The Research on Dilute Polymer Solutions Cavitating Flow through Venturi and Cavitation Induced Vibration Acceleration Characteristics

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Abstract. The present work deals with an original study of vibration signals induced by unsteady cavitating flow of polymer solutions through a Venturi section. A blow-down Venturi experimental rig was utilized to generate cavitation in polymer solutions. The cavitating flows through the Venturi tunnel were captured by high-speed photography. The accelerometer was mounted on the upper wall of Venturi tunnel to gather the cavitation induced vibration accelerations. Results show that the morphologies of cavitation bubbles in polymer solutions are different from that of filtered water. Cavitation bubbles with bigger size and less number are observed in polymer solutions cavitating flow. It is observed that the peak value, kurtosis and the root-mean-square of vibration acceleration increase in polymer solutions. Meanwhile, a broader frequency band and a higher power spectral density level is observed in spectrogram of polymer solutions. It is inferred that the collapse of the vaporous cavity clouds with high void fraction developed in polymer solutions is responsible for this alteration.

1. Introduction

Cavitation occurs when the local fluid pressure drops to the saturated vapor pressure; this might occur on hydrofoils, rudders, propellers, and turbines during their high-speed and/or off-design operations, particularly near the air-water surface in the absence of high static pressure. The collapse of cavity induced vapor bubbles may produce strong structural vibrations, which would cause noise, accelerated fatigue, material damage, and even hydroelastic instability issues. Therefore, it is essential to detect cavitation to avoid the unexpected effects. Customarily, cavitation induced high amplitude vibration signals would be easily identified and could be applied to detect the cavitation development [1].

It is well-known that small amount of polymer additives in solution would evidently affect the cavitation inception and development. Polymer additives were found to suppress both the inception and the development of cavitation in Venturi flows [2], in underwater jet flows [1,2], flows through an orifice [1] and the flow around a cylinder [2]. Further, in polymer solutions cavitation damage [3,4]
and noise [1] are significantly influenced by the elastic properties of polymer solutions. However, the cavitation inhibited mechanisms are not well understood.

In this article, a synthetic analysis of cavitation visualization and cavitation induced vibration accelerations are conducted, the influence of polymer solutions with different molecular weight and concentrations on cavitation development and vibration acceleration of characteristics are investigated. Visualization of cavitating flow in Venturi tunnel was applied to observe cavitation effectively, the cavitation induced vibration characteristics were measured to investigate the influences of polymer additives on cavitating flow through Venturi tunnel.

2. Experimental Setup

Figure 1. Schematic of the blow-down cavitation experimental rig. (a) Diagrammatic sketch (1 Safety valve, 2 Temperature sensor, 3 Outlet of vacuum pump, 4 Inlet of forcing pump, 5 Regulating valve, 6 Upstream pressure tank, 7 Upstream ball check, 8 Venturi nozzle, 9 Downstream ball check, 10 Downstream pressure tank, 11 Draw off valve). (b) Test section.

2.1. The Venturi cavitating rig

The blow-down cavitation experimental rig consists of two 150-liter tanks, a transparent acrylic glass test section, connecting pipes, valves, measurement systems and a pressure regulation system. A convergent-divergent Venturi nozzle (divergent angle = 8°) was used for the test section, to generate cavitation. Two Leno T21S piezoresistive pressure sensors were installed on the two tanks and coupled to a ZTIC EM9118B dynamic signal acquisition device in order to measure and record the pressure. The uncertainty in the pressure measurements was ±1000Pa. Pressure signals were acquired at a sampling rate of 100 kHz for each channel. The degassing of the system was achieved by applying vacuum at the upstream tank for at least 8 hours. After degassing the liquid, the upstream tank was closed, the initial pressure was set at around 500 kPa. The downstream tank was connected to the atmospheric pressure. Then, the downstream ball valve was opened rapidly so that water was driven through the Venturi section by the pressure difference between the two tanks, and cavitation was generated at the throat and also further downstream. During the blow-down process, the air in the
upstream tank was reduced, while the pressure in downstream tank remain normal atmosphere. To visualize the complex unsteady cavitating flow, a high speed camera Phantom 7.11 was used to capture the cavitating flow. The exposure time was set as $2 \times 10^{-6}$ s, the sampling rate was 51010 fps. Image size of each figure was $1072 \times 800$ pixels. The LED light source with the power of 300 W was applied to illuminate the optical view. The pressure recovery number $\kappa$ is defined by

$$\kappa = \frac{p_1 - p_v}{p_1 - p_2}$$

Here $p_1$ and $p_2$ are chosen as the pressures in the upstream and the downstream tanks, respectively, $p_v$ is the vapour pressure of the liquid.

2.2. the vibration acceleration acquisition device

The vibration and pressure signal acquisition device were triggered shortly after the full opening of the downstream valve. Four accelerometers (B&K ULT2059) were mounted on the upper wall of the Venturi test section. The accelerometers have a flat frequency response from 0.1 Hz to 12 kHz, and a resonant frequency of 40 kHz. The mounted positions of the accelerometers and the measuring directions of them are shown in figure 2.

![Figure 2. The accelerometers mounted on the upper wall of Venturi tunnel.](image)

The time-domain features of the vibration acceleration signal were characterized by root-mean-square (RMS) and kurtosis. The RMS is defined as

$$RMS = \sqrt{\frac{\sum_{i=1}^{N} x_i^2}{N}}$$

The kurtosis of a signal is defined as

$$Kurt = \frac{E(x - \mu)^4}{\sigma^4}$$

where $\mu$ is the mean of $x$, $\sigma$ is the standard deviation of $x$, and $E(t)$ represents the expected value of the quantity $t$.

The power spectrum estimation (PSD) was used to analyze the frequency-domain features of vibration acceleration signals. The periodogram of PSD is the Fourier transform of the biased estimate of the autocorrelation sequence. For a signal, $x_n$, sampled at $f_s$ samples per unit time, the periodogram is defined as

$$P(f) = \frac{\Delta f}{N} \left| \sum_{n=0}^{N-1} x_n e^{-j2\pi fn} \right|^2, -\frac{1}{2} \Delta f < f < -\frac{1}{2} \Delta f$$
2.3. The properties of test fluids

The properties of polyethylene oxide (PEO) solution at various molecular weights and concentrations, as well as filtered water are listed in Table 1. The surface tension $\sigma$ was tested using a Dataphysics OCA20 surface-tension tester, with an uncertainty of 1%, and the shear viscosity $\eta_0$ was tested with an Antonpa MCR302 rheometer, with an uncertainty of 0.1%. The effective relaxation time $\lambda_{\text{eff}}$ was evaluated by

$$\lambda_{\text{eff}} = 0.463 \frac{[\eta] M_v \eta_s}{N_A k_B T} \left( \frac{c}{c^*} \right) \text{ for } 0.01 \leq c / c^* \leq 1 \quad (5)$$

where $[\eta]$ is the intrinsic viscosity of polymer, $\eta_s$ the solvent viscosity, $N_A$ Avogadro’s number, $k_B$ the Boltzmann constant, $T$ the temperature of solution, $c$ the polymer concentration, $c^*$ the critical overlap concentration, and $M_v$ the mass average molecular weight (roughly equivalent to viscosity average molecular weight $M_c$).

| Test fluid                  | $c$ (ppm) | $[\eta]$ (ml/g) | $c/c^*$ | $\eta_\text{s}$ (mPa.s) | $\eta_0$ (mPa.s) | $\sigma$ (mN/m) | $\lambda_{\text{eff}}$ (ms) |
|----------------------------|-----------|-----------------|---------|-------------------------|------------------|-----------------|-------------------------|
| PEO solution, $1 \times 10^6 M_c$ | 500       | $5.72 \times 10^2$ | 0.31    | 1                       | 1.21             | 62.3            | 0.88                    |
| PEO solution, $2 \times 10^6 M_c$ | 500       | $5.72 \times 10^2$ | 0.48    | 1                       | 1.41             | 60.9            | 4.12                    |
| PEO solution, $5 \times 10^6 M_c$ | 100       | $5.72 \times 10^2$ | 0.18    | 1                       | 1.45             | 60.7            | 5.11                    |
| PEO solution, $5 \times 10^6 M_c$ | 200       | $5.72 \times 10^2$ | 0.35    | 1                       | 1.61             | 61.2            | 7.85                    |
| PEO solution, $5 \times 10^6 M_c$ | 500       | $5.72 \times 10^2$ | 0.88    | 1                       | 4.96             | 60.8            | 14.31                   |
| Filtered water             | -         | -               | -       | -                       | -                | -               | -                       |

3. Results and Discussion

3.1. Venturi cavitating flow of filtered water and PEO solutions
The test fluids cavitation flow through a Venruti at $\kappa = 1.326$ are shown in figure 3. The main characteristics of the cavitation flow are as follows, in the upper half of the flow channel a downstream directed high-speed jet is created by detachment at the throat edge. Cavitation nuclei in the incoming flow turn supercritical at the throat when their tensile strength is exceeded, forming a sheet cavity. Cavitation bubbles move downstream very close to the lower boundary of the detached high-speed jet of liquid. The bubbles grow during convection, which reveals that actually they are exposed to tension. This cavitation bubbles collapse when they are exposed to a higher pressure of the downstream, making the downstream boundary of the cavitation region in the jet move upstream with a velocity oscillating. Thus, upstream propagating pressure pulses shift the length of the cloud in the jet. Below the boundary layer of liquid jet, a closed negative pressure region is formed, the pressure drops into tensile stress in the region. This negative pressure sets up a flow of liquid from downstream of the cavitation zone, moving upstream along the lower channel wall. This flow has been termed a ‘re-entrant jet’ in reported literatures. This adverse flow carries cavitation nuclei from the downstream region, and at their exposure to sufficient tensile stress they grow into the cavitation bubbles that form the attached cavity cloud below the jet. Cavitation clouds shed at uncertain positions, the cavity length

**Figure.** 3 Cavitating flow through Venruti section, $\kappa = 1.326$, (a) Filtered water, (b) 1 million M$_s$, 500 ppm PEO solution, (c) 2 million M$_s$, 500 ppm PEO solution, (d) 5 million M$_s$, 100 ppm PEO solution, (e) 5 million M$_s$, 200 ppm PEO solution, (f) 5 million M$_s$, 500 ppm PEO solution.
is reduced and later produces new cavities. The whole process repeats itself and characterized by the shedding frequency \( f_s \). The shedding mechanism are inconclusive, the re-entrant jet \([1]\), shock wave in bubbly mixture \([2]\) are thought responsible for the cavitation cloud shedding.

In filtered water Venturi cavitation flow, numerous cavitation bubbles with low void fraction appear in Venturi section. The cavitation flow of filtered water is quite stable, only small changes of cavity length and small cavity clusters detachment. These small clouds collapse further downstream and cause small oscillating pressures at the downstream end of the cavitation flow system. In filtered water Venturi flow, cavitation nuclei turn supercritical at the Blake threshold, the skin of the nuclei break at tensile stressing, surface tension and gas pressure are decisive for critical conditions. Such cavitation nuclei are of size up to the 10, maybe even 20 \( \mu \)m-range, they are still difficult to be observed after they turn supercritical.

In polymer solution cases, the principal features of the cavitation processes are almost as in filtered water, but the shape and size of the cavity clouds are very different. The number of cavitation bubbles formed decreases gradually with increase of molecular weight and concentration, vaporous cavity clouds with high void fraction are observed. The length \( L_{cav} \) of the cavity clouds attached to the throat of a Venturi nozzle oscillates cyclically by detachment of bubble clouds from the downstream end of the attached cavity cloud, each detachment being followed by growth of the remaining attached cavity cloud. The attached cavity cloud is more transparent than in filtered water, and PEO-bubble clouds have a much higher void fraction, and with elongated, twisted structures. The attached cavity breaks off close to the throat at regular intervals, but rapidly it grows to full length again. Thus, the cloud length oscillates strongly, and the detached clouds are built from large bubbles that develop tempestuously.

It is inferred that long-chain molecules with adsorbed water molecules are in solution in the water, expectedly they dominate the surface of gas bubble nuclei as well as their liquid neighbourhood, forming an interfacial zone of appreciable coherence and elasticity that is decisive for the tensile strength of the nuclei and for their growth. The bubble growth processes are retarded by the masses involved, and even after a bubble has grown supercritical, an intact polymer skin may maintain bubble stability. Meanwhile, according to the figures above, cavitation is severely suppressed in 5 million \( M_v \), 500 ppm PEO solution. It is generally believed that the high viscosity of polymer solution has a stabilized effect on the flow field, this restrain momentum transfer from the jet to the below liquid region, tensile stress is reduced, and the cavitation development is therefore suppressed.

3.2. The time-domain characteristics of vibration signal

In this section, the time-domain characteristics of vibration acceleration signals are studied. The signals from No. 3 accelerometer were chose for research since it is the nearest accelerometer from the throat of the Venturi and the acceleration value are the highest of the four. The time series of cavitation induced vibration signals of filtered water and different PEO solutions at \( x =1.355 \) are shown in figure 4. It is observed that the peak acceleration induced by 5 kinds of PEO solutions cavitating flow through Venturi are higher than that of filtered water. Specifically, the peak acceleration of 2 million \( M_v \), 500 ppm PEO solution case is higher than that of 1 million \( M_v \), 500 ppm PEO. Similarly, the peak acceleration of 5 million \( M_v \), 200 ppm PEO solution case are higher than that of 5 million \( M_v \), 100 ppm PEO solution. However, the peak acceleration sharply decreases
in 5 million $M_v$, 500 ppm PEO solution case. It is inferred that the collapse of the vaporous cavity clouds with high void fraction would emit stronger shock waves, undoubtedly, this will cause more drastic impact on the wall of Venturi, consequently, the peak acceleration increases. As for 5 million $M_v$, 500 ppm PEO solution case, the cavitation development is severely suppressed, high void fraction vaporous cavity clouds cloud not be developed anymore. Also, the number of bubbles reduced sharply, therefore, the peak acceleration reduced.
Figure 4. The time serious of cavitation induced vibration signals of different, $\kappa = 1.355$. (a) Filtered water, (b) 1 million $M_v$, 500 ppm PEO solution, (c) 2 million $M_v$, 500 ppm PEO solution, (d) 5 million $M_v$, 100 ppm PEO solution, (e) 5 million $M_v$, 200 ppm PEO solution, (f) 5 million $M_v$, 500 ppm PEO solution.

Figure 5. The scatter diagram of RMS vary with $\kappa$.

Figure 6. The scatter diagram of $Ku$ vary with $\kappa$.

The scatter diagram of RMS vary with $\kappa$ of the 6 test fluids were shown in figure 5. It is observed that the RMS of PEO solutions are higher than that of filtered water at different $\kappa$ value, except for the 5 million $M_v$, 500 ppm PEO solution whose RMS are lower than filtered water at $\kappa$ larger than 1.35, this results from the cavitation are suppressed severely at high $\kappa$ conditions. The relation curves also show that the RMS of 2 million $M_v$, 500 ppm PEO solution are larger than that of 1 million $M_v$, 500 ppm PEO solution at $\kappa$ less than 1.48, however, the variation trend reverse at larger $\kappa$. Apparently, more vaporous cavity clouds with high void fraction are observed in 2 million $M_v$, 500 ppm PEO solution than 1 million $M_v$, 500 ppm PEO solution according to figure 4, as a result, the RMS of former are higher than the latter. However, at high $\kappa$ conditions, the cavitation developments are more difficulty in PEO solutions with higher $M_v$, therefore, variation trend reverse. The RMS of 5 million $M_v$, 100 ppm PEO solution are higher than that of 5 million $M_v$, 200 ppm PEO solution at $\kappa$ larger than 1.32, and the differences are small at low $\kappa$. Apparently, the cavitation are
suppressed at higher concentration solutions. The number of cavitation bubbles reduced, causing the reduction of RMS. The scatter diagram of Ku vary with \( \kappa \) is shown in Fig 6. Ku is a statistical measure that is used to describe the distribution. Distributions with large kurtosis exhibit data exceeding the normal distribution. The Ku of filtered water at different \( \kappa \) is the smallest of the 6 test fluids, the Ku of 1 million \( M_v \), 200 ppm PEO solution are slightly higher that of filtered water. However, the Ku of the rest PEO solutions are even high and the variation trend are complicated at different \( \kappa \). It is clear that the high acceleration induced by collapse of vaporous cavity clouds with high void fraction are responsible for the high Ku.

3.3. The frequency-domain characteristics of acceleration signal.

In this section, the frequency-domain characteristics of acceleration signals are studied. the PSD spectrogram of 6 test fluids at \( \kappa = 1.32 \) is shown in figure7. In filtered water case, the dominant frequency of PSD is approximately 6.3 kHz. However, other than a dominant frequency of 6.1 kHz, a higher frequency component of 7.9 kHz emerges in PSD spectrogram of 1 million \( M_v \), 500 ppm PEO solution, nevertheless, the level of PSD reduced slightly. As increases of molecular weight, the dominant frequencies of 6.7 kHz and 7.9 kHz appear in spectrogram of 2 million \( M_v \), 500 ppm PEO solution, the frequency band seems expand since both low frequency and high frequency components could be distinguished from the spectrogram. In addition, the PSD level increase significantly. As for 5 million \( M_v \), 100 ppm and 200 ppm PEO solutions, the dominant frequencies of them are both 5.5 kHz, 6.9 kHz, 8.2 kHz or so, however, the PSD level of 200 ppm PEO solution is higher than that of 100 ppm PEO solution. In comparison, as for the 5 million \( M_v \), 500 ppm PEO solution, the dominated frequencies are 6.3 kHz and 7.5 kHz, the frequency band shrink and the PSD level reduce. It follows that the collapse of the vaporous cavity clouds with high void fraction developed in polymer solutions are the reason for the broader frequency band and higher PSD level. However, this influences are not obvious at 1 million \( M_v \), 500 ppm PEO solution and 5 million \( M_v \), 500 ppm PEO solution, since the development of vaporous cavity clouds with high void fraction is difficulty in this two solutions.
Figure 7. The PSD of acceleration signal of test fluids. (a) Filtered water, (b) 1 million $M_v$, 500 ppm PEO solution, (c) 2 million $M_v$, 500 ppm PEO solution, (d) 5 million $M_v$, 100 ppm PEO solution, (e) 5 million $M_v$, 200 ppm PEO solution, (f) 5 million $M_v$, 500 ppm PEO solution.

4. Conclusions

In this paper, cavitating flow of filtered water and polymer solutions through a Venturi tunnel were captured by using high speed camera. Cavitation induced vibration acceleration signals were gathered to investigate the influences of molecular weight and concentration of polymer solution on cavitation development and vibration acceleration characteristics. The main conclusions are as follows.

(1) The main characteristics of the cavitating flow through a Venturi tunnel are described. The morphologies of cavitation bubbles in polymer solutions are different from that of filtered water. The attached cavity cloud is more transparent than in filtered water, and PEO-bubble clouds have a much higher void fraction, and with elongated, twisted structures. The attached cavity breaks off close to the throat at regular intervals, but rapidly it grows to full length again.

(2) The peak acceleration induced by 5 kinds of PEO solutions cavitating flow through Venturi are higher than that of filtered water. Specifically, the peak acceleration of 2 million $M_v$, 500 ppm PEO solution case is higher than that of 1 million $M_v$, 500 ppm PEO. The peak acceleration of 5 million $M_v$, 200 ppm PEO solution case are higher than that of 5 million $M_v$, 100 ppm PEO solution. However, the peak acceleration sharply decreases in 5 million $M_v$, 500 ppm PEO solution case.

(3) The RMS of PEO solutions are higher than that of filtered water at different $\kappa$ value, except for
the 5 million $M_v$, 500 ppm PEO solution whose RMS are lower than filtered water at $\kappa$ larger than 1.35. The RMS of 2 million $M_v$, 500 ppm PEO solution are larger than that of 1 million $M_v$, 500 ppm PEO solution at $\kappa$ less than 1.48. The RMS of 5 million $M_v$, 100 ppm PEO solution are higher than that of 5 million $M_v$, 200 ppm PEO solution at $\kappa$ larger than 1.32.

(4) The $Ku$ of filtered water at different $\kappa$ is the smallest of the 6 test fluids. The $Ku$ of 1 million $M_v$, 200 ppm PEO solution are slightly higher that of filtered water. However, the $Ku$ of the rest PEO solutions are even high and the variation trend are complicated at different $\kappa$.

(5) A broader frequency band and a higher power spectral density level is observed in spectrogram of polymer solutions. The collapse of the vaporous cavity clouds with high void fraction developed in polymer solutions are responsible for the alteration.

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