International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:11, No:11, 2017

Analysis of Impact Load Induced by Ultrasonic Cavitation Bubble Collapse Using Thin Film Pressure Sensors

Moiz S. Vohra, Nagalingam Arun Prasanth, Wei L. Tan, S. H. Yeo

Abstract**—**The understanding of generation and collapse of acoustic cavitation bubbles are prerequisites for application of cavitation erosion. Microbubbles generated due to rapid fluctuation of pressure induced by propagation of ultrasonic wave lead to formation of high velocity microjets and or shock waves upon collapse. Due to vast application of ultrasonic, it is important to characterize and understand cavitation collapse pressure under the radiating surface at different conditions. A comparative investigation is carried out to determine impact load and dynamic pressure distribution exerted upon bubble collapse using thin film pressure sensors. Measurements were recorded at different input conditions such as amplitude, stand-off distance, insertion depth of the horn inside the liquid and pulse on-off time of acoustic vibrations. Impact force of 2.97 N is recorded at amplitude of 108 μm and stand-off distance of 1 mm from the sensor film, whereas impulsive force as low as 0.4 N is recorded at amplitude of 12 μm and stand-off distance of 5 mm from the sensor film. The results drawn from the investigation indicated that variety of impact loads can be achieved by controlling generation and collapse of bubbles, making it suitable to use for numerous application.

Keywords**—**Ultrasonic cavitation, bubble collapse, pressure mapping sensor, impact load.

I. Introduction

ULTRASONIC sonochemistry has drawn wide attention for its use for commercial application in many fields worldwide such as medical, manufacturing, food processing, water and waste treatment, etc. [1]. Hence, understanding generation and collapse of cavitation has become extremely important for its effective use. Acoustic cavitation is generated when the fluid is forced to oscillate at ultrasonic frequency induced by the horn. When the static pressure at any location in the fluid falls below its vapour pressure at operating temperature, vapour bubbles are formed [2]. These bubbles filled with vapour expand and may aggregate with adjacent bubbles to form large or cluster of cavitation bubbles in the fluid. The resulting vapour bubbles are transported by acoustic waves and subsequently collapse when the pressure in the direction of flow recovers above the vapour pressure [3].

The bubbles upon collapse generate highly localized temperature and pressure shock waves capable enough of removing material from the adjacent surface [2]. The effect of cavitation erosion or pitting causes detrimental effect on component life and results into its premature failure [4]. If the generation, expansion, and collapse of cavitation bubbles are controlled, it can be optimized for numerous applications especially in the field of medical and manufacturing.

Comprehensive understanding the effect of cavitation machining requires precise estimation of load generated by the collapse of vapour bubbles on the target surface. Various attempts have been made to quantify cavitation generation and impact load due to shock waves generated by the burst of vapour bubbles in the fluid, but it keeps one of the most challenging issues till date [1]. Several research attempts to investigate acoustic flow, bubble growth and collapse [5]-[7] have been made, but characterization of pressure forces induced by the bubble collapse still remains as an area less explored. Sreedhar et al. [8] developed a theoretical formulation of cavitation bubble collapse impact load measurement using piezoelectric crystals. Okada et al. [9] made use of pressure transducer which can measure the impact force due to bubble collapse and damaged simultaneously. Momma and Lichtarowicz [10] used film pressure sensor made piezoelectric polymer to measure collapse pressure in cavitating water jet apparatus. Singh et al. [11] employed use of high response pressure transducer protected using plexiglass from cavitation erosion and kept at a stand-off distance of 0.5 mm from the ultrasonic horn in order investigate pressure distribution due to cavitation bubble collapse under fluid. Other similar research includes numerical approach of modelling and computing impact forces from the pit geometrical characteristics [12]. Despite of developments in characterization of impact load from cavitation, it may not be accurately quantified because (i) of large sensing area compared to the micron size cavitation bubbles (ii) load is not uniformly distributed onto the sensing element (iii) limited resonant frequency of the sensors and data acquisition system as compared to the rate of bubble collapse and (iv) high rise time of the transducer which affect the measurements. Keeping in mind above stated limitations, an experimental setup was designed to characterize ultrasonic cavitation system using thin film pressure sensor.

II. Experiment Setup

A schematic diagram of experimental setup is shown in Fig. 1. High intensity ultrasound cavitation is produced using

Moiz S. Vohra and Wei L. Tan are with the Rolls-Royce@NTU Corporate Lab, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798 (corresponding author, e-mail: MOIZSV@ntu.edu.sg).

Nagalingam Arun Prasanth, and Yeo Swee Hock are with the School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798 (corresponding author, e-mail: MOIZSV@ntu.edu.sg).

QSonica Q700 sonicator at a frequency of 20 kHz and amplitudes ranging from 1 µm up to 120 µm by using ultrasonic horn with replaceable tip of diameter 12.8 mm. Thin film flexible pressure mapping sensor from Tekscan Inc. was used as the source for measuring impact force and pressure distribution. Tekscan thin film sensors made of dual film coated with piezo resistive ink and high scanning speed up to 20 kHz frequency DAQ system offered excellent measurement accuracies. Sensor 5051 and 5027 is used due to its high sensel density of 62.0 cm^2 and 248 cm^2 and wide operating pressure range of 48 kPa to 345 kPa, respectively. Sensing element was covered by 0.75 mm thick cloth tape (acetate, nylon and polyester woven and non-woven fabric with adhesive) to prevent from cavitation erosion or pitting. The sensors were kept at a minimum distance of 1 mm from the ultrasonic probe and varied until 5 mm under de-ionized water. Experimental test plan was formulated for which conditions are summarized in Table I.

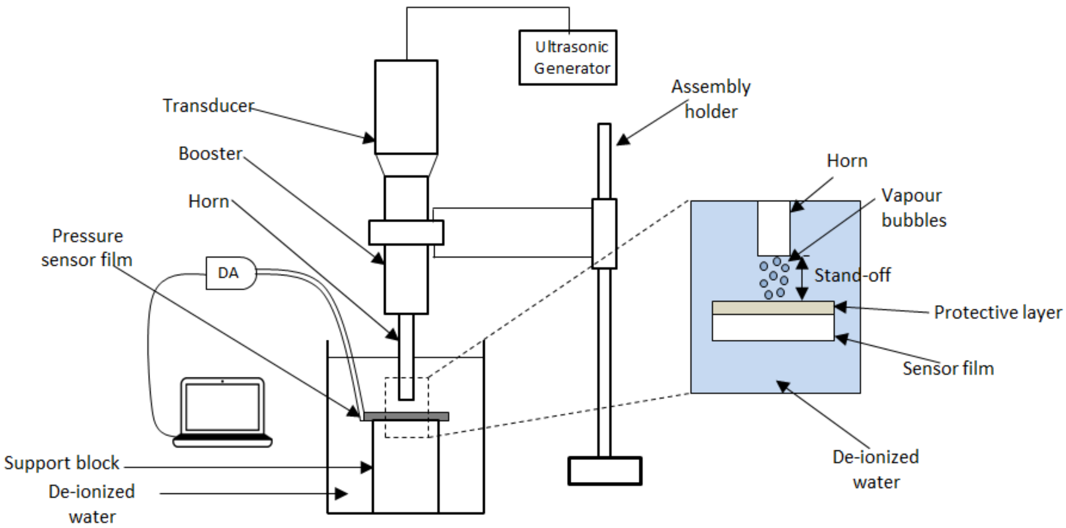

Fig. 1 Schematic diagram of experimental setup

TABLE I
EXPERIMENTAL CONDITION

Experimental Conditions	Parameter
Ultrasonic frequency (kHz)	20
Horn tip vibration amplitude (µm)	12, 60, 108
Liquid media	De-ionized water
Stand-off distance (mm)	1, 5
Pulse on-off time (sec)	2-2, 1-1, 4-0
Horn inside the liquid (mm)	18, 30
Temperature of media (°C)	25

III. CALIBRATION OF SENSOR

Tekscan sensors model 5051 and 5027 are calibrated using 10-point calibration method using system software under the operating conditions. Jansson et al. [13] concluded that calibrated pressure sensor provides diminishing output over time in controlled environment in that of humidified air and while submerged under water. Hence, sensors were calibrated using load cell under liquid to replicate the state of measurements. Sensors were loaded with load of 10 N to 90 N in steps of twenties such that 90% of the sensing area is covered. For all loading cycles and measurement trials, force was increased linearly over 10 s, held constant for 5 s and subsequently decreased linearly over 10 s. The sensors remained unloaded for 60 s between cycles. The calibration methodology was designed to minimise transient effect such as drift and hysteresis.

IV. RESULTS AND DISCUSSION

A. Effect of Ultrasonic Vibrating Amplitude

The cavitation bubble collapse intensity is greatly affected by the vibrating amplitude of ultrasonic horn. Fig. 2 shows pressure distribution map below the radiating surface a) at amplitude of 108 µm b) amplitude of 60 µm and c) amplitude of 12 µm at 20 kHz vibrating frequency. The horn was placed at the distance of 1 mm from the sensor film and pulse time of 2 s on/off, each was used to record the data.

The pressure distribution map reveals higher pressure exerted due to collapse of cavitation bubbles on or near the surface of the pressure film at amplitude of 108 µm compared to lower amplitudes of 60 µm and 12 µm. Vibrating amplitude can be directly related to the number of vapour bubbles generated and the intensity of collapse pressure. Due to smaller negative vibrating cycles, cavities grow to smaller size and are less intense upon collapse, whereas with larger negative cycles cavities grow in size, agglomerate with adjacent vapour cavities, and collapse with higher pressure when the pressure recovers above the vapour pressure at given temperature. This can also be observed from Fig. 3 which represents the localized impulsive force values (N) due to bubble collapse during two pulses of ultrasonic vibration of 2 s each.

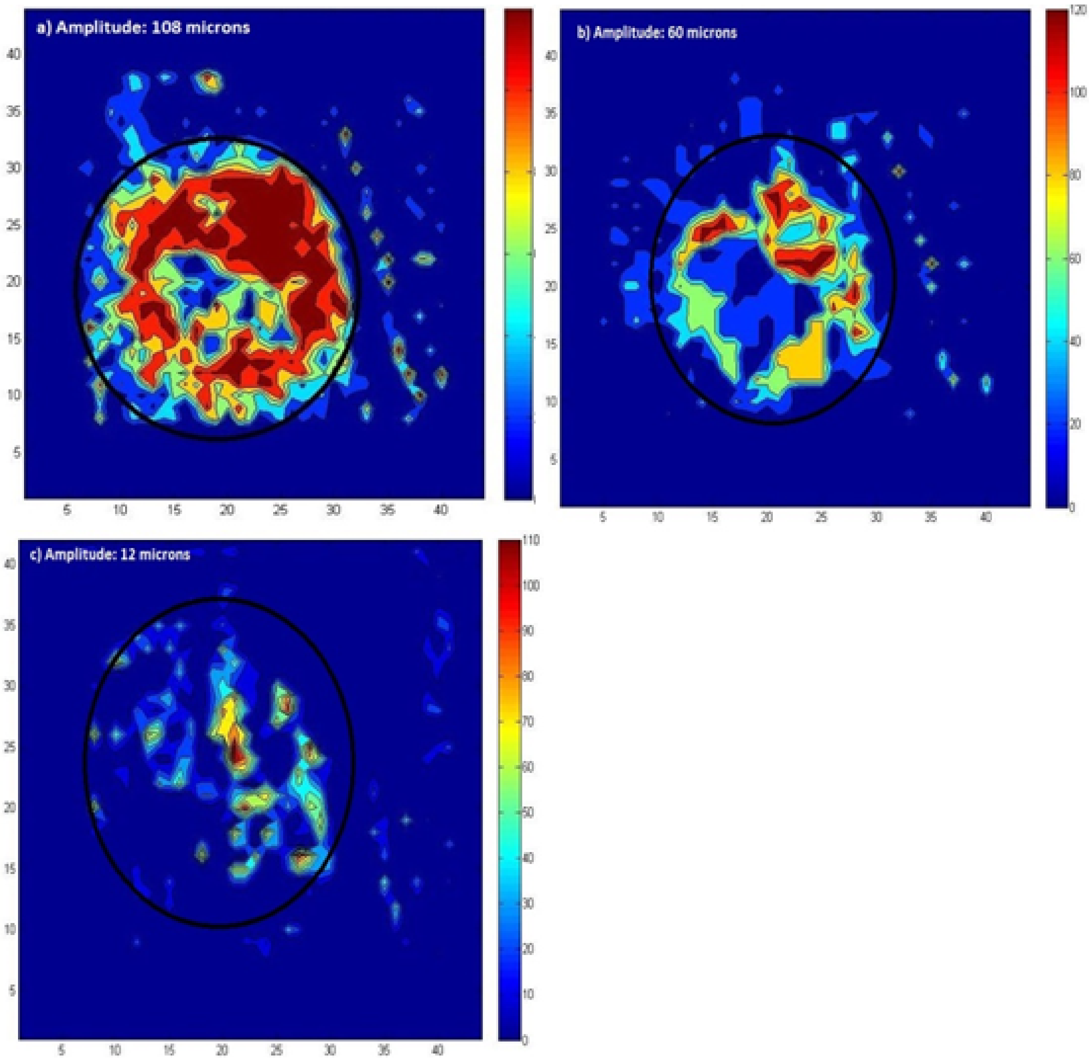

Fig. 2 Pressure distribution map (a) amplitude 108 µm (b) 60 µm and (c) 12 µm at stand-off distance of 1 mm from the sensor film

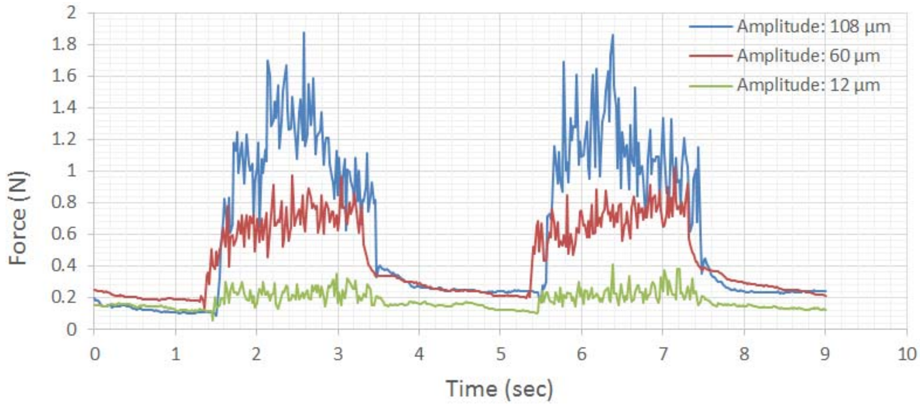

Fig. 3 Bubble burst force (N) at different vibrating amplitude at stand-off distance of 1 mm from the sensor film

At lower amplitude of 12 µm, impulsive force magnitude indicates that there are very few high energy bubble collapses near or on the surface of the pressure film. The observation helps to easily characterize ultrasonic system for various applications for cleaning objects such as optics and jewelry, biological cell disruption and many more. With the increase in amplitude, the intensity of bubble generation and collapse pressure increases, making it suitable to use for application such as surface erosion, metallic, and non-metallic surface treatment and decontamination.

B. Effect of Stand-Off Distance

Stand-off distance can be referred to as the distance between the ultrasonic horn and the sensor film. The cavitation bubbles generated are directed in the downward direction from the radiating surface and are carried in direction of the acoustic waves. Effect of bubble collapse pressure at different distance from the horn is important to understand the working distance in various applications. Fig. 4 below shows bubble collapse force (N) at stand-off distance of 1 mm, 3 mm, and 5 mm at an amplitude of 108 µm and frequency of 20 kHz and Fig. 5 shows peak pressure at three different amplitude range.

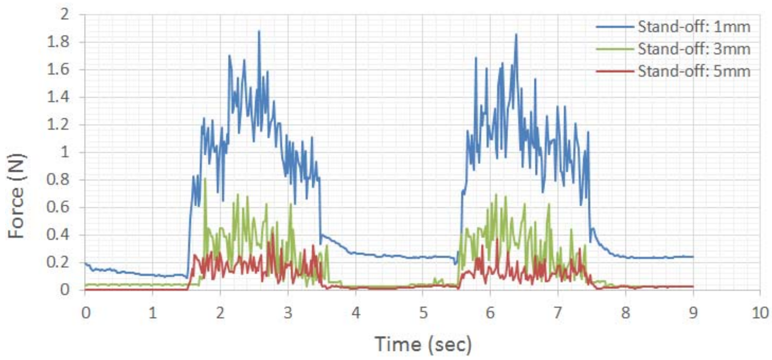

Fig. 4 Bubble collapse force (N) at different stand-off distance at 108 µm amplitude

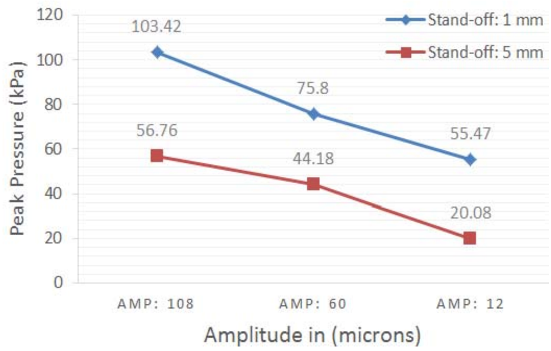

Fig. 5 Peak pressure (kPa) at different stand-off distance and amplitude

Both Figs. 4 and 5 represented higher pressure peaks and localized forces exerted by bubble collapse at closer proximity to the generating surface. Due to attenuation of acoustic waves with increase in distance from the generating source, cavities are not carried away to larger distance. The impact velocity of the bubbles also decreases which results in smaller pressure pulses and localized impulse force. Another explanation to this can be due to rise in static pressure inside the liquid, the cavities explodes when the surrounding pressure rises above vapour pressure which imparts lower pressure on the surface making it suitable to use for various application.

C. Effect of Horn Insertion Depth

Fig. 6 shows the effect of horn insertion depth inside the liquid media. The readings suggest that larger forces are recorded at horn depth of 18 mm (~1.5 x diameter of the horn) than at 30 mm (~2 x diameter of the horn).

Cavitation bubble growth is hugely dependent on the static fluid pressure. At larger static pressure, acoustic pressure amplitude has to be higher in order to induce negative pressure favorable for bubble growth. Hence, by inserting the horn more into the liquid media, bubble growth is more difficult to be facilitated.

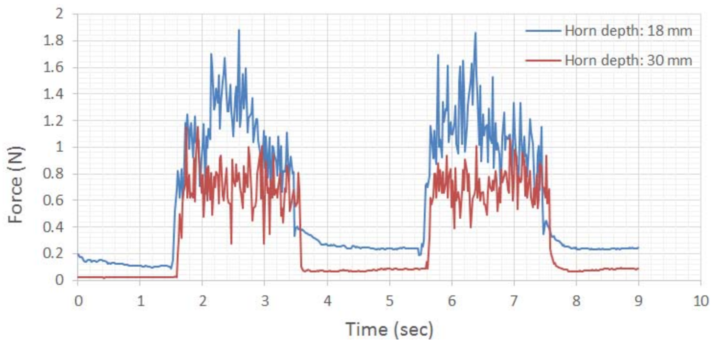

Fig. 6 Bubble collapse force (N) at different horn depth inside the liquid at 108 µm amplitude

D.Effect of Pulse Time

Fig. 7 shows the effect of ultrasonic pulse timing on bubble collapse force. Pulses of 2 seconds, 1 seconds each on/off and continuous pulse of 4 seconds are used to understand the effect of pulse timing on collapse pressure. The graph indicates that the bubble collapse forces for different pulse timing at similar vibrating amplitude and frequency are approximately the same, and there is no effect observed in forces peaks and pressure pulses. However, the pressure distribution map Fig. 8 reveals that cavitation bubble collapse is uniform throughout the surface of the horn for pulse time of 2 seconds, whereas as for pulses of 1-second and 4-second continuous pulse, peaks were recorded only at the center of the horn. During short and continuous pulses, due to violent agitation and turbulence in the liquid media, the cavities get dispersed and or collapsed before growing into size which are less intense upon burst.

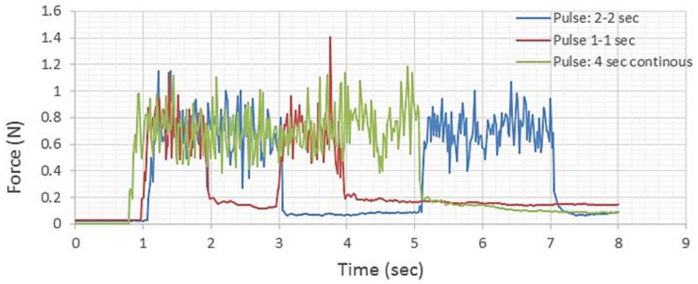

Fig. 7 Bubble collapse force (N) at different pulse on-off timing in seconds at 108μm amplitude

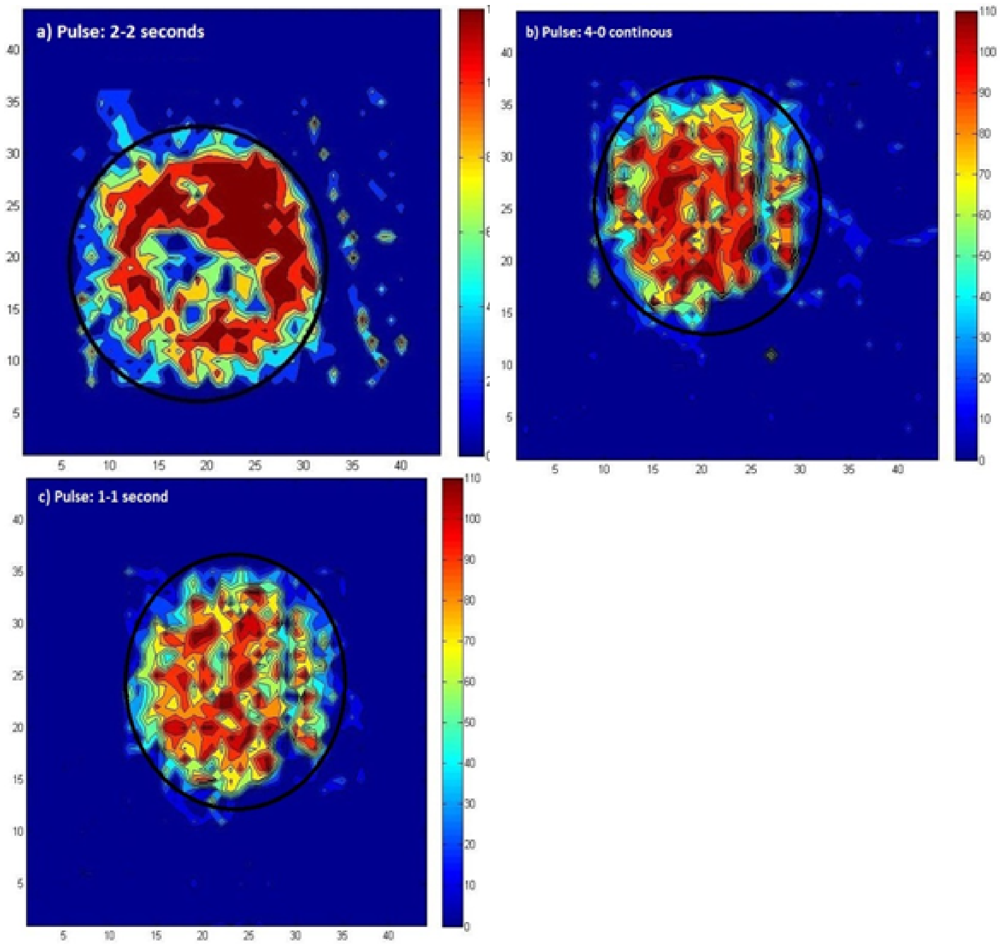

Fig. 8 Pressure distribution map (a) pulse on-off: 2-2 seconds (b) pulse on-off: 4-0 seconds and (c) pulse on-off: 1-1 seconds at stand-off distance of 1 mm from the sensor film

V. CONCLUSION

In this paper, analysis of impact load induced by cavitation bubbles generated by ultrasonic vibration on pressure sensor film was conducted. Effects of factors such vibrating amplitude, horn insertion depth, stand-off distance and pulse timing were investigated. The results show that:

- Ultrasonic amplitude is directly related to formation and collapse of cavitation bubbles. Higher vibrating amplitudes result in large amount of generation and intense collapse pressure.
- By increasing the stand-off distance keeping the insertion depth of the horn constant, the acoustic waves get attenuated with distance. Furthermore, due to increase in static pressure below the liquid surface the cavities burst when the surrounding pressure exceeds the vapour pressure of the liquid imparting lower pressure shocks.
- Similar observations are made by increasing the horn insertion depth below the surface of the liquid; facilitation of bubble growth is difficult due to high static pressure below the liquid surface.
- Ultrasonic pulse On-Off time has relatively shown no direct effect on the magnitude of the pressure distribution and peak impulsive forces. However, the temperature of the fluid rises rapidly during continuous ultrasonic pulse.

The work has highlighted great potential of ultra-sonication system by investigating various process parameters and comparing the magnitude of forces and pressure distribution below the horn surface. Thus, by understanding the process and its effects (cavity generation and collapse), it can be modelled for numerous industrial application.

ACKNOWLEDGMENTS

This work was conducted within the Rolls-Royce@NTU Corporate Lab with support from the National Research Foundation (NRF) Singapore under the Corp Lab@University Scheme.

REFERENCES

[1] Samir C.R, Jean-Perre Franc, Marc Fivel, ‘Cavitation erosion: Using target material as a pressure sensor’, J. of Applied Physics 118, 164905 (2015).
[2] Peter R.B, Douglas G.O, Christopher J.J, ‘Multiple observations of cavitation cluster dynamics close to an ultrasonic horn tip’, J. Acoust. Soc. Am. 130 (Nov 2011) Pg. 3379-3388.
[3] X. Ma, B. Huang, G. Wang, M. Zhang, ‘Experimental investigation of conical bubble structure and acoustic flow structure in ultrasonic field’, Ultrasonics Sonochemistry 34 (2017) 164-172.
[4] Leen V.W, ‘Mechanics of collapsing cavitation bubbles’, Ultrasonics Sonochemistry 29 (2016) 524-527.
[5] L. Bai, W. Xu, J. Deng, C. Li, D. Xu, Y. Gao, ‘Generation and control of acoustic cavitation structure’, Ultrasonics Sonochemistry 21 (2014) 1696-1706.
[6] Christian Vanhille, ‘A two-dimensional nonlinear model for the generation of stable cavitation bubbles’, Ultrasonics Sonochemistry 31 (2016) 631-636.
[7] C. Vanhill, C. Campos-Pozuelo, C. Granger, B. Dubus, ‘A numerical study of the formation of a conical cavitation bubble structure at low ultrasonic frequency’, Physics Procedia 70 (2015) 1070-1073.
[8] B. K. Sreedhar, S.K. Albert, A.B. Pandit, ‘Cavitation damage: Theory and measurement – Review’, Wear 372-373 (2017) 177-196.
[9] T. Okada, Y. Iwai, S. Hattori, N. Tanimura, Relation between impact load and damage produced by cavitation bubble collapse’, Wear 184 (1995) 231-239.
[10] T. Momma, A. Lichtarowicz, ‘A study of pressure erosion produced by collapsing cavitation’, Wear 186-187 (1995) 425-436.
[11] S. Singh, J. Choi, G. Chahine, ‘Characterization of cavitation fields from measured pressure signals of cavitating jets and ultrasonic horns’, J. Fluids Eng., Trans. ASME, vol. 135 (Sept 2013) 091302-1 to 091302-11.
[12] J. Choi, G. Chahine, ‘Relationship between material pitting and cavitation field impulsive pressures’, Wear 352-353 (2016) 42-53.
[13] K. S. Jansson, M.P. Michalski, S. D. Smith, R.F. LaPrade, C.A. Wijdicks, ‘Tekscan pressure sensor output changes in the presence of liquid exposure’, J. of Biomechanics 46 (2013) 612-614.