Advances in Fluid Mechanics III, C.A. Brebbia & M. Rahman (Editors)
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Prediction of noise generated by orifice plates in liquid systems using a modified form of IEC 534-8-4:1994

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Abstract

This paper presents a prediction technique to determine the pressure ripple in the fluid and the vibration levels in the pipe due to cavitation from an orifice plate. Currently, there is no standard available for predicting either forms of noise from orifice plates. This paper describes the experiments undertaken to develop one. Two prediction techniques are developed and compared with one another. The first of these is based solely on a curve fitting approach of the experimental data, whereas the second is based on a 'modified' form of the IEC standard concerned with predicting control valve noise. Both prediction techniques are subject to experimental testing over a range of differently sized orifice plates; β=0.30, 0.40, 0.54 and 0.70.

A comparison of the two techniques confirmed that the modified IEC prediction approach was the more accurate of the two and was equivalent to an acoustic 'engineering' grade accuracy having a standard deviation of 2.5 dB.

1 Introduction

In the process industry, orifice plates have two major functions. The first of these is as a flow measurement device; the second is as a pressure reduction (or flow control) device. Because of the latter function, orifice plates can often be the

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cause of a fluid phenomenon known as 'cavitation'[1], which is a two stage process which involves the formation and collapse of vapour cavities, figure 1.

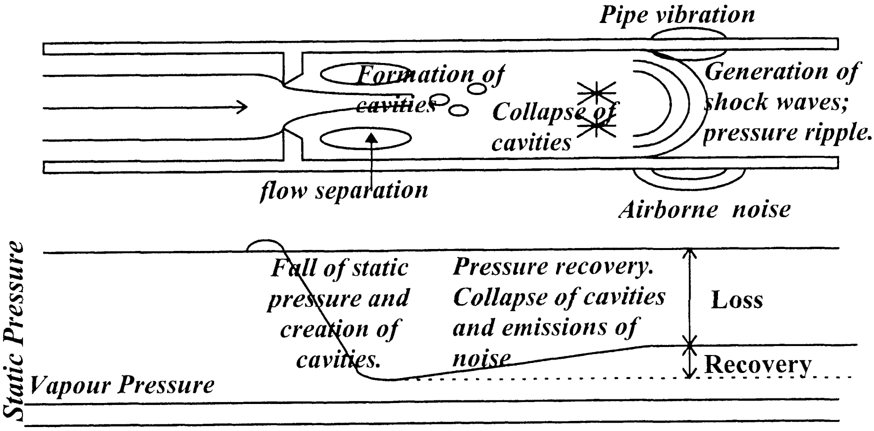

Figure 1 Generation and propagation of orifice plate noise

Researchers in the past focused on the cavitation process by looking at single bubble dynamics [2] and submerged jets [3,4]. The research however was not specifically intended for orifice plates. The first research on sharp-edged orifice plates focused on determining the effect cavitation had on the discharge coefficient, [5]. A later paper [6], based on earlier work, presented data which predicted various levels of cavitation for sharp-edged orifice plates over a wide range of β values, (β= diameter of orifice [d] / internal diameter of pipe [D]).

A problem which many researchers have found with cavitation noise is the deviations encountered between experimental values and predicted values. Hence, researchers have aimed at determining scaling relationships between differently sized orifice plates [7,8] subject to different pressure conditions.

This paper aims to offer a methodology for predicting noise due to cavitation from orifice plates based on the existing IEC standard for control valves, [9].

2 Background Theory

Cavitation and cavitation noise in valves have received much attention in the literature and an obvious dissimilarity is the different cavitation parameters that are used. The cavitation parameter, X_F, adopted here is the form used in the IEC standard [9],

$$X_F = \frac{P_1 - P_2}{P_1 - P_V} \tag{1}$$

Where, P_1 = static pressure (1 diameter) upstream of orifice [Bar],

P_2 = static pressure (6 diameters) downstream of orifice [Bar],
P_V = fluid vapour pressure [Bar].

The methodology adopted by the IEC standard [9] for valves is to calculate the 'internal sound power level', L_{Wi}, generated by the valve. For non cavitating flow,

$$L_{Wi} = 10\log\left[\eta_F \frac{W_m}{W_o}\right] \tag{2}$$

where, $W_m = \dfrac{\dot{m} * \Delta P}{\rho_F}$ is the stream power [Watts],

$\dot{m}$ = mass flow rate [kg/s],
ΔP = differential pressure across orifice plate [Pa],
ρ_F = fluid density [kg/m^3],
η_F = the acoustical efficiency factor [dimensionless],
W_O = reference sound power [10^{-12} Watts].

The acoustic efficiency, η_F, is a significant parameter and will be explained later in the paper. For cavitating flow, the additional term must be added,

$$+\Delta L_F + 180.\left[\frac{X_{Fz}^{0.0625}}{X_F^{X_{Fz}}}.\left(1 - X_F\right)^{0.8}.\log\left\{\frac{1 - X_{Fz}}{1 - X_F}\right\}\right] \tag{3}$$

Where, ΔL_F = valve specific correction factor [dB],
X_{Fz} = cavitation parameter value at which cavitation begins,

Once the internal sound power level is known, the pressure ripple in the fluid can be determined [10] from,

$$\text{pressure ripple level} = L_{Wi} + 10\log(\rho_F . c) - 10\log(A_{pipe}) \tag{4}$$

Where, pressure ripple level = noise level [dB re 1μ Pa],
c = speed of sound in fluid [m/s],
A_{pipe} = area of the pipe [m^2].

3 Experimental Set-up

Four orifice plates covering a wide range of β were chosen for testing; β=0.30, 0.40, 0.54 and 0.70. The orifice plates themselves were sharp-edged and made of monocast 'polypenco' nylon. In the design and manufacture of the orifice plates, all aspects of the British Standard [11] were adhered to. The

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experimental tests were carried out at the National Engineering Laboratory on their 102.5mm bore high pressure line. The rig operates at a duty point of 30 bar with variable flow rates in the range of 3 - 68 litres per second. The rig contains a turbine flow meter upstream to determine the rate of flow. In order to vary the flow and pressure through the test section, figure 2, a control valve is situated upstream and downstream of the test section. The back pressure supplied by the downstream valve is measured with a pressure gauge. A differential pressure meter is situated across the orifice plate to determine the pressure drop in accordance with the British Standard [11]. Bellows were inserted to act as path treatment for the reduction of both pressure ripple and vibrations in the pipe from both the pump and upstream valves.

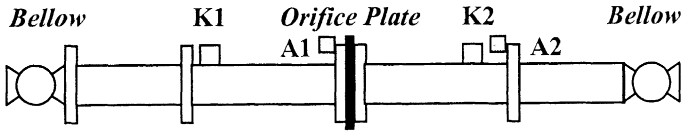

Figure 2 Test Section

To measure the pressure ripple, piezoelectric pressure transducers, (K1 and K2), were located near to the ends of the test section, (upstream and downstream). Accelerometers, (A1 and A2), were placed on the downstream flange and on the upstream face side flange of the orifice. In general, the standard [9] was consulted but no information was given as to the location of either of the aforementioned transducers; the standard focuses on establishing the external airborne noise level and hence only a reference microphone position is offered.

An HP 3567A 4 channel FFT analyser was used to capture the third octave frequency spectrum (in the range 50-10k Hz) from the transducers via Brüel and Kjær type 2635 charge amplifiers.

4 Results

Analysis of the noise concentrated on the 500 to 8000 Hz $\frac{1}{3}$ octave bands of the downstream pressure ripple as this is were cavitation occurred. The first noticeable quality of the data, figure 3, is that it follows the expected characteristic shape [9] , with a turbulence region and a cavitating region. It should be noted that the 'turbulence' part of the plots are contaminated with background noise.

4.1 An 'Empirical' Prediction

The first of the two prediction methods is based on curve fitting polynomials to the experimental data. A prediction equation was sought to determine the

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downstream pressure ripple noise level in terms of parameters which would be quantifiable at the design stages; namely β and X_F.

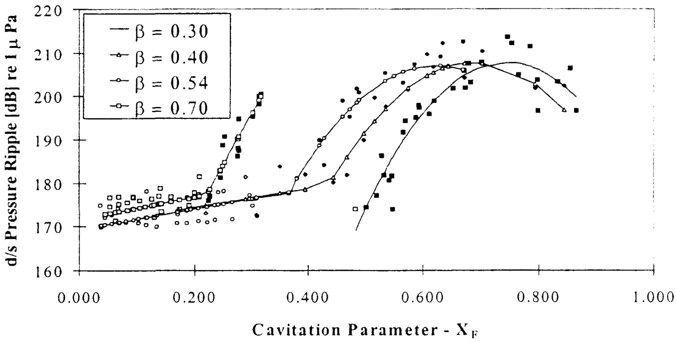

Figure 3 Downstream pressure ripple noise levels v.'s X_F for all orifice plates

A prediction was obtained by considering X_F at the vena contracta, where,

$$X_{Fvc} = \frac{P_1 - P_{vc}}{P_1 - P_V} . \tag{5}$$

The pressure at the vena contracta, P_{VC} can be established [11] from,

$$\Delta P = P_1 - P_{VC} = \frac{8.\rho_F.Q_V^2.\left[1-\beta^4\right]}{C_D^2.\pi^2.d^4} \tag{6}$$

Where, Q_V = the volumetric flow rate [m^3/s],
C_D = orifice discharge coefficient [dimensionless],

where C_D is determined from the Reader-Harris/Gallagher equation [12] using L_1=1 and M'_2=3.59 (which represents the tapping locations of the vena contracta).

A relationship between the pressure ripple noise level and X_{FVC} can be derived by fitting a polynomial for cavitation. Quadratic polynomials were chosen as the relationship between the sound pressure level and the cavitation parameter as suggested in the literature [4]. Fitting trendlines produced the following coefficients (for cavitation only), table 1.

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Table 1 Coefficient Values of Polynomial Fits for Cavitation only

β	FBN Equation : a X_{FVC}^2 + b X_{FVC} + c		
d/D	a	b	c
0.30	-468.99	796.28	-129.52
0.40	-359.08	591.13	-33.51
0.54	-330.59	514.39	11.40
0.70	-63.67	231.91	106.13

In plotting β against the coefficient values, a relationship is derived from which the downstream pressure ripple noise level due to cavitation can be calculated,

$$\text{Pressure ripple level [dB]} = \left[1677.9\beta^2 - 752.6\beta - 373.9\right] \times X_{FVC}^2 + \left[-204.4\beta^2 - 1110.1\beta + 1125.3\right] \times X_{FVC} + \left[-438.2\beta^2 + 996.6\beta - 382.0\right] \quad (7)$$

The following term should be included where the downstream pipe is not 102.5mm diameter;

$$\text{Pressure ripple in pipe dia, } D_{pipe} \text{ [mm]} = \text{Pressure ripple level} - 20\log\frac{D_{pipe}}{102.5} \quad (8)$$

Figure 4 shows a comparison between the prediction eqn (7) and the experimental values collected. The accuracy of the fits can be found in table 2.

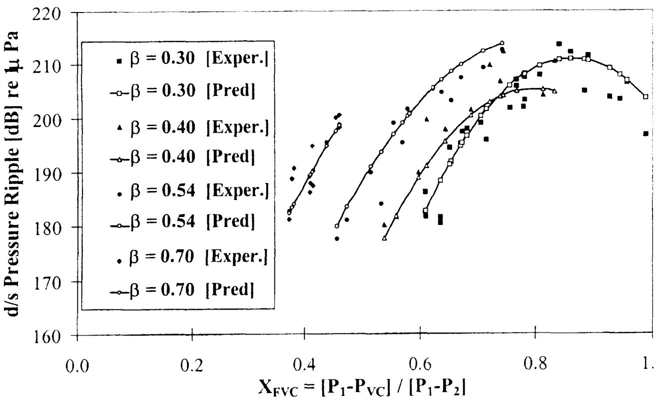

Figure 4 Comparison of Experimental Data to Prediction Equation (7)

As for the downstream pipe vibration noise levels, these can be calculated from,

$$Vib[dB re 10^{-5} m/s^{-2}] = \text{Pressure ripple level - [79.9+(7.85*}X_F\text{)]} \quad (9)$$

where the last term is the difference between the pressure ripple noise level and the vibration noise level measured; ‘transmission loss’. The transmission loss,

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(figure 5), is for all of the orifice plates indicating that the vibration noise level is indirectly related to the β ratio.

The proposed prediction technique for vibration noise level is solely based on experimental data for orifice plates used on 102.5 mm, Schedule 40, DN16 pipe. Such parameters as the air content [3,13], surface tension and treatment of the water (for nuclei distribution [3,14]) were not considered.

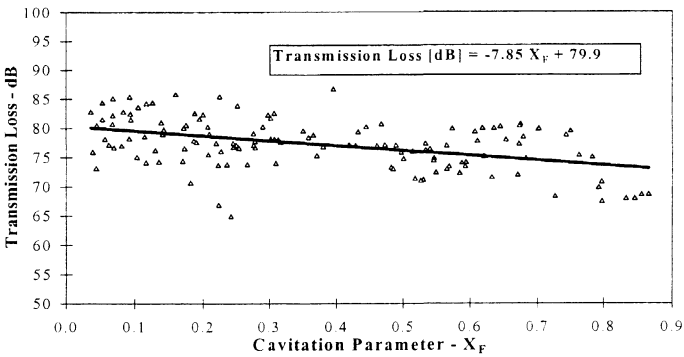

Figure 5 Experimental transmission loss by way of subtraction

4.2 A 'modified' IEC prediction

The second prediction method involves a modification to the current IEC standard for control valves [9]. In order for the orifice plate prediction to be of the same form as the equations in the standard [9], (eqn(2) and (3)), two parameters must firstly be derived 'empirically'; namely the point of inception (X_{Fz}), and the acoustic efficiency factor (η_F). A constant value of η_F is used in the standard and a valve specific correction factor, ΔL_F compensates for deviations. For the orifice plate prediction, the authors have considered η_F a variable and hence have taken ΔL_F to be zero.

The point of inception is regarded as the point at which cavitation begins and can be inferred from the pressure ripple noise level versus X_F plots where both curves meet, (figure 3). Figure 6 shows how the inferred XFz values vary with β for the experimental data resulting in the relationship:

$$X_{Fz} = -0.67.\beta + 0.70 \tag{10}$$

The inception point of cavitation has received much attention in the literature; in particular from Tullis & Govindarajan [6] and more recently, Yan et al [15]. A comparison to the authors' data revealed the need for a standardised approach in the determination of X_{Fz}. The method used for control valves [16], could be considered for orifice plates.

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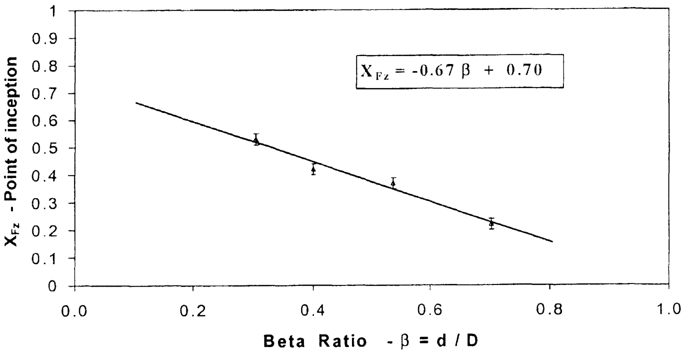

Figure 6 Relationship between the point of inception and β

The relationship for X_{Fz}, eqn (10), was used to work back from the experimentally measured pressure ripple levels, in combination with eqn's (2), (3) and (4) to derive values of η_F. Figure 7 shows a typical result for one of the orifice plates.

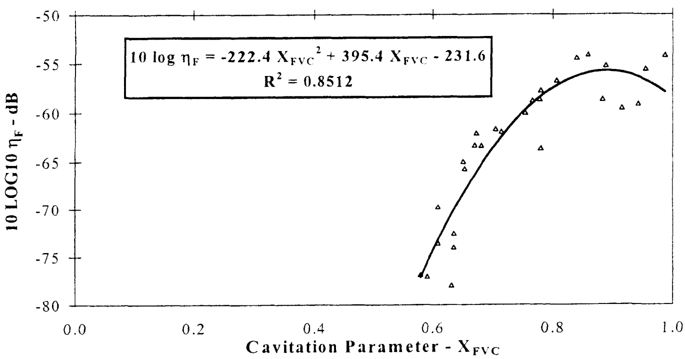

Figure 7 Change in Acoustic Efficiency

In deriving a relationship for the acoustic efficiency, it was once again decided to use those parameters available at the design stage; β and X_{FVC}. Adopting a similar polynomial curve fit method to that used in section 4.1, the acoustic efficiency factor (in dB) can be calculated from,

$$10\log \eta_F = \left[(-517.36 * \beta) - 37.06\right].X_{FVC}^2 + \left[(221.89 * \beta) + 290.1\right].X_{FVC} \quad (11)$$
$$\left[(105.67 * \beta) - 250.29\right]$$

Equations (10) and (11) when substituted into eqn.'s (2) and (3) allow for the determination of the internal sound power level, L_{Wi}. The pressure ripple level in the fluid can then be successfully calculated from eqn (4). Results of applying this prediction to the experimental data are shown in figure 8.

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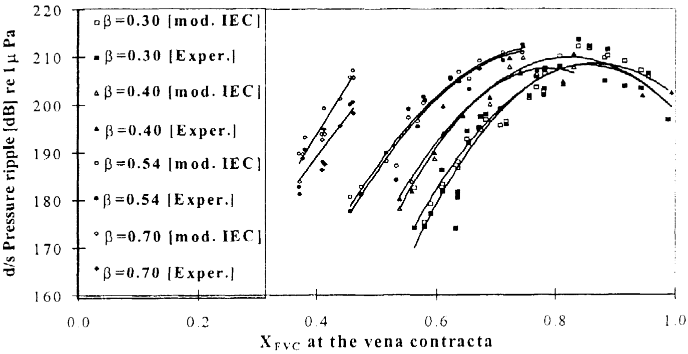

Figure 8 Comparison of experimental data to 'modified' IEC Prediction

4.3 Comparison of Both Prediction Methods

As a means of comparing the two methods, the standard deviations of the experimental minus the predicted values was calculated. The results, table 2, show the modified IEC method to be the more accurate since it has an average standard deviation of approximately 2.5 dB.

Table 2 Summary of standard deviations of predictions

β	Standard Deviation	
d/D	dB [Exp-EmpiricalPred]	dB[Exp-ModifiedIEC]
0.30	3.40	3.18
0.40	3.90	1.95
0.54	2.92	1.77
0.70	2.95	2.16

In terms of acoustic standards, e.g. [17], a standard deviation of 2.5 dB is consistent with an engineering grade accuracy.

4.4 3D Analytical Results

It was observed during the analysis of the noise curves that some of the apparent scatter of the noise data, (for any one orifice plate size), was attributable to lines of constant flow rate overlaid on lines of constant back pressure, figure 9. Similar lines with flow rate were observed by Yan [15] and Winn & Johnson [18]. An improved accuracy of prediction may be possible by separating out the flow rate and back pressures as variables. One approach being used to help visualisation of the data is to use a 3D surface plot, figure 10, rather than the 2D form used if figure 9. This is currently being investigated but it is expected to result in a more complex prediction equation.

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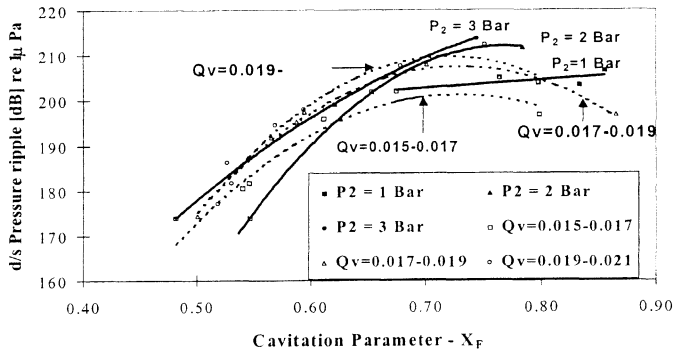

Figure 9 Lines of Constant Flow Rate and Back Pressure

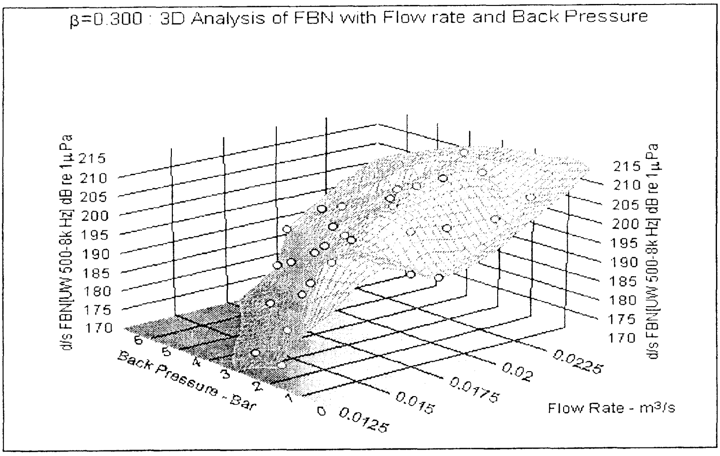

Figure 10 Relationship between the flow rate and back pressure with noise level

5 Conclusions

With the experimental data, two methods of prediction were investigated. In terms of accuracy, the best method appeared to be that of the modified standard which results in an 'engineering' grade accuracy. This prediction was derived from data in the ranges shown in table 3 which may impose some constraints if extrapolation outside these ranges is attempted.

The modified IEC standard prediction in its present form could be considered as a supplement for the necessary standards as a prediction of noise for orifice plate cavitation.

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Table 3 Flow rate and back pressure range of data

β	Flow	P_2
d/D	m^3/s	Bar
0.30	0.013 - 0.023	0 - 7
0.40	0.012 - 0.040	0.5 - 5
0.54	0.010 - 0.060	0.1 - 5
0.70	0.016 - 0.077	0 - 9

The IEC standard [9] gives a method of translating the internal sound power level to the external sound power level using an equation for the transmission loss through the pipe wall. By applying eqn (4) in reverse, the levels obtained for the pressure ripple level can be translated into sound power levels so that the pipe wall transmission loss can be applied.

Future work will involve developing the idea of representing the data as a surface plot which could then be used to improve the existing accuracy of the modified IEC prediction equation. It is hoped that with this modified IEC prediction equation, a benchmark is set from which control valve noise can be determined by considering the valve as an orifice plate by looking at the valve's geometric flow area.

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Acknowledgement

Christopher Cairns is an Associate of the Postgraduate Training Partnership (PTP) between the National Engineering Laboratory (NEL) and Strathclyde University. The PTP scheme is a joint initiative of the UK's Department of Trade and Industry (DTI) and the Engineering and Physical Sciences Research Council (EPSRC). The PTP scheme is supported by a grant from the DTI. Christopher Cairns gratefully acknowledges grant support from both the EPSRC and NEL.