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CFD study on mean flow engine for wind power exploitation

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ABSTRACT

Acoustic oscillation can be induced in a closed branch tube by a mean gas flow in a trunk tube passing the opening of the branch tube. Based on this principle, novel aerodynamically driven generator and thermoacoustic refrigerator can be manufactured. Large-eddy simulation (LES) of turbulence was applied to simulate aerodynamically driven acoustic oscillation in a mean flow engine (MFE) with a cross-junction configuration. It is shown that a standing-wave acoustic field is established inside the closed branch tube at certain mean flow velocities. Different acoustic and hydrodynamic modes occur with the increase of mean flow velocity. Furthermore, Strouhal number has strong effects on acoustic and hydrodynamic modes of the MFE. Under present computational conditions, critical acoustic pressure amplitudes in the first and fifth acoustic modes occur when St = 0.39 and St = 0.94 respectively. It would be beneficial to design MFEs operating in the third acoustic mode to obtain strong acoustic oscillation.

1. Introduction

Acoustic oscillation in a closed branch tube can be excited by a one-way flow with remarkable kinetic energy in a trunk tube. The one-way flow, branch tube, and trunk tube, herein denominated mean flow, resonator, and driver, jointly constitute a new type of engine – mean flow engine (MFE), one kind of which with cross-junction configuration is shown in Fig. 1. Investigations on acoustic oscillation induced by mean flow were initially aimed to damp pipeline vibration and reduce the noise of fluid machinery such as fan and pump. Acoustic oscillation takes place due to the interaction between the vortex shedding periodically at the entrance of the resonator and the spring gas inside the resonator. This phenomenon is closely related to aeroacoustics. Lighthill first formally defined aeroacoustic sound source [1]. Rockwell and Naudascher reviewed early literatures and systematically classified aerodynamically self-sustained oscillations into three regimes [2].

Acoustic oscillation generated in the resonator can also be used to pump heat, generate electricity, compress gas, etc. Combining MFE and thermoacoustic effect, Slaton and Zeegers verified thermoacoustic refrigeration by setting stack in the resonator and gained a temperature difference of 90 K [3]. They discussed the acoustic fields of four MFEs. One of them can generate 32 W acoustic power, which is comparable with a standing-wave thermoacoustic engine [4,5]. In order to exploit wind power, Sun et al. [6] proposed some new applications of MFE to generate cooling capacity, electrical power, etc. Thermoacoustic refrigeration system driven by MFE has no moving component and could be driven by wind power directly.

Although experiments have verified the feasibility and advantage of MFE, theoretical research advances slowly and cannot provide enough support for further experiments. It is recognized that acoustic amplitudes can be divided into three regimes. For low acoustic amplitudes ($u'/U_0 \leqslant 10^{-3}$), Elder [7] and Howe [8] established a shear layer model based on linear theory, where oscillation amplitude of shear layer increases exponentially with the increase of the distance from the upstream edge. For moderate acoustic amplitudes ($10^{-3} \leqslant u'/U_0 \leqslant 10^{-1}$), discrete vortices form in the resonator entrance, and non-linear effects begin to affect the growth of shear layer perturbations [9]. For high acoustic amplitudes ($u'/U_0 = O(1)$), formation of vortex is strongly influenced by acoustic field [10]. Most models are based on Nelson's empirical model [11] for Helmholtz resonator assuming that vortex is concentrated into line vortices. Point-vortex model proposed by Bruggeman et al. [9] and Howe [8] overestimated oscillation amplitudes for the reasons that vortex is not concentrated into a point and vortex path deviates from straight line. Vortex-blob method proposed by Krasny [12] was applied by Kriesels et al. [13], which supposes that acoustic power is equal to the losses brought about by visco-thermal, radiative and non-linear effects. For high acoustic amplitude, Hofmans [14] exaggerated acoustic oscillation by 30% for a single side branch tube. These models focus only on acoustic amplitude and cannot show the full view of acoustic and flow field in a MFE.

Computational fluid dynamics (CFD) becomes a promising method to simulate MFE. In this study, large-eddy simulation (LES) of turbulence model is applied to simulate acoustic oscillation in a MFE with a cross-junction configuration. Acoustic fields

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Nomenclature

u'	acoustic velocity amplitude (m/s)
U_0	mean flow velocity (m/s)
ρ	density (kg/m^3)
u	velocity (m/s)
p	pressure (Pa)
Δp	relative pressure (Pa)
p_0	ambient pressure (Pa)
e	internal energy (J)
R	universal gas constant (J/(kmol·K))
T	absolute temperature (K)
μ	dynamic viscosity (N·s/m^2)
σ_{ij}	stress tensor (N/m^2)
q_j	computable heat flux vector (W/m^2)
τ_{ij}	subgrid-scale stress (Pa)
H_R	width of resonator (mm)
H_D	width of driver (mm)
L_R	length of half resonator (mm)
L_u	length of upstream driver (mm)
L_d	length of downstream driver (mm)
u_y	velocity in y-direction (m/s)
c	sound speed (m/s)
k	wave number
p'	acoustic pressure amplitude (Pa)
f_s	vortex shedding frequency (Hz)
f_m	Acoustic oscillation frequency (Hz)
λ	wavelength (m)
t_f	vortex flowing period (s)
t_s	vortex shedding period (s)
t_m	acoustic oscillation period (s)
St	Strouhal number
m	acoustic mode number
h	hydrodynamic mode number
i, j	tensor notation
$\bar{}$	spatial filtering operation
$\sim$	density-weighted filtering operation

in different acoustic modes and the developing processes of vortices in different hydrodynamic modes are shown and analyzed. In addition, the relationship between acoustic field and vortex in different acoustic and hydrodynamic modes is revealed. The effect of mean flow velocity on acoustic oscillations is discussed.

2. Numerical model

2.1. Governing equations

Acoustic oscillation inside a MFE is strongly related to the vortex shedding at the resonator entrance. Turbulent model LES is employed. The filtered compressible Navier–Stokes equations for a Newtonian fluid and a mass-weighted change of variable (Favre [15]) are employed. The governing equations are then given by

$$\frac{\partial\bar{\rho}}{\partial t}+\frac{\partial(\bar{\rho}\tilde{u}_i)}{\partial x_i}=0 \tag{1}$$

$$\frac{\partial\bar{\rho}\tilde{u}_i}{\partial t}+\frac{\partial(\bar{\rho}\tilde{u}_i\tilde{u}_j)}{\partial x_j}=-\frac{\partial\bar{p}}{\partial x_i}+\frac{\partial\tilde{\tau}_{ij}}{\partial x_j}+\frac{\partial\tilde{\sigma}_{ij}}{\partial x_j} \tag{2}$$

$$\frac{\partial(\bar{\rho}\tilde{e}+\bar{\rho}\tilde{u}_i\tilde{u}_j/2)}{\partial t}+\frac{\partial[(\bar{\rho}\tilde{e}+\bar{\rho}\tilde{u}_i\tilde{u}_j/2+\bar{p})\tilde{u}_j]}{\partial x_j}=\frac{\partial(\tilde{\sigma}_{ij}-\tilde{\tau}_{ij})\tilde{u}_i}{\partial x_j}+\frac{\partial q_j}{\partial x_j} \tag{3}$$

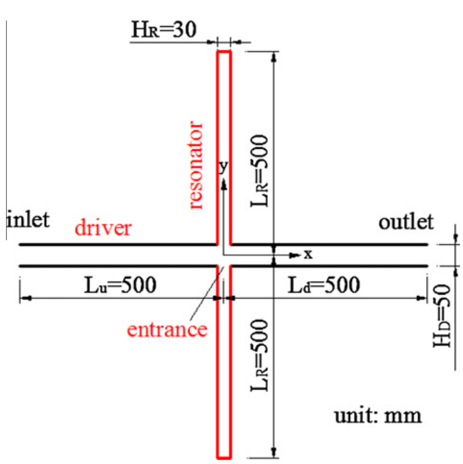

Fig. 1. Schematic diagram of MFE.

$$\bar{p}=R\bar{\rho}\tilde{T} \tag{4}$$

where $\tilde{\sigma}_{ij}$ is the stress tensor due to molecular viscosity, defined by

$$\tilde{\sigma}_{ij}=\mu\left(\tilde{T}\right)\left(\frac{\partial\tilde{u}_i}{\partial x_j}+\frac{\partial\tilde{u}_i}{\partial x_i}\right) \tag{5}$$

q_j is the computable heat flux vector defined by

$$q_j=-\lambda(\tilde{T})\frac{\partial\tilde{T}}{\partial x_j} \tag{6}$$

and $\tilde{\tau}_{ij}$ is the subgrid-scale stress defined by

$$\tilde{\tau}_{ij}=\bar{\rho}(\tilde{u}_i\tilde{u}_j-\overline{u_iu_j}) \tag{7}$$

Wall-Adapting Local Eddy-Viscosity (WALE) model is employed to solve the subgrid-scale stress [16].

2.2. Numerical scheme

In order to reduce computational cost, a two-dimensional model is adopted. The geometry of computational domain of a MFE with coordinate system is shown in Fig. 1. Coordinate origin is the intersection point of the resonator's axis and the driver's axis. For the resonator, the opening to the driver is named "entrance" with width H_R = 30 mm, and both ends of the resonator are closed. The half length L_R of the resonator is 500 mm. For the driver, both the upstream length L_u and the downstream length L_d are 500 mm, and the width H_D is 50 mm.

LES requires a finer mesh than Reynolds-Averaged Navier–Stokes (RANS). The whole domain thus is meshed by quadrilateral type grid. The number of cells with maximum area of 1.00 mm^2 and minimum area of 0.99 mm^2 is 7.85×10^4.

2.3. Boundary conditions and solution method

In our model, ideal air is employed as the working fluid. Initial temperature and pressure are 300 K and 101.325 kPa, respectively. For compressible gas in MFE, Dirichlet boundary condition is adopted as the inlet boundary. The value of pressure is set in a range from 70 Pa to 4200 Pa. Consistent with a fully-developed flow assumption, the diffusion fluxes of all flow variables in the direction normal to exit plane are assumed to be zero, and the pressure at the outlet boundary is calculated with the assumption that radial velocity at the exit plane is neglected. No slip boundary condition is applied on the walls. Wall vibration is neglected.