# Control of water air content during transient cavitation tests of inducers

Guy Caignaert, Olivier Coutier-Delgosha, Jean-Baptiste Leroux

# Control of water air content during transient cavitation tests of inducers

Guy Caignaert [1]*, Olivier Coutier-Delgosha[1], Jean-Baptiste Leroux[2]

ISROMAC 2016

International Symposium on Transport Phenomena and Dynamics of Rotating Machinery

Hawaii, Honolulu

April 10-15, 2016

**Abstract**

The control of water air content is often necessary during transient cavitation tests of inducers. But no method is really defined or imposed to control it quantitatively, especially during tests where a continuous decrease of available NPSH at pump inlet is used in order to analyze, for example, the occurrence of instabilities.

The paper intends to show how a well-known in-duct hydro-acoustics intensimetry, using three pressure transducers can be used accurately for the instantaneous determination of waves celerity in ducts during such transient tests, with an appropriate treatment of the measured pressures. The instantaneous wave celerity can then be related to an instantaneous value of air content using a model.

An application to cavitation tests of an inducer at various speeds of rotation and a given non-dimensional flow rate is proposed, analyzed and discussed..

**Keywords**

Waves celerity – unsteady cavitation tests - pumps

[1]*Arts et Métiers Paristech, Laboratoire de Mécanique de Lille, Lille, France*

[2]*LBMS, ENSTA Bretagne, Université de Brest, France*

***Corresponding author**: guy.caignaert@ensam.eu

## INTRODUCTION

Tests standards, such as ISO 3822-1 [1] for laboratory tests on noise emission from appliances and equipment used in water supply installations, often require a control of the quality of water, regarding especially its air content. The same type of attention has to be taken into account for cavitation tests of pumps or other hydraulic devices.

During laboratory tests, the control of gas content in water can be mainly achieved by measuring dissolved oxygen with use of sensors. But these devices are difficult to use accurately because the information from the transducers can be influenced by parameters such as temperature and pressure of water. Such devices are also difficult to use during transient tests because of their limited time response.

The present paper proposes to use a three-pressure transducers method in order to get a good control of waves celerity in ducts of constant cross-section. That method has been used efficiently with steady flows in ducts, with help of signal treatments in the low frequency range, especially for hydro (or aero) acoustics tests of pumps and fans ([2], [3], [4], [5], [6], [7]). The results presented here show that such a method can be used rather accurately during transient operation of pumps, such as cavitation tests with continuously decreasing available Net Positive Suction Pressure.

During the tests with a continuously decreasing available NPSP, the measured pressure fluctuations in the ducts can also be used for a quite instantaneous characterization of pressure and flow rate fluctuations far upstream and downstream of the tested pump. The results are used as a complementary tool in order to analyze the various types of cavitation that occur within the pump, especially the occurrence of instabilities.

## 1 EXPERIMENTAL FACILITIES AND TESTS RESULTS

Figure 1 presents a scheme of the pump environment within the pump test-rig SESAME ([11] and [12]). That test-rig is a closed loop enabling:

- Measurements of steady and unsteady characteristics of pump (flow rate, head, required NPSP) at various speeds of rotation (up to 6000 rpm)
- Control of available NPSP at pump inlet by modifying the pressure in the upstream tank, with the possibility of varying that NPSP continuously

Inlet pipe and outlet pipe have internal diameters respectively equal to 250 and 200 mm.

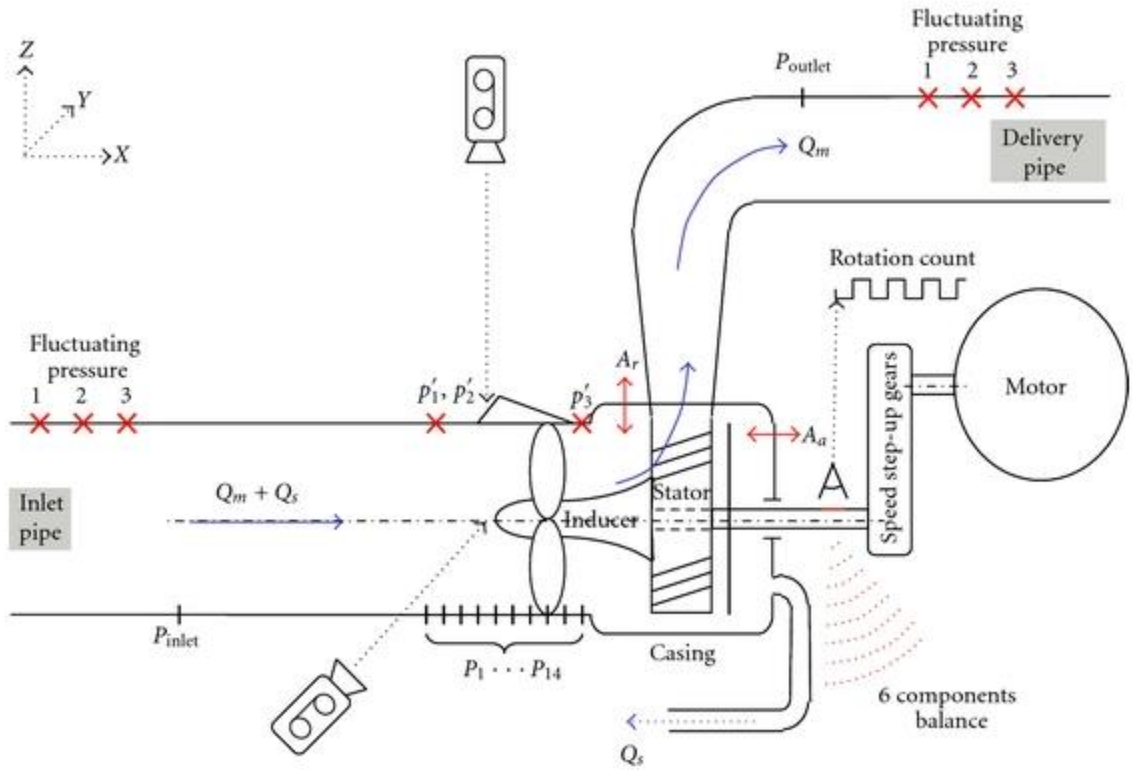
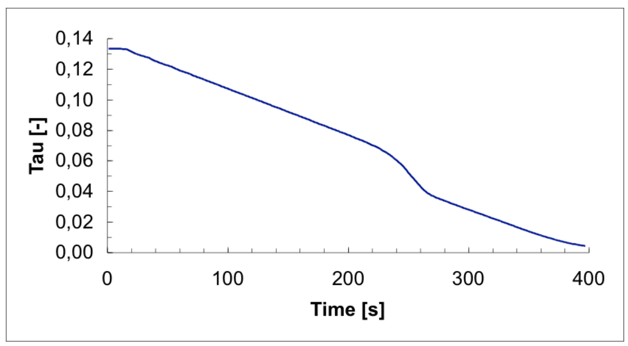


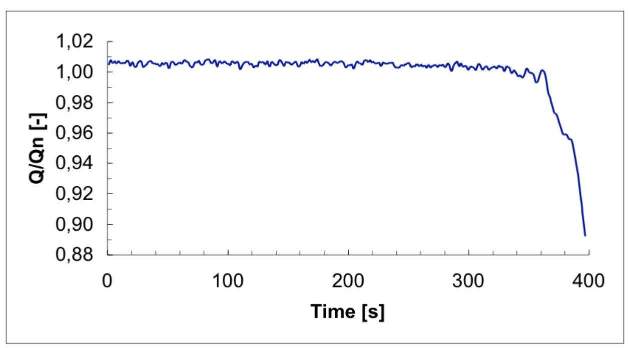

**Figure 1.** Scheme of the pump test rig showing especially the pressure transducers locations in the inlet and outlet pipes

Such tests with a continuous decrease of pressure in the upstream tank are particularly interesting for the analysis of the conditions of inception of some instabilities due to cavitation development within the tested pump. During these tests:

- The pump speed of rotation is kept constant
- No action is made on the valves used for the control of the flow rate in the loop, and the pump flow rate remains constant, as far as there is no blockage effect due to cavitation development.

Figure 2 presents an example of such a transient test. As it can be observed on that Figure 2, the transient evolution of pressure in inlet pipe (or Tau) is very slow, with duration of about 400 s, which allows for quasi-steady interpretations of phenomena. The superposition of such results at three different pump speeds of rotation (4000, 5000 and 6000 rpm) and the same relative flow rate (same positions of control valves) is then presented in Figure 3. Some small differences can be observed, especially when flow rate and head coefficients begin their decrease due to the development of cavitation in the pump. One question was the potential influence of water gas content evolution at pump inlet and it was decided to try to get instantaneous values of waves celerity in the pipes during such tests, using the well-known “three transducers” method. That method was used for a long time in the lab for hydro-acoustics purposes ([4], [6], [7]), but always during steady operating conditions, and one challenge was to adapt the method for transient conditions.



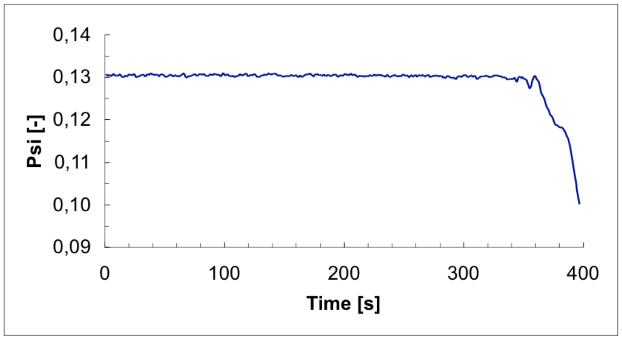



**Figure 2.** Non-dimensional NPSP (upper part), flow rate (middle) and pump head (lower part) during a typical transient cavitation test

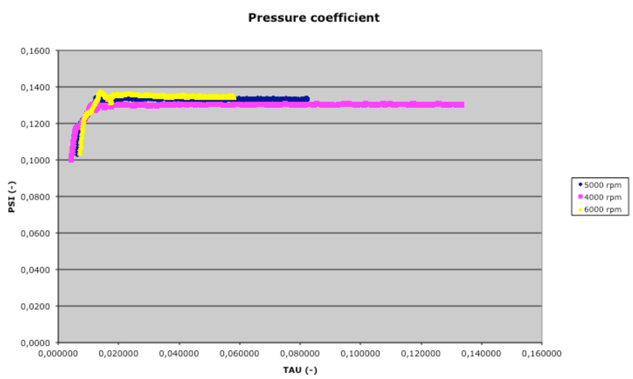



**Figure 3**. Evolutions of non-dimensional flow rate Q/QN and head PSI with Tau

## 2 EXPERIMENTAL DETERMINATION OF WAVES CELERITY IN A DUCT OF CONSTANT CROSS-SECTION USING THREE PRESSURE TRANSDUCERS

The experimental determination of waves celerity in a duct of constant cross-section can be made using three pressure transducers, flush mounted on the wall of the duct, in three equidistant pipe cross-sections, as proposed in [4], [6], [7] and [8]. The model refers to 1D propagation equations assuming no Mach number effect and no viscous effects ([8], [9], [10]). With that procedure, the waves celerity is experimentally defined, in the frequency domain, using transfer functions between transducers (1) and (0) and transducers (2) and (0), where transducer (0) is situated in the middle of transducers (1) and (2), according to the theoretical following equation:

$$\frac{1}{2}(H_{p_1 p0} + H_{p_2 p_0}) = \cos kL \qquad \text{(a)}$$

With: *H* Transfer function

*L* the distance between transducers (1) and (0) or (2) and (0)

*k* the wave number equal to the ratio of waves celerity *c* over frequency *f*

Figure 4 presents an example of the use of that method in a stainless steel pipe at the inlet of a radial flow pump operating in steady operating conditions. The figure presents the imaginary part (in red) and the real part (in blue) of the left part of equation (a) obtained from measurements; the green curve represents the "*coskL"* function that optimally approximates the real part of the experimental result. Such a result can be used to get a first appreciation on the quality of the experimental procedure as the result can be compared to estimation of the waves celerity obtained from the celerity in water with corrections due to the thickness of the pipe and the properties of its material. Coherence functions and observation of the experimental imaginary part of the left part of equation (a) can also be used as quality criterion.
It can be noticed that boundary conditions directly influence the quality of the results. In such a method, the distance between transducers must also be chosen carefully according to the frequency range of interest. Useful indications about the experimental conditions can be found in references [2] to [8]. In the present example, the transfer functions are experimentally obtained from cross spectra and auto spectra with a possibility of averaging these spectra over a more or less important number of measurements (50 for example in figure 4).

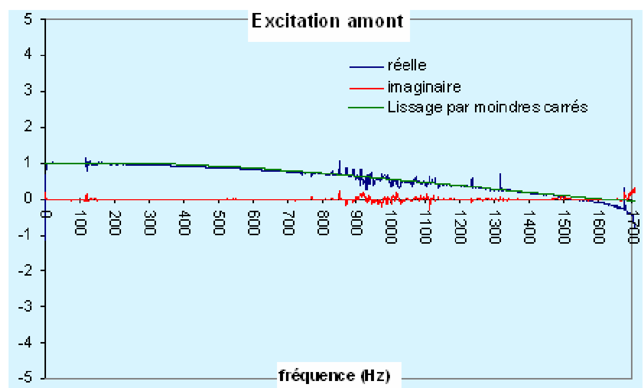



**Figure 4.** Real (in blue) and imaginary (in red) parts of left side of equation (a) in a stainless steel pipe (inlet diameter = 40 mm; wall thickness = mm) at inlet of a radial flow pump as functions of frequency (in abscissa). Green curve represents the "coskL" function that optimally approximates the real part of experimental results. From that green curve, wave celerity of 1270 m/s is deduced.

## 3 RESULTS AT A GIVEN SPEED OF ROTATION

The method has been used during cavitation transient tests described in Figure 2. During these tests, the pump speed of rotation is equal to 4000 rpm. For the determination of waves velocities in both pipes, the signal is then divided in windows of 2 s. In every window, the method described in section 2 is used with an hypothesis of quasi-steady conditions within it. An average over 8 instantaneous spectra can be made. In every window, tests on coherences and imaginary parts are made in order to eliminate information at some frequencies as it appears on figure 5 where it can be observed that red points are used to fit a "*coskL*" law used to determine the celerity c.

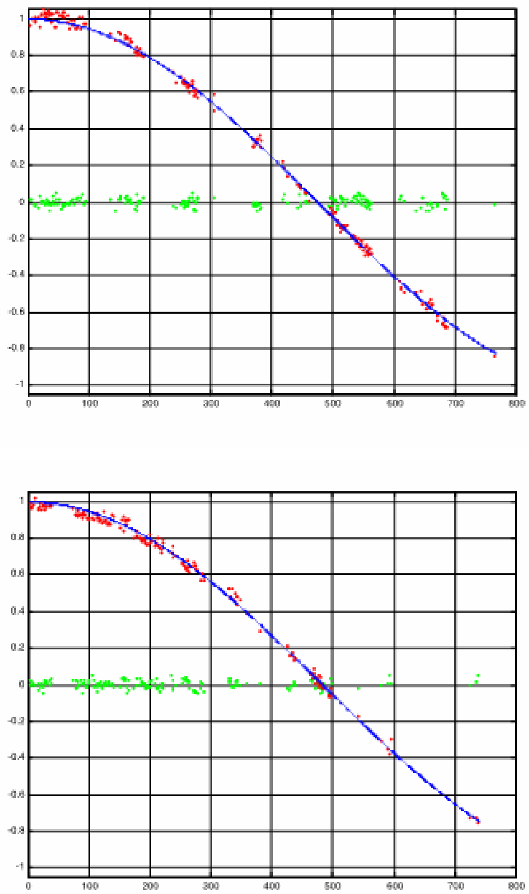
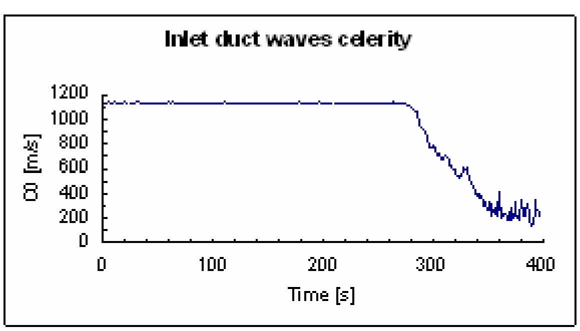


**Figure 5.** Real (red points) and imaginary (green points) of the left side of equation (a). Evolutions with frequency (Hz, in abscissa) for one time window (duration 2 s) during a transient cavitation test of an inducer. Blue lines represent the “coskL” function fitted to red points and used for the determination of instantaneous waves celerities. Results in inlet pipe (figure on the left) and in outlet pipe (figure on the right)

Figure 6 presents the results as time evolutions of these waves celerities during that test in respectively inlet and outlet pipes. As it can be observed, the celerity decreases much more at inlet, what can be probably be associated to an effect of an evolution of dissolved air within water. It can also be noticed that the sharp decrease of celerity at inlet appears nearly 80 s before the decrease in pump flow rate and head observed on Figure 2.



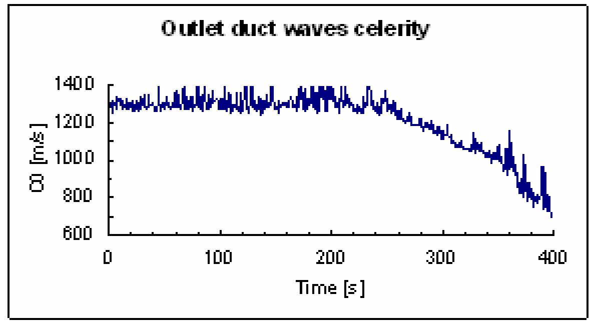




**Figure 6.** Waves celerity in inlet pipe (on the left) and outlet pipe (on the right) determined with a three-transducers method during a transient operation of an inducer operating at 4000 rpm with a continuously decreasing available NPSH.

## 4 RESULTS FOR THREE SPEEDS OF INDUCER ROTATION

The measurements of pressure fluctuations in inlet and outlet pipes have been made for the three tests whose flow rate and pressure coefficients are presented in Figure 2. These results are characterized by similar flow velocity triangles at inducer inlet if Reynolds number effects are negligible. Figure 7 presents the evolutions of the waves celerity in inlet pipe with the non-dimensional available NPSP. The results can appear relatively surprising as the various curves for the three speeds of rotation are not similar: the beginning of the decrease of inlet celerity appears here to be dependent of the speed of rotation with a tendency to appear at lower values of TAU for higher speeds of rotation. In fact, if these evolutions are drawn as function of available NPSP (Figure 8), the similarity appears much better: that means that the beginning of celerity decrease appears for a given value of available NPSP which probably indicates what can be called a test-rig signature for the beginning of gas content sharp increase. That interpretation of the results is confirmed in Figure 9 where each celerity value is transformed in a value of gas content (alpha) using the well-known Jakobsen model ([13]).

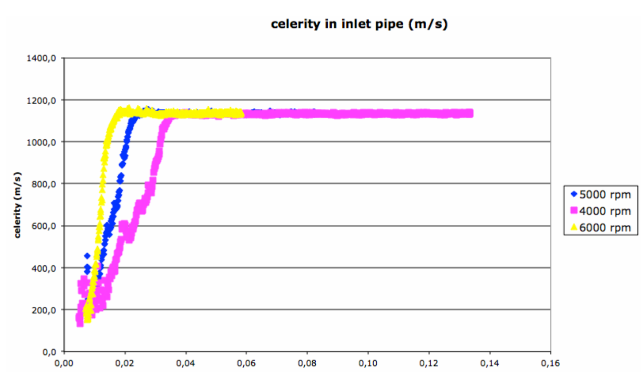



**Figure 7.** Evolutions of waves celerity in inducer inlet pipe in function of non-dimensional available NPSP for three different speeds of inducer rotation and the same relative flow rate

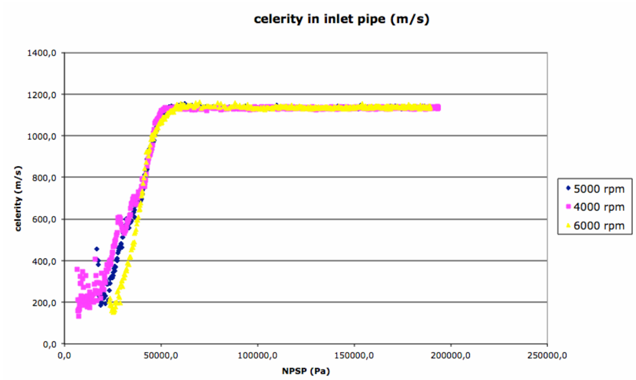



**Figure 8**. Evolutions of waves celerity in inducer inlet pipe in function of available NPSP for three different speeds of inducer rotation and the same relative flow rate

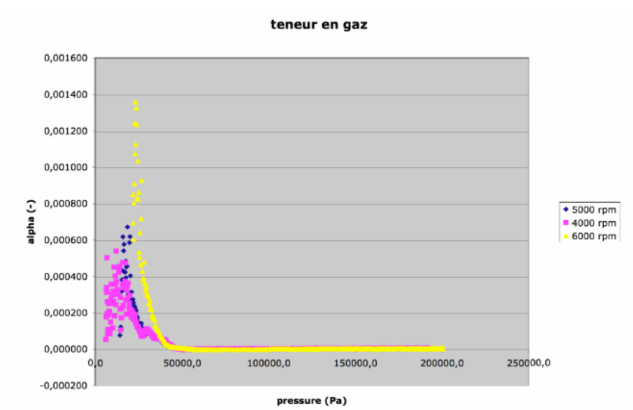



**Figure 9.** Evolutions with available NPSP of inlet pipe gas content calculated from celerity in Figure 8

Results in the outlet pipe are of course of less interest regarding cavitation instabilities analysis, but they become useful for the hydro-acoustics characterization of the whole pump using transfer matrices that allow for a dynamic analysis of the whole installation. Evolutions of waves celerity in the outlet pipe are so presented in Figure 10. As already noticed, the variations of celerity are much smaller than in inlet pipe. The decrease that is observed is much important for the lower speed of rotation, which can be associated to the lower pump head for smaller speeds of rotation. The results can appear a little bit more “noisy” than at inlet, but it must be remembered that the transducers at inlet are probably more influenced by pump vibration in that zone.

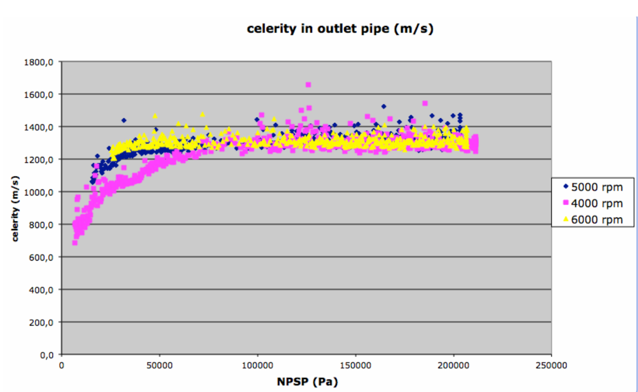



**Figure 10.** Evolutions of celerity in outlet pipe with NPSP

## CONCLUSION

The liquid gas content is known to have influence on the cavitation characteristics of a pump. But no method is really imposed in order to control it, especially during transient cavitation tests as the ones described in the present paper. The use of pressure transducers for hydro-acoustics characterization of pumps, turbines and systems has been developed for a long time. The challenge was here to look at the potential use of methods based upon the “three transducers method” during transient NPSP variations. Of course, the transient evolutions considered here remain slow enough so that quasi-steady approaches can be used.
In spite of the fact that the averaging of cross spectra and auto spectra is limited due to the time window duration, it has been demonstrated that the method is applicable for the analysis of such tests with a still good quality of the results and the potential use for the determination of void fraction using a model correlated to the experimental waves celerity measured all along the transient.

## NOMENCLATURE

a — constant (-)
Alpha — void fraction = volume of gas divided by the total volume (-)
C — propagation celerity of waves in a pipe (m/s)
f — frequency (Hz)
g — gravity acceleration (m/s$^2$)
H — transfer function (-) or pump head (m)
K — wave number = C/f
L — distance between two consecutive pressure transducers (m)
N — pump speed of rotation (rpm)
NPSP — Net Positive Suction Pressure (Pa)
P, p — pressure (Pa)
PSI — non-dimensional head coefficient = $gH/(a\omega^2R^2)$ (-)
Q — pump mass flow rate (kg/s)
QN — reference pump mass flow rate (kg/s) proportional to N
TAU — non-dimensional NPSP = $(NPSP/\rho)/(a\omega^2R^2)$ (-)
$\omega$ — pump angular speed of rotation (rad/s)
$\rho$ — water density (kg/m$^3$)

## REFERENCES

[1] EN ISO 3822-1-*Acoustics-Laboratory tests on noise emission from appliances and equipment used in water supply installations-Part 1: method of measurements* European standard may **1999**
[2] J. Lavrentjev, M. Abom-*Characterization of fluid machines as acoustic multi-port sources*- Journal of Sound and Vibration, 197(1), p. 1-16, **1996**
[3] J. Lavrentjev, M. Abom, H. Boden-*A measurement method for determining the source data of acoustic two-*

*port sources*- Journal of Sound and Vibration, 183(3), p. 517-531, **1995**

[4] F. Carta, S. Bolpaire, J. Charley, G. Caignaert - *Hydro acoustical characterization of centrifugal pumps*- 7th international congress on sound and vibration, Garmisch-Partenkirchen, Germany, 4-7 July **2000**

[5] M. Abo, H. Boden - *Error analysis of the two microphones measurements in ducts with flow*-Journal of American Acoustic Society, pp.2429-2438, June **1988**

[6] G.Caignaert, J.Charley- *Caractérisation expérimentale du comportement hydroacoustique de turbomachines hydrauliques*- La Houille blanche, n°3/4, p.53-58, **2000**

[7] G. Caignaert, J. Charley - *Sources of uncertainties for hydro acoustics measurements in ducts*- INCE symposium “Measuring Uncertainty in Noise Measurement and prediction”, Le Mans (France), 27-29 June **2005**.

[8] *Guide acoustique des installations de pompage* – Publications CETIM - **1997**

[9] D.L. Margolis, F.T. Brown -*Measurements of the propagation of long-wavelength disturbances through turbulent flow in tubes* - ASME Journal of Fluids Engineering, vol.98, p. 70-75, march **1976**

[10] C. Brennen-*Hydrodynamics of Pumps*- Oxford Science Publications, **1994**

[11] O. Coutier-Delgosha, A. Dazin, G. Caignaert, and G. Bois, *Analysis of Cavitation Instabilities in a Four-Blade Inducer* International Journal of Rotating Machinery, vol. 2012, Article ID 213907, 11 pages, doi:10.1155/2012/213907, **2012**

[12] O.Coutier Delgosha, G.Caignaert, G. Bois, J.B.Leroux *Influence of the blade number on inducer cavitating behavior* ASME Journal of Fluids Engineering, august 2012, vol. 134, issue 8, 081304 (11 pages), **2012**

[13] H.Shamsborhan, O.Coutier-Delgosha, G.Caignaert, F.AbdelNour
*Experimental détermination of the speed of sound in cavitating flows*
Experiments in Fluids**,** vol 49, n°6, p.1359-1373, **2010**