Micro-bubbles seeding for flow characterization

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Abstract. Micro-bubbles injection has long been used in hydrodynamic facilities for the control of dissolved and free air. In some cavitation tunnels [9], very large quantities of micro-bubbles (billions per second) are injected for rapid degassing and, in smaller quantities (millions per second), for cavitation nuclei seeding. Micro-bubbles can also be used as tracers for optical measurements including visualization, LDV or PIV. For these applications, bubbles must be sufficiently small to faithfully follow the flow. Depending on the quality and spatial characteristics of the micro-bubbles seeding, several optical methods can be applied: simple visualization gives access to semi-quantitative information on the behaviour of flows; LASER velocimetry provides information on the mean velocity and other temporal local characteristics of the flow. This paper presents some new micro-bubbles seeding devices recently developed by YLEC Consultants. These devices have been designed to fulfill specific requirements related to integration into cavitation tunnels and permit optical velocimetry measurement techniques such as Particle Image Velocimetry (PIV). The LEGI cavitation tunnel is the first tunnel which has been equipped with these micro-bubbles seeding systems dedicated to optical velocimetry. This paper presents the final integration schemes selected for micro-bubbles seeding into LEGI tunnel and discuss about practical concerns related to the use of the injection system for optical velocimetry.

1. Introduction

Optical velocimetry techniques such as LDV (Laser Doppler Velocimetry) or PIV (Particle Image Velocimetry) are more and more used to measure complex flow velocity fields. These techniques consist in measuring the velocity of flow tracers. Solid particles, such as silica particles mentioned by Boutier [5] or by Raffel [10], are commonly used to seed the water of hydrodynamic test facilities. In practice, selected particles must be compatible with the flow characteristics, with the selected optical equipment and with the geometry of the flow facility. The selection of solid particles to be used in water flow facilities must also take into account additional problems:

- Particles may be submitted to aggregation and rapid decantation, this may result in a continuous decrement of particles content and in an increment of the deviation between the particles velocity and the flow velocity,
- As a consequence, it may be necessary to proceed with the tunnel cleaning.

In modern large cavitation tunnels, having flow rates of some tens m³/s and a water volume of several thousand cubic meters, difficulties here-above mentioned and other difficulties related to local particles seeding may practically limit, or even forbid, the use of such velocimetry techniques.

An alternative solution to solid particles seeding consists in injecting micro-bubbles into the water flow. Figure 1 shows a conceptual sketch of this solution in which micro-bubbles can be injected
continuously upstream of the test section. Micro-bubbles disappear within one lap of the water into the
cavitation tunnel circuit.

![Figure 1. Sketch of micro-bubbles seeding which can be used for velocimetry in a cavitation tunnel.](image)

The present paper discusses the specifications of micro-bubbles that should be used to seed a small
cavitation tunnel with such tracers in order to measure by PIV the flow velocity field around a two
dimensional hydrofoil.

2. Experimental program

2.1. Test section and hydrofoil
Tests will be conducted in the LEGI cavitation tunnel. The rectangular test section is of 175 x 280
mm$^2$ (0.049 m$^2$) and 1 m long. The 4 walls are made of transparent Perspex. The NACA 0012
hydrofoil is a 2D wing traversing the test section. Lightning is made from below or above and images
are collected through the lateral walls of the test section.

![Figure 2. Sketch of the LEGI cavitation tunnel test section equipped with a 100 mm chord hydrofoil.](image)

2.2. Cavitation tunnel
The LEGI cavitation tunnel is a medium size facility which has been built during the sixties. Its total
height is of 9 m and its length of 19 m. Compared to many existing facilities, it has some unique
features among whose two downstream tanks in series and a double resorber. This ensures an excellent
control of free and dissolved gases. In the present applications, all micro-bubbles produced in the test
section will dissolve within one flow revolution. The tunnel can be run either in free surface mode or
with a conventional closed jet test section, which will be the case of the present experiments. It has
been recently refurbished to prepare the present experiments.

The nominal operating point of the pump is of 650 l/s under a head of 20 m. The pump maximum
power is of 165 kW. For the present tests, the maximum velocity in the test section will be of 10 m/s
for a flow rate of about 500 l/s.
2.3. Measuring zone
The objective is to measure the velocity field above and below the hydrofoil in a plane of 100 mm length and 75 mm height as sketched on Figure 4.

3. Specification of tracers
3.1. Micro-bubbles size: hydrodynamic approach
Micro-bubbles must be small enough to closely follow the flow lines. As sketched on Figure 5, the deviation between the flow velocity and the micro-bubbles velocity results from bubbles slip velocity induced by gravitational force in the case (a) and/or centrifugal force in the case (b). An identical analysis would be obviously required for solid particles commonly used as tracers for PIV.

Figure 3. The LEGI cavitation tunnel.

Figure 4. Sketch of the PIV measurement plane on the hydrofoil suction side.

Figure 5. Sketched of the theoretical deviation between the flow velocity and bubble velocity due to gravitational force (a) and due to centrifugal force (b).
The micro-bubbles utilized in the present application will be small enough to follow the Stokes law, given by equation 1 and which is the expression of the bubble slip velocity in an acceleration field noted $\gamma$. In this equation, $d_b$ is the micro-bubble size, $\rho_G$ and $\rho_L$ are the gas and the liquid densities, $\mu_L$ is the liquid dynamic viscosity.

$$w = \frac{d_b^2 (\rho_L - \rho_G)}{18 \mu_L} \gamma$$  \hspace{1cm} (1)

In the case of deviation induced by gravitational force, $\gamma$ is equal to the gravity $g$ oriented following the $y$ vertical axis on Figure 5, equation 2 gives the non dimensional velocity error, $\Delta U/U$, computed between the bubble velocity and the flow velocity. $\Delta U/U$ is proportional to the square of micro-bubbles diameter and inversely proportional to the flow velocity, $U$.

$$\frac{\Delta U}{U} = \frac{d_b^2 (\rho_L - \rho_G)}{18 \mu_L} \gamma \frac{1}{U}$$  \hspace{1cm} (2)

Figure 6 gives for several flow velocities commonly used in water tunnel applications, the error $\Delta U/U$ computed for various flow velocities and bubbles sizes. Assuming that the allowed velocity deviation $\Delta U/U$ is of about 1%, it shows that micro-bubbles smaller than 50 µm are well suited for water tunnel applications, even for flow velocities as low as 0.1 m/s.

Figure 6. Theoretical non dimensional velocity deviation due to gravitational force.

Figure 7. Theoretical non dimensional velocity deviation due to centrifugal force, the considered radius of curvature is 20 mm.

In the case of a rotating flow like a vortex, in which the acceleration field is equal to $\gamma = \frac{U_T^2}{r}$, where $U_T$ is the tangential velocity and $r$ the radius of curvature, equation 3 gives the expression of the theoretical velocity deviation relative to $U_T$.

$$\frac{\Delta U}{U_T} = \frac{d_b^2 (\rho_L - \rho_G)}{18 \mu_L} \frac{U_T}{r}$$  \hspace{1cm} (3)

Equation 3 shows that the $\Delta U/U_T$ is proportional to $U_T$ and inversely proportional to $r$. For practical concerns, it has to be calculated for each application. For example, considering a small radius of curvature, $r$, equal to 20 mm, Figure 7 shows the $\Delta U/U_T$ computed for various tangential velocities and for various bubbles sizes.

In this specific case, micro-bubbles smaller than 50 µm are mandatory to measure tangential velocity with a theoretical deviation smaller than 1%. In very high acceleration fields, it may be necessary to use micro-bubbles as small as 10 µm. The same analysis, with similar conclusions, can be applied to solid particles used as flow tracers.

As mentioned by Raffel in [10], additional deviation may result from the response time of tracers' velocity to flow accelerations. In the most general cases, the motion of a particle $p$ of diameter $d_p$ in a
fluid is calculated by application of the classical equation described in [3] and in [12]. The terms in the second member are respectively the viscous forces, the force due to the pressure gradient, the added mass and the Basset force. \( F \) is an external field force such as gravity for example.

\[
\frac{\pi \rho_p d_p^3}{6} \frac{d U_p}{dt} = \frac{3\pi \mu d_p (U_f - U_p)}{V_{\text{viscous}}} - \frac{\pi d_p^3 \nabla p}{6} + \frac{\pi \rho_f d_p^3}{12} \frac{d}{dt} (U_f - U_p) + \frac{3}{2} \rho_p d_p^2 \sqrt{\pi \rho_f \mu} \int_{t_0}^{t} \frac{1}{\sqrt{t - \tau}} \frac{d}{d\tau} (U_f - U_p) d\tau + F
\]

Assuming that equation 4 governs as well solid particles motion and micro-bubbles motion, according to literature [11] the step response of particles velocity, resulting from the integration of equation 4, follows an exponential law given by equation 5. In this equation, \( \tau_p \), given by equation 6 is the response time of the particle velocity to an instantaneous flow velocity change.

\[
U_p(t) = U \left(1 - \exp \left(-\frac{t}{\tau_p}\right)\right)
\]

\[
\tau_p = \frac{d_p^2 (\rho_p + 1/3 \rho_f)}{18 \mu}
\]

Table 1 gives a comparison of response time computed in the water media for solid particles commonly used for LASER velocimetry applications and computed for micro-bubbles. This table shows that the response time of micro-bubbles are comparable to the ones of classical solid particles.

It can be said that micro-bubbles with sizes in the range of 20 to 50 \( \mu \)m are good candidates to seed water flows. These micro-bubbles follow nicely the streamlines in most situations.

**Table 1.** Estimated tracers’ response times, \( \tau_p \).

| Tracers          | \( d_p \) (\( \mu \)m) | \( \rho_p \) (kg/m \(^3\)) | \( \tau_p \) (\( \mu \)s) |
|------------------|-------------------------|-----------------------------|--------------------------|
| Aluminum flake   | 2 - 7                   | 2700                        | 0.7 - 8.71               |
| Hollow glass spheres | 10 - 100               | 1100                        | 8.88 - 888              |
| Micro-bubbles    | 20 - 50                 | 1.2                         | 11 - 69                  |

3.2. Micro-bubbles size: optical criteria

3.2.1. Characteristics of the camera

As mentioned in [4], LEGI is equipped with a PIV system whose main characteristics are listed in Table 2. Camera commonly used by LEGI is a CCD camera which has a definition of about 1600 x 1200 Pixels. The size of one sensor cell is 7.4 \( \mu \)m. The size of the sensor is 11.84 x 8.88 mm\(^2\). The length of sensor, noted \( L_s \), is equal to 11.84 mm.

**Table 2.** Characteristics of PIV system available at LEGI laboratory.

| LEGI PIV equipment | Main characteristics |
|--------------------|----------------------|
| LASER              | Nd:YAG Dantec dual pulsed LASER / \( \lambda = 532\)nm |
| CCD Camera         | ImagePro X2M / 1600 x 1200 px\(^2\) / 7.4 \( \mu \)m cell sensor size |
| Lens               | \( f = 55 \) mm / \( f_a = 3.5 - 32 \) |

The size of the measured flow field, \( L_f \), as shown on Figure 4, will be equal to the 100 mm hydrofoil chord. With the aforementioned camera characteristics, the magnification factor will be of about 0.12: \( M = \frac{L_s}{L_f} \approx 0.12 \). The depth of field, \( \delta \), given by equation 7 is of about 2 mm at maximum aperture and for the considered case. It is two times larger than the width of the laser beam. The distance \( Z_0 \) of the lens to the measuring plane in air, given by equation 8, is of about 520 mm which is twice longer than the width of the LEGI tunnel test section.
will be somewhat longer in the present case because of the presence of Perspex and water. We will keep the above values for simplification. A specialized calculation has been used to take into account the crossing of media of various optical indexes. Consequently, the combination of the lens and of the camera's sensor is well suited to the present measurement.

3.2.2. Size of pixels versus micro-bubbles size

Again with the simplification of a single medium of refractive index equal to 1, the particle which corresponds to one pixel of size \( d_{\tau} \) of about 7.4 \( \mu m \) has a diameter \( d_p \) of 50 \( \mu m \).

\[
d_p = \sqrt{\frac{d_{\tau}^2 - (2.44(M + 1)\lambda_{\tau}\phi)^2}{M} \approx 50 \mu m}
\]

The LEGI camera permits the measurements, but it could be wise to utilize a camera with higher definition, which will be done in a second part of the study. Available cameras have the characteristics given on Table 3. With the last two cameras, noted N1 and N2, a micro-bubble of 50 \( \mu m \) will cover about 2 pixels, which is the value recommended by literature as [1], [6], [10] to avoid peak locking phenomena.

Table 3 Characteristics of additional available cameras for PIV measurements.

| Camera       | Pixel size | Pixel grid   |
|--------------|------------|--------------|
| LEGI Camera  | 7.4 \( \mu m \) | 1600 x 1200  |
| CCD N 1      | 3.45 \( \mu m \) | 2448 X 2050  |
| CCD N 2      | 5.5 \( \mu m \) | 3312 X 2488  |

3.3. Micro-bubbles concentration

According to [10], cross correlation method needs at least 10 particles per interrogative cell to compute the most probable particle displacement. 25 particles is the optimal recommended value.

Assuming that the minimal size of one interrogative cell is 16 x 16 px², for the considered case, the interrogative cell length in the physical domain would be of about 1 mm. Hence, as the typical LASER beam thickness will be of 1 mm, the volume of one interrogative cell would be 1 mm³.

Assuming that each interrogative cell contains typically 10 micro-bubbles and that one micro-bubble represents one pixel on the camera CCD sensor, the value of micro-bubbles content should be 10 000 micro-bubbles per cm³. This is the local micro-bubbles content which will be targeted in the measurement volume and which will be considered for the design of the micro-bubbles seeders.

3.4. Micro-bubbles sheet characteristics

Experimental evidence shows that if water contains too many micro-bubbles, then it becomes opaque and it is impossible to create images because of blurry. To illustrate the phenomenon, Figure 8 presents a transparent cubic tank of 400 mm side containing an emulsion of microbubbles at a concentration of about 1000/cm³.

In order to make measurement, the micro-bubbles seeding must be confined in the region of interest. For example, in the present application, the micro-bubbles seeding must be ideally limited to a plane corresponding to the laser plane, such as illustrated on Figure 9.

If the thickness of the micro-bubbles plane is of about 5 mm at the hydrofoil location, if its height h is of 100 mm, if the bubble concentration \( C_b \) is of 10 000 /cm³ \( (10^{10}/m^3) \), then the bubble flow rate \( N_b \) for a flow velocity of 10 m/s will be of about 50 x 10⁶ micro bubbles per second.
The practical conclusion is that a micro-bubbles injector which will seed a plane of 5x100 mm² section will produce 20 to 50 µm micro-bubbles with a micro-bubbles rate of about some ten millions micro-bubbles per second.

Figure 8. A tank containing micro-bubbles of 20 to 50 µm.

Figure 9. Sketch of the tunnel micro-bubbles seeding solution for the PIV application.

3.5. Conclusions
Based on both hydrodynamic criteria and optical constraints, ideal specifications for micro-bubbles seeding for the present application will be the following:
- Micro-bubbles size adjustable between 20 and 50 µm.
- Micro-bubbles content in the measuring zone up to 10 000 or 25 000 per cm³.
- Seeding limited to the region illuminated by the laser.
- Maximum micro-bubbles injection rate: 50x10⁶ micro-bubbles per second.

4. Micro-bubbles injectors
Among the various micro-bubbles injectors recently developed by YLEC Consultants [2] and [8], this section presents those dedicated to water rigs seeding applications; the LAMYLEC device and the CARMIST device.

4.1. The LAMYLEC injector
LAMYLEC is an injector which produces a flow of micro-bubbles of same diameter as illustrated on Figure 10. The LAMYLEC concept enables to cover a wide micro-bubbles size range comprised between 40 µm and 1 000 µm.

For the present application a dedicated LAMYLEC injector will be designed to cover a micro-bubbles size range adjustable between 45 µm and 80 µm. Due to its compactness, this new design generates very limited wakes. The external size of the LAMYLEC is ¼”. One LAMYLEC injector can be inserted into a ¼” honeycomb cell as illustrated on Figure 11.

Figure 12 shows the micro-bubbles size and the micro-bubbles rate produced by one LAMYLEC injector. The LAMYLEC produces very fine micro-bubbles, in the range of 50 µm, which are compatible with PIV requirements. Nevertheless, the micro-bubbles rate produced by one device is too low to fulfill the local micro-bubbles seeding requirements for PIV measurements in the present application. The maximal micro-bubbles rate is of about 50 000 micro-bubbles per second whereas preliminary analysis has shown that the micro-bubbles rate needs to be of some millions per second per injection point.
Figure 10. Micro-bubbles plumes produced by one LAMYLEC for several operating points.

Figure 11. ¼" cell honeycomb equipped with one LAMYLEC device.

Figure 12. Micro-bubbles size and micro-bubbles rate produced by one LAMYLEC device.

New developments are in progress to increase the micro-bubbles rate at least by a factor of 10. LAMYLEC is also very attractive to control the nuclei content of water for cavitation tests as mentioned in [7] and in [9]. It can produce micro-bubbles optimized in size with an adjustable concentration. It can be installed on a grid placed upstream of the honeycomb or in the honeycomb itself. During the course of the present study, cavitation tests will be conducted in the cavitation tunnel with various concentrations of nuclei in the range of 1 to 10 per cm$^3$.

4.2. The CARMIST device

The CARMIST device illustrated on Figure 15 generates clouds or sheets of micro-bubbles. As shown on Figure 13, this injector produces very fine poly-disperse micro-bubbles emulsions at a very high micro-bubbles rate. The average size of bubbles and their production rate can be adjusted within a certain range by simple means.

CARMIST device is very attractive for micro-bubbles seeding dedicated to velocimetry applications. Figure 14 shows the theoretical average micro-bubbles size and micro-bubbles rate produced by such a device. On this graph, the left vertical axis corresponds to the average micro-bubbles size. The right one gives the production rate. This graph shows that according to the operating point index, the average micro-bubbles size range varies between 25 μm and 50 μm and the micro-bubbles rate of one single outlet of the device is of several millions micro-bubbles per second.
Figure 13. Micro-bubbles seeding plane produced by one CARMIST injector.

Figure 14. Micro-bubbles rate and micro-bubbles size produced by one CARMIST device.

Figure 15. CARMIST device picture.

5. Integration of micro-bubbles injectors inside LEGI cavitation tunnel
The LEGI cavitation tunnel will be equipped with a set of CARMIST injectors arranged in a specific network upstream of the test section in order to produce micro-bubbles sheets in several observation planes. Figure 16 shows a sketch of the cavitation tunnel upper part with its main dimensions. The 560 x 560 mm² injection zone contains the CARMIST injectors, the LAMYLEC array and the honeycomb.

Figure 16. Sketch of the new LEGI cavitation tunnel upper part.

Figure 17 shows a sketch of the injectors' grid. This grid can be placed upstream or downstream of the ¼" honeycomb. The CARMIST devices can work either independently or all together. They can be installed horizontally or vertically. The mounting is very versatile and permits many combinations of injection.

On Figure 17 is schematized the micro-bubbles sheet escaping from one injectors row, showing the expected effects of turbulence and contraction on the thickness of the sheet. The gas and water supply to the injectors are not represented on the figure. Both fluids pass through a specific low pressure loop equipped with conventional components and control systems.
An array of LAMYLEC injectors, not represented here will also be installed for the cavitation tests with variable concentration of monodispersed microbubbles utilized as artificial nuclei.

![Integration of injectors’ grid in LEGI cavitation tunnel.](image)

**Figure 17.** Integration of injectors’ grid in LEGI cavitation tunnel.

6. **Conclusion and perspectives**

YLEC Consultants has developed two new micro-bubbles injectors for the seeding of cavitation tunnels. The LAMYLEC produces monodisperse bubbles of adjustable size and adjustable rate. At present, one LAMYLEC can produce up to 30 000 bubbles/s of 50 μm diameter. This flow rate will be multiplied by 10 in a near future. CARMIST produces a wider spectrum of bubbles with typical flow rates of 1 to 10 million bubbles per second and an adjustable average diameter between 10 and 40 μm.

The aim of the present study is to analyze, on a practical application in a small cavitation tunnel, the utilization of these micro-bubbles as optical tracers for PIV applications and evaluate the advantages and limitations of this non-polluting method.

In this paper, it has been shown that microbubbles produced by CARMIST are good candidates. The LEGI cavitation tunnel has been equipped with such generators. Tests will be made during the second and third terms of 2016. These tests are aimed to prove the feasibility of PIV measurements with micro-bubble tracers, using the CARMIST injectors at high micro-bubbles rates.

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