Analysis of particular experimental measurements in cavitating stream flow

G. Ciaravino
Department of Hydraulic and Environmental Engineering “G. Ippolito”, University of Naples Federico II, Italy

Abstract

In the present paper an analysis is conducted on the application of the acoustic method and the Laser-Doppler Anemometer (LDA) to measurements of turbulence in cavitating stream flow in a short pipe. When developed cavitation is detected in experiments conducted using the acoustic method, we find structures comprising vortices (travelling cavitation) and structures comprising large cavities (fixed cavitation) which form periodically and are transported by the stream flow. Under different operating conditions, the LDA measured the longitudinal component of velocity agitation and the corresponding power spectral density. This made it possible to detect the presence of quasi-periodic components in the turbulence structure with frequencies coinciding with those of the vortices and the cavities, under the corresponding operating conditions. This points to a reciprocal validation of the two measurement methodologies (acoustic and laser) and the influence of cavitation phenomena on the turbulent structure and on the flow characteristics.

Keywords: cavitating flow, experimental measurements of turbulence, Laser-Doppler Anemometer, acoustic method.

1 Introduction

Experimental analysis of cavitation phenomena has received increasing development over recent decades thanks to particular measurement techniques and to advanced instrumentation. The measurement of these phenomena is particularly complicated as cavitation generally takes place in an enclosed environment and so any instrumentation that is inserted into the stream flow will cause a considerable disturbance. Moreover, it is well known that the interest in
practical applications regarding cavitation (which can cause corrosion of the structure in which it arises and, in the case of hydraulic machinery, a remarkable fall in performance) has led researchers to analyse the phenomenon with particular attention.

Basically there are two problems of main concern:
- the theoretical and practical definition of a coefficient of incipient cavitation that characterises the cavitation phenomenon from its very onset (in order to avoid the above mentioned deleterious effects of cavitation);
- the influence of cavitation phenomena on the turbulence structure and, therefore, on the stream’s transport capacity.

In the Department of Hydraulic and Environmental Engineering of the University of Naples, ongoing research has long been addressing these issues [1, 2, 3] by applying advanced measurement techniques based on the so-called acoustic method and using Laser-Doppler Anemometer (LDA).

In the present paper, previously conducted acoustic experiments and experimental measurements taken using an LDA are used to analyse particular characteristics of turbulence in a stream flowing through a short pipe.

2 Considerations on the acoustic method and on LDA

The acoustic method and the LDA form the basis for experimental techniques with characteristics that are particularly suitable for analysis of the cavitation phenomenon, as neither technique requires the introduction of probes into the stream and consequently the phenomenon’s hydrodynamic field is not affected or modified (not even locally). In particular, the acoustic method is based on the analysis of noise that accompanies the onset of cavitation: numerous studies [4, 5, 6] have shown that noise is strictly related to the dynamic evolution of cavitation bubbles and so any modification in the bubbles affects the noise characteristics. In actual fact, cavitation causes profound changes in the structure of the acoustic signal: the experimental measurements indicate the presence of particularly sharp rises in the high frequency field of the curve of the power spectral density of sound signal. Acoustic instrumentation is easy to use and does not require complicated preliminary calibration prior to use. The acoustic measurements taken in Naples, for instance, were carried out using a sound level meter with an overall pass band of 22.5 kHz sending the signal to a 1/3 octave real time spectrum analyser which in turn supplied the power spectral density curve for the different frequencies investigated. The acoustic measurements may be disturbed to a certain degree by the presence of parasite noise which has nothing to do with the cavitation phenomenon, such as noise emitted by the stream flow and noise from the surrounding environment. This drawback may however be overcome [3] by identifying the curve for the so-called background noise (i.e. in absence of cavitation) and the intensity is then referred at the same frequency of the noise emitted in the particular condition under examination to that of the background noise. It should also be noted that the acoustic method displays a sensitivity that other methods do not possess: it has been shown [3] that the rises in the curve of power spectral density are detected even before the
first cavitation bubbles become visible. This property seems to be decisive in the evaluation of a coefficient of incipient cavitation that can enable the identification (so important for technical purposes) of the actual onset of the cavitation phenomenon.

The working of LDA, which makes it possible to evaluate the instantaneous velocity in a stream flow is based on the Doppler signal emitted by the intersection of two coherent, monochromatic and isofrequential beams of light in the measuring point. In this intersection a series of interference fringes are formed, alternately bright and dark, parallel to the bisector of the angle formed by the two converging beams. In the measurement point, which has a size in the order of one mm$^8$, the distance $d$ between two successive light fringes is a function of the wavelength $\lambda$ of the light emitted by the laser and the angle of incidence $\theta$ of the two beams according to the expression:

$$d = \frac{\lambda}{2 \cdot \sin(\theta/2)}$$

(1)

and is therefore known once the nature of the light from the laser and the angle of convergence of the two light beams are determined.

The measurement of velocity is dependent on the presence in the stream (the so-called insemination problem) of a sufficient number of particles of a size comparable with the distance between the interference fringes which, in passing through these fringes at a velocity substantially coincident to that of the fluid, are alternately illuminated and obscured. In this way, each particle reflects a light of frequency $f_d$ given by the relation between the component of velocity $u$ and the distance $d$ and thus:

$$f_d = \frac{u}{d} = \frac{u \cdot 2 \cdot \sin(\theta/2)}{\lambda}$$

(2)

The light emitted by the particles is collected, transformed into an electric signal and amplified by an optical photo-multiplier which emits an alternating electrical voltage with a frequency $f_d$. This voltage is sent to an instrument (tracker) which transforms the signal whose frequency is $f_d$, which is variable in time and has a constant amplitude, into an electrical voltage of amplitude proportional to the frequency $f_d$. The tracker produces an electric signal of amplitude $A$ equal to:

$$A = k \cdot f_d = \frac{k \cdot u \cdot 2 \cdot \sin(\theta/2)}{\lambda}$$

(3)

and hence directly proportional to the component of normal velocity at the lay of the interference fringes by means of a coefficient of proportionality $k$ completely defined by the characteristic data of the instrument. Formula (3) thus shows that the use of this measurement instrumentation does not need any laborious prior calibration. The use of the LDA is therefore sufficiently simple and
straightforward but it requires transparent walls and fluids. One complication in its use lies in the possible interruption of signal measurement (the so-called drop-out problem) depending on the number and size of the particles crossing the interference fringes in the measurement point. This problem will be discussed later. Finally, it is interesting to note that the LDA is essentially a laboratory measurement tool, whereas the acoustic measurement equipment (as it is non intrusive, easily transportable and does not require complicated prior calibration) lends itself to measurements on operating systems comprising hydraulic machinery which need to be checked for the absence of cavitation during operating conditions [7].

3 Analysis of the experimental measurements

The experimental measurements analysed were performed on a transparent perspex pipe open to the atmosphere, of length $L=2.00$ m and diameter $D=0.062$ m (hence with an $L/D$ ratio of 32.3) connected to the high-pressure supply circuit of the Experimental Hydraulics Laboratory at the University of Naples. The investigation conducted with the acoustic method was compared with the results of other previous research [1,2], which made it possible to point out, in the working of the short pipe, the presence of five different hydrodynamic conditions. These conditions are characterised by cavitation coefficient values $\sigma$, relative to the contracta cross section of flow conventionally set at $0.5 \, D$ from the pipe inlet, defined by the expression:

$$\sigma = \frac{p - p_v}{0.5 \cdot \rho \cdot V^2}$$

where $p$ is the pressure in the contracta cross section defined above and in which $p_v$, $V$ and $\rho$ are respectively the vapour tension, velocity and density of the fluid.

As the head and flow rate increase, and hence as $\sigma$ decreases, five operating fields are progressively determined. In the first field there is full pipe outflow with no cavitation. The second field has full pipe outflow with travelling cavitation located in the inflow. In the third field the acoustic method makes it possible to detect, again in a regimen of travelling cavitation, the presence of vortices, undetectable in the second field, which form and are transported downstream by the flow with a periodicity of the phenomenon in the order of $100 \div 200$ Hz decreasing as the head increases. In the fourth field, again the acoustic method makes it possible to detect the presence of cavities in conditions of fixed cavitation which likewise form and are transported downstream by the flow with lower frequency periodicities than those measured for vortices, i.e. $50 \div 100$ Hz, these likewise decreasing as the head increases. In the fifth field, the stream becomes detached from the pipe walls for a long section and takes on an appearance similar to that of a free jet and after reattaching itself not much before the outlet of the pipe and giving rise once again to travelling cavitation in the final pipe section. In particular, for each condition characterised by a certain value of the cavitation coefficient $\sigma$, the acoustic investigation was carried out by recording the noise accompanying the phenomenon and performing a
subsequent statistical analysis. For most of the above conditions, the acoustic signal pointed out a fundamentally irregular pattern, overlapped by brief and marked accentuations of the signal, presenting a quasi-periodicity in the field of low frequencies. A comparison with other Authors [4, 6, 8] made it possible to infer the presence of quasi-periodic phenomena due to the detachment of vortices in a regimen of travelling cavitation (characterised by the presence of a swarm of tiny bubbles in a transitory regimen of expansion, contraction and eventual collapse) and, for lower values of the cavitation coefficient, the formation and collapse of large cavities in a fixed cavitation regimen (characterised by the detachment of the liquid from the solid geometric boundaries creating a pocket bounded by the boundaries themselves, on the one hand, and by the liquid in a regimen of travelling cavitation, on the other). These two conditions are separated by an interval of cavitation coefficient $\sigma$ values in which we find the alternating presence of detaching vortices or the formation and detachment of cavities. The frequency $f$ with which these phenomena are repeated is a function of $\sigma$ as can be seen in figure 1, which reports the frequencies (circles) then measured on the experimental pipe [1]. In this diagram there are two branches referring to the two operating conditions (vortices, the upper branch, cavities the lower branch) each of which increases with $\sigma$.

![Figure 1: Cavitation phenomena frequency.](image)

The diagram again shows that the passage between the two conditions takes place in a discontinuous and overlapping way that results in a hysteresis effect depending on whether the $\sigma$ values are increasing or decreasing. The periodic phenomena described, as pointed out by Ciaravino and Pulci Doria [9], affect the hydrodynamic quantities characterising the turbulent condition of the flow downstream from the cavitating area. Analysis of the experimental measurements obtained on the basis of the particular characteristics offered by
the laser equipment have confirmed the interrelation between cavitation and turbulent agitation. The results of the analysed laser tests are reported in table 1 which shows the flow rate $Q$ (measured using a calibrated orifice meter situated in the laboratory supply circuit), the water column relative pressure $p_{0.5D}$ in the contracta cross section flow conventionally located at $0.5D$ from the inlet (measured using a mercury manometer), the cavitation coefficient $\sigma$ and, finally, the frequency $f$ of the phenomenon.

Table 1: Experimental tests.

<table>
<thead>
<tr>
<th>n. Test</th>
<th>$Q$ (mc/s)</th>
<th>$p_{0.5D}$ (m)</th>
<th>$\sigma$</th>
<th>$f$ (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0340</td>
<td>- 5.18</td>
<td>0.745</td>
<td>----</td>
</tr>
<tr>
<td>2</td>
<td>0.0366</td>
<td>- 6.47</td>
<td>0.471</td>
<td>171</td>
</tr>
<tr>
<td>3</td>
<td>0.0370</td>
<td>- 6.50</td>
<td>0.457</td>
<td>160</td>
</tr>
<tr>
<td>4</td>
<td>0.0372</td>
<td>- 6.60</td>
<td>0.439</td>
<td>154</td>
</tr>
<tr>
<td>5</td>
<td>0.0373</td>
<td>- 6.66</td>
<td>0.429</td>
<td>155</td>
</tr>
<tr>
<td>6</td>
<td>0.0375</td>
<td>- 6.70</td>
<td>0.419</td>
<td>128</td>
</tr>
<tr>
<td>7</td>
<td>0.0383</td>
<td>- 7.23</td>
<td>0.337</td>
<td>119</td>
</tr>
<tr>
<td>8</td>
<td>0.0391</td>
<td>- 7.63</td>
<td>0.277</td>
<td>109</td>
</tr>
<tr>
<td>9</td>
<td>0.0398</td>
<td>- 7.93</td>
<td>0.234</td>
<td>105</td>
</tr>
<tr>
<td>10</td>
<td>0.0408</td>
<td>- 8.24</td>
<td>0.189</td>
<td>75</td>
</tr>
<tr>
<td>11</td>
<td>0.0412</td>
<td>- 8.45</td>
<td>0.164</td>
<td>74</td>
</tr>
<tr>
<td>12</td>
<td>0.0422</td>
<td>- 9.23</td>
<td>0.077</td>
<td>56</td>
</tr>
</tbody>
</table>

The tests reported in table 1 cover almost the entire range of possible operating conditions in the presence of the described quasi-periodic phenomena. In actual fact, test 1 refers to conditions with no vortices or cavities, tests 2 to 9 refer to conditions with the presence of vortices, test 10 refers to conditions with the simultaneous alternating presence of vortices and cavities and, finally, tests 11 and 12 refer to conditions with the presence of cavities.

For each of these tests figure 2 reports the power spectral densities of the longitudinal component of axial velocity agitation in the cross section at a distance of $4D$ from the inlet (cross section immediately downstream from the cavitating area in which the effect of the periodic phenomena of cavitation on the characteristics of turbulence is considerable). In this figure the abscissa reports the frequency $f$ in Hz and the ordinate shows the square root of the power density of velocity $\upsilon'$ expressed in $10^{-3}$ m/s. The power spectral density was derived using a narrow band analyser (1%) with central frequency variable with continuity and constant with integration of 300 seconds.

The spectral density curves clearly show the presence of peaks of considerable entity representing quasi-periodic phenomena in the turbulence structure. The frequencies $f$ at which peaks are recorded in the different operating conditions are reported in the last column of the table.
Figure 2: Power spectral density of velocity $[u' \ (10^{-3} \text{ m/s}) ; f \ (\text{Hz})]$. 
Figure 1 reports, overlapped, the points relative to the cavitation measurements made using the acoustic method and those for the measurements of turbulence made with the LDA (the latter are indicated with a triangle). This figure clearly shows the coincidence of the results of cavitation measurements and the results of turbulence measurements. This coincidence confirms the hypothesis that the periodic phenomena of turbulence are a direct consequence of the periodic phenomena present in the cavitating stream.

With reference to the reported diagrams, an observation needs to be made regarding test 10 in particular. This test refers to conditions of vortices and cavities simultaneously present and, unlike when the acoustic method is used, the power spectral density of the agitation velocity presents a single peak, namely the one for the formation of cavities.

Therefore, the experimental analysis highlights that, at least for turbulent agitation, the formation of cavities is the dominant event.

In the case examined, it is worthwhile making some considerations on the above mentioned problems of flow insemination and drop-out which are, to a certain extent related to one another.

As mentioned in the previous paragraph, the measurement of velocity is related to the presence of a sufficient number of particles whose size is comparable with the distance of the interference fringes produced by the intersection of beams emitted by the laser. The presence of a sufficient number of these particles generally occurs for water streams, especially for closed circuit supply systems such as those typically found in research laboratories.

On the other hand, the presence of large obstacles, such as large impurities or solid particles, impede reflection of the Doppler signal and hence temporarily block system response causing drop-out.

In actual fact this phenomenon is also caused by the presence of the cavitation bubbles themselves or the presence of cavities.

The phenomenon of drop-out, while negatively affecting the response of the measurement made by the equipment, has nevertheless confirmed the diversity of hydrodynamic structures caused by cavitation in the third (vortices) and fourth (cavities) field of operation. In particular the presence of cavities in the stream flow results in a drop-out greater than the presence of vortices, even if the phenomenon has a lower frequency.

It would therefore appear worthwhile fitting the equipment with more efficient drop-out measurers (more accurate than those currently in use) so as to assess the actual percentage of drop-out in the measurement. This assessment will enable a suitable correction of the measurements of mean quantities and of the effective values. Moreover a better definition of the phenomenon of cavities would help clarify the hydrodynamic operation of the short pipe in their presence.

Ciaravino and Pulci Doria have pointed out [9] that the presence of cavities in the stream flow causes an increase in the coefficient of discharge $\mu$ in the pipe. This increase was justified by considering that the formation of cavities partially eliminates a flow zone markedly characterised by dissipating elements and
would therefore reduce dissipation and consequently bring about an increase in the coefficient of discharge $\mu$.

The increase in the coefficient $\mu$ corresponding to the formation of cavities was also verified in the experimental measurements reported in table 2.

Table 2: Experimental coefficient of discharge $\mu$.

<table>
<thead>
<tr>
<th>n. Test–Field</th>
<th>$Q$ (mc/s)</th>
<th>$h$ (m)</th>
<th>$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – II</td>
<td>0.0340</td>
<td>12.12</td>
<td>0.730</td>
</tr>
<tr>
<td>2 – III</td>
<td>0.0366</td>
<td>14.35</td>
<td>0.722</td>
</tr>
<tr>
<td>3 – III</td>
<td>0.0370</td>
<td>14.47</td>
<td>0.727</td>
</tr>
<tr>
<td>4 – III</td>
<td>0.0372</td>
<td>14.65</td>
<td>0.727</td>
</tr>
<tr>
<td>5 – III</td>
<td>0.0373</td>
<td>14.74</td>
<td>0.726</td>
</tr>
<tr>
<td>6 – III</td>
<td>0.0375</td>
<td>14.85</td>
<td>0.728</td>
</tr>
<tr>
<td>7 – III</td>
<td>0.0383</td>
<td>15.74</td>
<td>0.722</td>
</tr>
<tr>
<td>8 – III</td>
<td>0.0391</td>
<td>16.14</td>
<td>0.727</td>
</tr>
<tr>
<td>9 – III</td>
<td>0.0398</td>
<td>16.58</td>
<td>0.730</td>
</tr>
<tr>
<td>10 – IV</td>
<td>0.0408</td>
<td>17.22</td>
<td>0.735</td>
</tr>
<tr>
<td>11 – IV</td>
<td>0.0412</td>
<td>17.44</td>
<td>0.736</td>
</tr>
<tr>
<td>12 – IV</td>
<td>0.0422</td>
<td>18.29</td>
<td>0.737</td>
</tr>
</tbody>
</table>

This table reports, for the same twelve operating conditions presented in table 1, the values of the flow rate $Q$, of the supply head $h$ and the coefficient $\mu$ calculated using the relation:

$$\mu = \frac{Q}{A_s (2gh)^{0.5}}$$

where $A_s$ is cross section of the pipe and $g$ is the acceleration of gravity. These experimental measurements fall into three of the five previously described operating fields and, in particular, the second, third and fourth field. The coefficient $\mu$ values obtained show that $\mu$ assumes lower values in the presence of vortices (tests 2 to 9) and higher values with the formation of cavities (tests 10 to 12) even when vortices and cavities are alternately present (test 10). In conclusion, the experimental tests corroborate the hypotheses that the presence of vortices leads to an increase in dissipations (hence lower $\mu$ coefficients), that the formation of cavities tends to reduce the dissipations (thus producing an increase in the $\mu$ coefficients) and that in the phenomenon of turbulent agitation the formation of cavities is the dominant event.

4 Conclusions

Analysis of the experimental measurements and the results obtained has highlighted in particular the unique characteristics of the acoustic measurement equipment and the LDA. Neither type of instrumentation requires direct
physical interaction with the stream flow (hence they do not affect the phenomenon under investigation) or time-consuming initial calibration. The experimental measurements, in particular those regarding cavitation phenomena and turbulence originating at the inlet of a short pipe, lead to the identification of phenomena which are quasi-periodic and mutually interdependent. In particular, it is possible to identify conditions of quasi-periodicity in the turbulence structure caused by the presence of vortices, in conditions of travelling cavitation, and caused by cavities, in conditions of fixed cavitation.

Use of the laser anemometer, while basically simple and straightforward, is complicated by the presence of cavitation bubbles. In cavitating stream flows such as the one investigated here, the formation of vortices and cavities causes Doppler signal drop-out in the laser anemometer, which temporarily blocks system response. However, this signal drop-out can be partially corrected by means of the drop-out measurement equipment with which the laser anemometers are fitted. The experimental measurements analysed also show that the formation of cavities causes a greater drop-out than that caused by the formation of vortices and an increase in the coefficient of discharge $\mu$ of the pipe. Finally, this difference in the entity of drop-out can be regarded as a further verification of the formation of the two different structures related to the conditions of travelling cavitation (vortices) and fixed cavitation (cavities).

References