Numerical acoustic characteristics and optimum design of the pressure reducing valve

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Abstract. The pressure reducing valves are widely used in the technological water supplied ways of gravity flow. A credible pressure reducing valve can provide stable cooling water for units with extremely low maintenance cost and labor intensity in a fairly long period of time. In this paper, a three-dimensional numerical simulation of flow field and acoustic characteristics towards a combined type pressure reducing valve was carried out based on ANSYS Fluent and the FW-H equation. The numerical results achieve the regulation of noise generation, transmission and attenuation. It shows that the sound pressure level of monitoring points seem to be higher and large gradient at low frequencies under the same flow velocity, while it presents reverse results with the increment of frequency and maintains a constant valve finally. At the same time, the monitoring points in the vicinity of throttling cone shows higher sound pressure level and upstream noise is lower than downstream’s. Aiming at the problem of valve noise, a modified measure to reduce the flow-induced noise was proposed.

1. Introduction
The pressure reducing valves are increasingly playing an important part in the technological water supplied ways of gravity flow in the hydropower plant, which is used for regulating and controlling the pressure and flow rate a steady condition at the valve outlet so as to meet the requirements for water pressure as well as the quality. Generally speaking, the origin and evolution of noise produced by the valve relies on the transient flow in the valve. The flow parameters will not change with time under the situation of steady flow, including velocity and pressure pulsation, as a result, the acoustic source is virtually non-existent. When, however, the transient flow in the pressure reducing valve is induced by the effect of choked flow arose out of the throttling cone, which has presented a considerable possibility to generate adverse noise, even vibration and so on[1-2].

The numerical simulation analysis technology has gradually become an important auxiliary
means of the engineering design with the development of computer technology and computational fluid dynamics (CFD). It can provide a powerful and reliable theoretical basis for engineering applications because of its advantages of wide adaptability, less workload, high precision, high speed[3]. Jewook Ryu et al.[4] computed the internal aerodynamic noise for a quick-opening throttle valve with frequency-domain acoustic analogy, Lighthill's acoustic analogy and the Curle's extension of Lighthill's. A numerical analysis of the flow field and acoustic field of the inner high parameter pressure reducing valve was conducted and the main cause of the aerodynamic noise was analyzed by Lin Wei et al.[5] Cui Wei Liu et al.[6] has established the generation model of flow induced noise towards the transmission gas pipeline valve and simulated numerically the airflow under steady and unsteady flow, the numerical results conclude that the fluid pulsation arose from turbulent flow is the basic cause leading to produce flow noise, they also verified the simulation results by experiment. A Large Eddy Simulation for a circular section bend behind a valve has given for instance by Wei Zhi et al.[7] to investigate the cause of noise at different velocity inlet with different valve openings, the results show the formation and shedding of vortices is the main reason for the generation of radiation noise. A full automatic performance and lift-span test system has been developed by Xiao Ming Xu et al.[8], they propose a modification measure for the throttling cone and make a comparison research on the original and modified, the results perform that the surface type valve cone structure can achieve steady flow state, and to reduce the resistance loss under various conditions. Erlen G. Berestovitskiy et al.[9] performed the results of the experiment study of hydrodynamic noise arose from the flow through the perforated throttling plates and studied the influence of the holes shape, diameter as well as the density.

The paper investigates the laws of the noise generation, propagation and attenuation on the basis of aerodynamic noise theory for a combined type pressure reducing valve. Unsteady-state simulations were carried out by applying the "FW-H" equation and the throttling cone was considered as a dipole acoustics source. Furthermore, this paper proposes a solution to reduce flow-induced noise.

2. Ffowcs-Williams & Hawkings formulation

It is generally believed that the aeroacoustics started form the jet noise research form Lighthill, who deduced out the Lighthill Equation based on Navier-Stokes Equation,

\[
\frac{\partial^2 \rho'}{\partial t^2} - c_0^2 \frac{\partial^2 \rho'}{\partial x_j \partial x_j} = \frac{\partial^2 T_u}{\partial x_i \partial x_i}
\] (1)

Where \( T_u = \rho v_j y_j + (p' - c_0^2 \rho') \delta_{ij} - \sigma_{ij} \) is the Lighthill tensor.

Afterward, the aerodynamic analogy equation was proposed by Curle from equation (1)

\[
4\pi c_0^2 \rho' \rho(x,t) = \int \frac{T_u}{|x-y|^2} \,d^2y + \int \frac{p' \eta_{ij}}{|x-y|^2} \,d^2y
\] (2)

Furthermore, Ffowcs-Williams and Hawkings deduced the famous FW-H equation, considering the characteristics of rotation wall,
\[
\frac{\partial^2 (\rho' H)}{\partial t^2} - c_s^2 \frac{\partial^2 (\rho' H)}{\partial x_i^2} = \frac{\partial}{\partial x_j} \left( T_{ij} H \right) - \frac{\partial}{\partial x_i} \left( \rho \delta_{ij} + \sigma_{ij} \right) \frac{\partial F}{\partial x_j} + \frac{\partial}{\partial t} (\rho V_i \delta(F))
\] (3)

The first item on the right side of the equation (3) is a quadrupole, the second is dipole, and the third one is a monopole. The FW-H formulation is capable of predicting sound generated by equivalent acoustic sources, which is one of the most popular approaches to predict acoustic.

3. Calculation model and grid generation

The investigated pressure reducing valve is a nominal diameter \(D_N=450\) mm, which consists of valve body, valve seat, throttling cone and spindle. The main geometric datas and operation conditions are shown in Table 1. Figure 1 shows the internal structure of the valve.

As shown in Figure 1, the outlet pressure will drop evidently due to decrement of area of passage between the valve seat and throttling cone. A part of energy is dissipated by the impact action of water flow when flowing through the cone, more importantly, rapid increase in velocity is bound to have an increasingly serious effect upon the outlet pressure.

| Table 1. Parameters of the investigated valve |
|---------------------------------------------|
| Parameters          | Remark                      |
|---------------------|-----------------------------|
| Nominal diameter(D\(N\)) | 450mm                      |
| Inlet pressure(P\(_1\))  | 1.56-2Mpa                   |
| Flow rate(Q)          | 1600m\(^3\)/h               |
| Nominal pressure(P\(_N\)) | 2.5MPa                      |
| Outlet pressure(P\(_2\)) | 0.6MPa                      |
| Opening(H)            | 28mm                        |

Automatic tetrahedral mesh generation, superior adaptability for more complex geometry, is performed in the computational domain by utilizing the grid generation tool ICEM-CFD. In terms of calculation precision, local mesh refinement for the throttling cone is presented in this paper because it is the most influence on the characteristics of flow field. The three dimension calculation domain and grid generation are reported in Figure 2. Total elements is about 18 million with 0.34 million nodes.
The flow field and acoustic field were simulated using the ANSYS Fluent with SST turbulent model and the FW-H acoustic model. At the inlet of the domain, the static pressure and direction of the velocity vector are imposed. The mass flow rate is given at the outlet. In the near wall region, an automatic near wall treatment was employed, no-slip and smooth conditions for solid boundary, and GGI(General Grid Interface) connections for the interfaces between the valve and pipes.

For the acoustic simulation, several additional variables are also required, e.g. reference acoustic pressure, far-filed sound speed and far-field density. According to the sampling theory, sampled signal would keep integral without distortion if the sampling frequency is twice as large as the frequency of original signal in the process of digital simulation and signal conversion. Commonly, it reaches 5-10 times of the original signal maximum frequency in actual application. The relationship formula between the sampling highest frequency and transient time step is shown as follows,

$$f_s = \frac{1}{2\Delta t}$$

6 monitoring points were arranged along the direction of the pipeline axis and 4 points were in the vicinity of the throttling cone, the locations of those points are shown in Figure 3.

![Figure 3](image.png)

**Figure 3.** The locations of investigated points

4. **Numerical results and analysis**

4.1. **Flowing characteristics results of the valve**

Figure 4 shows the performance curve of the pressure reducing valve at different openings with the same inlet pressure(2.04MPa) and outlet mass flow rate(1360kg/h), the influence of the throttling cone openings on the outlet pressure can be seen. The pressure distributions of upstream region between the throttling cone and valve seat are provided in Figure 5.

The pressure regulation in a pressure reducing valve is fully controlled by the opening according to the performance curve, which strongly affects the pressure distribution. At the same inlet conditions, the outlet pressure drops with the decreasing opening, especially, it began to very sensitive to the small openings owing to the dramatically velocity variation, which causes immediate and serious interference with the pressure. As reported in Figure 4, pressure alteration of 0.74MPa can occur
during the process of closing the valve from 30mm to 27mm, while this valve is 0.81MPa from 45mm to 30mm.

**Figure 4.** Performance curve of the investigated valve
In this paper, we focus on the pressure distribution located in the region between throttling cone and valve seat since obvious pressure gradient can be observed as shown in Figure 5. It seems clear that smaller openings give rise to greater pressure alteration, which is sufficient to induce cavitation flowing phenomenon and cavitation erosion risk, with some adverse consequences in stability of the valve such as aggravation vibration and noise.

4.2. Acoustic characteristics analysis

The noise flow-induced is ubiquity during the progression of operation, which is caused by the internal turbulent flow and energy absorption of the pressure reducing valve. On the one hand, counter flow tends to appear in the vicinity of the cone owing to the change in fluid particle direction, which will inevitably lead to vortex flow constantly and intensely. On the other hand, flowing transfer from main flow region to the vortex region is bound to cause pressure fluctuation on the throttling cone surface. All of them play a major role in generation and transmission of the noise. The sound pressure levels at the investigated points shown in Figure 3 are reported in Figure 6, which considered the pressure fluctuation on surface of throttling cone as acoustic source signal and were fast fourier transform.$^{[10]}$

Figure 5. Pressure contours at upstream regions for different openings

Figure 6. Sound pressure level at different monitoring points
In general, there is no obvious dominant frequency for all points. The sound pressure level is larger in low frequency domain than high frequency domain with greater gradient and keeps invariant with the increment of frequency. It can be known that higher energy of noise presents in low frequency comprised with high frequency. In addition, higher sound pressure levels are provided for the downstream monitoring points at the same locations while greater pulsation at high frequency for the upstream points.

5. Optimum design for throttling cone profile

The unfavorable noise problems present some consequences on the operation environment, which even cause seriously influence on stable operation of the valve. For example, the disadvantage noise can act as a great stimulus to increase the vibration of the body. A noteworthy phenomenon in pressure reducing valve is the fluid-induced noise depends to a large extent on the flow pattern. Therefore, a measure of optimizing the throttling cone profile to overcome as much as possible the turbulence flow of the valve is provided, as drawn in Figure 7.

![Figure 7](image)

**Figure 7.** The contrasting graphic of the original and modified throttling cone profile

The most significant task during modifying the profile is to keep the same effect on pressure drop and all the contrastive analysis must satisfies this factor. Figure 8 shows the circumferential pressure distribution comparison on the end face for two types of throttling cone. Due to the influence of the turbulence flow on the flow pattern it presents uneven and pulsatile pressure distribution in Figure 8. It is great evident that the modified throttling cone is beneficial to control the distribution of low pressure region and hinder the development of cavitation flowing. Another advantage for the optimum step is lower pressure amplitude, which means more stable states.

![Figure 8](image)

**Figure 8.** Circumferential pressure distribution of throttling cone
The comparisons of acoustics power level for the original and modified cone are reported in Figure 9 and Figure 10 presents the sound pressure level at the investigated point 4-7 in the vicinity of the throttling cone.

As shown in Figure 9, the acoustic power level decreases effectively on the region of the end surface, however, only slightly changes to the rest of the throttling cone. The maximum acoustic power level is about 139dB in the whole simulation domain and it is nearly all located in the end surface, which also validate the research hypothesis that considering the throttling cone as the acoustic source.

![Figure 9. Acoustics power level contours for the original and modified cone](image)

(a) Original throttling cone  
(b) Modified throttling cone
In order to quantitatively describe the acoustic characteristics of the original and modified valve, Figure 10 shows the comparison of sound pressure level. After optimization, the noise reduction effect is obvious at all the range of frequency and the sound pressure level averagely decreases by about 20dB with the same variation tendency, which consists with the analysis results in Figure 8 and figure 9.

The geometry change of flowing region between the throttling cone and valve seat makes the flowing more uniform and reduce the pressure fluctuation, the acoustic level induced by the instability flow is weakened. Furthermore, cavitation inception and development are greatly inhibited and reduces the cavitation noise because of sharp down of the low pressure region.

6. Conclusion
This paper is concerned the acoustic characteristic of the combined type pressure reducing valve. A survey of the flow and acoustic numerical simulations towards the valve has been carried out by ANSYS Fluent. This survey finally proposes an approach to reduce the flow-induced noise level of the valve.

The instability flowing appears in the gap region between throttling cone and valve seat owing to pressure and velocity have taken place great changes. For the acoustic characteristics, the sound pressure level is larger in low frequency domain than high frequency domain and downstream noise is greater than upstream. It is feasible to realize to decrease noise by modifying the profile of the throttling cone.

Acknowledgement
The research was supported by The National Natural Science Foundation of China (51479166, 51339005) and the Specialized Research Fund for the Doctoral Program of Higher Education of China (20126118130002).

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