David J. J. Toal[1]
Faculty of Engineering and Physical Sciences,
University of Southampton,
Southampton SO16 7QF, United Kingdom
e-mail: djjt@soton.ac.uk

Xu Zhang
Faculty of Engineering and Physical Sciences,
University of Southampton,
Southampton SO16 7QF, United Kingdom

Andy J. Keane
Faculty of Engineering and Physical Sciences,
University of Southampton,
Southampton SO16 7QF, United Kingdom

Chin Yik Lee
Rolls-Royce Plc,
Derby DE24 8BJ, United Kingdom

Marco Zedda
Rolls-Royce Plc,
Derby DE24 8BJ, United Kingdom

The Potential of a Multifidelity Approach to Gas Turbine Combustor Design Optimization

The desire to reduce gas turbine emissions drives the use of design optimization approaches within the combustor design process. However, the relative cost of combustion simulations can prohibit such optimizations from being carried out within an industrial setting. Strategies which can significantly reduce the cost of such studies can enable designers to further improve emissions performance. This paper investigates the application of a multifidelity surrogate modeling approach to the design optimization of a typical gas turbine combustor from a civil airliner engine. Results over three different case studies of varying problem dimensionality indicate that a multifidelity surrogate modeling-based design optimization, whereby the simulation fidelity is varied by adjusting the coarseness of the mesh, can indeed improve optimization performance. These results indicate that such an approach has the potential to significantly reduce design optimization cost while achieving similar, or in some cases superior, design performance.
[DOI: 10.1115/1.4048654]

1 Introduction

The application of optimization techniques to combustor design has the potential to unlock improvements in combustor performance, reduce emissions, increase turbine life, and reduce fuel consumption. However, the cost of the computational simulations required as part of such an optimization can be prohibitively expensive thereby reducing the scope of any design study and hence the potential level of design improvement. Design optimization approaches which can reduce the cost of such studies are, therefore, very attractive.

Surrogate modeling approaches [1], whereby a cheap analytical model which predicts how the objective function or constraints vary with changing design variables are very useful at reducing the overall cost of such design studies. While such techniques have been applied to combustor design studies throughout the literature, the application of multifidelity surrogate modeling approaches to combustor design remain rare. Such an approach enables multiple levels of simulation fidelity to be fused together to enhance the accuracy of a surrogate model. If the fidelity levels are sufficiently well correlated [2], this can both accelerate the convergence of an optimization and reduce the total simulation cost. While multifidelity surrogate model-based optimizations of combustors have been demonstrated within the literature in the past, the current paper represents the first time this has been performed for the optimization of emissions on a geometry of a fidelity similar to that employed during a typical industrial design process.

Formal design optimization approaches have been applied to the design of gas turbine combustion systems throughout the literature with the fidelity of the simulations employed in such studies varying considerably from simple aerothermal network models, to two-dimensional (2D) axisymmetric and three-dimensional (3D) CFD simulations. Of course, the choice and fidelity of simulation will depend, very much, on the design stage at which the optimization is performed.

Aerothermal network-based design optimizations, given their relative inexpense, tend to be performed at the conceptual design stage. Rogero and Rubini [3], for example, employed an aerothermal network model and an evolutionary optimization algorithm to optimize for 22 performance targets while minimizing cooling flow and NO_x emissions. Wyse et al. [4] employed a similar network model of a combustion system to minimize NO_x and CO through a Tabu search while, more recently, Saboohi et al. [5] employed a chemical network model within a multi-objective optimization attempting to also reduce NO_x and CO.

Other researchers have employed 2D axisymmetric CFD simulations within multi-objective combustor optimizations. As these simulations represent a considerable cost increase over an aerothermal network model, direct optimization using the objective function becomes infeasible and surrogate modeling strategies are employed to reduce the optimization cost. Torkzadeh et al. [6], for example, employed a surrogate modeling approach in combination with NSGA-II [7] to optimize a combustor for efficiency, NO_x and CO. Recently, Amani et al. [8] employed a similar surrogate modeling base strategy in a four variable optimization of a combustor for minimum NO_x production.

Moving up the fidelity scale, other researchers have employed 3D RANS CFD within combustor design optimization frameworks. The work of Duchaine et al. [9] is perhaps one of the earliest examples of this with a, relatively small, by today's standard, 3D CFD simulation of 1.1 m elements, being employed within a Kriging-based surrogate model optimization for both combustor efficiency and exit temperature profile. Motsamai et al. [10] performed a similar five variable optimization of the exit temperature profile of a combustor using 3D RANS simulations. Laranci et al. [11] also employed 3D RANS simulations in their optimization of exit temperature and NO_x but within a simpler two variable, full factorial, DoE approach instead of a formal optimization. Recently, Briones et al. [12] and Thomas et al. [13] both optimized combustors considering the exit temperature profile and pressure losses using 3D RANS simulations, with 9 and 15 geometry parameters, respectively, but did not consider emissions reduction.

As noted above, multifidelity design optimization approaches have been applied to combustor design in the past. The work of Wankhede et al. [14] represents the first application of such an approach, however, this employed only two design variables and optimized the exit temperature profile of a relatively simple 2D flame stabilization step. Despite the apparent simplicity of the

[1]Corresponding author.

Manuscript received February 4, 2020; final manuscript received September 11, 2020; published online March 11, 2021. Assoc. Editor: Marc D. Polanka.