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PREDICTION OF AERODYNAMIC NOISE FROM MULTI-HOLE MULTISTAGE EXPANSION IN CONTROL VALVE

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ABSTRACT

Simulation studies concerning the acoustic characteristic of a globe valve are presented to evaluate the effect of multi-stage multi-hole expansion on valve noise. The results concerning multi-stage and multi-stage multi-hole configurations are discussed. It is evident from the analysis carried out in this work that a multi-hole multi-stage arrangement provides a possibility for significant noise reduction in valve. This can be a guiding principle in valve trim design.

INTRODUCTION

Control valves are the flow elements used in chemical process industries and in power plants for regulating fluid flow in pipe lines. Control valves regulate the flow and converts pressure energy into kinetic energy . A portion of this energy is converted into acoustic energy which is responsible for generating noise. The noise generated by control valve can be classified into - mechanical noise and aerodynamic noise. The mechanical noise generated is due to the vibration of valve components as a result of pressure fluctuations within the valve and is much lower than the aerodynamic noise. The aerodynamic noise generated by the control valve depends upon the pressure ratio between the upstream and downstream of the valve. Depending upon the pressure ratio, the noise generation mechanism in control valve is divided into four distinct regimes[1] as shown in Table 1. For a pressure ratio less than the critical pressure ratio, the noise is generated due to turbulent mixing of high velocity jets. For the pressure ratio greater than the critical pressure ratio, the flow downstream of a valve will be supersonic. The under expansion of the fluid creates shock waves generating the broad band shock noise[2]. This shock noise is created due to the interaction of shock waves with turbulence. The broad band shock noise is very much high compared to the noise generated by turbulent mixing. In general, the acoustic efficiency relates to the ratio of acoustic power to

Table 1. Noise Generation Mechanism [1]

Regimes	Pressure ratio R	Sound power generation Mechanism
I	$R < R_{crit}$	Turbulent shear
II	$R_{crit} < R < \frac{p}{p_2\alpha} = \{0.754(\gamma + 0.326)\}^{\frac{\gamma}{\gamma-1}}$	Choked turbulent mixing
III	$\frac{p}{p_2\alpha} < R < R_{M_j=\sqrt{2}}$	Pre- mach disc shock cell-turbulence interaction
VI	$R > R_{M_j=\sqrt{2}}$	Post-mach disc shock-cell turbulence interaction

the stream power . It is reported [3] that in these two regions the variations of acoustic efficiency with the Mach number are $M_j^{3.6}$ and $M_j^{(6.6\times F_l^2)}$ respectively, where F_l is the pressure recovery coefficient . This suggests that in the flow region above critical pressure , the acoustic efficiency , hence the noise generated , is much greater than in the region below critical pressure ratio . In order to reduce the noise level at high pressure ratios, it is worthwhile to use a provision of multistage expansion, wherein the pressure ratio in each stage is kept below the critical pressure ratio to avoid formation of shock in the flow.

On the other hand , the shifting of internal peak frequency beyond the audible range (20 kHz) can also reduce noise due to a high transmission loss through pipe [4]. The internal peak frequency of noise generation in valve depends upon jet diameter. A suitable reduction in jet diameter therefore can also be a means of achieving noise reduction in valves. This paper is an attempt to analytically evaluate the effect of a multi-hole multistage expansion from noise control standpoint.

ANALYTICAL PROCEDURE

Multi-stage expansion

The number of stages required to achieve an overall pressure ratio will depend on the value of stage pressure ratios. These ratios are defined as:

Overall pressure ratio

$$R_{overall} = \frac{p_1}{p_{n+1}} \tag{1}$$

Stage pressure ratio

$$R_i = \frac{p_i}{p_{i+1}} \tag{2}$$

where p is a pressure, n is the number of stages and suffix i represents the stage.

In a multistage arrangement, the magnitude of stage pressure ratio is required to be such that R_i is less than the critical value which is 1.89 for air with pressure recovery coefficient of 1 in valve

For *n* expansion stages , the relationship of overall pressure ratio with stage pressure ratio will be :

$$R_{overall} = (R_i)^n \tag{3}$$

This provides the number of stages required in an arrangement. If this number is a fraction , it has to be rounded off to the next higher integer. For a uniform pressure ratio condition in all stages , an actual value of a stage pressure ratio is obtained using the new integer value of *n* in the equation (3)

In choked condition of valve operation the overall flow rate is obtained using :

$$q = \sqrt{C_d^{\,2}\, A_{vc}^2\, \frac{p_1}{\rho_1}\left(\frac{2\gamma}{\gamma+1}\right)} \tag{4}$$

The flow area at vena-contraca, A_{VC} is given by

$$A_{vc} = \frac{C_v F_l}{59055} \tag{5}$$

where C_v is valve flow coefficient and F_l the pressure recovery coefficient. In addition to these coefficients , the estimation of noise from control valve requires pipe diameter *d* and valve trim coefficient F_d as input.

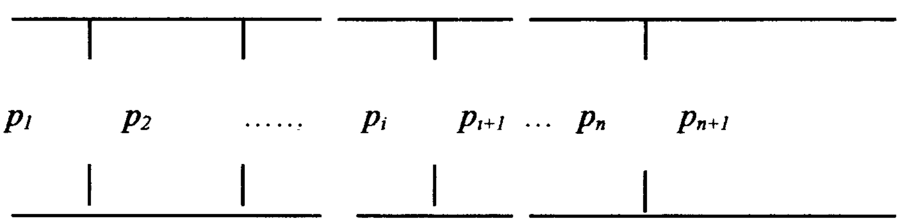

Fig. 1 Schematic representation of multi-stage expansion with upstream and downstream pressure in each stage

A schematic showing multi-stage expansion arrangement is shown in Fig. 1 . The flow rate in each stage depends upon the stage upstream pressure and its pressure ratio, and the area at vena-contracta. Since the upstream pressure in each stage reduces , the desired uniform flow rate is possible through an increase in the stage flow area. Consequently the value C_v is to be modified at each stage corresponding to the local flow conditions. The stage area (A_{vci}) and the flow coefficient(C_{vi}) are given by

$$A_{vci} = \sqrt{\frac{q^2 F_l^2}{2C_d^2}\,\frac{\rho_i}{R_i - 1}\,\frac{1}{\left[1 - \frac{\gamma}{F_l^{\,2}}\left(1 - \frac{1}{R_i}\right)\right]}} \tag{6}$$

$$C_{vi} = \frac{A_{vci} \times 59055}{F_l} \tag{7}$$

The other parameters such as downstream pressure, sonic speed and pressure at vena-contracta at each stage are calculated using relations :

$$p_{i+1} = \frac{p_i}{R_i} \tag{8}$$

$$a_{i+1} = \frac{a_{vc_i}}{\left(\dfrac{p_{vc_i}}{p_i}\right)^{\frac{\gamma-1}{2\gamma}}} \tag{9}$$

$$p_{vc_i} = p_i = \left(\frac{p_i - p_{i+1}}{F_l^2}\right) \tag{10}$$

The other properties of the flow at vena-contracta such as gas velocity(u_{vc_i}), Mach number(M_{vc_i})and sonic speed (a_{vc_i}) are estimated appropriate basic equations. The noise characteristic such as sound power, W_{ac_i} and the sound power level L_{W_i} in i th stage is estimated using following correlations given in reference[5]

$$W_{ac_i} = 1.6 \times 10^{-7} a_{i+1}^2 M_{vc_i}^6 C_{V_i} F_l \rho_i \left(\frac{p_{vc_i}}{p_i}\right)^{1/\gamma} a_{vc_i} \tag{11}$$

$$L_{W_i} = 10 log_{10}\left(\frac{W_{ac_i}}{W_{ref}}\right) \tag{12}$$

where W_{ref} is the reference acoustic power.

The sound power generated inside a valve is transmitted through the downstream pipe to the acoustic medium outside. The pipe attenuates the sound power because a fraction of the sound power generated inside the valve is generally lost in transmission . It is reported [1]that the transmission loss in the pipe varies over the entire spectra. The overall sound power level is a result of the spectral components of the valve noise and is usually analysed in one-third octave bands in audible frequency range of 0.2 kHz to 20 kHz. The sound power level spectra in one-third octave band is expressed as [1].

$$L_w(f_c) = L_W - 5.3 - 10\log_{10}\left[1+\left(\frac{f_c}{2f_p}\right)^2\right]\left[1+\left(\frac{f_p}{2f_c}\right)^4\right] \tag{13}$$

where f_c is a band central frequencies f_p is the internal peak frequency of the noise. The peak noise frequency is known to occur[1] at Strouhal number of 0.2 which provides an estimate of internal frequency as

$$f_p = \frac{0.2 M_{vc} a_2}{D_j} \tag{14}$$

A characteristic diameter of valve [1] D_j ,is calculated using the relationship

$$D_j = 0.0046\left(\frac{C_V F_l}{n_0}\right)^{1/2} \tag{15}$$

where n_0 is apparent number of noise producing orifices and relates to valve trim coefficient (F_d) as :

$$F_d = \left(\frac{1}{n_0}\right)^{1/2} \tag{16}$$

To determine the overall effects from the multi-stage valve configuration the above procedure has to be repeated for each stage of expansion. Consequently an array of sound power level of dimension of n X N will be obtained, where n is the number of stages and N is the number of frequency bands.

A logarithmic addition of the sound power level generated at all the stages at a particular frequency band provides an overall sound power level at that central frequency, For example, L_W generated by a multistage expansion at a centre frequency f_c is

$$L_{W_{overall}}(f_c) = 10log_{10}\sum_{i=1}^{n} 10^{\frac{L_{i,f_c}}{10}} \qquad (17)$$

Once the spectrum of the overall sound power level is known, the SPL estimation is made by subtracting the transmission loss of pipe from the sound power level as :

$$L_{wout}(f_c) = L_{w_{overall}}(f_c) - L_{Tl}(f_c) \qquad (18)$$

where $L_{wout}(f_c)$ is sound power level outside the pipe and $L_{Tl}(f_c)$ the transmission loss in pipe. The analysis of transmission loss used in this work is the same as used by Reethof[1]

The spectrum of sound pressure level at a distance (s) from the centreline of pipe is calculated using

$$L_s(f_c) = L_{wo}(f_c) - 10log_{10}\left(\frac{s}{r_p}\right) \qquad (19)$$

where r_p is pipe internal diameter.

Multi-hole multi-stage expansion

In a multi-hole multi-stage expansion the gas is allowed to expand through flow restriction made up of a number of holes in each stage such that the sum of the area of holes is equal to the total flow area in each stage. The peak internal frequency of the noise inside the pipe downstream of valve is directly proportional to the Mach number and varies inversely with the jet diameter. A typical variation of internal peak frequency with the number of holes is shown in Fig.2 for a pressure ratio of 8. It can be seen that if the total area is divided into 30 small holes the internal peak frequency will be shifted to 20 kHz. The selection of a proper jet diameter enables shifting of the internal peak frequency beyond the audible range . The radiated noise reduction is due to high transmission loss of pipe at frequencies above the ring frequency [4].

The multi-hole arrangement with multi-stage expansion is therefore advantageous for achieving significant reduction in noise. For this arrangement the noise calculation procedure is the same as in multistage expansion described earlier except that the characteristic jet diameter D_j in equation (15) is taken as hole diameter.

RESULTS AND DISCUSSION

The results of simulation studies concerning the acoustic characteristic of a globe valve are presented to evaluate the effect of multi-stage multi-hole expansion on valve noise. The results concerning single-stage, multi-stage and multi-stage multi-hole configurations are discussed.

All noise predictions are referred at 1 m distance from the central line of the pipe. The necessary valve characteristics chosen for the calculations are included in Table 2.

Table 2. Valve and Flow characteristics

Parameter	Value
Down stream pipe i) Diameter d ii) Schedule (thickness)	 0.1524 m 40 (0.007112 m)
Upstream pressure p_1	10 bar
Pressure recovery coefficient F_l	0.95
Valve flow coefficient C_V	167

Fig. 3 shows a comparison of sound pressure level spectrum of a simple globe valve with that of multi-stage expansion . It may be noted that the sound pressure level in case of multi-stage expansion is considerably lower than a simple valve throughout the spectrum mainly due to avoidance of shock..

Fig. 4 shows the variation in an estimated overall sound pressure level for different valve configurations for pressure ratio varying from 3 to 10, an overall noise reduction of 7 to 22 dB is observed in case of a multi-stage expansion.

Fig. 5. shows a comparison of sound pressure level spectrum of a simple globe valve and with a multi-hole multi-stage expansion arrangement . A noise reduction of greater magnitude is observed in multi-hole multi-stage configuration than multi-stage expansion. In Fig.4 the comparison of multi-hole multi-stage expansion with a simple globe valve suggests that an overall noise reduction of 10 to 25 dB is possible.

CONCLUSIONS

The aerodynamic noise is a significant component of total valve noise specially under large pressure ratio conditions. The generation of shock is responsible for higher aerodynamic noise, which can be reduced through multi-stage expansion arrangement. Multi-hole configuration is further advantageous for noise reduction in control valve. It is evident from the analysis carried out in this work that a multi-hole multi-stage arrangement provides a possibility for significant noise reduction in valve. This can be a guiding principle in valve trim design.

ACKNOLEDGEMENT

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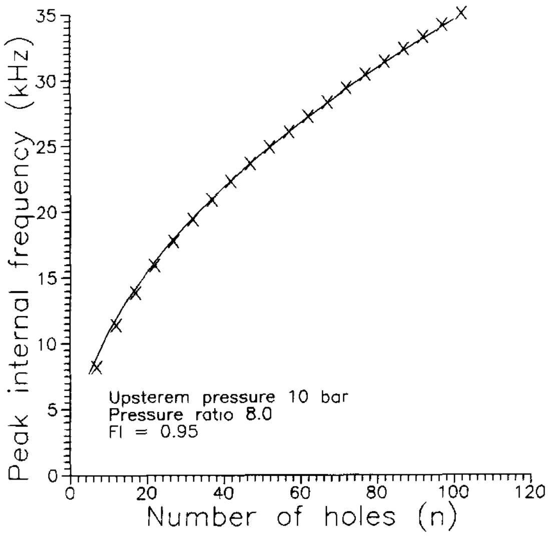

Figure 2 Variation of internal peak frequency

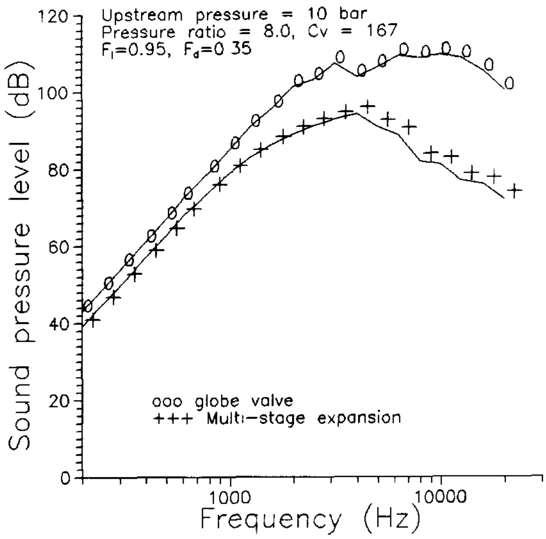

Figure 3 One-third octave sound pressure level comparision of multi-stage with a globe valve

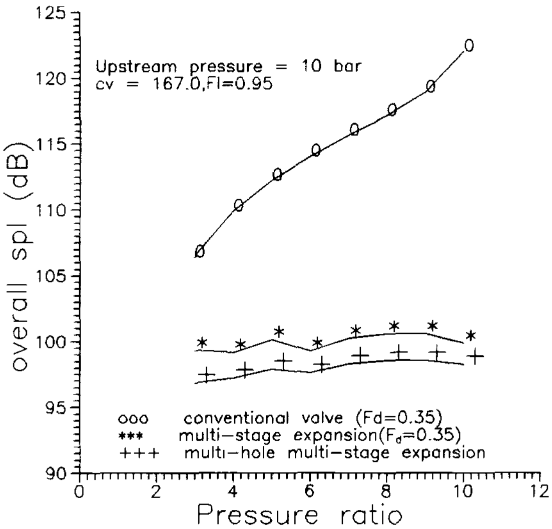

Figure 4 Overall sound pressure level at a distance of 1m from centre line of pipe

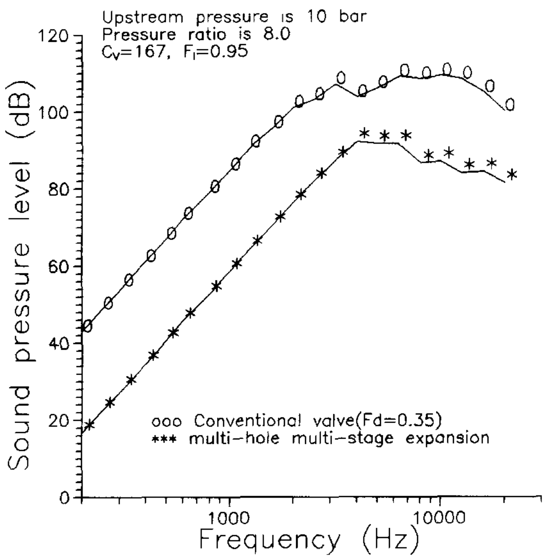

Figure 5 One-third octave sound pressure level comparision of multi-hole multi-stage expansion with Globe valve

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