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FDF-based combustion instability analysis for stabilization effects of a slotted plate in a multiple flame combustor

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ABSTRACT

In the present study, new promising methods are suggested to analyze thermoacoustic instability and the stabilization effects in the multiple flame combustor with a slotted plate. Using the generalized regression neural network (GRNN), the flame describing function (FDF) is effectively modeled from a limited number of experimental data. This neural-network based FDF method is able to generate more refined FDF data in an extended range. These refined FDF data are utilized in a Helmholtz solver for thermoacoustic instability analysis. According to the velocity perturbation ratio, eigenfrequencies are investigated to know the unstable regimes of the combustor. To take account of the effects of plate thickness, the present approach has slightly modified the Dowling method for modeling the impedance of a slotted plate. To find the effective damping conditions of a slotted plate, parametric studies have been carried out with the help of simulated annealing (SA) algorithm in wide-range operating conditions. It is identified that the absorption bandwidth becomes wider by decreasing slit width, and narrower width yields the higher average absorption coefficient. All the numerical results confirm that these new methodologies are quite reliable and widely applicable for the analysis of combustion instability encountered in many practical combustion systems.

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1. Introduction

In order to comply with stricter environmental regulations, the gas turbine industry has devised low-emission combustion systems such as lean premixed gas turbine engines. However, thermoacoustic instability is more prone to occur in these lean premixed combustors [1]. The flame-acoustics interaction could result in serious technical problems such as noise, heat flux enhancement on linings, flashback, structural vibration, and system failure. In these aspects, the systematic research efforts for combustion modeling and measurements are needed to resolve these thermoacoustic instabilities in the practical combustion systems.

In the past decades, several numerical methodologies were developed to analyze the driving mechanism of the combustion instability as well as to optimally suppress the thermoacoustic oscillations. These numerical models are largely classified by the self-excited mode strategy and the hybrid method [2–4]. In the self-excited mode strategy, the large eddy simulation (LES) has recently been applied to realistically capture the physical processes involved in thermoacoustic instability. However, since this LES-based analysis requires excessive CPU time, it is not appropriate for the parametric studies in the wide range of operating conditions. On the other hand, since the hybrid method adopts the flame response function which can be obtained by numerical simulations or experiments, it is feasible to decouple the acoustic field from the flame field. Thus, the hybrid approach has the advantage to substantially reduce the computational cost for the parametric studies. In this strategy, the flame response function is utilized to capture the dynamics between the acoustic field and unsteady combustion with a network method or Helmholtz solver [5–9]. Thus, it is quite important to obtain the more reliable and accurate flame response function. The previous studies were mostly performed by the flame transfer function (FTF), which is usually based on the linear correlation between velocity perturbations and heat release rate perturbations [1,10,11]. Thus, the FTF approach is only applicable to an early stage of thermoacoustic instability. To extend the coverage of the flame response function, the flame describing function (FDF) concept was introduced [12–15]. To be applicable to the whole range of the instability process from an initial state to the limit cycle, FDF considers not only the frequency, but also the velocity perturbation ratio. By this FDF-based approach, the resonant frequency and growth rate can be accurately calculated, and more trustworthy conclusions can be drawn from numerical results [12,14,15]. Two kinds of the flame response function have been widely

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employed to analyze the combustion instability. Hermeth [16] obtained FTF by LES and compared the single-input single-output (SISO) concept FTF with the multi-input single-output (MISO) concept FTF. Rofi et al. [17] analyzed the thermoacoustic instability by comparing numerical results obtained by two different approaches. The first way is following the conventional approach utilizing the LES-based approach to compute the FTF model. On the other hand, the second method uses the RANS-based approach to get only the time delay based on the flight time concept, and the gain index is assumed as a certain constant value. These two different FTF models together with a Helmholtz solver were utilized to analyze the combustion instability as well as to generate a stability map of the model combustor. Noiray et al. [12] and Boudy et al. [15] analyzed the nonlinear behavior of combustion instability such as frequency shift, mode change, hysteresis, and triggering in detail by utilizing FDF with the network method. Palies et al. [18] and Silva et al. [14] obtained FDF of a lab scale premixed burner from experiments. To realistically analyze the combustion instability encountered in the burner, they introduced the internal damping rate of the system and the effective growth rate. Their results clearly revealed how eigenfrequencies are varied according to the strength of velocity perturbations. Using LES results, Han et al. [13] obtained FDF for the model combustor and utilized it with a low-order network tool. The resonant frequencies predicted by numerical simulations were very close to the measurements, and their numerical results clearly demonstrated the inherent advantage of the FDF approach compared to the FTF approach.

Besides analysis for the mechanisms leading to combustion instability, there have been another research needs for posteriori damping methods to suppress the thermoacoustic instability. These stabilization methods can be largely classified by the passive control method and the active control method [19]. In the active control method, a control system monitoring the instantaneous state of combustors adjusts the fuel or air flow rate to avoid the dangerous instability conditions [20–22]. However, the active control method has the certain drawbacks such as the need for rapid response of devices and the possibility of equipment failure. On the other hand, the passive control method employs the acoustic dampers such as quarter-wave tubes, Helmholtz resonators, and perforated or slotted plates [19,23–28]. It is widely recognized that perforated or slotted plates can have a much wider absorption bandwidth than Helmholtz resonators and quarter-wave tubes [19]. Perforated plates are usually installed near the inlet of a plenum to stabilize the longitudinal mode of combustion instability [19,29,30]. In order to improve the damping performance, it is required to precisely analyze the acoustic characteristics of perforated or slotted plates. There have been numerous studies on impedance models for the perforated or slotted plates under various flow conditions and geometric features. Especially, a plate with circular orifices has been extensively studied by many researchers. Maa [31] proposed the micro perforated plate (MPP) concept to absorb sound waves without using any porous materials. Melling [32] introduced the linear and nonlinear impedance models of MPP considering the end correction and hole interaction effect. Bauer [33] also suggested the impedance model of MPP through a sequence of experiments. Howe [34] theoretically derived the Rayleigh conductivity of an infinitesimally thin plate with a hole and then specifically analyzed the absorptive features of a perforated plate under a bias flow condition with this Rayleigh conductivity. Jing and Sun [35] proposed the modified Howe model to take account of the thickness effect of a perforated plate. Furthermore, Jing and Sun [36] suggested the different numerical impedance model by capturing a real vortex trajectory behind a hole. Mendez et al. [37] devised the simple and practical impedance model for LES to reproduce the global behavior of the Howe model or its modified version. This model was adapted to perforated parts of a real gas turbine combustor for analyzing acoustic features of the combustor. Furthermore, several authors have dealt with the absorption of normally incident sound waves by a perforated plate in a bias flow condition [29,30,38–41].

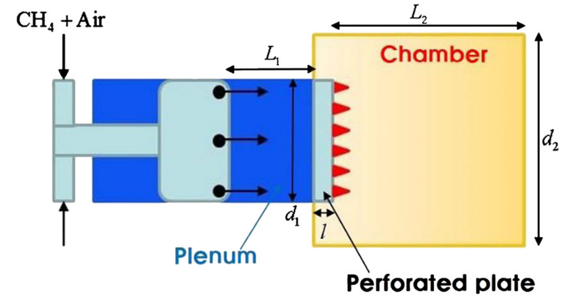

Fig. 1. Generic configuration of the multiple flame combustor in the experiment [29].

For the perforated plates, many previous studies numerically and experimentally investigated the effects of hole geometries, perforation angles, flow conditions, temperature, perturbation strength, and hole arrangements on the attenuation characteristics. On the other hand, the slotted plate has not been less explored even if it has the great potential for the stabilization devices. In this regard, the present study has been mainly motivated to numerically investigate the damping characteristics and application potentials for the slotted plates. There are two noticeable differences existing in slotted plates compared to perforated plates. For slotted plates, the potential fields behind each slit decay slowly with distance. Thus, the end correction length of a slotted plate gets much longer than that of a perforated plate. Due to this elongated end correction length, a slotted plate has the lower resistance and higher reactance [42]. Moreover, it is known that the manufacturing cost of slotted plates could be cheaper. Instead of using a laser or drill machine, pressing or shearing into panels has been recently utilized to manufacture lower-cost panels. To describe the acoustic characteristics of slotted plates, Maa et al. [43,44] Randeberg [44,45], and Dowling et al. [46] suggested the impedance models.

In the present study, new methodologies are introduced to analyze the combustion instability in a lab-scale swirled combustor. Using the generalized regression neural network (GRNN) [47], the flame describing function (FDF) is effectively modeled from a limited number of experimental data. This neural-network based FDF method is able to generate more refined FDF data in an extended range. With this modeled FDF, a Helmholtz solver is utilized to investigate eigenfrequency trajectories of several cases according to the increasing velocity perturbation ratio. In addition, the Dowling impedance model for a slotted plate is slightly modified here to include the finite thickness effect. Computations are made to analyze the stabilization effects of a slotted plate on combustion instability, and parametric studies are also performed to identify the best damping condition in terms of slit width and thickness in two given frequency ranges. In this optimizing process, the dimensions of a slotted plate are optimized by simulated annealing (SA) algorithm to get the highest average absorption coefficient in a given frequency range [48,49]. Finally, it is confirmed that a slotted plate optimized by SA algorithm is quite effective to attenuate the combustion instability.

2. Approaches and numerical modeling

2.1. Combustor geometry and operating conditions

Fig. 1 shows the generic configuration of the multiple flame combustor which simplifies the practical gas turbine combustor

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