# Partial Cavities: Pressure Pulse Distribution Around Cavity Closure

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# Partial Cavities: Pressure Pulse Distribution Around Cavity Closure[1]

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*Pressure pulse height spectra (PPHS) are measured in the case of partial cavitation attached to the leading edge of a hydrofoil. It is shown that the distributions of pressure pulses around cavity closure may significantly differ according to the type of cavity. In the case of a thin, well-closed and stable cavity, the pressure pulse distributions exhibit a strong maximum centered on the visible cavity termination. As the cavity becomes thicker and increasingly open and unsteady, the pressure pulse distribution widens. In the limit case of a cavity periodically shedding bubble clusters, no definite maximum in the pressure pulse distribution is observed. In addition, scaling of pressure pulse height spectra is approached from measurements at two different velocities. It is shown that the pressure pulse height spectra can be correctly transposed from a velocity to another one from two basic scaling rules concerning pulse heights and production rates of bubbles.*

## 1 Introduction

A cavitating flow produces generally a large number of vapor structures as bubbles or small-scale hollow vortices that are convected downstream. When they reach high pressure zones, they collapse and can cause erosion to the solid walls. If close enough to the wall, the collapsing structures induce pressure pulses on its surface. Then the erosion capability of the whole cavitating flow can be characterized by a pressure pulse height spectrum (PPHS). PPHS is defined at any location on the wall and generally differs from a location to another one.

PPHS can be considered as a measure of the aggressiveness of a cavitating flow; it is purely hydrodynamic characteristic if the interaction between the fluid and the material (or the transducer sensitive part) can be neglected. This interaction is measured by the ratio of the acoustic impedances $(\rho c)_{\text{liquid}}/(\rho c)_{\text{solid}}$. In the case of water and stainless steel, it is smaller than 4 percent: the backward motion of the wall under the action of a pressure impact does not damp significantly the liquid overpressure and so does not alter PPHS. This difficulty on principle will appear of minor importance with respect to other measuring difficulties which will be discussed later on.

Once the erosion capability of a cavitating flow has been determined, the problem is to estimate the damage (in terms of pitting rate, mass loss . . . ) caused on the material by the given PPHS. The simplest approach consists in characterizing the material by a threshold (see for instance Hammitt, 1979 or Lecoffre et al., 1985): the collapse of a vapor structure produces a permanent pit only if the height of the associated pressure pulse exceeds the material threshold. More sophisticated models taking into account mechanical and metallurgical properties of the material can be used (Karimi and Léo, 1987; Franc et al., 1991).

The experimental determination of PPHS raises a few basic difficulties. First, the pressure transducer must have a very high natural frequency to reproduce as reliably as possible the sudden rise in pressure of duration of a few $\mu$s or less. If not, the signal height is underestimated. Second, the sensitive surface must be very small and in theory smaller than the size of the impacted area, to avoid once more an underestimation of the pulse height. If not, the measured pressure is actually the equivalent mean pressure which would give the same output if it were uniformly applied to the whole sensitive surface. A simple way to get a first estimate of the actual pulse height is to consider a pulse height amplification factor equal to the ratio of the sensitive surface area to the mean area of erosion pits. Such an estimation is presented in Section 4. Finally, the transducer must obviously be sufficiently resistant not to be damaged.

Though all these requirements cannot always be fulfilled, several investigators carried out measurements of PPHS and interesting results have been obtained. De and Hammitt (1982) measured PPHS in a cavitating venturi in order to correlate the acoustic power derived from PPHS with the cavitation damage rate. Fry (1989) developed an analogue pulse height analyzer to investigate PPHS on two cavitation sources: a wedge and a circular cylinder. Fry shows that it is possible to find a height threshold where the noise ratio for the two sources matches their erosion ratio. Iwai et al. (1991) used PPHS measurements to explain the progression of the erosion in a vibratory device.

[1]This paper is the revised version of a paper contributed at the 3rd Int. Symp. on Cavitation Noise and Erosion in Fluid Systems, ASME Winter Annual meeting, San Francisco, Ca, Dec. 10-15, 1989.

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The present study is devoted to the measurement of PPHS in the case of a partial cavity attached to the leading edge of a foil for which we know that there is generally a maximum of erosion in the cavity closure region. The flow configuration is described in another paper (Le et al., 1992) in the same issue of the Journal which presents in detail the different cavity patterns and the corresponding mean pressure distributions. In the present paper, we analyze how PPHS changes along the hydrofoil in relation to the global behavior of the cavity. In addition, the problem of scaling PPHS is approached from measurements at two different velocities.

## 2 Experimental Conditions

The experimental setup has been described by Le et al. (1992). The tests were carried out in the hydrodynamic tunnel of the "Institute of Mechanics of Grenoble" (France) on the foil section presented in Fig. 1. The flat upperside was chosen for an easy mounting of the pressure transducers. Nine identical pressure transducers were mounted. They are held on a circular plate which can be rotated to change the location of the measuring points. In particular, all transducers can be set at the same abscissa in order to compare their response and proceed to an in-situ relative calibration (see Section 3).

The transducers are made of piezoelectric ceramic disks whose main characteristics are:

—thickness: 1 mm
—diameter: 0.9 mm
—natural frequency: 1.7 MHz
—sensitivity: 20 V/MPa.

The sensitivity and natural frequency given above are relative to the primary ceramic without its protecting coating. A complementary calibration is needed to determine the actual sensitivity of the final transducer[3].

The signal processing consists in transforming the pressure pulses into square pulses whose height is equal to the maximum height of the pressure pulse and whose duration can be adjusted from 1 to 20 $\mu$s. It is chosen so that further oscillations of the signal which are not due to a collapse but to unwanted internal oscillations do not trigger a false pulse. Then an adjustable threshold is imposed before counting. The counting time was generally chosen equal to 100 seconds.

## 3 Dynamic Calibration

A dynamic calibration suitable to the analysis of cavitation pressure pulses needs to be carried out on a calibrated pressure solicitation of low rise time and high amplitude comparable with the ones due to the collapse of a bubble, say a few hundred of MPa for a time of the order of the microsecond. At the present time, we are developing a special calibration device which should allow to get near these orders of magnitude, but it is not yet available. The only dynamic calibration which was carried out for the present study was relative to low frequencies (< 1 kHz) and low amplitudes (see Nguyen The et al., 1987). It gave a sensitivity from 0.5 to 1.5 V/MPa, slightly variable from one transducer to another one. The value of 1 V/MPa can be used as an order of magnitude to convert Volts into MPa. We must be fully aware that such a procedure leads to a very crude estimate of pressure pulse amplitudes. Though actual amplitudes are of great importance for a further prediction of cavitation erosion, it is not the central part of this paper which is devoted to a relative comparison of histograms.

[3]At the present time, we use piezoelectric films to build pressure transducers.

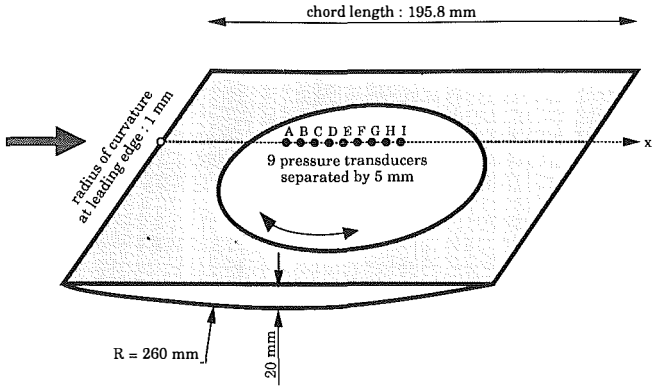


Fig. 1 Sketch of the foil

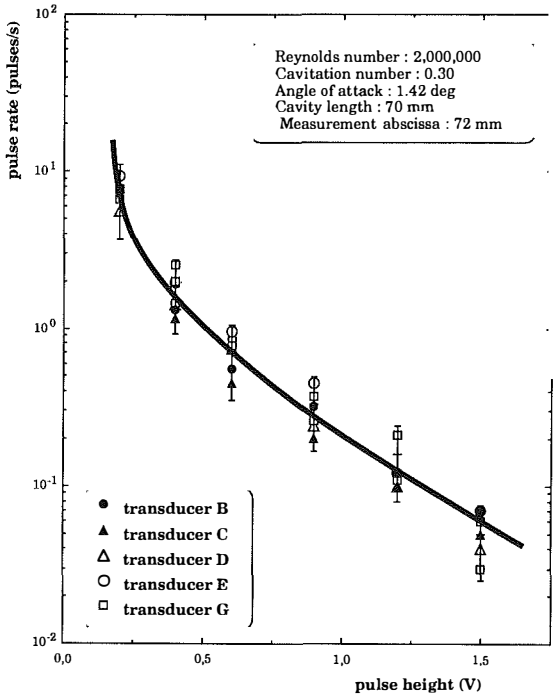


Fig. 2 In-situ relative calibration of 5 pressure transducers

In view of the difficulties to make an accurate absolute dynamic calibration at high frequency and high amplitude, we decided to make an in-situ relative dynamic calibration. This is realized by turning the circular plate (see Fig. 1) so that the nine pressure transducers are at the same abscissa. For this configuration and for given test conditions (angle of attack, velocity and cavitation number), a PPHS is measured by each transducer. *The comparison of the different PPHS allowed us to compare the responses of the different transducers. This operation was performed under various test conditions. A typical example is given in Fig. 2.* It corresponds to five pressure

## Nomenclature

$c$ = density of vapor structures (structures/cm$^3$)
$f$ = shedding frequency (Hz)
$H$ = pulse height
$l$ = cavity length
$N$ = pulse rate (pulses/s)
$\dot{n}$ = pulse rate per unit surface area (pulses/mm$^2$/s)
$\alpha$ = angle of attack (deg)
$\sigma_v$ = cavitation parameter
$V$ = flow velocity

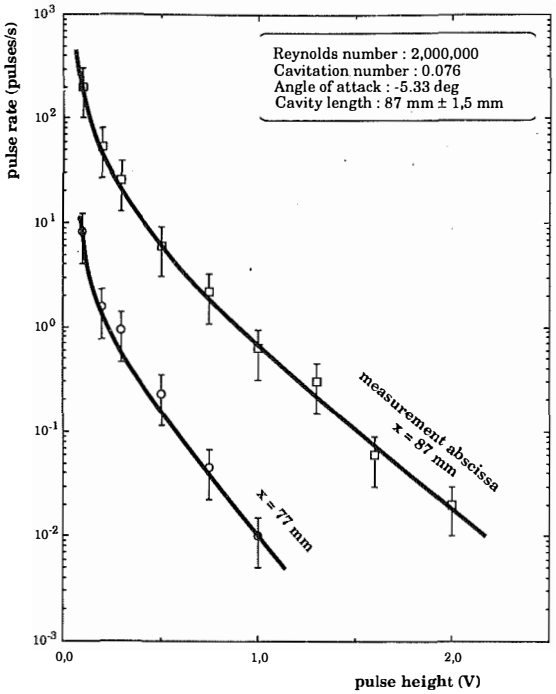


Fig. 3 Pressure pulse height spectra at different abscissa (cavitation number: 0.076)

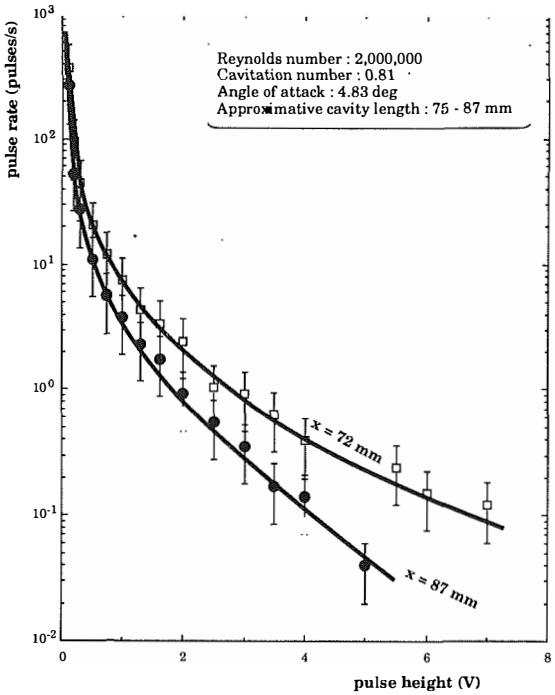


Fig. 5 Pressure pulse height spectra at different abscissa (cavitation number: 0.81)

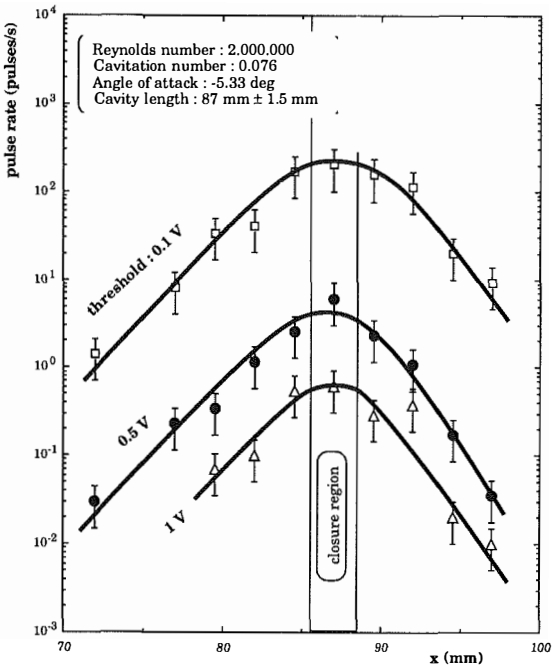


Fig. 4 Pressure pulse distribution around cavity closure for different height thresholds

transducers over the nine which are mounted. We observe that the five accumulative spectra can be superimposed with a good enough precision so that we can suppose that all pressure transducers have the same response. The differences which are observed from a transducer to another one may be due to differences in sensitivity but also to a possible default in bidimensionality even if the cavity globally looks very bidimensional. It results from all the in-situ relative calibrations which were performed that PPHS are known within a maximum uncertainty of the order of ±50 percent. As spectra generally extend over 4 decades (or even more), this uncertainty in logarithmic coordinates represents only 12 percent (or less) of the total measuring scale.

## 4 Pressure Pulse Distribution

Pulse rates given in the present paper correspond to the total number of pulses recorded on the 0.64 mm$^2$ sensitive surface area of the transducers; PPHS refer here to accumulative data i.e., the ordinate corresponds to the frequency of pulses whose height is greater than a variable threshold given in abscissca.

We present here measurements of PPHS for different operating conditions corresponding to different types of partial cavities. Figures 3 and 4 are relative to a low value of the cavitation number ($\sigma_v$ = 0.076) for which the leading edge cavity is thin, well-closed and very stable; the cavity termination fluctuates only on about 3 mm. Figure 5 presents PPHS in the case of a cavity which periodically sheds large clouds of vapor structures ($\sigma_v$ = 0.81).

When comparing PPHS of Figs. 3 and 5, it clearly appears that cloud cavitation is much more aggressive than a stable cavity, even at its termination which is the point of maximum aggressiveness. First, pressure pulse heights are much higher; for $\sigma_v$ = 0.81, the maximum measured pulse height is 7 V whereas it is only 2 V for $\sigma_v$ = 0.076. Secondly, pulse rates are also higher; at given amplitudes of 1 V and 2 V, we counted, respectively:

—for $\sigma_v$ = 0.076: 0.62 and 0.02 pulses/s.
—for $\sigma_v$ = 0.81: 7.51 and 2.43 pulses/s.

There is a ratio of 12 and 120, respectively, in pulse rates between the case of cloud cavitation and the case of a stable cavity. Our measurements confirm the well-known fact that, from an erosion view point, cloud cavitation is much more severe than a stable cavity. Moreover, they show that PPHS can be considered as a quantitative measure of the erosion capability of a cavitating flow.

To go further into the quantification of aggressiveness, it is necessary to convert the values of pulse height in pressure units. If we suppose that pressure pulses result from an impact on a surface of mean characteristic size of the order of 100 $\mu$m

(see for instance Belahadji et al., 1991), the amplification factor due to the difference between the transducer sensitive area and the impacted area is 81. If, in addition we consider a sensitivity coefficient of the order of 1V/MPa as it results from preliminary calibration, pulse heights of 2 V and 7V would correspond to pressure amplitudes of 160 MPa and 560 MPa. These values have to be compared to the elastic and rupture limits of the 316 L stainless steel presently used which are respectively 500 MPa and 650 MPa. These very rough estimates are in agreement with the fact that no erosion is observed on the foil at the velocity of 10 m/s considered here. However, the maximum overpressure in the case of cloud cavitation appears close to the material limits; then it can be conjectured that a moderate increase in aggressiveness (due to an increase in velocity or in some cases to unsteadiness) could cause pitting of the foil. Actually, pitting has been observed in the case of an oscillating stainless-steel hydrofoil whereas the flow velocity never exceeded 8 m/s (Franc and Michel, 1988). Then the present estimates of pressure pulse amplitudes seem reasonable with respect to our own experience. Nevertheless, they have to be considered with care as the method of conversion of pulse height into pressure amplitude (including calibration) needs further developments. It is one of our objectives.

In the case of a very steady cavity termination (i.e., at low cavitation number), pulse rate is maximum at cavity closure. Whereas the maximum in the mean pressure distribution occurs somewhat downstream of the observed point of cavity closure (see Le et al., 1992, Fig. 9), the maximum in pulse rate distribution is exactly centered on this point. The width of the pressure pulse distribution is greater than the apparent width of the region in which the cavity termination fluctuates. In particular, pulses have been recorded upstream the cavity termination point, in a zone which is always covered by the cavity. Downstream, pulses are due to the collapse of vapor structures which are not visible to the naked eye.

The influence of the cavitation number on the pressure pulse distribution is shown in Fig. 6. The cavity length is kept constant which needs to increase the angle of attack when the cavitation number is increased. *By cavity length we mean the maximum length of the cavity estimated visually under stroboscopic lighting.* It appears firstly that the distribution is widening as the cavitation number increases. This is due to a more and more unstable cavity closure which tends to widen the distribution of bubbles and then of pressure pulses. For the highest value of the cavitation number ($\sigma_v$ = 0.59), no definite maximum in the pressure pulse distribution can be noticed in the measuring zone. In that case, the cavity is very unsteady and sheds periodically cavitating vortical structures. The cavity length oscillates between a maximum length of about 87 mm and a minimum length of about 30 mm. Unsteadiness appears to be the main factor of extension of the region of bubble collapse.

Second, it appears on Fig. 6 that the pulse rate increases with $\sigma_v$ which depicts an increase in the concentration of bubbles. This is coherent with visualizations which show that the whole cavity becomes more and more bubbly as the cavitation number is increased.

## 5 Similarity Law for PPHS

The aim of the present section is to study how PPHS are scaled with a change of velocity. It requires one to know jointly how pulse heights are changed and how the production rate of bubbles varies. To approach this problem, PPHS were measured at two different velocities (5 m/s and 10 m/s). From such measurements, we cannot directly answer the double question of scaling pulse height and production rate. But we can easily check if spectra are correctly scaled when two distinct hypothesis on pulse heights and production rates are made.

If the velocity is doubled, we have checked (Le et al., 1992)

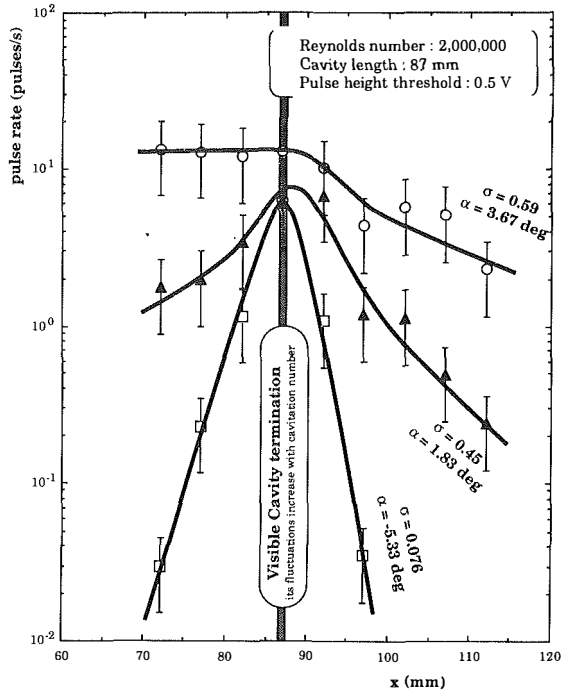


**Fig. 6 Influence of partial cavity pattern on pressure pulse distribution at constant cavity length**

that the shedding frequency of large vapor structures is approximately doubled according to the classical similarity law. Concerning the much smaller structures as bubbles or microscale cavitating vortices which are responsible of the measured pressure pulses, we shall assume, following Lecoffre et al. (1985), that the Strouhal similarity law still applies to their production rate. In other words, we suppose that for both velocities, each large structure breaks up into the same number of small bubbles. Then our first assumption consists in considering that the production rate of bubbles is proportional to the velocity.

Concerning pulse heights, it is generally assumed that the impact pressure results from a shock wave mechanism. Then the impact pressure is given by a water-hammer type formula $\rho c V_j$ where $\rho c$ is the acoustic impedance of the fluid and $V_j$ the velocity of the fluid/vapor interface. In a first approach, considering a nondimensional form of the Rayleigh-Plesset equation in which surface tension and air content are neglected, it can be assumed that the interface velocity $V_j$ in the final stage of collapse is proportional to the characteristic flow velocity $V$ in so far as the cavitation parameter is kept constant. Hence, the pulse heights are themselves proportional to the velocity. This is our second hypothesis.

In consideration of these two assumptions, we can easily deduce how PPHS are affected by a change of velocity. If the velocity is multiplied by a factor $k$, pulse heights as well as pulse rates are multiplied by the same factor $k$; so, if $\dot{N}_V(H)$ is the rate of pulses whose height is greater than $H$ at velocity $V$, we have:

$$\dot{N}_{kV}(kH) = k\dot{N}_v(H)$$

Figures 7 and 8 present for two different values of the cavitation number the measured PPHS at 5 m/s and 10 m/s as well as the estimated PPHS at 10 m/s obtained from the measured ones at 5 m/s by means of the above scaling formula. Although the transposition is not perfect, transposed PPHS appear to be a correct estimate of the actual PPHS in both cases.

Finally, we try to estimate the density of vapor structures in a cloud from the present results for the case of a periodic

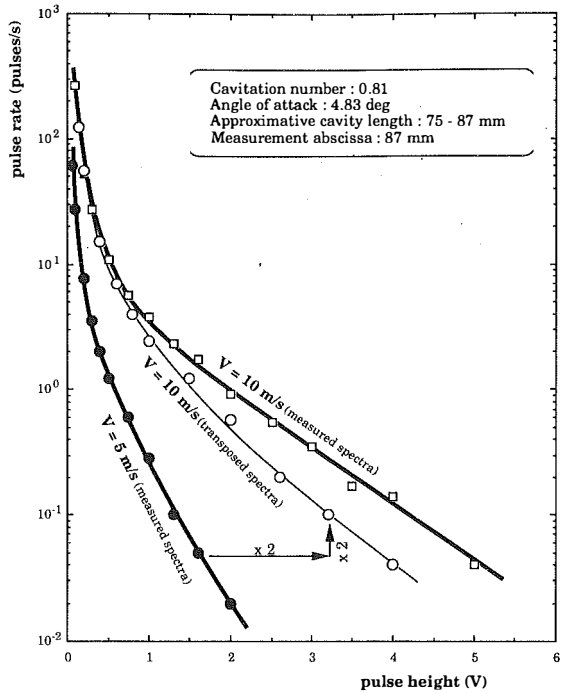


Fig. 7 Similarity law for cumulative pressure pulse height spectra (cavitation number: 0.81)

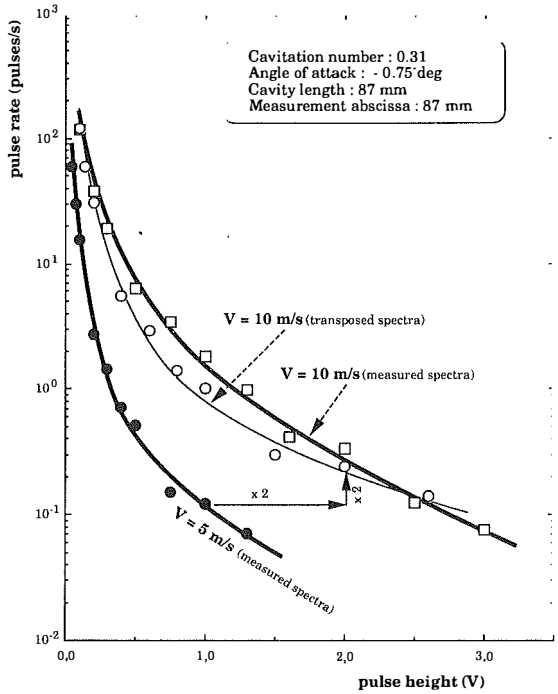


Fig. 8 Similarity law for cumulative pressure pulse height spectra (cavitation number: 0.31)

behavior characterized by the shedding frequency $f$. According to our global analysis of the periodic shedding mechanism (Le et al., 1992), the volume of cavity which is shed during a unit time and for a unit span is $l.e.f$(m$^3$/m/s), where $l$ and $e$ are, respectively, the length and the thickness of the cavity. The total number of pressure pulses measured on the surface covered by the cavity[4] is $\dot{n}.l$ (pulses/m/s), where $\dot{n}$ is the pulse rate per unit surface area. The ratio of the number of pulses to the cavity volume leads to the following density:

$$c = \frac{\dot{n}}{ef}$$

In the case $\sigma_v$ = 0.59, $V$ = 10 m/s, we have:

$\dot{n}_{(H>0.1\text{V})} \cong 380$ pulses/mm$^2$/s[5]
$\dot{n}_{(H>1\text{V})} \cong 5.2$ pulses/mm$^2$/s[5]
$e \cong 10$ mm
$f \cong 39.4$ Hz

then:

$c_{(H>0.1\text{V})} \cong 960$ structures/cm$^3$
$c_{(H>1\text{V})} \cong 13$ structures/cm$^3$

These values can be compared to direct measurements of bubble density. Yamaguchi, et al. (1990) measured the bubble density (excluding cavitating vortices) by a laser holographic system. The bubble concentration depends strongly upon the size and the type of cavitation considered. For unstable sheet cavitation shedding clouds ($\sigma$ = 1.50) which is typically the type of cavitation considered here, they counted 121 bubbles with a diameter greater than 70 $\mu$m in the measuring volume of 3.1 cm$^3$. The bubble density is then of the order of 39 bubbles/cm$^3$. Although no definite conclusion can be drawn at present from the comparison of direct measurements of bubble density with estimations obtained from wall measurements of pulse rates, a few basic question can be raised.

In particular, what is the ratio of bubbles in a cloud which actually give a pulse on the wall when they collapse? In other words, in comparison with the cavity thickness for instance, what is the characteristic thickness of the layer which contains the bubbles collapsing on the wall as opposed to the ones collapsing in the bulk? It probably depends upon the cut-off pulse height; the smaller it is, the more bubbles away from the wall are concerned.

## 6 Conclusion

This paper presents measurements of pressure pulse height spectra for different patterns of partial cavitation. The following summarizes the important conclusions.

1. PPHS appears to be an appropriate way to characterize the hydrodynamic aggressiveness of a cavitating flow. In particular, measured PPHS show that, from an erosion viewpoint, cloud cavitation is much more severe than a thin, well-closed and stable sheet cavity: maximum pulse heights are higher as well as pulse rates.
2. In the case of a well-closed sheet cavity, a strong maximum exists in the pressure pulse distribution, whatever the pulse height threshold may be. It is centered on the cavity closure determined visually. As the cavitation number is increased at constant cavity length, the partial cavity is progressively opening and becoming more and more unsteady, and correlatively the pressure pulse distribution is widening. In the case of high values of the cavitation number for which the cavity periodically sheds bubble clusters, no definite maximum in the pressure pulse distribution is observed.
3. Measurements of PPHS at two different velocities allowed us to approach the problem of scaling PPHS. It is shown that PPHS are correctly scaled if we suppose that:
—the production rate of the bubbles which are responsible of pressure pulses is controlled by the Strouhal similarity law;
—the pulse heights are proportional to the flow velocity as it can be expected if the impact pressure results from a shock wave process.

[4]Still during a unit time and for a unit span.
[5]This value is estimated from a mean value on the nine measuring locations.

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