NUMERICAL AND EXPERIMENTAL INVESTIGATIONS OF THE CAVITATING FLOW ON A TWO-DIMENSIONAL HYDROFOIL

S. Frikha[a], J. A. Astolfi [a], O. Coutier-Delgosha [b]

a. *Institut de Recherche de l'Ecole Navale EA3634, BP 600, 29240 BREST NAVAL, France*
b. ENSAM ParisTech/ LML Laboratory, 8 bld Louis XIV, 59046 Lille cedex, France

Résumé :

La dynamique d'une poche de cavitation sur un hydrofoil 2D a été étudiée expérimentalement et numériquement sur la base de différents modèles de cavitation. L'étude expérimentale a été réalisée dans le tunnel de cavitation de l'Ecole Navale et l'étude numérique est basée sur une approche homogène. Plusieurs modèles de cavitation basés sur une équation de transport de taux de vide ou sur une loi barotrope sont confrontés aux résultats expérimentaux dans une configuration de comportement périodique complexe faisant apparaitre deux fréquences caractéristiques. Une méthode basée sur la caractérisation en nombre d'onde-fréquence de la dynamique de la poche de cavitation est présentée. L'application de cette technique sur les signaux de pression pariétale montre sa capacité à détecter la fréquence d'oscillation des poches de cavitation et la taille maximale de la poche attachée. Un bon accord entre résultats expérimentaux et numériques est en général obtenu: le comportement de la poche, sa longueur maximale et les fréquences caractéristiques d'oscillation sont bien prédits. Des différences de second ordre entre les modèles sont discutées.

Abstract:

The dynamics of two-dimensional sheet cavitation on the suction side of a 2D foil section was investigated experimentally and numerically with several different cavitation models. Experiments were conducted in the cavitation tunnel of the French naval Academy, while computations were all based on a homogeneous approach. Several models using either a void fraction transport equation or a barotropic state law were tested and the results were compared to the experimental data in a complex situation of periodical vapour shedding characterised by two different frequencies. A method based on the wavenumber-frequency characteristics of cavity dynamics is presented and applied to wall pressure signals. The method has demonstrated its capability to estimate accurately both the frequency of the cavity oscillations and the maximum length of the attached cavity. A good general agreement between all computation and the experiments was obtained. The global behaviour of the cavity, its length and oscillation frequencies were correctly predicted, while minor differences between the numerical results are discussed.

Key words: **unsteady cavitation, numerical modeling, sheet cavitation, void fraction.**

1 Introduction

In liquid flows, cavitation generally occurs if the pressure drops below the vapor pressure; it can be observed in a wide variety of propulsion and power systems like pumps, nozzles, injectors, marine propellers and hydrofoils. Unsteady cavitation induces several negative effects, such as noise, vibrations, performance alterations, erosion and structural damages. Moreover, cavitation is responsible for several instabilities that may affect the global behaviour of propellers and pumps. Such flow instabilities have been studied experimentally and numerically by many authors in various configurations. Numerical simulations are usually based on a homogeneous approach: the cavitation mixture is considered as a single fluid, while the mass exchanges between vapour and liquid are controlled either by a transport equation for the void fraction, or by a specific state law for the two-phase mixture. A comparison of several cavitation models was done previously in [1, 2] and large similarities between them have been found.

The present work is devoted to the study of the cavitating flow on the suction side of a NACA 66 2D hydrofoil. Sheet cavitation is investigated both experimentally in the cavitation tunnel of the French naval Academy (Ecole navale) and numerically with the IZ code, property of the CNES. A large range of flow configurations were explored, from low cavitating conditions with only small fluctuations in the closure area to large cavities characterized by large-scale oscillations and periodical vapour cloud shedding. Attention is focused hereafter on a configuration characterized by two separate frequencies are detected in the experiments, in order to discuss the capability of the model to reproduce this complex behaviour. For that purpose, a method based on the wavenumber-frequency spectrum is applied. This method gives a time-space characterization of the attached cavity, which enables to estimate the frequency of the cavity oscillations and the maximum length of the attached cavity.

2 Numerical and experimental set up

Experiments and computations were conducted on a 2D configuration performed on the NACA 66 hydrofoil section in situation of a cavitating flow.

2.1 Numerical set up

The code is based on a finite volume discretization on curvilinear two-dimensional orthogonal mesh. The numerical resolution consists of a pressure correction method derived from the SIMPLE algorithm. Each physical time step consists of successive iterations which march the solution towards convergence. Second order implicit time integration scheme and convection scheme are applied. A modified k-ε RNG turbulence model is used: the turbulent viscosity is $\mu_t = f(\rho)\times C\mu \times k^2 / \varepsilon$ where $f(\rho) = \rho_v + (1-\alpha)^n (\rho_l - \rho_v)$, where α is the void fraction and n is set to the value of 10. More detail regarding the numerical model can be found in [3]. The classical boundary conditions for incompressible flows are applied: imposed inlet velocity, and fixed outlet pressure. A C-type orthogonal mesh is used.

The cavitation models can be put mainly into two categories: interface tracking methods and homogeneous equilibrium flow models. In the present study, the attention is focused on this second category: the liquid/vapour mixture is considered as a homogeneous fluid. Classical RANS equations for a single phase flow are coupled either a supplementary void fraction transport equation $\frac{\partial \alpha}{\partial t} + \nabla\left(\alpha \vec{u}\right) = A$ or with a barotropic state law that governs the density evolution according to the local pressure variations.

The models based on the transport equation of the void fraction are characterized by different expressions of the source term A. In the literature, A is usually divided into two terms: $A = \dot{m}^+ + \dot{m}^-$ where $\dot{m}^+$ and $\dot{m}^-$ stand for the vaporization (vapour production) and condensation (vapour destruction) processes, respectively. Table 1 presents a selection of several forms of $\dot{m}^+$ and $\dot{m}^-$ proposed by different researchers. All the models require empirical constants C_{prod} and C_{dest} to calibrate the mass transfers. In the present study, these empirical factors are adjusted to obtain the same maximum value for the source terms, in order to make the comparison of the models easier. More details can be found in [1, 2].

Authors	vaporization / condensation terms ($\dot{m}^+$ / $\dot{m}^-$)
Reboud and Stutz [4]	$A = \frac{1}{\theta \rho_v} \min[\alpha_{min}, \alpha, (1-\alpha)](-\sigma - C_p)$
Kunz et al. [5]	$\dot{m}^+ = \frac{C_{prod} \rho_v \alpha_l \min(0, p - p_v)}{(\frac{1}{2}\rho_l U_\infty{}^2) t_\infty} \Big/ \dot{m}^- = \frac{C_{dest} \rho_v \alpha_l{}^2 (1-\alpha_l)}{t_\infty}$
Singhal et al. [6]	$\dot{m}^+ = C_{prod} \frac{U_\infty}{\gamma} \rho_l \rho_v \left[\frac{2}{3}\frac{p_v - p}{\rho_l}\right]^{1/2} *(1-f_v) \Big/ \dot{m}^- = C_{dest} \frac{U_\infty}{\gamma} \rho_l \rho_v \left[\frac{2}{3}\frac{p - p_v}{\rho_l}\right]^{1/2} * f_v$

Table 1: Sample of some cavitation models existing in the literature

2.2 Experimental setup

The experiments were carried out in the Ecole Navale cavitation tunnel, fitted with a 1m long and 0.192 m wide square cross test [7]. Partial cavitation was investigated by multi-point wall-pressure measurements and numerical videos. Pressure measurements were carried out using piezo-resistive transducers of 10 bars maximum pressure. Comparisons between numerical and experimental results focus on the global behaviour of the cavity, the maximum length of the attached cavity and the oscillation frequencies.

3 Comparison between numerical and experimental results

Experimental measurements and numerical results are compared in the case of a large cavity. The maximum attached cavity length is about 80% of the chord. An unsteady non classical periodical behaviour of the sheet cavity is obtained in the experiments: development of a cavity up to the maximum length (about 80% of the chord) (picture 4 in FIG.1), cavity break-off (picture 5 in FIG.1), cloud detachment (picture 6 in FIG.1), and immediate growth of a residual cavity (picture 7 in FIG.1), This second cavity results in a second smaller cloud shedding (picture 13 in FIG.1),. This complex dynamic is characterized by two different frequencies: 5 Hz for the main cloud detachment and 10 Hz because of the second cloud detachment (FIG. 2). A first calculation is performed using a barotropic state law. The dynamic of the cavity is correctly predicted by this model (FIG. 1).

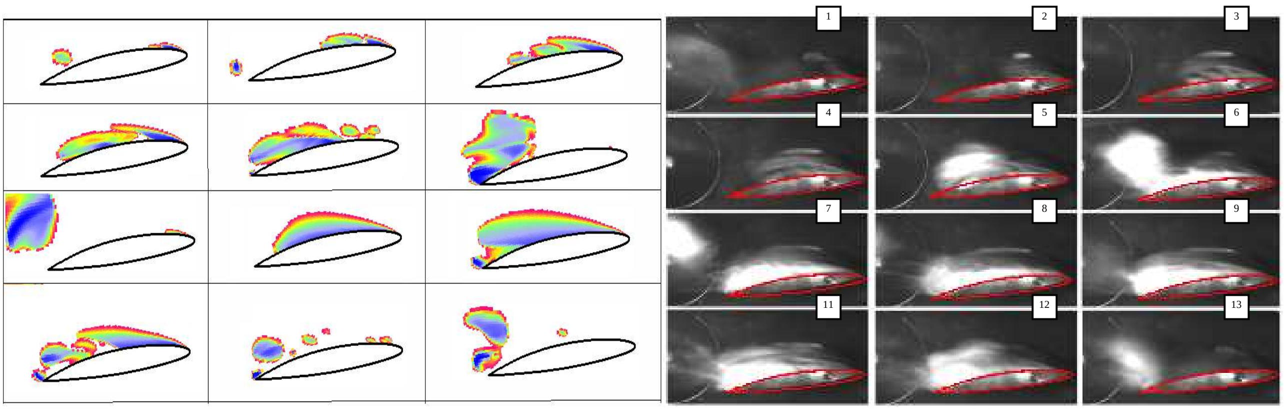

FIG. 1: Experimental-numerical (state law) comparison of cloud cavitation. Computations: $\alpha = 8°$, $\sigma = 1.3$, $\Delta t = 0.018$ s, Re= 800000, $\alpha=8°$. Experiments: $\alpha = 8°$, $\sigma = 1.27$, $\Delta t = 0.018$ s, Re=800000, $\alpha=8°$.

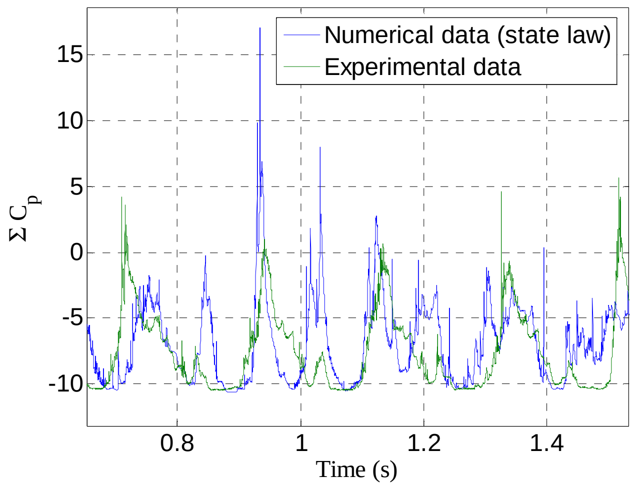

FIG.2: Time evolution of the pressure coefficient

Three transport equation-based models with source terms of Reboud, Kunz and Singhal are now tested. The empirical factors were adjusted to obtain the same maximum value for the source terms. FIG.3 shows a large resemblance between the three tested models: the unsteady behaviour of the sheet cavity is similar in all cases: development of a cavity up to the maximum length (about 80% of the chord), cavity break-off, cloud detachment and immediate growth of a residual cavity. As a matter of facts, it seems that models predict correctly the complex dynamic of the cavity.

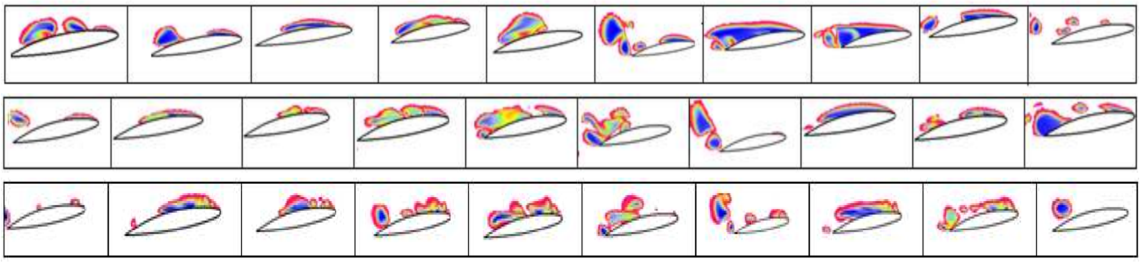

FIG. 3: Comparison between models; α = 8°, σ = 1.3, Δt =0.018 s, Re= 800000, α=8°.

The maximum length of the attached cavity, the main oscillation frequency and the Strouhal number obtained by different models are indicated below for each model. Table 2 shows a large resemblance between the for tested models: the main sheet cavity oscillation frequencies are also all similar, leading to Strouhal numbers based on the maximum cavity length comprised between 0.23 and 0.29. These results are in close agreement with the experimental measurement. They confirm the similarities between the four tested models, which was previously obtained [2].

	L/c	f (Hz)	Str
Experiments	0.8	9.8	0.23
State law	0.8	10.8	0.24
Reboud and Stutz	0.8	12.5	0.28
Kunz	0.8	11.8	0.26
Singhal	0.8	12.8	0.29

Table 2: Comparison of experimental and numerical results obtained with different models (α = 8°, Re=8000000).

Other configurations were also investigated. The maximum length of the attached cavity, the oscillation frequency and the Strouhal number are indicated for each configuration (FIG. 4). Results are quite similar and in close agreement with the experimental measurements. The Strouhal numbers based on the maximum cavity length and the upstream velocity are systematically close to the classical value 0.3 (FIG. 4). The results still confirm the large resemblance between the models.

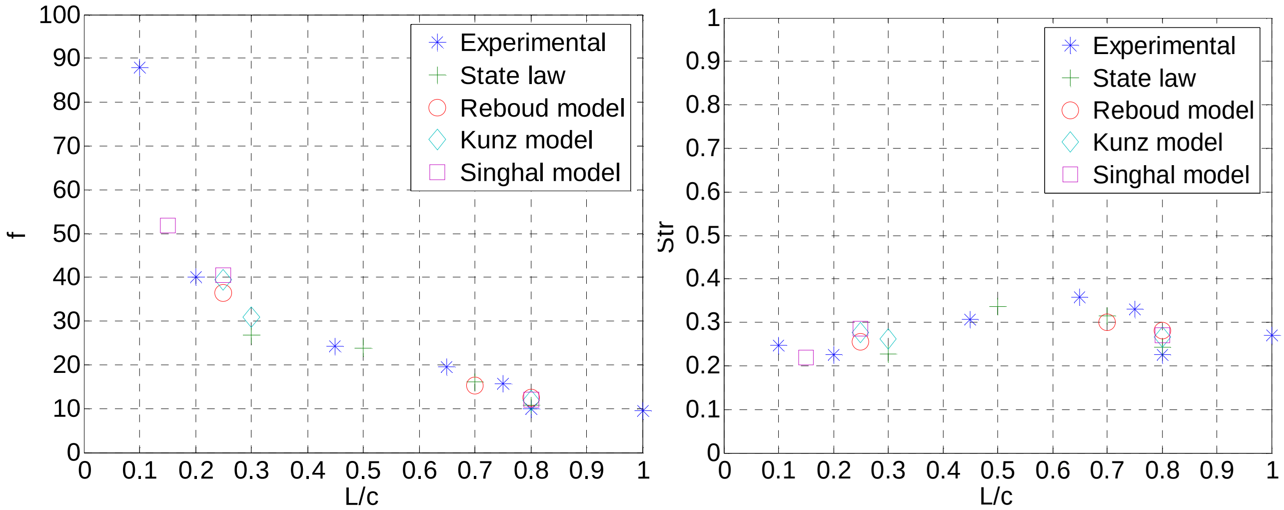

FIG. 4: Experimental and numerical frequency of cavity oscillation and Strouhal numbers as a function of the maximum length of the cavity, Re=800000, α=8°.

It has been noticed that the main frequency of the vapour shedding is dominant in all computations, so the second frequency obtained in the experiments can be hardly detected from the pressure signals. The wavenumber-frequency spectrum method is thus applied on wall pressure signals in order to detect the sheet oscillations frequencies and especially the second frequency and to estimate the maximum length of the cavity.

4 Measurements of wall pressure wavenumber-frequency spectra

The objective of the present investigation is the measurement of the streamwise wavenumber frequency spectrum of wall pressure fluctuations. The wavenumber-frequency spectrum is defined as the space- time Fourier transform of a signal (pressure fluctuation); the spectrum is given by:

$$\Phi(k,\omega)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} P(x,t).e^{-i(k*x+\omega*t)}dx.dt \qquad (1)$$

Because the data are limited in both spatial and temporal extent, window functions W(x,t) are used to suppress sidelobes in the wavenumber and frequency domains, respectively: $W(x,t)=W_x(x)*W_t(t)$ where $W_x(x)$ is a spatial window and $W_t(t)$ is a temporal window (Willis [8]).

4.1 Experimental Data

Pressure measurements were carried out using the transducers and the wavenumber-frequency method was applied on the pressure coefficient signals. Because the number of transducers is very limited, experimental data where interpolated using B-spline function. The 2D spectra (FIG. 5) give $f = 9.77$ Hz and $\lambda/c=82\%$. Those values are close to the main frequency of the cavity oscillations (f=9.8 Hz) and the maximum length of the attached cavity ($\approx 80\%$ of the chord). The frequency of 5 Hz is also detected and it has the dominant amplitude in the experiments. It can thus be noticed that the wavenumber-frequency spectrum may a very interesting method to estimate the frequencies of the cavity's oscillations and the maximum length of the attached cavity.

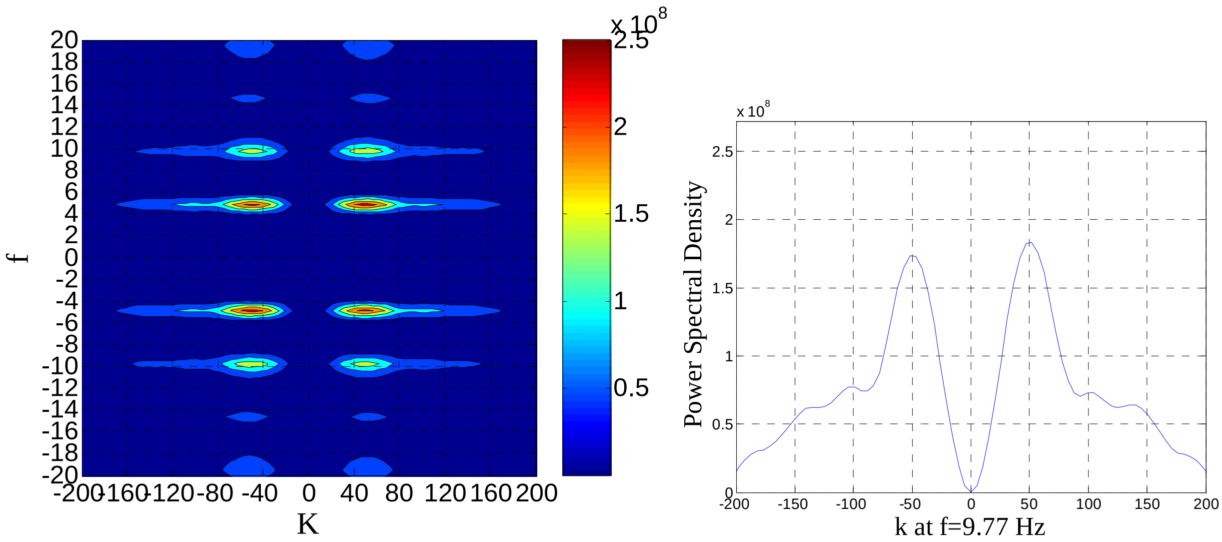

FIG. 5: Experimental wave number-frequency spectra of wall pressure fluctuations at α = 8°, σ = 1.27, Re=800000

4.2 Numerical Data

Calculations around the NACA 66 foil section were performed using different cavitation models and the wavenumber-frequency method was applied on the pressure coefficient signals.

FIG. 6 shows the 2D spectra obtained with the four tested cavitation models.

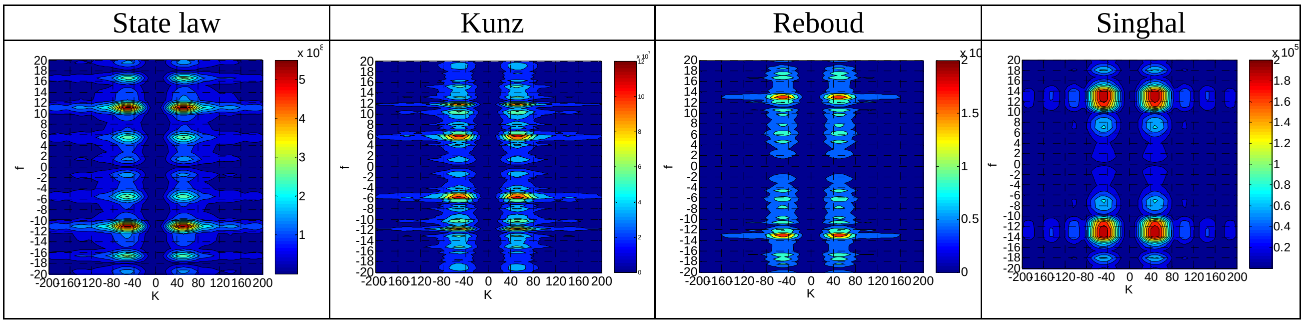

FIG. 6: Numerical wave number-frequency spectra of wall pressure fluctuations obtained with several cavitation models at $\alpha = 8°$, $\sigma = 1.3$, Re=800000

All the spectra give a characteristic wavelength $\lambda/c \approx 80\%$; this value is close to the maximum length of the attached cavity. They also clearly detect the main frequency of the cavity oscillations. The second frequency is also detected with all the models but with differences in amplitudes; a well defined peak is for example detected in the spectra obtained with the Kunz model but not with the Reboud model. It suggests that the source term expression may have some minor impact only on the flow simulations, if it is based on the local pressure non-equilibrium $P - P_v$, which is the case in all the present models. It also confirms that results obtained with the barotropic state law are very similar to the ones derived from the use of transport equation for the void fraction.

5 Conclusions

Numerical and experimental studies of partial cavitation were performed in this paper. Computations were conducted on a 2D configuration of NACA 66 hydrofoil section A general good agreement between the numerical results and the experimental data is obtained: the unsteady periodical behaviour of the sheet cavity, the cavity length and the frequency of the cavity oscillation are correctly predicted. The study shows large similarities between tested models. A wavenumber-frequence spectrum method was applied and has demonstrated its capability to measure both the frequencies of the cavity oscillations and the maximum length of the attached cavity.

References

[1] Frikha, S., Coutier-Delgosha O., Astolfi, J. A., Numerical Investigations of the Cavitating Flow on Two-Dimensional Hydrofoils : Physical Modelling Methodologies , 12th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery, Honolulu, Hawaii, USA, February 17-22., 2008.

[2] Frikha S., Coutier-Delgosha O., and Astolfi J. A., Influence of the Cavitation Model on the Simulation of Cloud Cavitation on 2D Foil Section," International Journal of Rotating Machinery, vol. 2008, Article ID 146234. doi:10.1155/2008/146234, 2008.

[3] Coutier-Delgosha O, Stutz B., Vabre A., Legoupil S., "Analysis of cavitating flow structure by experimental investigations ", J. Fluid Mech., pp 171-222, 2007.

[4] Reboud J.L., Stutz B., Développement d'un modèle diphasique à deux fluides, analyse expérimentale de poches ventilées, réf.RT-LT-211708-01 CREMHyG-03.

[5] Kunz R.F., Boger D.A, Stineberg D.R., Chyczewski T.S., Lindau J.W., Gibeling H.J., Venkateswaran S., Govindan T.R., A preconditioned Navier-Stokes method for two-phase flows with application to cavitation prediction, Computers & Fluids 29, 849-874, 2000.

[6] Singhal A K., Athavale M.M., Li H., Jiang Y., Mathematical basis and validation of full cavitation model, ASME Fluids Engineering Division Summer Meeting, ASME Paper FEDSM2001-18015, 2001.

[7] Leroux J.B., Coutier-Delgosha O., Astolfi J.A., A joint experimental and numerical study of mechanisms associated to unsteady partial cavitation on two-dimensional hydrofoil", physics of fluids 17 (5), paper 052101, 2003.

[8] Wills J.A.B, " Measurements of the wave-number/phase velocity spectrum of wall pressure beneath a turbulent boundary layer ", Journal of Fluid Mechanics, Vol. 45, Part 1,pp. 65-90, 1970.