Future Challenges in Computational Aeroacoustics for Fan Broadband and Combustor Noise

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Abstract

Two critical areas for the design of quiet gas turbine engines, fan broadband and combustor noise, are briefly reviewed. Both of these noise sources are sensitive to local aerodynamic and geometric variations and thus are ideally suited for analysis by computational aeroacoustic methods. To demonstrate this point for combustor noise and show areas where improved understanding is needed, the scattering of an acoustic wave by a localized heat source is studied. The heat source produces gradients in the mean flow and the speed of sound that scatter the incident duct acoustic mode into vortical, entropic, and higher order acoustic modes. Solutions to the Euler equations are computed to (i) understand how variations in the amplitude and axial extent of a steady heat source and (ii) how unsteady heat release can modify the scattered solution. For an acoustic excitation interacting with a steady heat source, significant entropy waves are produced as the net heat addition increases at the expense of the transmitted acoustic energy. When the net heat addition is held constant, increasing the axial extent of the heat source results in a reduction of the entropy waves produced downstream and a corresponding increase in the downstream scattered acoustic energy. When unsteady heat release which is proportional to mass flow fluctuations in the duct is considered, a significant reduction in the entropy occurs and a corresponding increase in the transmitted and reflected acoustic waves occurs. These results suggest that the dominance of the indirect and direct combustor noise mechanisms are highly sensitive to the heat source lengthscales relative to the acoustic lengthscales and the character of the unsteady heat release.

1. Introduction

Computational fluid dynamics (CFD) has had a significant impact on internal and external aerodynamic systems. In external aerodynamics, by simulating boundary layers and modeling complex geometries, which cannot readily be treated by analytic methods, designers are able to compute the drag over wings in transonic flow and develop designs that reduce the installation drag of aircraft [1]. In internal aerodynamics, designers use CFD to compute secondary flow losses in turbomachinery and nozzles. This capability allows designers to contour the aerodynamic surfaces of the engine to maximize engine performance without a large number of expensive rig and engine tests. As a result, CFD has become a ubiquitous component of airframe and engine aerodynamic design.
At the same time as the advances in computational science, engine manufacturers have been aggressively pursuing more efficient engines with low levels of noise and emissions [2]. To improve propulsive efficiency, jet engines have evolved towards higher bypass ratios [3]. One challenge to achieving ultra high bypass ratios is ensuring that skin friction drag and weight do not eventually offset the benefits of increased propulsive efficiency. To minimize the weight and drag associated with increasing nacelle diameter, the length of the nacelle and, as a consequence, the acoustic treatment area must be reduced. Thus, in future designs, noise reduction will be achieved less by acoustic liner and more by aerodynamic changes to the nacelle and fan case systems that directly minimize the noise sources. Computational aeroacoustic design tools offer the means to designing the next generation of low noise ultra high bypass engines.

Despite the recent advances in computational science and the technological need for new aeroacoustic designs, computational aeroacoustics (CAA) has had little, relative to CFD, influence on advanced aeroacoustic designs. To address this concern, CAA methods need to predict how local changes in mean flow and engine geometry modify the transfer of energy between vortical, entropic and acoustic disturbances. Toward this end, four major challenge areas exist for computational aeroacoustics: (i) prediction of tonal and broadband noise by rotating and stationary cascades, (ii) optimization of nozzle design (tabs, chevrons) for jet noise, (iii) noise propagation and radiation from lined bypass ducts and (iv) prediction and minimization of combustor noise and combustion instability by understanding the coupling between duct acoustic modes and the heated flow.

In this paper, we briefly review two areas where computational methods can contribute to advanced aerodynamic design: (i) the sensitivity of fan broadband noise to local changes in camber, thickness, leading edge radius, (ii) the effect of heat addition on combustor noise and combustion instability. In Section 2, we review the challenges for fan broadband and combustor noise prediction methods. In Section 3, we formulate the initial boundary value problem for the scattering of an incident acoustic wave by a heated flow. The numerical solutions are presented, in section 4, to illustrate several key issues which need to be addressed in combustor noise.


While progress in computational methods has enabled engineers to optimize aerodynamic sweep and lean for fan broadband noise [4], [5] and compute sound propagation in lined inlets [6] and nozzles [7], [8], [9], [10] the next generation of methods need to enable engineers to modify local aerodynamic features to minimize noise. Two problems which are sensitive to local changes in flow are fan broadband noise and combustor noise.

2.1. The CAA Challenge for Fan Broadband Noise

The challenge in fan broadband noise is to change the aerodynamic contour of the cascade of airfoils comprising the fan exit guide vanes to reduce broadband noise at the critical noise conditions (approach, cutback and sideline power) without impacting aerodynamic performance at the aerodynamic design condition (cruise power). At these off-design conditions as the mean flow approaches the cascade, it may have a significant incidence angle relative to the fan exit guide vane leading edge (FEGV). Thus, improved understanding and prediction methodologies for fan broadband noise that account for real airfoil geometry, varying incidence and nonuniform flow along the span of the FEGV are essential for the aerodynamic design of low fan broadband noise.

High frequency broadband noise generation is produced by the vane response to the incoming turbulence. The response is strongly affected by the flow distortion, in particular, in the vicinity of the leading edge. The turbulence-vane interaction process is characterized by multiple scales. The overall blade response and its spectral frequency depend on the incoming turbulence length scale, \( l \), the blade chord length, \( c \), which defines the characteristic convective length scale and the fan tip radius, \( r_t \), which affects the modal content of the duct. Since the incoming turbulence energy is high at reduced frequencies, \( \omega l \approx U \) where \( \omega \) is the angular frequency and \( U \) is the characteristic mean velocity and \( r_t \gg c >> l \), much of the spectral content of fan broadband noise is high frequency. Thus, it should be sensitive to changes in geometry near the leading edge that scale with the turbulence lengthscale.
Mean flow distortion affects fan noise generation via parameters such as incidence angle, leading edge radius, blade thickness and camber. Current methods used in industry are based on flat plate cascades in both two [5], [11], [12] and three dimensions [13] which provide an assessment of the aerodynamic response resulting from fan wake turbulence which is computed using Reynolds-Averaged-Navier-Stokes (RANS). However, these methods do not account for the impact of local leading edge thickness and incidence that guide the aerodynamic design of fan exit guide vanes. Moreover, experimental and numerical studies on symmetric airfoils have shown that thickness can significantly reduce the noise produced by incident turbulence when the reduced frequency based on the local leading edge thickness or maximum thickness of the airfoil is $O(1)$ [14]. Attempts to model the effects of incidence and camber have suggested that these can also be used to modify the radiated sound. However, predictive methodologies are still lacking to enable designers the knowledge to optimize the leading edge shape for both aerodynamics and noise. Figure 1 shows an example of how the pressure distribution can be varied by local changes near the leading edge of an airfoil and how predictive methods of fan broadband noise which can account for these effects would be helpful to engineers trying to optimize the airfoil design.

2.2. The CAA Challenge for Combustor Noise

Unsteady fluctuations at the flame surface in a combustor generate acoustic, entropy and vorticity waves. The outgoing acoustic waves that propagate through the turbine are referred to as direct combustor noise [15] while the outgoing entropy waves which scatter into acoustic waves as they pass through high pressure turbine at high Mach are the source of indirect combustor noise [16]. Most combustor noise work has centered on modeling indirect combustor noise by computing the scattering of entropy waves into acoustic disturbances through a nozzle [17], [18], [19], [20]. However, relatively little work has been devoted to computing the amplitude and distribution of the entropy disturbances. These disturbances are produced when unsteady fluctuations in the combustor interact with the flame surface and generate entropy waves. Thus, computing the entropy disturbances requires modeling the heat addition and its interaction with unsteady disturbances occurring in the combustor. To better understand the importance of the heat source distribution on the production of entropy we consider, in Section 4, various steady and unsteady heat sources which are forced by an acoustic wave and compute the outgoing acoustic, vortical and entropic waves. Solutions are obtained both by finite volume solution of the Euler equations and in the compact source limit by solving a system of equations which are coupled through the jump conditions at a localized heat source.

3. Formulation: Acoustic Wave Interaction with a Heat Source

In this section, we formulate the initial boundary value problem for the scattering of an incident acoustic wave by mean flow gradients and unsteady heat addition produced from a heat source. Figure 2 shows a
conceptual sketch of the model consisting of a heat source in an annular duct characterized by an inner radius, \( r_h \), and outer radius, \( r_t \). We assume an inviscid nonheat conducting flow governed by the Euler equations. The conservation equations in the volume, \( \Omega \), bounded by the surface, \( \partial \Omega \), are expressed,

\[
\frac{\partial}{\partial t} \int_{\Omega} W_i \, d\Omega + \int_{\partial \Omega} F_{Cij} n_j \, d\Gamma = S_i
\]

(1)

where \( n_j \) is the unit normal of the surface \( \partial \Omega \), the vector, \( W_i \), and tensor, \( F_{Cij} \), are the conservation variables and convective fluxes for mass, momentum and energy, respectively and the source term, \( S_i \), contains a heat source, \( \tilde{Q}(x) \) in the energy equation. These quantities are given explicitly in cartesian coordinates as

\[
W_i = [\rho \rho u \rho v \rho w \rho E]^T
\]

\[
F_{ij} = [\rho u_j p \delta_{1j} + \rho u u_j p \delta_{2j} + \rho v u_j p \delta_{3j} + \rho w u_j (E + p) u_j]^T
\]

\[
S_i = [0, 0, 0, 0, \tilde{Q}(x, t)]^T
\]

where \( \rho \) is the density, \( u_j = [u \, v \, w]^T \) are the cartesian coordinates of the velocity field, \( F_{ij} \) is the \( j \)th column of the (5 x 3) matrix \( F_{ij}^C \), \( p \) is the pressure and \( E = \rho (c_v T + 1/2|u|^2) \) is the total internal energy with temperature, \( T \) and specific heat at constant volume, \( c_v \). In general, the imposed compact source can be decomposed into steady and unsteady terms, \( \tilde{Q}(x, t) = Q(x) + q'(x, t) \). In this paper, the imposed compact, steady heat source is Gaussian, \( Q(x) = A \exp(-x/\sigma)^2 \), and is characterized by its amplitude, \( A \), and its axial extent, \( \sigma \). The geometry is an annular duct with outer radius, \( r = r_t \), and inner radius, \( r = r_h \).

At the surface of the duct, \( r = r_h, r_t \), and at any solid bodies which lie in the computational domain, the impermeability condition,

\[
\int_{\partial \Omega} u_j n_j \, d\Gamma = 0,
\]

(3)

is applied. In what follows, we nondimensionalize all lengths by the outer radius of the duct, \( r_t \), the velocity by the inlet speed of sound, \( c_1 \), and the density by the inlet mean density, \( \overline{\rho_1} \).

Nonreflecting inflow/outflow boundary conditions are prescribed as described in [21], [22]. The pressure at the inflow and outflow boundaries, respectively, is given by the relations

\[
\mathcal{L} \tilde{p} = \frac{\partial \tilde{p}}{\partial t} - (1 - M_x) \frac{\partial \tilde{p}}{\partial x} + (1 - M_x) \sum_{m} \sum_{n} \frac{\lambda_{mn}}{\beta} R_{mn}(r) \tilde{e}^{\text{inlet}}
\]

\[
\int_0^T (\beta^2 \frac{\partial p_{mn}}{\partial t'} - M_x \frac{\partial p_{mn}}{\partial t'}) J_1(\lambda_{mn} \beta (t - t')) dt' = \frac{2}{1 + M_x} \frac{\partial \tilde{p}}{\partial t},
\]

(4)
\[ L_{RR}' = \frac{\partial p'}{\partial t} + (1 + M_x) \frac{\partial p'}{\partial x} - (1 + M_x) \sum_m \sum_n \frac{\lambda_{mn}}{\beta} R_{mn}(r)e^{im\theta} \]  

where the subscript \( i \) on the right hand side of equation (4) denotes the incident pressure wave and \( M_x \) is the axial Mach number. The axial velocity can be expressed in terms of the pressure via the relation,

\[ p' + u_x = (1 - M_x) \sum_m \sum_n \frac{\lambda_{mn}}{\beta} R_{mn}(r)e^{im\theta} \]

Note the convolution integrals arise because the frequencies of the scattered waves are not generally known apriori due to nonlinear interactions. However, in the case where the unsteady fluctuations are assumed small throughout the domain the problem is characterized only by the excitation frequency and the convolution integral simplifies to the known frequency domain boundary conditions ([23], [24]).

An incident acoustic eigenmode is specified at the inflow boundary. Thus, the normal mode vector of an incident acoustic disturbance is

\[ \mathbf{Y}_i = \mathbf{A}(r)e^{(im\theta + k_{min}^+ x - \omega t)} \]  

where \( \mathbf{Y}_i = [p' u_x u_y u_e p']^T \). The circumferential wavenumber \( m \), radial mode order \( n \) and reduced frequency \( \tilde{\omega} = \Omega r_1/c \) are inputs. In what follows, we drop the tildes for convenience. The axial wavenumber is given by

\[ k_{min}^+ = \frac{\omega (-M_x \pm \sqrt{1 - (\frac{\beta \lambda_{mn}}{\omega})^2})}{\beta^2} \]

where \( + (\cdot) \) indicates modes propagating with a group velocity downstream (upstream) and \( \beta = \sqrt{1 - M_x^2} \) is the Prandtl-Glauert factor. The parameter in the square root, \( \omega/(\lambda_{mn} \beta) \), is the cutoff ratio. When it is greater than one, acoustic waves propagate in the duct carrying acoustic energy. When it is less than one, evanescent disturbances decay in the duct. The amplitude vector is

\[ \mathbf{A}^T = a_{i,a} R_{mn}[1, \frac{1}{(\omega/k_{mn} - M_x)^2}, \frac{m/r}{k_{mn}^{+}[(\omega/k_{mn}^{+} - M_x)]^2}, -\frac{1}{k_{mn}^{+}(\omega/k_{mn}^{+} - M_x)}] \]

with \( a_{i,a} \) a constant factor. Note that the nondimensional speed of sound and density at the inlet is unity.

The initial boundary value problem is specified by solving the Euler equations, equation (2), for a harmonic excitation, given by equation (7) subject to the duct boundary conditions and nonreflecting boundary conditions at the inflow/outflow boundaries (4-6).

4. Results: Acoustic scattering into entropy by various heat sources

In this section, we solve the initial boundary value problem to determine how unsteady fluctuations in the vicinity of a heat source are converted into entropic disturbances. We first consider how the axial distribution modifies the downstream entropy and then consider the effect of unsteady heat release on the production of entropy.

4.1. Effect of Finite Source Thickness on Acoustic Scattering

In this section, the effect of heat source width is studied by solving the Euler equations subject to an incident acoustic wave where the amplitude of the heat source is adjusted, depending on the width of the heat source, to maintain constant flow conditions upstream and downstream of the heat source. To isolate the effect of the heat source width on the scattered solution, the amplitude of the incident acoustic wave is small, \( a_i = .001 \).
4.1.1. Scattering by a Finite Thickness Heat Source

Three heat sources adding different levels of heat are studied. For each of the three cases, four different heat source widths producing the same net heat addition are analyzed. Figure 3 shows the Gaussian heat source distributions of different widths for the case with moderate heat energy which is characterized by the Mach number rise, $M_2 = 0.70$. Note that as the width of the heat source increases the peak amplitude decreases to sustain the same net heat addition. The imposed upstream Mach number in each case is $M_1 = 0.48$. The downstream Mach numbers for the three cases considered are: $M_2 = 0.56, 0.70$, and 0.89.

Figure 4 shows the reflected and transmitted acoustic waves for all three downstream Mach numbers, $M_2$. For each of the cases several different heat source widths, $\sigma = 0.65, 1, 2, 4$ are considered. As the width increases, the results start to deviate from the compact source limit. In each case, the trend shows the transmitted wave amplitudes increasing and the reflected wave amplitude decreasing as the axial extent of the heat source broadens. The variation in scattered wave amplitude is more visible in the shorter wavelength reflected waves than the downstream going scattered wave. The scattered wave sensitivity to the width of the heat source is most visible in the upstream going scattered wave associated with the largest heat addition case corresponding to a downstream Mach number, $M_2 = 0.89$. Here the upstream scattered acoustic wave amplitudes are noticeably smaller than the compact source limit.

Figure 5 shows an overlay of the various solutions for the case with a downstream Mach number equal to 0.70. Figures 5 (a-c) show the axial pressure, entropy and velocity distributions for four different heat source widths ranging from zero thickness, the compact source limit, to the width resulting from $\sigma = 4$. The pressure, entropy, and x-velocity solutions are plotted as a function of axial coordinate. The Euler solutions show a smooth transition across the heat source while the compact source exhibits a jump in the pressure and entropy solutions. Despite the local variation, the solutions upstream and downstream match the compact limit solution quite well. The largest variations between the solutions are visible in the entropy which decreases significantly in amplitude as the width of the heat source increases. As the amplitude of the entropy wave decreases, the amplitude of the downstream going scattered acoustic wave increases slightly. This general trend of decreasing entropy with increasing width is observed in the three mean flow jumps considered. Figure 5 also shows the full solution approaches the compact source in the limit of narrower heat source distributions and suggests the class of problems for which the compact source approximation may be used.

4.2. Effect of Unsteady Heat Addition on Acoustic Scattering

In general the unsteady motion of the flame surface generates unsteady heat fluctuations in addition to the mean rise in temperature. Dowling [25] defined a canonical unsteady heat addition case where the fluctuations in heat release are proportional to the unsteady fluctuations in the mass flow rate. In this case, $q' = \overline{m'} Q$. In this section, we examine the impact of the unsteady heat release on the amplitude of the entropy waves downstream of the heat source. We first consider a steady heat source and subject to an incident acoustic excitation. We then add an unsteady fluctuation to the heat source which is proportional to the unsteady fluctuation in mass flow and examine the difference in the downstream propagating entropy wave. Figure 6 shows the mean density, velocity and temperature solution for a flow through a heat source with width characterized by $\sigma = 0.2$. Figure 7 shows the entropy produced by the two cases. The unsteady heat addition acts to suppress the entropy wave and the transmitted and reflected waves are significantly larger since there is little scattering from acoustic energy to entropic energy. This case elucidates the importance of improved modeling and understanding of the unsteady heat release for the computing combustor noise. It also illustrates an area where computational aeroacoustic schemes can be applied to better understand how combustor noise and combustor instability arise.

5. Conclusions

Both fan broadband and combustor noise are sensitive to local changes in aerodynamics that make them ideally suited for CAA methods. For example, understanding whether combustor noise is produced by acoustic waves which are scattered by the high pressure turbine requires understanding the relative
levels of acoustic energy to entropic energy at the combustor exit. Results showing the sensitivity of the entropy downstream of a heat source to the width of the heat source and the details of the unsteady heat release illustrate the sensitivity of the combustor noise mechanism to local details such as ratio of acoustic wavelength to heat source extent and the unsteady heat release. Indeed recent experiments by Miles [26] suggest that combustor noise is characterized by the indirect noise mechanism at low frequencies where the acoustic wavelength is large relative to the heat source extent and the direct noise mechanisms at higher frequencies.

6. References

Figure 5: Mid Q Case, $M_2 = 0.70$. Effect of Heat Source Width on Unsteady Parameters 

a) Pressure, b) Entropy c) $x$-Velocity. Incident plane wave.
Figure 6: Mean Flow Solution with $\sigma = 0.2$

a) Density, b) Axial Velocity c) Temperature.
Figure 7: Entropy wave evolution for a case with mean heat addition and unsteady heat addition.