Modelling of the hydroacoustic sources of butterfly valves

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The French PWR units include a large number of control valves which are sometimes at cavitation working for certain operating conditions. The very high excitations which are then created may lead to the cracking of some small lines located nearby and to the deterioration of the human work acoustical environment. These devices are tested on laboratory test loops with the aim of finding out more about their hydroacoustic behaviour. The butterfly valve test parameters are aperture, flow rate, cavitation number and upstream pressure. An hydroacoustic behaviour model has been set up on the basis of very precise identifications obtained from numerous experimental tests. The transfer model describes the valve as a pocket of depression, the characteristics of which depend on the dynamic conditions. Two kinds of sources are then studied: The sound generated by turbulence is represented by an acoustic dipole. Its modulus depends on the flow rate and on the opening. It decreases according to the frequency. The source generated by cavitation behaves like an acoustic monopole. It depends on the dynamic pressures on both sides of the valve. Its low frequency spectral shape is a plateau. An hydroacoustic criterion characterises the emergence and intensity of the cavitation: practically this allows the wrong conditions to be determined for a given circuit, because beyond a limit value of this criterion, the acoustic and vibration levels increase strongly.

1 Introduction

The industrial pipe networks are subject to vibrations of which sources are often located close to their main components: pumps, diaphragms, valves… The pressure fluctuations generated by these sources are dependent on the hydraulic conditions of the flow: pressures on both sides of the component and flow rate in the pipe. Especially, if the cavitation phenomenon appears, the vibrations increase strongly, what may lead to the cracking of some small lines located nearby and to high acoustical levels in the work environment.

In order to predict these wrong operating conditions for structures and for the human environment, these components are studied from an acoustical point of view on laboratory testing benches.

In this study we present results dealing with butterfly valves.

2 Benches and tests grid

The measurements of the pressure fluctuations far enough from the component allow the low frequency characteristics to be identified, according to a plane waves assumption.

Four testing benches were used in order to investigate the behaviour of valves of different diameters, under different cavitation states: turbulent flow, weak cavitation, fully expanded cavitation or chocking.

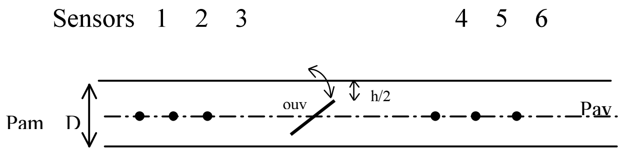

Figure 1: Scheme of the measurement zone.

The tests grids concern large domains of variation of the variables acting on fluid states and many experimental tests inside these domains.

Table 1: Variation domains of the main variables

Flow rate	10 < Q (m3/h) < 620		
Opening $x = \frac{h}{D} = 1 - \cos(ouv)$	13 < ouv (°) < 72	Δ P	
Flow coefficient Cd (x)			σ
Diameter	0,08 < D (m) < 0,20		
Upstream pressure	1 < Pam (bar) < 10		

With the head loss Δ P=Pam-Pav and the cavitation number $\sigma = \frac{Pav - Ps}{\Delta P}$ (Pav: downstream pressure, Ps: vapour pressure).

The hydraulic flow coefficient of the tested butterfly valve is represented on the Figure 2:

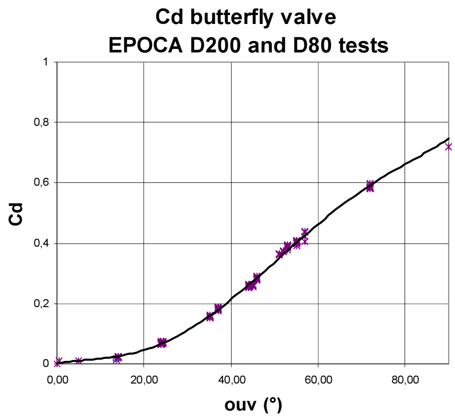

Figure 2: Measured flow coefficient of the EDF butterfly valve.

3 Stages of identification

3.1 Modelling scheme

According to the one dimensional formulation of the acoustic propagation in the pipe, we can describe the valve by a transfer matrix associated with elementary source vectors.

3.2 Transfer matrix: identification and model

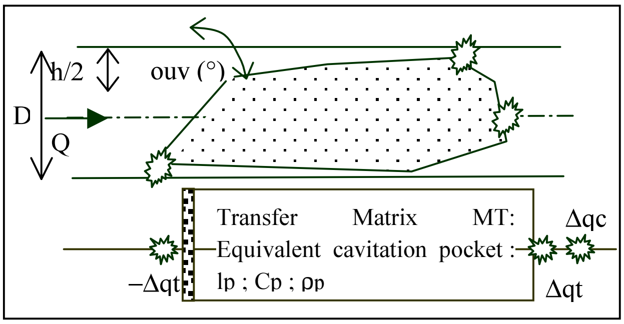

Figure 3: Modelling scheme of a butterfly valve.

With the aim to extract the real excitation sources of the valve, it is important to take into account the hydroacoustic wave transfers through this component.

The first stage of the study consists therefore in modelling the transfer matrix.

Numerous specific measurements (with an outer dominant source) were carried out in order to identify the behaviour model of the hydroacoustic transfers according to the tests parameters.

The butterfly valve appears as a depression pocket which speed of sound Cp, density ρp and length lp are depending of local hydraulic conditions. This pocket is also associated to a local impedance term [1].

The original process we use allows strong cavitation states to be analysed.

3.3 Analysis of the transfer functions

The analysis of the internal pressure transfer functions across the valve with and without cavitation shows two different spectral responses of the same circuit which correspond to two kinds of excitation.

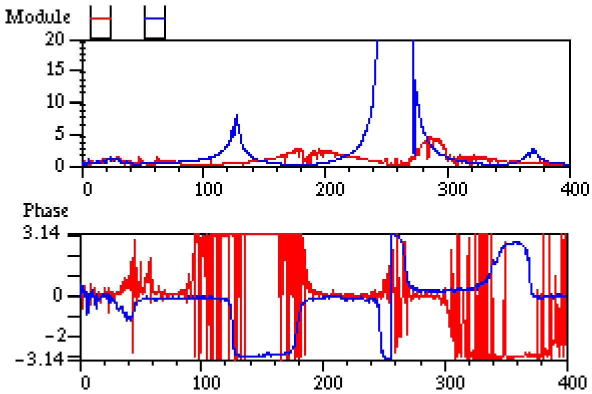

Figure 4: Example of transfer functions p6/p1at the same points for cavitating and non cavitating states.

If we take into account the influence of the transfer terms, it appears that the sound generated by turbulence is represented by an acoustic dipole (or two monopoles opposite in phase and decreasing according to the frequency) and that the source generated by cavitation behaves like an acoustic monopole the shape of which is a plateau.

3.4 Obtaining cavitation criterions

In order to calculate the hydroacoustic behaviour of a valve, we must know what kind of source is present for a given set of hydraulic conditions.

The numerous experimental tests that have been carried out highlight a criterion which characterizes the emergence and the intensity of the hydroacoustic cavitation plateau [2]. This criterion has been established by analysis of the internal transfer functions which allows the emergence of the monopole source to be very accurately determined.

$$crit = \frac{Pam}{Pav}\sqrt{x}\sigma_{cor}^{-1,7}\frac{D}{D_0}$$

D_0=reference diameter (0,203 m),

σ_{cor} : corrected term according to the diameter,

$$\sigma_{cor} = SSE'^{*}\sigma\text{, } SSE' = \left(\frac{D}{D_0}\right)^{Y}\text{, } Y=0,12*Cd^{-x}.$$

With the reference diameter used, the emergence limit of the cavitation plateau is equal to the following value of the criterion : crlim= 0,125.
Above the limit value crlim, the acoustic fluctuations and the vibration levels increase strongly as shown on the figure 5 .

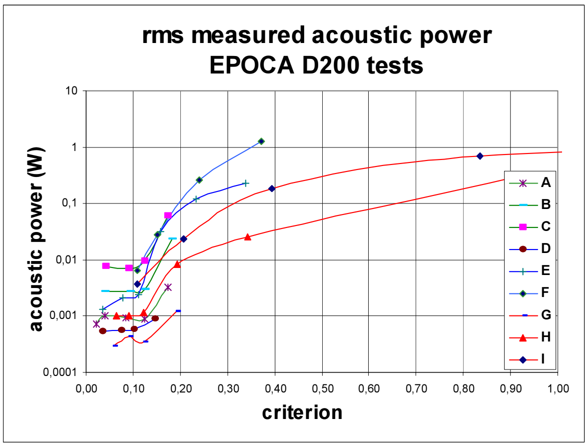

Figure 5: Example of the RMS measured hydroacoustic power according to the criterion - EPOCA D200 tests.

These vibration levels present a lower rate of increase in case of chocking conditions. We observe then a saturation phenomenon accompanied by a decrease of the speed of sound far downstream of the valve. This is corresponding to a very large pocket of vapour micro bubbles.

Figure 6: Example of chocking cavitation with a large pocket of micro bubbles downstream of the valve.

A second criterion defined by $crlt = \frac{Pam}{Pav}\sqrt{x}\,\frac{\sigma_{cor}}{1,5}^{-0,3}$ allows the saturation level of vibration to be determined.

In case of chocking cavitation we have, crit > crlt.

4 Source terms: identification and modelling

4.1 Identification

The acoustic signals of the six sensors of the figure 1 allow the unknown entities Δqc, Δqt (see figure 3) and the reflexion coefficients of the bench to be identified by the classical methods of analysis.

4.2 Modelling

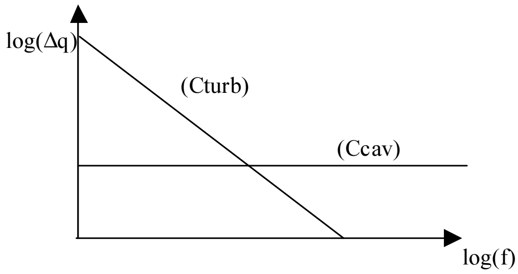

Figure 7: Typical shapes of the sources generated by turbulence and cavitation.

- The source generated by turbulence is always present. It is acting as a dipole excitation. In a generalized representation which is valid for other hydroacoustic components too, we describe this one as two acoustic monopoles Δqt (expressed in kg/s/$\sqrt{Hz}$) according to the figure 3:

$$\Delta q_t = 10^{-12}\rho_0\sqrt{Q}\,\frac{D}{D_0}\,G(x)St^{-1,3},$$

with $St = \frac{fx(1-x)D^3}{4Q}$ and G(x)= (1- x^2).

- The source generated by critical cavitation (as defined in [3]) appears if crit > crlim. It is acting as a monopole excitation related to the implosion of vapor bubbles downstream of the valve.

We describe this one as an acoustic monopole Δqc (expressed in kg/s/$\sqrt{Hz}$) according to the figure 3:

$$\Delta q_c = -4.10^{-8}\rho_0\sqrt{Q}\,\frac{D}{D_0}\left(\frac{cr}{cr\lim}\right)^2\frac{P_{av}}{P_{am}}$$

In this expression cr is equal to crit if crlim < crit < crlt and cr is equal to crlt if crit > crlt.

We can observe that the normalized criterion is a weighting coefficient of the cavitation source. This one depends on the rate of the downstream and upstream pressures and on the square root of the flow rate.

This modelling is valid in a frequency range less than the growing frequency of the bubbles (about 1500 Hz in our experiments).

5 Acoustic power

5.1 Power level

The complete hydroacoustic model is then used to calculate the emission and the propagation of hydroacoustic valves in a given pipe. The reflexion coefficients at the both limit sections, and the speed of sound in the domain must be identified or prescribed.

A classical one dimensional model allows the acoustic pressures to be computed.

As example, we present on figure the 8 the internal pressures and transfer function measured and calculated at two sensor sections for the experimental conditions of the cavitating B5 test.

Table 2: B5 test conditions (Ps=0,017 bar)

ouv (°)	Q (m3/h)	Pam (bar)	Pav (bar)	crit	crlt
53	510	1,92	1,38	0,182	0,443

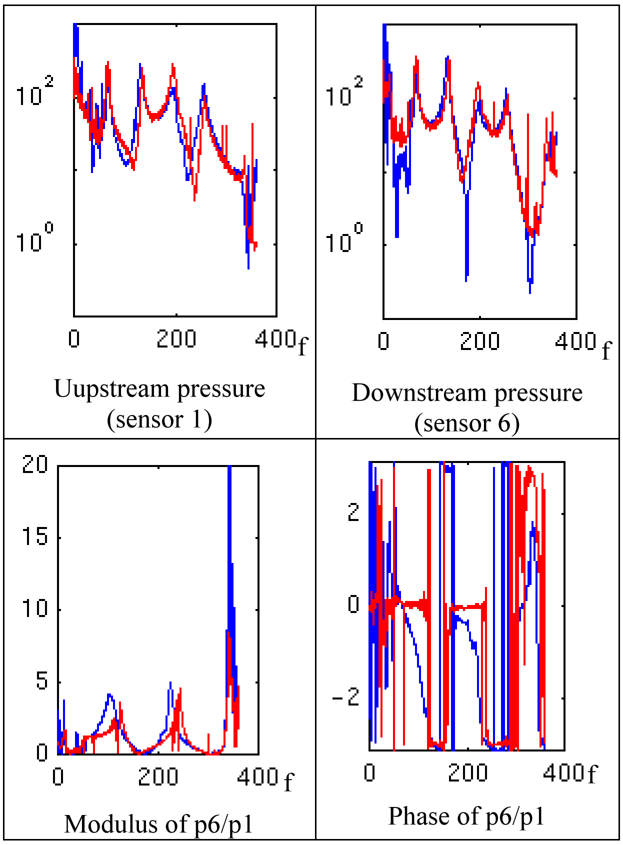

Figure 8 : Measured (red) and calculated (blue) pressures (Pa/$\sqrt{\text{Hz}}$) at the sensors 1 and 6 - B5 test.

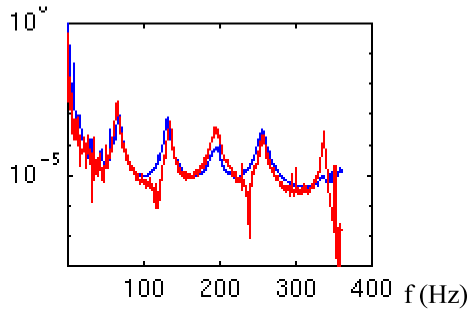

Figure 9 : Measured (red) and calculated (blue) hydroacoustic power (W/Hz) - B5 test.

The spectral hydroacoustic power emitted by the valve (figure 9) is integrated over the analysis domain.

The RMS powers carried out for the tests points show a good agreement between measure and model (see figure 10, and figure 11 which is to compare to the figure 5).

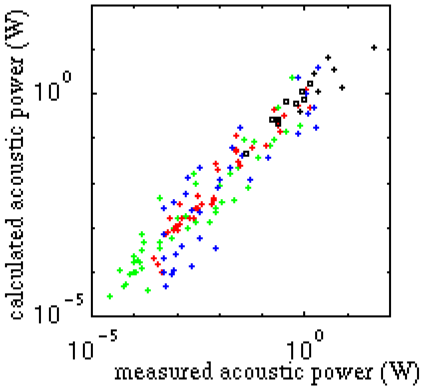

Figure 10: Calculated and measured RMS acoustic power for the tests points (W).

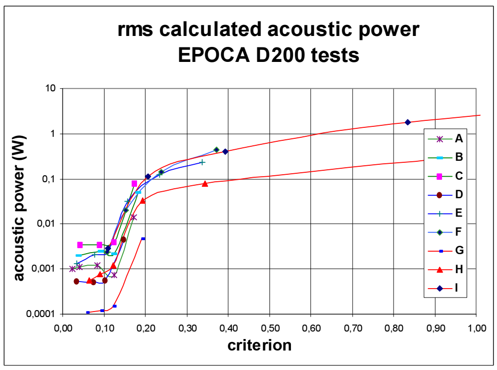

Figure 11: Example of the RMS hydroacoustic calculated power according to the criterion - EPOCA D200 tests.

5.2 Behaviour according to the main variables

In this part we present numerical simulations in the aim to estimate the valve hydroacoustic behaviour according to the main variables of the problem:

opening angle ouv, upstream pressure Pam, diameter D, flow rate Q.

We compute the response of the model with anechoic terminations and we deduce the RMS value of the intrinsic power of the valve for the specified hydraulic conditions.

Some applications are presented below. For these numerical simulations, we use a formulation of Cd(x) directly issued from [5].

- Application 1: Q varying, Pam varying, ouv =30, D=0,203m.

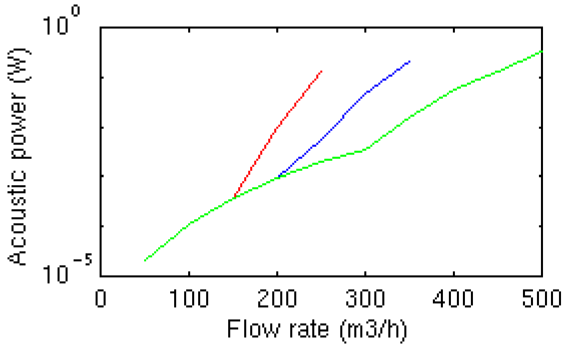

Figure 12: RMS power according to the flow rate for three upstream pressures (red: Pam= 5bar, blue: Pam=10 bar, green: Pam=20 bar).

The hydroacoustic levels arising from the turbulence are independent of the upstream pressure. The flow rate associated with the emerging cavitation increases according to the upstream pressure (see 5.3). For a given flow rate, the levels arising from cavitation are weaker when the upstream pressure is stronger.

- Application 2: D varying, ouv varying, Pam= 10bar, Q= 50m3/h.

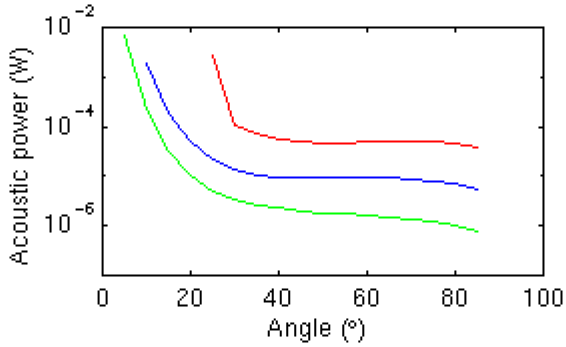

Figure 13: RMS power according to the opening angle for three diameters (red: D=0,103m blue D = 0,203m, green: D =0,325m).

For a given flow rate, the hydroacoustic power increases strongly if the cavitation occurs. We observe for example on the figure 13 that an opening angle of 30° is cavitating at 50 m3/h for the smaller diameter.

- Application 3: Q varying, ouv varying, Pam= 10bar, D=0,324 m.

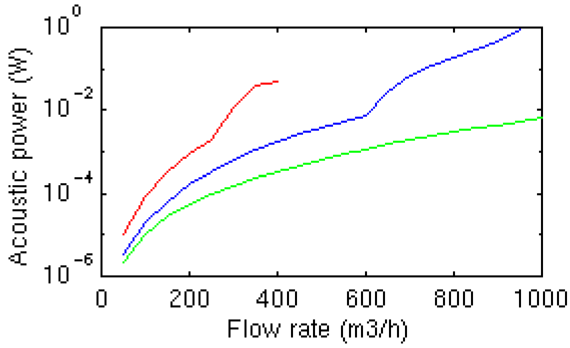

Figure 14: RMS power according to the flow rate for three opening angles (red: ouv=20°, blue ouv = 30°, green: ouv =50°).

The preceding remarks are valid for these simulations: the smaller is the opening, the higher is the hydroacoustic power for a given flow rate.

The green curve shows a turbulent state, the blue one a cavitating state above 600 m3/h, the red one a cavitating state at 100 m3/h.

- Application 4: Q varying, D varying, ouv =30°, Pam= 10bar.

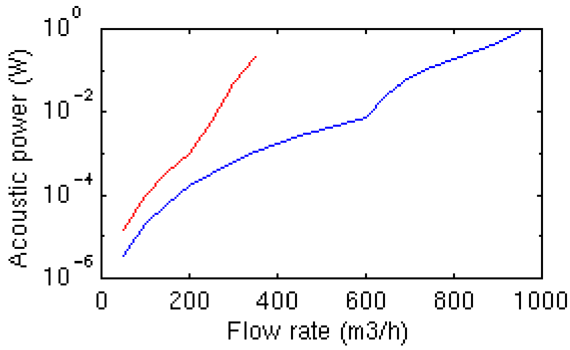

Figure 15: RMS power according to the flow rate for two diameters (red: D=0,203m, blue: D= 0,324m)

Because of the direct dependence of the hydroacoustic sources on the flow velocity, for a given flow rate the smaller is the diameter, the higher is the emitted acoustic power. The emerging cavitation occurs for a specific speed. So the higher is the diameter, the higher is the flow rate of emerging cavitation

5.3 Flow speed of cavitation

A practical way to predict the states of cavitation of a valve under given conditions is to use predetermined abacus.

- To determine the emerging cavitation state we have therefore to calculate x which verify:

$$\frac{Pam}{Pav}\sqrt{x}\,\sigma_{cor}^{-1,7}\,\frac{D}{D_0}=0,125$$

The solution is depending on D, Pam and Ps. It was computed using the Cd coefficient of the EDF valve (figure 2).

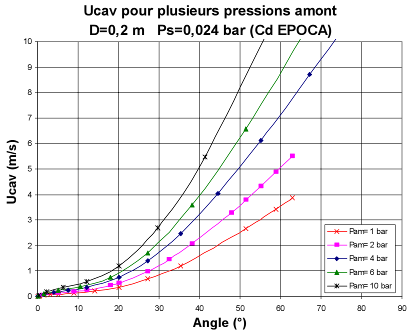

Figure 16: Speed of flow corresponding to the emerging cavitation according to the opening angle and for several upstream pressures. D=0,20m.

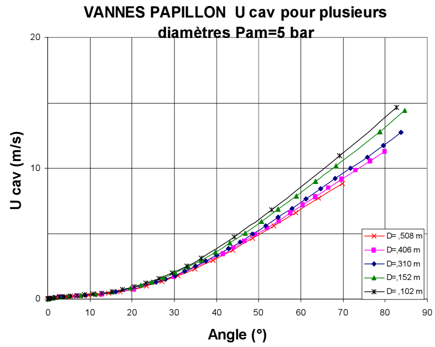

Figure 17: Speed of flow corresponding to the emerging cavitation according to the opening angle and for several pipe diameters. Pam= 5bar.

- To determine the chocking cavitation state we have therefore to verify crit= crlt. So the chocking speeds of flow associated with the preceding diameters and pressures are synthesized on the two following figures.

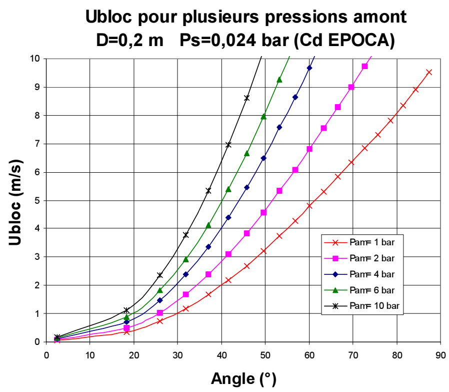

Figure 18: Speed of flow corresponding to the chocking cavitation according to the opening angle and for several upstream pressures. D=0,2m.

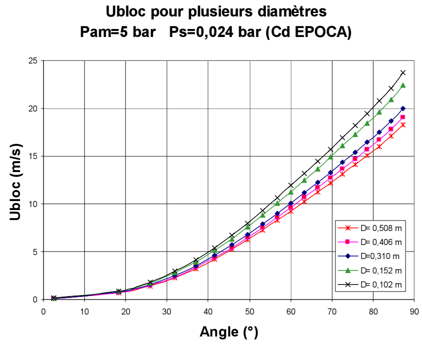

Figure 19: Speed of flow corresponding to the chocking cavitation according to the opening angle and for several pipe diameters. Pam=5bar.

6 Conclusions

The very precise analysis made from numerous laboratories tests have allowed the hydroacoustic intrinsic characteristics of butterfly valves to be identified, for cavitating or simply turbulent states.
An emergence and a chocking criterions have been set up. These ones are useful to determine easily the hydraulic conditions associated with high vibrations levels for a given industrial pipe network.

The modelling of the two kinds of sources generated by turbulence and cavitation allows behaviour laws according to the operating conditions to be highlight.

The applications which have been made with this model corroborate the experimental and empirical results obtained by several laboratories in the past [3,4].

The next steps of the study concern the enlargement of the model to other components, the investigation of higher static pressure cases, and the application to industrial problems.

References

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