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Investigation on the flow noise propagation mechanism in simple expansion pipelines based on synergy principle of flow and sound fields

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Abstract

The noise pollution in pipelines exists for a long time and can't be ignored in modern industries. It is important to investigate the transfer mechanism of sound energy in pipelines and develop high efficiency mufflers with low penalty of pressure drop. Different with the traditional method, this study is focused on the flow and sound fields synergy principle to investigate the flow noise propagation mechanism in reactive mufflers. In this study, theoretical analysis and numerical simulation methods are coupled to investigate the noise propagation process. In the theoretical analysis aspect, the synergetic relationships between the flow and pressure gradient fields are deduced and the field synergy theory is established. In the numerical simulation aspect, the flow noise propagation process in the simple expansion chamber mufflers is studied. The results show that with the decrease of synergy between flow and sound fields, the work done by the fluid on the wall decreases, which means the exchange of sound energy between the wall and the fluid decreases.

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1. Introduction

Pipeline acoustics is an important branch of acoustics to study the principle of acoustic propagation in pipelines.

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Traditionally, the noise reduction measurements in pipelines are mainly based on the perspective of sound propagation, focused on the transmission medium impedance matching characteristics and the dissipative process of sound energy in the propagation medium, but few are on the synergy between flow and sound fields. Selamet et al. [1, 2] investigated in detail the effect of the length on the acoustic attenuation performance of concentric expansion chambers with fixed inlet and outlet ducts. Middelberg et al. [3] studied the acoustic performance of various simple expansion chamber mufflers with computational fluid dynamics analysis. Bilawchuk et al. [4] concluded that the finite element method (FEM) was better suited for this kind of application. Different with the traditional method, this study is focused on the flow and sound fields synergy principle to investigate the flow noise propagation mechanism in pipelines. Guo et al. [5] firstly developed the field synergy principle to improve heat transfer performance. Through literature review, it can be found that field synergy principle is applicable in many multi-field coupling situations. Totally, as a first trial the propagation mechanism of flow noise in pipelines is revealed from the flow and sound fields matching perspectives.

2. Field theory analysis

Any form of acoustics equations are available to be deduced from the fluid continuity equation, motion equation, energy equation and state equation. Through liberalizing the fluid equation and different assumptions, different forms of acoustics equations are obtained.

Euler equations [6]:

$$\begin{cases} \rho\left(\dfrac{\partial v}{\partial t}+v\cdot\nabla v\right)=-\nabla P+f \\ \dfrac{\partial\rho}{\partial t}+v\cdot\nabla\rho+\rho\nabla\cdot v=\rho q \\ \dfrac{\partial s}{\partial t}+v\cdot\nabla s=0, c^2=\left(\dfrac{\partial P}{\partial\rho}\right)_s \end{cases} \tag{1}$$

Where ρ, v, P, c, s represent the density, velocity, pressure, speed of sound and entropy of the fluid respectively, and f, q represent the external force acting on the fluid and the quality of the source respectively.

For small cross-section and export pipelines, which typically use the acoustic plane wave propagates, so that there is a one-dimensional acoustic wave equation [7]:

$$\frac{\partial^2 p(x,t)}{\partial x^2}-\frac{1}{c^2}\frac{\partial^2 p(x,t)}{\partial t^2}=0 \tag{2}$$

Where p represents the sound pressure.

Based on the basic and necessary equations, the synergy between flow and sound fields are deduced as follows,

$$p=\frac{\gamma P_0}{\rho_0}\cdot\rho+P_0-\gamma p_0=\frac{1}{a}\rho+b, \quad a=\frac{\gamma P_0}{\rho_0}, b=P_0-\gamma p_0 \tag{3}$$

Where ρ_0, v_0, c_0 and P_0 represent density, velocity, pressure and speed of sound of the fluid under steady flow respectively. And γ represents the specific heat capacity.

And then

$$\nabla\rho=\frac{1}{a}\nabla p \tag{4}$$

For stationary flow, substitute equation (4) into equation (1),

$$-v\cdot\nabla p=a\left(\rho\nabla\cdot v-\rho q\right) \tag{5}$$

In fluid mechanics, the dot product $-v\cdot\nabla p$ is defined as the amount of fluid work, the product of the pressure gradient modulus and velocity gradient modulus is the fluid pumping power [8]; on the velocity vector field, micelle fluid motion analysis demonstrates that the physical meaning of velocity divergence is the time rate of relative volume during the fluid elements motion process, and thus $\rho\nabla\cdot v$ represents the time rate of the relative quality; ρq represents the additional quality of the source. So the synergy between flow and sound fields can be characterized with the synergy between velocity field and pressure gradient field.

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