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Self-sustained oscillation and cavitation characteristics of a jet in a Helmholtz resonator

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ABSTRACT

Self-sustained oscillations resulting from a sudden expansion in geometry, as encountered in cavities, occur in a broad array of engineering applications. In the present study, the turbulent flow past a 120°-impinging edge Helmholtz nozzle was investigated. A modified theoretical model accompanied by numerical simulation was proposed to obtain the range of the oscillation frequency and was verified using experimental results. It was found that the cavitation clouds in the chamber dominate the oscillating frequency under the low pressure-high flowrate condition. Based on the simulation results, the details of cavitation development, the motion of vortex structures, and the fluid injection and reinjection were investigated in one typical cycle. The interaction between the cavitation and the vortex formation was analyzed with the vortex transport equation. The dilatation term, which is related to the mass transfer rate through the linkage of velocity divergence, has a high value only around the bulk flow; while the baroclinic torque is predominant due to the unremitting collapse and coalescence of the cavitation clouds.

1. Introduction

Self-sustained oscillation, originating from a separated shear layer, has been the subject of numerous studies because of its manifestation in a variety of phenomena. As shear layer separation usually results from a sudden expansion in geometry, such as that encountered in cavities, the flow past the cavity has been considered to be of substantial importance. Though geometrically simple, these cavities are associated with complex phenomena. According to the mechanism proposed by Powell in 1961, the oscillation is attributed to the integrated amplification between the separation and the impingement for small disturbances in the shear layer. For flow of low Reynolds number with simple geometries, the motion equation can be solved by carrying out a linear stability analysis. For high Reynolds number turbulent flows with complex geometries, the governing equations are nonlinear, and little is known about their modes and solutions. Recently, modal decomposition techniques were introduced, and large-scale vortical structures responsible for self-sustained oscillation mechanisms were identified (Rowley et al., 2009; Lee et al., 2011; Seena and Sung, 2013). Despite the research efforts mentioned above, which is focused on the air flow past open cavity, oscillations also occur in the flow past axisymmetric internal cavities due to the fluid- dynamics (Rockwell and Naudascher, 1978). Morel (1979) conducted experiments on an air jet passing a Helmholtz resonator (Fig. 1) and concluded that jet instabilities coupled with the Helmholtz resonance could generate very powerful pressure oscillations with the jet frequency is slightly higher than the fundamental frequency of the resonator.

In addition to the rewarding developments achieved regarding the self-sustained air jet, the research on self-sustained water jets was also conducted by distinguished scholars. The self-resonating nozzle design concept, labeled "STRATOJET" (STRuctured Acoustically Tuned Oscillating JET) was developed (Johnson et al., 1982a,b,c), which is a trademark of DYNAFLOW, INC. (www.dynaflow-inc.com). In the following years, Chahine and Johnson (1985) and Chahine et al. (1983, 1984, 1995) performed a series of the analytical and experimental studies of self-resonating nozzle systems. These new nozzle systems can not only improve on conventional cavitating jets by increasing the cavitation inception number but also generate high-frequency (order of kHz) water slugs. As a result, these nozzle systems are capable of substantially outperforming conventional nozzles in both volume removal and cut depth, especially for deep-hole drilling.

These pioneering studies have paved the way for the investigations focusing on water jets passing Helmholtz resonator, conducted by Liao and Tang (1987). They optimized the shape of the impinging edge

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Nomenclature

d, D	diameter
l, L	length
d_s	diameter of chamber hole
α	convergent angle
ρ	density
t	time
p	pressure
μ	viscosity
$\dot{m}$	mass transfer rate
α_v	vapor volume fraction
α_l	water volume fraction
R_b	bubble radius
p_v	saturation vapor pressure
N_b	bubble number density
k	turbulent kinetic energy
ε	turbulent eddy dissipation
n	exponential coefficient
ω_z	vorticity
Q_M	mass flow
P	fluidic potential
$\bar{\rho}$	average density
p^*	absolute static pressure
A	cross section area
σ	cavitation number
V_C	volume of chamber
ξ	coefficient of local loss
R	fluidic resistance
R_d	fluidic resistance of local loss
L	fluidic inductance
C	fluidic capacitance
Z	total impedance
E	bulk modulus of elasticity
ω_f	circular frequency
f_f	oscillation frequency
f_v	vapor volume frequency
V_v	vapor phase volume
τ_v	accumulating time
T_{LPHF}	period of LPHF
E	bulk modulus of elasticity
k_a	adiabatic exponent of air

Subscripts

1	parameters of upstream nozzle
2	parameters of downstream nozzle
in	parameters of inlet
C	parameters of chamber
g	property of gas
l	property of water
m	property of mixture
t	turbulence

based on the equations of the disturbance wave and two-dimensional vortex, which are the two predominant sources accounting for the generation of pulsation and cavitation. They found that the conical impinging edge with an angle of 120° (Fig. 2) outperformed other nozzles with different impinging edges. In China, further studies and applications have been based on the model of a 120°-impinging edge Helmholtz nozzle due to its high performance.

In China, two types of 120°-impinging edge Helmholtz nozzle have been widely investigated and applied in practical use. The first type, called the HPLF nozzle (working condition is high pressure-low flowrate), is usually used for cutting. The other type, the LPHF nozzle (working condition is low pressure-high flowrate), is usually used for cleaning. Despite their similar configurations, these two types nozzles have different dimensions, as well as different optimal ranges of structural and operating parameters. Large ring vortices are formed in the cavity and discrete water slugs emitted from the HPLF nozzle periodically with high frequency (order of $10^2 - 10^3$ Hz). For the LPHF nozzle, the cycling of loading is achieved by the uneven outputs of the jet energy and impulse at different time segments. Since the time of phase transition is greater than the relaxation time of the jet passing through the cavity, the water slugs are not formed in time. As a result, the oscillation period of the LPHF nozzle is 3–5 s. Studies focusing on structural parameter optimization have been carried out continuously, while little attention has been given to oscillation frequency prediction, especially for the LPHF nozzle. For the HPLF nozzle, Li et al. (2000) used fluidic networks to investigate the oscillation mechanism, which was in accordance with some experimental results. For the LPHF nozzle, Li (2004) proposed the "Gas-Spring Theory" and concluded that the periodical deformation and movements of the cavitation clouds

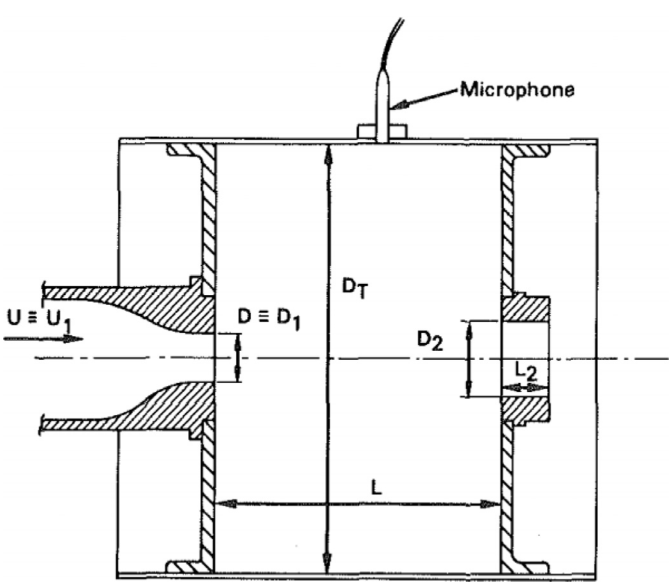

Fig. 1. Experimental setup of the Helmholtz oscillator (Morel, 1979).

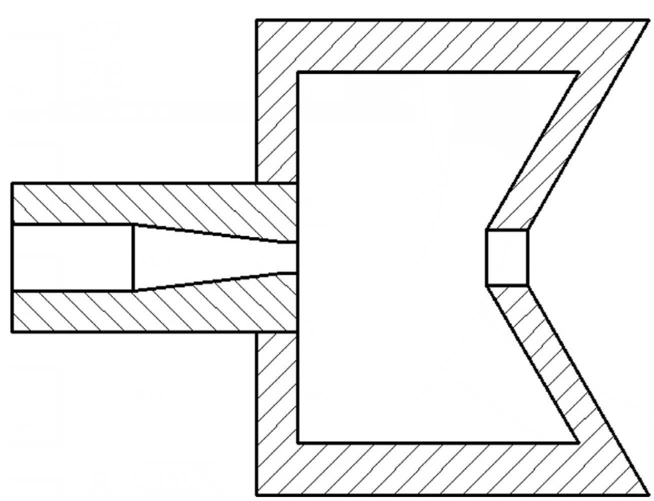

Fig. 2. Schematic diagram of 120°-impinging edge Helmholtz nozzle.