves of bubbles spreading intensively in the tank.

The analysis of the pictures shows that the method of inducing the ultrasonic cavitation proved to be effective. The apparatus worked in accordance with the theoretical assumptions specified in chapter 2. The cavitation was most intensive in the area of the vibrating discs where, according to the theory, the arrows of the vibrating wave are located. The intensity of the cavitation process depends on the system power and on the amplitude of the vibrating wave. The effectiveness of the process consisting in the degree of the tank degassing depends on the duration of the process.

Fig. 6 shows the course of the hydrodynamic cavitation inside the gear pump.

As suggested in Chapter 4, it is most clearly visible in the meshing area of the gears. Fig. 6 *a* illustrates that the pair of teeth $k1$-$k2$ remains in the mesh at point A_k and the pair of teeth m_1-m_2, at point A_m. Between points A_k and A_m there is a closed space which, when the gears rotate, reduces its volume to V_{Zmin}. This results in the flow from the upper part of the closed space to the lower one in the form of a jet (J). What follows is the formation of cavitation bubbles (B) and veils (V_e) in the lower part. Fig. 6 *b* shows that as the gears continue to rotate, the closed space gets larger up to V_{Zmax} and the cavitation veil (V_e) develops in its lower part and changes into the cavitation vortex (V_x). Fig. 6 *c* shows that the cavitation is most developed when the tooth pair k_1-k_2 is disengaged and the closed space is connected to the inlet channel of the pump. Then, there is a sudden opening of the closed space, effecting in a sudden pressure drop and, consequently, the formation of a significant cavitation vortex (V_x). The cavitation also spreads through the axial clearance to the space between m_1-m_2 in the form of bubbles (B).

Since both objects of the cavitation study, i.e. the tank and the gear pump, are included in a common hydraulic system, the question arises whether there is an interaction between the ultrasonic and the hydrodynamic cavitation. As already mentioned, the ultrasonic cavitation is caused intentionally by means of special devices, namely cavitators. This type of cavitation has a positive effect, as it leads to the degassing of the oil, while the hydrodynamic cavitation occurs spontaneously as a result of the gear pump operation. Its effect is unfavourable because it causes the disruption of the pump's operation and reduces its operational parameters. The effects of the interaction of both types of cavitation are illustrated by Fig. 7 showing the course of the hydrodynamic cavitation in the closed space of the pump before and after the ultrasonic cavitation in the tank, lasting 90 minutes, i.e. before and after the degasification.

It has been shown in Fig.7 that before the degasification, intensive cavitation phenomena similar to those shown in Fig. 6 occur in the closed space. However,

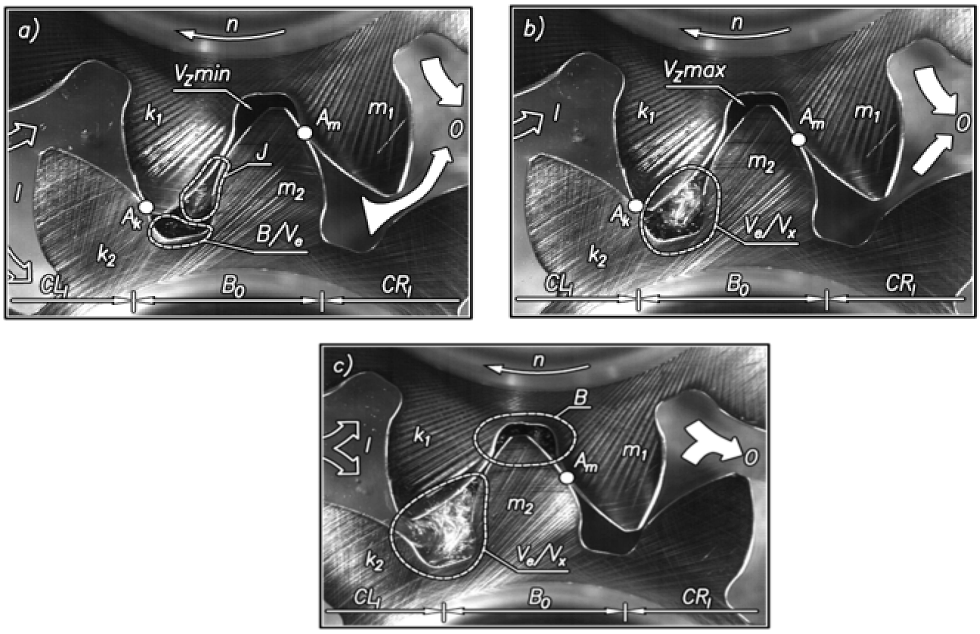

Fig. 6. Findings of the research on the hydrodynamic cavitation in a gear pump p_I = 0 bar, p_O = 10 bar, n = 500 rev/min, T_{oil} = 30 C; *a, b, c* – consecutive phases of the gears engagement; *I, O* – inlet to the pump, outlet from the pump, CL_I, CL_O – inlet channel, outlet channel, B_O – bridge (of the closed space)

Fig. 7, on the right, depicts that after the degasification lasting 90 minutes, the cavitation phenomena were clearly limited.

While comparing relevant pairs of figures on the left and right, it is noted that in Fig. 7 *a* the bubbles (*B*) and veils (V_e) appearing on the left side are reduced to bubbles (*B*) shown on the right. Similarly, in Fig. 7 *b*, veils (V_e), and vortices (V_x) are reduced to veils (V_e), whereas in Fig. 7 *c*, vortices (V_x) are reduced to veils (V_e). Thus, it can be concluded that the use of the ultrasonic cavitation and the oil degasification leads to the reduction of the hydrodynamic cavitation. Further limitation of the

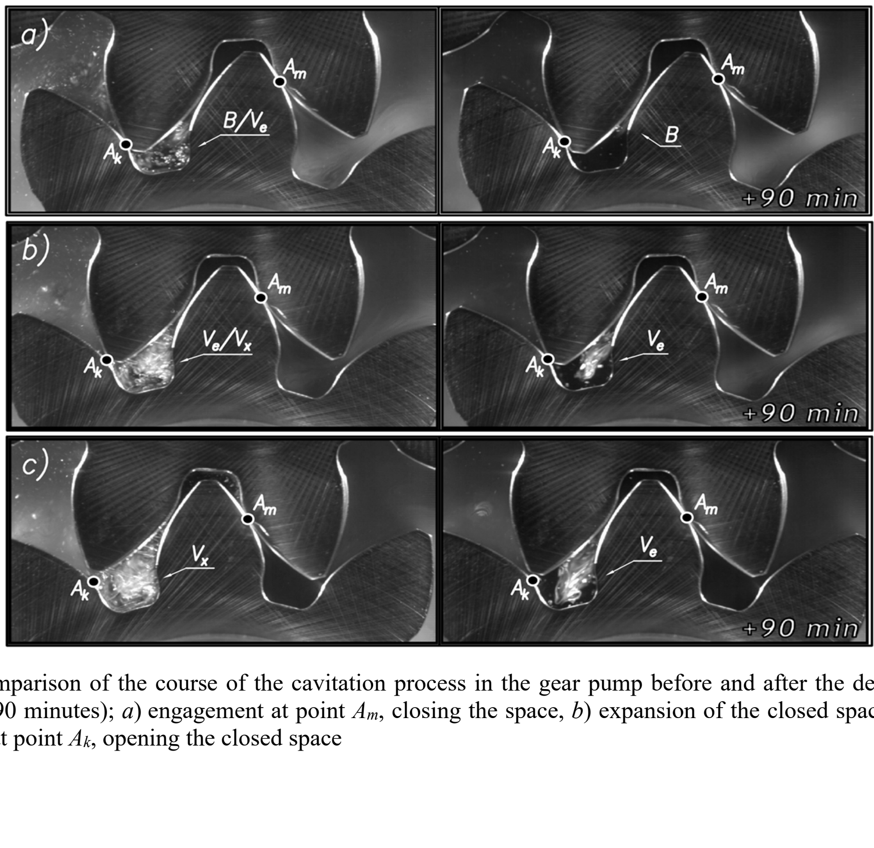

Fig. 7. Comparison of the course of the cavitation process in the gear pump before and after the degasification (duration: 90 minutes); *a*) engagement at point A_m, closing the space, *b*) expansion of the closed space, *c*) disengagement at point A_k, opening the closed space

phenomena of the hydrodynamic cavitation in a gear pump is achieved by design methods, through the application of relief grooves [14, 26].

Conclusions

The objectives of the work have been achieved. Based on [1, 2, 14, 24, 26], the course of the ultrasonic cavitation phenomena occurring in a hydraulic tank and the hydrodynamic cavitation in a gear pump have been described. The course of the phenomena was confirmed during experiments carried out with the use of a specially designed tank and pump. It was confirmed that the oscillator-cavitation system, designed and manufactured on the basis of [20, 22], is useful for inducing the phenomenon of ultrasonic cavitation. It was also confirmed that the PIV visualization method based on a special system of illuminating transparent objects and recording the flow through those objects by means of a fast camera are useful in the research on the cavitation phenomena [24, 26].

There was a visible interaction between the ultrasonic and the hydrodynamic cavitation. The induction of the ultrasonic cavitation in the tank results in the degassing of the oil, and the degassed oil supplying the pump reduces the hydrodynamic cavitation in its internal channels and clearances. This is an example of a beneficial effect of the ultrasonic cavitation on the operation of a hydraulic system.

In further research works, the aim should be to use the ultrasonic cavitation in a continuous manner during the operation of the hydraulic system and to design appropriate devices to induce this cavitation.

The presented work is an example of effective cooperation between the communities of Wroclaw University of Science and Technology and Igor Sikorsky Kyiv Politechnic Institute, National Technical University of Ukraine.

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Дослідження ультразвукових і гідродинамічних явищ при кавітації в гідравлічній системі

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Анотація. *У статті описано процеси ультразвукової кавітації в гідравлічному резервуарі та гідродинамічної кавітації у шестеренному насосі. Виникнення зазначених процесів підтверджено експериментальними дослідженнями при використанні резервуара і насоса з прозорої пластмаси. Доведено, що кавітаційна система, створена за оригінальним проектом, є корисною для генерування явища ультразвукової кавітації. Також показано, що метод PIV-візуалізації, який полягає в спеціальному освітленні прозорих об'єктів і записи структури потоку крізь ці об'єкти за допомогою швидкісної відеокамери, при вивченні явища кавітації досить ефективний. Візуально встановлено взаємодію ультразвуку та гідродинамічної кавітації. У свою чергу, виникнення ультразвукової кавітації в резервуарі викликає дегазацію масла, що подається в насос, яке зменшує гидродинамическую кавітацію у внутрішніх каналах і зазорах. Це свідчить про позитивний вплив ультразвукової кавітації на роботу насоса та гідравлічної системи в цілому. Представлена робота є прикладом ефективної співпраці між дослідниками Вроцлавського університету науки і технологій (Польська Республіка) і Національного технічного університету України “Київського політехнічного інституту імені Ігоря Сікорського”.*

Ключові слова: *ультразвукова кавітація; гідравлічний резервуар; гідродинамічна кавітація; шестерений насос; пластмаса; PIV-візуалізація.*

Исследование ультразвуковых и гидродинамических явлений при кавитации в гидравлической системе

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Аннотация. *В статье описываются процессы ультразвуковой кавитации в гидравлическом резервуаре и гидродинамической кавитации в шестеренном насосе. Возникновение указанных процессов подтверждено экспериментальными исследованиями при использовании резервуара и насоса из прозрачной пластмассы. Доказано, что кавитационная система, созданная по оригинальному проекту, полезна для генерирования явления ультразвуковой кавитации. Также показано, что метод PIV-визуализации, который заключается в специальном освещении прозрачных объектов и записи структуры потока через эти объекты с помощью скоростной видеокамеры, при изучении явления кавитации весьма эффективен. Визуально установлено взаимодействие ультразвука и гидродинамической кавитации. В свою очередь, возникновение ультразвуковой кавитации в резервуаре вызывает дегазацию масла, подаваемого в насос, которое уменьшает гидродинамическую кавитацию во внутренних каналах и зазорах. Это свидетельствует о положительном воздействии ультразвуковой кавитации на работу насоса и гидравлической системы в целом. Представленная работа является примером эффективного сотрудничества между исследователями Вроцлавского университета науки и технологий (Польская Республика) и Национального технического университета Украины “Киевского политехнического института имени Игоря Сикорского”.*

Ключевые слова: *ультразвуковая кавитация; гидравлический резервуар; гидродинамическая кавитация; шестерен насос; пластмасса; PIV-визуализация.*