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Vortex convection in the flow-excited Helmholtz resonator

Xiwen Dai [a,b,*]

[a] Laboratoire d'Acoustique de l'Université du Maine, Av. O. Messiaen, 72085 LE MANS Cedex 9, France
[b] School of Energy and Power Engineering, Beihang University, 100191 Beijing, China

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ABSTRACT

Vorticity convection as well as its excitation to a Helmholtz resonator is studied numerically. Convection velocities of both the concentrated vortical structure and the total distributed vorticity in the orifice region are calculated. Results indicate that the vortex convection velocity is the more useful one in controlling the oscillation frequency. The excitation pressure from the vortical flow is found almost in phase with the fluctuation of the total circulation in the orifice region. This helps us to deduce that vorticity accumulation in the opening region and its relatively simultaneous efflux, due to the shear layer rolling-up into a vortex, are responsible for the pressure fluctuation that excites the acoustic mode of the cavity. It is found that the frequency characteristics can be significantly varied by the system damping. Increasing the damping leads to a reduction in the range of the Strouhal number of oscillation, which is associated with the disappearing lock-in effect in frequency. The dependence of the vortex convection velocity and the critical Strouhal number for the maximum oscillation on damping is also shown.

1. Introduction

Flow-excited oscillations in a cavity happen in many engineering applications, such as pipe networks for gas transportation, sunroofs of cars, and landing gear wells or weapon bays in aircrafts. The oscillations result from the interaction between vortical flow and sound wave. For a single-cavity case, the problem can be classified into two categories: Rossiter mode and depth mode. Rossiter mode usually occurs in a shallow cavity covered by high Mach number flow [1]. It is produced through a feedback loop: vortical disturbances amplification as it is convected, pressure wave generation by the impingement at the downstream corner, upstream propagation of acoustic waves, and vorticity waves production by the acoustic waves at the upstream edge. The second type is usually excited by grazing flow over a Helmholtz resonator [2–19], a deep cavity or a side branch [20–32]. The unstable shear layer spanning over the cavity couples with the acoustic velocity at the cavity opening. Due to the acoustic resonance of the cavity, the depth mode can produce large acoustic velocity at the cavity opening and high-amplitude pressure pulsations inside the cavity at a low Mach number.

The present paper focuses on the depth mode. Modelling the coupling between vortical and acoustic flow is a challenging problem. Many models on such coupling were proposed, such as linear instability analysis [33–35], vortex-sound theory [23,26], feedback loop analysis [5,6,21], momentum balance [9], and force balance [10]. The linear perturbation theory was used to analyse the instabilities of the shear layer spanning over the cavity opening. The theory provides discrete bands of Strouhal number at which the acoustic mode is extracting energy from the mean flow [33–35]. The significance of

* Correspondence address: Laboratoire d'Acoustique de l'Université du Maine, Av. O. Messiaen, 72085 LE MANS Cedex 9, France.
E-mail address: xiwen.dai@univ-lemans.fr

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such analysis is that it theoretically proves energy conversion during the vortex-sound interaction in a cavity. However, this linear theory cannot give the resonance amplitude which is mainly determined by nonlinear saturation, and the frequency prediction is based on the assumption that the convection velocity does not depend significantly on the pulsation amplitudes. In the models based on the vortex-sound theory, the acoustic source is related to vortex convection. Bruggeman et al. [23] solved the convected wave equation with an acoustic source term for frequency and amplitude prediction. Kriesels et al. [26] calculated the vorticity distribution using the vortex blob method, which provides more details of the vortical field, and estimated the oscillations based on the time-averaged acoustic source power of the simulated vortical field. In the feedback loop analysis [5,6,21], the vortical excitation was considered as a forward gain function, which matches a backward gain function representing the acoustic response of the cavity. Based on a simplified momentum balance integrated over the opening region, Ma et al. [9] derived the oscillations as the hydrodynamic forcing divided by the mechanical impedance of the cavity. In Dai et al.'s model [10], the vortical motion at the cavity opening is coupled with the cavity acoustic mode through an explicit force balancing relation between the two sides of the opening. In these models, the shear layer was modelled by a thin vortex sheet with periodic lateral displacement over the cavity opening [33–35], or a single vortex core that moves past the opening at a given velocity U_c with increasing circulation during each cycle of oscillation [5,6,21,23], or by an array of discrete point vortices convecting at the local flow velocity with circulation determined by the Kutta condition at the separation point [10,26]. The acoustic field was normally described by a lumped model or a one-dimensional sound propagation model.

The vortex convection velocity across the cavity opening is an essential parameter in flow-excited cavity oscillations. First, the oscillation frequency is determined by the convection velocity, which controls the frequency of the motion. Convection velocity is also important to the amplitude prediction since it is related to the acoustic source term and the vortex-induced force [6,23]. However, there is a significant scattering of the convection velocity in the literature, such as $U_c/U=0.3$ from Graf and Durgin's LDV experiments [25], 0.32 for the resonance state and 0.5 for the non-resonance states at the low and high grazing flow speeds from Ma et al.'s PIV experiments [9], 0.4 obtained by Bruggeman [22], and 0.48 according to Kook and Mongeau's flow visualizations [6]. Bruggeman suggested the effects of the boundary layer thickness on the convection velocity [22]. Ma et al. [9] found a strong correlation between U_c/U and δ/L in the existing experimental data, where δ is the boundary layer thickness of the grazing flow and L is the streamwise length of the opening, and proposed a relation between convection velocity and the normalized boundary layer thickness. Experimental results of Kriesels et al. [26] and Ziada and Shine [27] for side branches reveal that under the same flow and geometry conditions, the critical Strouhal number for the maximum oscillation Sr_{cri} increases when the damping of the system is increased. Since the critical Strouhal number is approximately equal to the convection velocity normalized by the free stream velocity, $Sr_{\text{cri}} \approx U_c/U$, these experiments imply the dependence of convection velocity on oscillation amplitudes.

In this paper, vorticity convection and the excitation mechanism in the flow-excited Helmholtz resonator (HR) are explored using a verified model. In the following section, the compendium of the model is presented. In Section 3, convection velocities of both the rolled-up vortex and the total distributed vorticity are calculated, and the system excitation resulting from vorticity accumulation in the opening region and its relatively simultaneous efflux is also discussed. The influence of system damping on vortex convection velocity and the Strouhal number of oscillation is given in Section 4. Conclusions are stated in the last section.

2. Numerical model

As sketched in Fig. 1, a Helmholtz resonator with a rectangular opening in a thin but rigid facing plate is subjected to a low Mach number flow grazingly passing it. Vorticity shed at the separation point convects downstream. The vortical flow excites the acoustic mode of the resonator which in turn provides feedback on the vorticity motion. This vortex-acoustic coupling results in a self-sustained oscillation in the resonator. Nonlinear effect and dissipation prevent the disturbance from growing unbounded with time. This section presents the compendium of the numerical model, which is the same as in

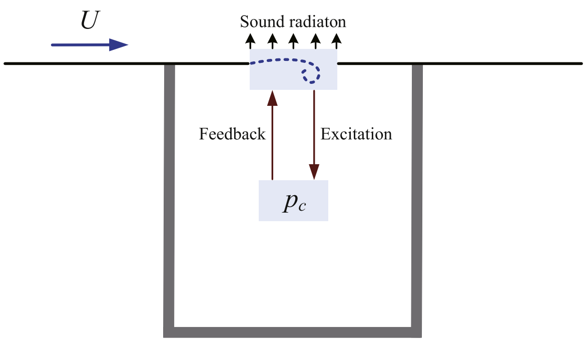

Fig. 1. Sketch of flow-excited acoustic resonance in a Helmholtz resonator.