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Investigations of self-excited vibration in splitter plate with a cavity in the supersonic mixing layer

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A B S T R A C T

The combustion efficiency strongly depends on the mixing process of fuel–air for a combined cycle engine. For an efficient mixing process, self-excited vibration of splitter plate is more practical than that of forced vibration. We have carried out a comprehensive numerical and experimental study of self-excited vibration. Finite element method (FEM) is applied to analyze the natural modal of vibration. Large eddy simulations (LES) are employed for the mechanistic study of self-excited vibration and their influence factors are evaluated from the experimental studies. Displacements are accurately measured by a non-intrusive laser vibrometer. It is found that the first-order vibration shape is quasi-two-dimensional and responsible for improved mixing. We found that self-excited vibration of the splitter plate is motivated by a cavity due to the acoustic self-oscillation. Moreover, self-excited vibration depends on the gap distance between fixed rod and splitter plate, static pressure difference between upper and lower nozzle outlet, length to depth ratio (K) and aft wall angle (θ). At zero gap distance, the frequency is up to 2.5 times higher than that of 3 mm gap distance. So, reduction in gap distance can efficiently increase the frequency of self-excited vibration, which is an encouraging point for the future study.

1. Introduction

Recently, combined cycle engine has attracted an increasing attention due to its excellent performance in low Mach number which is not available for the Scramjet engine [1–3]. Rapid mixing of two different high-speed flows in a short distance is responsible for high performance of this type of engine [4], as length of the combustion chamber is limited. For this purpose, many mixing enhancement technologies have been investigated during the past decades. Self-excited vibration is one of the most promising techniques of mixing augmentation and particularly useful inside the engine.

In order to improve the mixing efficiency, a lot of active and passive techniques have been proposed during the past decades. In 2004, J.M. Seiner et al. [5] have reported a detailed summary of this technology while P.E. Dimotakis et al. [6] have provided an overview of turbulent mixing, through combined experimental, theoretical and numerical studies. It is widely recognized that the coherent structure plays a crucial role in the evolution of turbulent mixing layer, followed by the forced perturbation to enhance the mixing process. Forced perturbations from either electric spark [7], electromagnetic flap actuators [8], sound wave [9], small oscillating flap with single or double frequency [10] and DBD plasma actuator [11] were successfully applied to improve the mixing process. D. Zhang et al. [12,13] studied the flow structure and mixing characteristics of supersonic mixing layer, disturbed by forced vibration of a cantilever plate. It is concluded that forced vibration can motivate large-scale unstable vortex structure and has a vital role in promoting the mixing process. However, forced vibration cannot be achieved inside the engine due to the complex installation of the actuator, so a different type of active mixing enhancement technologies is required. To overcome this weakness, here, we proposed splitter plate having self-excited vibration.

Although there are a few reports on the self-excited vibration to improve the mixing efficiency, but the characteristics of self-excited vibration are poorly understood, especially in the case of supersonic flow. So, overall a very little progress has been achieved for mixing enhancement through self-excited vibration due to challenges in the experimental and numerical study of fluid structure interaction (FSI). U. Vandsburger et al. [14,15] have installed a self-excited vibrating wire in the zone near the trailing edge of the splitter plate to control the turbulent mixing layer. Their results demonstrated that the high frequency of self-excited vibration can promote high spreading rate of mixing layer. However, they did not highlight the characteristics of self-excited vibration and their experiments were conducted in incompressible flow at 7 and 36 m/s

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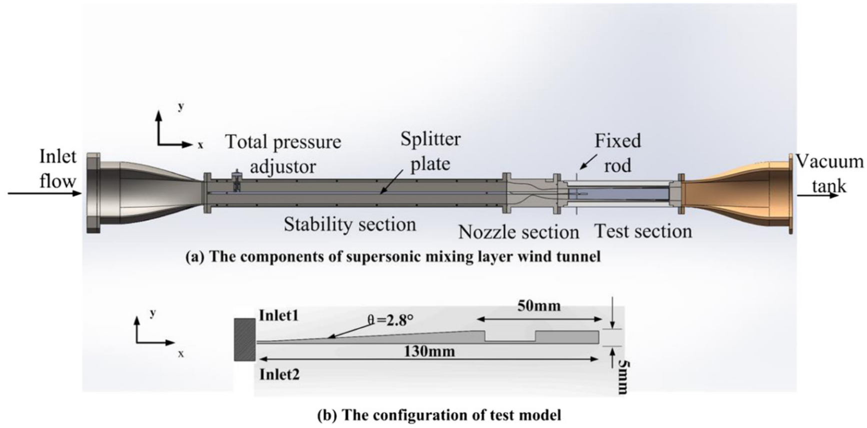

Fig. 1. Schematic representation of supersonic mixing layer wind tunnel and test model.

Table 1
Material parameters of test models.

Elastic modulus (Pa)	Poisson ratio	Shearing modulus (Pa)	Density (kg/m^3)
1.93×10^{11}	0.29	7.5×10^{10}	8000

Table 2
Parameters of incoming flow.

	Ma	U/(m/s)	T_0/K	T_s/K	P_o/Pa	P_s/Pa	Mc
Inlet-1	1.98	515.2	300	168.5	29872	3940	0.18
Inlet-2	2.76	603.3	300	118.9	101325	3969	

for lower and higher inlet respectively. A.M. Williams et al. [16] have reported the laminar and microfluidics flow characteristics through a vibrating single cantilevered IPT (Nafion-based Ionic Polymer Transducer). Again, their research aimed at low speed and laminar flow with Re = 10. Moreover, self-excited vibration is also used to control the cylinder and step flow. R. Gopalkrishnan [17] placed a self-oscillating foil in the wake of a D-section cylinder to control the free shear flow while the flow velocity was 0.15 m/s. J.C.S. Lai et al. [18] investigated the visualization of backward-facing step flow (0.32 m/s), dominated by flapping foil. It was found that the flapping foil could induce strong mixing and reduce the reattachment length. These researchers have investigated the flow feature and ignored the self-excited vibration such as actuator.

Generally, self-excited vibrations are generally regarded as negative phenomena as unwanted vibrations can shorten the life span and is responsible for structural damage such as flutter, limit cycle vibration, etc. In this work, a self-excited vibration splitter plate with a quite small amplitude is deliberately applied which can be considered as an energy harvesting device [19]. Its elastic deformation results from time-dependent aerodynamic force of unsteady supersonic flow. This technique is based on FSI, in which the flow interacts with the splitter plate at the interface. It is worthwhile to mention the work of U. Vandsburger [14,15] and D. Zhang [12,13,20] emphasize that high frequency is beneficial for efficient mixing than large amplitude. There exists a best band of self-excited vibration frequency which promotes the mixing layer at maximum rate. In order to design applicable splitter plates, self-excited vibration characteristics need to be further investigated.

In this paper, self-excited vibrational characteristics of splitter plates are analyzed through numerical and experimental studies. The splitter plate along with cavity is employed due to the acoustics self-oscillation of supersonic cavity flow, results high-frequency pressure fluctuation and induce vibration. In Section 2 and 3, numerical and experimental methods are described including experimental facilities, data preprocessing methodologies, numerical schemes, computational model, boundary conditions and code validation. Modal analysis of splitter plate is conducted to learn its characteristics and is explained in Section 4.1. The mechanism of self-excited vibration for the splitter plate along with cavity is explored in Section 4.2. The effects of gap distance, static pressure difference in the outlet of supersonic mixing layer nozzle, length to depth ratio and aft wall angle of the cavity are studied in Section 4.3. Finally, Section 5 is devoted to conclusions.

2. Experimental setup and methodology

2.1. Supersonic mixing layer wind tunnel

A supersonic mixing layer wind tunnel with low turbulent intensity was set up to carry out the experiments, which is illustrated in Fig. 1(a). The detail of this facility can be from Refs. [21, 22]. A splitter plate with thickness of 10 mm is installed in the centerline of stability section to separate the incoming flow. In this setup, the air is used as test gas. In nozzle section, there are two-dimensional nozzles with two different Mach numbers and a splitter plate in the centerline. All these parts are made of steel and the material parameters are listed in Table 1. Upper inflow total pressure can be adjusted continuously by total pressure controller, mounted in the upstream of stability section. The static pressure of the upper and lower flow can be equalized to the outlet of nozzle. It is difficult to achieve an absolute equality between the static pressure of upper and lower outlets. So, 1% error is kept tolerable. With a calibrated supersonic mixing layer nozzle having a convective Mach number of 0.18, the Mach numbers of the upper and lower flow are 1.96 and 2.76, respectively. These parameters are listed in Table 2. The part of splitter plate stretching out the nozzle can be considered as a cantilever plate, shown in Fig. 1(b) and Fig. 2(a). In this paper splitter plate $D4K5\theta60$ means that the depth, length to depth ratio and aft wall angle are 4, and 5 mm, and 60°, respectively. In test section, the fixed rod, such as screw arbor has a diameter of 4 mm, is stick to the plate surface to control the large deformation during vibration as illustrated in