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Abstract

A framework for predicting fan related noise from high bypass ratio engines is presented in this paper. The methodology accounts for both fore and aft radiation and includes the effects of liner treatment on the engine walls. Solutions are obtained through a combination of an Euler and linearized Euler solvers, coupled with a Kirchhoff formulation for farfield noise prediction. The nacelle region is solved using the Euler equations, while the linearized Euler solver is used for the fan exhaust stage. Switching to the linearized Euler solver in the aft region has been necessary to overcome difficulties experienced due to the coupling of the acoustic modes with flow near the exhaust inflow boundary. Results are presented for spinning modes from a turbofan engine with acoustic treatment.

1 Introduction

Strict controls for jet noise reduction have lead to increased emphasis on fan generated thrust in high bypass ratio engines that have become common place in commercial air travel. However, fan noise has become a significant source of sound, especially for communities close to airports. The analysis of fan noise is challenging because it is a multifaceted problem that requires (a) identification of the spinning modes due to the rotor and the interaction between the rotor and the downstream stator (b) propagation of these modes in the engine ducting (c) analysis of the impact of lining material in damping these modes and (d) propagation of the resultant sound to the farfield accounting for aerodynamic acoustic coupling and wave refraction. In the past, it has been difficult to perform a full analysis of the entire engine and a piecemeal strategy was adopted to understand the issues relevant to each of the individual components of the engine fan noise problem. Tyler and Sofiln [1] analytically identified and classified the noise generating mechanisms in axial flow turbomachinery systems. In recent years, Rumsey et al. [2] have used a Navier-Stokes approach to look at acoustic modes emanating from rotor-wake stator-blade interaction. Analysis of mode propagation in the engine nacelle and aft duct is important primarily to identify the
cut-on modes and study the effects of flow disturbances/perturbations (boundary layer, turbulence etc.) on these modes [3, 4]. The complexity of solving the farfield engine noise problem in itself precluded researchers, till very recently from including effects due to the acoustic treatment of engine walls. For the most part, liner research evolved independently (through the use of empirical models) from computational aeroacoustics based methods for predicting engine noise. Sophisticated liner materials are now used as effective damping mechanisms and can even be tuned to attenuate noise over a range of frequencies [5]. Significant work has been done for prediction of sound radiating from engine inlets using hard wall boundary conditions by many research groups [6, 7, 8, 9, 10]. However, most of these prediction methods preclude capturing of second order effects such as aerodynamic-acoustic coupling, wave refraction etc. This shortcoming has been overcome by the authors in the past [11], by the utilization of a combined Euler equations-Kirchhoff formulation to evaluate farfield noise.

However, most of this work was limited to engine nacelles. Including aft radiation from the engine exhaust in these analyses, raises issues related to boundary conditions, grid topologies, convergence, and unsteady numerics. Most of these issues were dealt with by the authors in Ref. [12]. However, the comparisons made in that paper were limited to radiation without mass flow (e.g. dipole in a cylinder simulating an engine with acoustic modes, engine with centerbody etc.) Interestingly, it has been shown by Giles [13] that the time dependent inflow boundary conditions for the Euler equations are not well-posed. This creates a significant problem at the engine exhaust inflow boundary where the spinning modes are specified over the mean flow. However, it has been found that the linearized Euler boundary condition is well-posed at the inflow boundary. The authors have, therefore, circumvented the problem of the ill-posed boundary conditions at the engine exhaust inflow boundary by predicting aft radiation through a linearized Euler solver. In this paper, the authors present a framework for predicting fan noise from a full engine configuration (fore radiation with Euler approach, aft radiation approximated with linearized Euler equations) taking into account the effects of acoustic treatment on the engine walls. The framework used in this paper, extends the the previous work of the authors of predicting farfield noise from engine nacelles. The noise generating mechanisms are based on the theory of Tyler and Sofrin, and are not computed directly but explicitly prescribed as sources. Furthermore, the compressor exhaust is eliminated by carrying the aft end of the centerbody all the way to the axis of symmetry. The paper focuses on fan noise and jet noise is beyond the scope of the paper. The lining on the engine walls is modeled as a $z$-transform based impedance condition directly in the time domain computations [14, 15]. It should be noted that the entire framework has been validated in all its stages of development. For example, the full Euler-Kirchhoff formulation has been shown to adequately predict sound for the JT15D engine inlet and has compared favorably with semi-analytical methods [16, 15]; the impedance condition has been extensively tested out against data from the NASA Langley flow impedance tube [14].

The paper is organized as follows: In the next section details of the computational framework are discussed –the governing equations, boundary conditions and the impedance condition. This is followed by simulations of fore and aft radiation from a full engine configuration. Our interest is in evaluating spinning modes emanating from the engine rotor-stator system and our simulations demonstrate the effectiveness of our framework in prediction of farfield noise. We round up the paper with our observations regarding difficulties observed during the course of the simulations and some concluding remarks.

2 Governing Equations

2.1 Euler Equations

Inlet part of the propagation and radiation problem is solved using a full Euler solver in the present study. This solver uses the 3-D, time-dependent, conservative form of the Euler equations in cylindrical-polar coordinates $(x, r, \theta)$ as the governing equations. These equations are written
in the form
\[
\frac{\partial Q}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial F}{\partial r} + \frac{1}{r} \frac{\partial G}{\partial \theta} + \frac{H}{r} = 0
\]  
(1)
where \( Q \) is the conservative solution vector, \( E, F, G \) are the vector components of the flux tensor, and \( H \) is the source term due formulation in cylindrical-polar coordinates. The conservative dependent variables are \( Q = [\rho, \rho u, \rho v, \rho w, \rho e]^T \) denoting the density, momentum components in the axial, radial and azimuthal directions, and the energy per unit volume, respectively. The vector components of the flux tensor are given by
\[
E = \begin{ \pmatrix } \rho u \\ \rho u^2 + p \\ \rho uv \\ \rho uw \\ (\rho e + p)u \end{pmatrix}, \quad F = \begin{ \pmatrix } \rho v \\ \rho v^2 + p \\ \rho vw \\ \rho uw \\ (\rho e + p)v \end{pmatrix}
\]  
(2)
\[
G = \begin{ \pmatrix } \rho w \\ \rho uw \\ \rho vw \\ \rho w^2 + p \\ (\rho e + p)w \end{pmatrix}, \quad H = \begin{ \pmatrix } \rho v \\ \rho v u \\ \rho v^2 - \rho w^2 \\ 2\rho vw \\ (\rho e + p)v \end{pmatrix}
\]  
(3)
The energy per unit volume is found from the equation of state given by
\[
\rho e = \frac{p}{\gamma - 1} + \frac{1}{2} \rho (u^2 + v^2 + w^2)
\]  
(4)
where \( \gamma \) is the ratio of specific heats.

2.2 Linearized Euler Equations

The exhaust part of the problem is solved employing the linearized Euler equations as the governing equations. In the primitive form, the 3-D, time-dependent Euler equations are linearized about an axisymmetric, non-uniform mean flow. The linearized equations are given in cylindrical-polar coordinates by
\[
\frac{\partial u'}{\partial t} + u_0 \frac{\partial u'}{\partial x} + v_0 \frac{\partial u'}{\partial r} + \frac{u' \partial u_0}{\partial x} + v' \frac{\partial u_0}{\partial r} + \frac{1}{\rho_0} \frac{\partial p_0}{\partial x} = 0
\]  
(5)
\[
\frac{\partial u'}{\partial t} + u_0 \frac{\partial v'}{\partial x} + v_0 \frac{\partial v'}{\partial r} + \frac{u' \partial v_0}{\partial x} + v' \frac{\partial v_0}{\partial r} + \frac{1}{\rho_0} \frac{\partial p_0}{\partial r} = 0
\]  
(6)
\[
\frac{\partial w'}{\partial t} + u_0 \frac{\partial w'}{\partial x} + v_0 \frac{\partial w'}{\partial r} + \frac{u' \partial w_0}{\partial x} + v' \frac{\partial w_0}{\partial r} + \frac{1}{\rho_0} \frac{\partial p_0}{\partial \theta} = 0
\]  
(7)
\[
\frac{\partial p'}{\partial t} + u_0 \frac{\partial p'}{\partial x} + v_0 \frac{\partial p'}{\partial r} + \frac{u' \partial p_0}{\partial x} + v' \frac{\partial p_0}{\partial r} + \frac{1}{\rho_0} \frac{\partial p_0}{\partial \theta} = 0
\]  
(8)
where \( [\rho', u', v', w', p'] \) represent the perturbation quantities, density, axial, radial and azimuthal velocity, and pressure perturbations, respectively, \( [\rho_0, u_0, v_0, 0, p_0] \) are their mean counterparts, and \( c_0 \) is the mean speed of sound.

All the governing equations are transformed into a body-fitted curvilinear coordinate system through the mappings
\[
x = x(\xi, \eta); \quad r = r(\xi, \eta); \quad \theta = \theta(\zeta),
\]  
(9)
where \((x, r, \theta)\) are the axial, radial and azimuthal coordinates, and \((\xi, \eta, \zeta)\) are the curvilinear coordinates.

2.3 Boundary Conditions

2.3.1 Fan-Face Conditions

Acoustic Source Conditions. Exact cylindrical duct eugensolutions are used in definition of the acoustic source at upstream and downstream faces of the fan rotor-stator stage, which will be called hereafter as the inlet fan-face and exhaust fan-face, respectively. Acoustic pressure at a cross section in an annular duct is given in cylindrical-polar coordinates as
\[
p'(r, \theta, t) = \Re \sum_m \sum_\mu A_{m\mu} J_m(k_{m\mu} r)
\]  
\[
+ Q_{m\mu} Y_m(k_{m\mu} r) e^{i\omega t + m\theta + \phi_{m\mu}}
\]  
(10)
where \( m \) and \( \mu \) are the azimuthal and radial mode orders, respectively; \( A_{m\mu} \) is the modal amplitude constant for the \((m, \mu)\) mode, \( \omega \) is the
circular frequency; $J_m$ and $Y_m$ are the $m$th order Bessel functions of the first and second kind, respectively; $k_{m\mu}$ are the eigenvalues that satisfy the wall condition, $\partial \phi' / \partial r |_{wall} = 0$; $Q_{m\mu} = -J'_m(\sigma k_{m\mu} r_{tip}) / Y'_m(\sigma k_{m\mu} r_{tip})$ with $J'$ and $Y'$ being the derivatives of $J$ and $Y$ with respect to $r$, respectively; and $\sigma$ is the hub-to-tip ratio ($r_{hub}/r_{tip}$). When there is no centerbody (i.e., $\sigma = 0$), $Q_{m\mu}$ is zero. The azimuthal mode order $m$ is found using the rotor-stator interaction theory of Tyler and Sofrin [1]. According to this theory the circumferential mode order $m$ is given by $m = nB + sV$, where $B$ and $V$ are the numbers of rotor blades and stator vanes, respectively, $n$ is the time harmonic index and $s$ is any integer number. The number of rotor blades, number of exit guide vanes and the rotor speed are entered as part of the input for the solver, and the modes that are cut-off are automatically determined based on the local mean flow conditions at the inlet and exhaust fan-faces. Multiple harmonics of the fundamental frequency (blade passing frequency, BPF) are often seen in turbomachinery acoustics. When a multi-frequency analysis is required, a summation is performed over all the relevant frequencies the source is comprised of.

At the inlet fan-face, acoustic pressure given by Eq. (10) is specified as a perturbation to the mean pressure, and the other variables are solved using the interior equations. This approach works sufficiently well when the cut-off ratios for the inlet modes are away from unity. However, at the exhaust fan-face we apply a different approach. The conditions applied at the exhaust fan-face stem from the characteristics based inlet conditions of Giles [13]. These conditions are modified and extended to 3-D and are given in cylindrical-polar coordinates as

$$\frac{\partial w'}{\partial t} + \frac{1}{\rho_0} \frac{\partial \phi'}{\partial \theta} = 0$$ (13)

$$\frac{\partial \phi'}{\partial t} + \frac{c_0 - u_0}{2} \frac{\partial}{\partial x} (p' - \rho_0 c_0 u')$$
$$+ \frac{3c_0 - u_0}{2} \rho_0 c_0 \left( \frac{\partial v'}{\partial r} + \frac{v'}{r} \right)$$
$$+ \frac{3c_0 - u_0}{2} \frac{\partial w'}{r \partial \theta} = -\frac{L_5}{2}$$ (14)

where $L_5$ is set such that these boundary conditions yield a similar acoustic excitation to that dictated by Eq. (10).

**Mean Flow Conditions.** Mean flow calculations, however, employ a simpler, 1-D version of the characteristics based boundary conditions at both the inlet and exhaust fan-faces. First, the inlet fan-face mean flow quantities are determined analytically using the total mass flow rate ($\dot{m}$) through the inlet, free stream Mach number ($M_{\infty}$), inlet fan-face cross sectional area ($A_{\text{in}}$) information and ideal 1-D gas dynamics relations. The mean Mach number at the inlet fan-face ($M_{0,\text{in}}$) is obtained by solving the equation

$$\dot{m} / \rho_{\infty} c_{\infty} A_{\text{in}} = M_{0,\text{in}} \left[ 1 + \frac{2 - 1}{2} M_{\infty}^2 \right]^{\frac{\gamma + 1}{2}}$$ (15)

Then the mean density, pressure and speed of sound ($c_0$) are found using the relations

$$T_{0,\text{in}} / T_{\infty} = \frac{1 + \frac{\gamma - 1}{2} M_{\infty}^2}{1 + \frac{\gamma - 1}{2} M_{0,\text{in}}^2}$$ (16)

$$\rho_{0,\text{in}} = \rho_{\infty} (T_{0,\text{in}} / T_{\infty})^{1/(\gamma - 1)}$$ (17)

$$p_{0,\text{in}} = p_{\infty} (T_{0,\text{in}} / T_{\infty})^{\gamma / (\gamma - 1)}$$ (18)

$$c_{0,\text{in}} = (\gamma p_{0,\text{in}} / \rho_{0,\text{in}})^{1/2}$$ (19)

In iterating the solution to steady state, the mean pressure given by the above relations is used in the 1-D characteristic equation given for the inlet fan-face as

$$p = p_{0,\text{in}} + \rho_{0,\text{in}} c_{0,\text{in}} (u - M_{0,\text{in}} c_{0,\text{in}})$$ (20)

The other flow variables are solved at the inlet fan-face using the interior equations. This procedure yields very accurate numerical mass flow rates.

The exhaust fan-face mean quantities are determined based on the inlet fan-face conditions, bypass ratio (BPR), fan compression ratio (FCR),
exhaust fan-face cross sectional area ($A_{ex}$) information and the assumption that the Mach number across the fan rotor-stator stage is constant. Hence, the mean quantities at the exhaust fan-face are given by

$$c_{0,ex} = \gamma \frac{FCR P_{0,in} M_{0,in} A_{ex}}{\dot{m} BPR} (1 + BPR)$$  \hspace{1cm} (21)$$

$$p_{0,ex} = FCR P_{0,in}$$  \hspace{1cm} (22)$$

$$\rho_{0,ex} = \gamma p_{0,ex}/\rho_{0,ex}^2$$  \hspace{1cm} (23)$$

$$u_{0,ex} = c_{0,ex} M_{0,ex}$$  \hspace{1cm} (24)$$

To obtain the exhaust background flowfield, the above exhaust fan-face mean quantities are at the boundary in the following manner:

$$\rho u = \dot{m} BPR / A_{0,ex}$$  \hspace{1cm} (25)$$

$$\rho v = 0$$  \hspace{1cm} (26)$$

$$\rho w = 0$$  \hspace{1cm} (27)$$

$$p = p_{0,ex} - \rho_{0,ex} c_{0,ex} (u - u_{0,ex})$$  \hspace{1cm} (28)$$

where density is obtained solving the continuity equation as in the interior. It is clear from these equations that, when the exhaust solution is converged, the mean pressure becomes nearly uniform in the radial direction and equal to $p_{0,ex}$. However, when the 3-D characteristics based boundary conditions given by Eqs. (11)-(14) were used in the mean flow computations, significant radial variations were observed in the resultant mean flow quantities. Such variations made the acoustic computations using the full Euler solver in conjunction with the boundary conditions given by Eqs. (11)-(14) ill-behaved, resulting in growing waves at the exhaust fan-face. Therefore, we had to switch to the above simpler, 1-D characteristic equation for mean flow computations and to the linearized Euler equations as the governing equations for acoustic calculations. This circumvented the aforementioned difficulty and enabled us to obtain the exhaust acoustic field successfully along with the inlet acoustic field.

2.3.2 Hard-Wall Conditions

Slip wall conditions are applied at a hard wall. In both Euler and linearized Euler computations, slip wall conditions are applied in the same manner. Numerically the normal contravariant velocity is set to zero and the tangential contravariant velocity components are extrapolated from the interior solution. Pressure is then found from the normal momentum balance, as described in Ref. [15].

2.3.3 Impedance Condition

Acoustic impedance condition is applied on acoustically treated surfaces (liner). Since fluid particles penetrate a soft wall, the same momentum equations as the interior are solved, but the energy equation is replaced with the standard impedance condition [17] on a soft wall. A time-discrete form of the standard impedance condition was derived using the $z$-transform approach [14]. This condition is given by

$$\left( p_a^{n+1} - p_a^n \right)/\Delta t + L_0 p_a^{n+1} = -a_0 \left( v_{a,n+1} - v_{a,n} \right) / \Delta t - R_a^n$$  \hspace{1cm} (29)$$

where $p_a$ is the pressure perturbation, superscript $n$ shows the time step, $\Delta t$ is the time increment from one step to the next, $v_{a,n}$ is the normal component of the velocity perturbation, $L_0$ is the spatial operator $L_0 = \mathbf{V} \cdot \nabla - \mathbf{n} \cdot (\mathbf{n} \cdot \nabla \mathbf{V})$ with $\mathbf{V}$ being the mean velocity, $\mathbf{n}$ being the surface normal, and

$$R_a^n = \sum_{l=1}^{M_N} a_l \left[ \frac{v_{a,n+1-l} - v_{a,n-l}}{\Delta t} \right]$$

$$- \sum_{k=1}^{M_D} b_k \left[ \frac{p_{a,n+1-k} - p_{a,n-k}}{\Delta t} + L_0 p_a^{n+1-k} \right]$$  \hspace{1cm} (30)$$

in which the constant parameters $a_{0,1,\ldots,M_D}$ and $b_{1,\ldots,M_N}$ are related to the $z$-transform of the functional form of the frequency-dependent impedance data [14]. The coupling of the impedance condition with the time-integration algorithm of the governing equations is described in detail in Ref. [15].

2.3.4 Far-Field Boundary Conditions

Computations are performed on finite size computational domains. On the exterior boundaries of the computational domain non-reflecting boundary conditions are imposed. The boundary condition operator of Bayliss and Turkel [18] is used at
the inflow boundary. At the outflow boundary, the linearized momentum equations are solved for the velocity perturbations, but the radiation operator is applied to the pressure perturbation as suggested by Ref. [19]. All farfield boundary conditions are also written in cylindrical-polar coordinates so that the same mapping transformations as the interior apply to them.

2.4 Discretizations

Both the full Euler and linearized Euler solvers are based on a high-order explicit time marching algorithm. The governing equations and the boundary conditions are all put in the semi-discrete form

\[ \frac{dQ}{dt} + R(Q) = 0 \]  

where \( R(Q) \) represents the discretized residual of the governing and boundary condition equations. Residual discretization is carried out using fourth-order central differences, while the time integration is performed using the four-stage Runge Kutta scheme. Artificial dissipation is added to the residual to augment the scheme against spurious wave developments. A fourth-order, constant coefficient dissipation model was used in all the computations presented in the paper.

A domain decomposition methodology has been used to parallelize the codes and they scale very well on a cluster of pentiums.

2.5 Far-Field Predictions

Far-field sound is computed using the Kirchhoff method developed by the authors [16]. In this method the Kirchhoff formula given by Farassat and Myers [20] is integrated using a forward time binning approach, as described in Ref. [16].

3 Results and Discussion

Fore and aft radiation results for a generic engine are presented in this section. The inlet of the engine has a diameter of 55.9 cm at the fan stage. The inlet hub-to-tip ratio is 0.35, while the exhaust hub-to-tip ratio is 0.51. The computational mesh employed in the study is shown in Fig. 1. In the considered study the free-stream Mach number and the mass flow through the inlet are taken as 0.2 and 17.8 kg/s, respectively. Along with fore radiation, aft radiation is also investigated, considering a bypass ratio (BPR) of 4 and a fan compression ratio (FCR) of 1.1. Based on 1-D ideal gas dynamics relations, these conditions dictate an inlet fan-face Mach number of 0.198 and a throat Mach number of 0.209. The flow Mach number is assumed to remain unchanged across the fan-stator (or exit guide vanes) stage. Based on this assumption and the operating conditions, the mass flow through the exhaust duct is calculated as 14.24 kg/s. These conditions dictate an exhaust fan-face density of 1.002 kg/s. Together with the slight difference in the axial velocity and the difference in density between the outer flow and the exhaust flow, a shear layer is emanated from the shroud trailing edge as computed and shown in Fig. 1. The mean flow shown in this figure was calculated using the full Euler solver. As evident from the figure the inlet and exhaust grids are not connected. This situation was forced by the selected grid topologies. A good quality grid is essential for successful simulations. Hence, in the present configuration the upstream boundary exterior to the nacelle shroud experiences free stream. As clear from the Mach contours this does not create an important difference in the mean flow in this region.

The first case considers a combination of the (6,0) and (6,1) modes at a frequency of 3120 Hz. At this frequency both modes are cut on into both the inlet and exhaust ducts. The inlet (6,0) and (6,1) modes have cut-off ratios of 2.19 and 1.41, respectively, while the exhaust (6,0) and (6,1) modes have cut-off ratios of 1.89 and 1.26, respectively. The second case considers the (6,0) mode alone for comparison purposes. In both cases, hard and soft wall computations are realized. When the (6,0) and (6,1) modes are considered together, their modal shapes are both multiplied by the same reference pressure, but a 45-deg phase difference is introduced between the two. Modal shapes of the inlet and exhaust fan-face sources are shown in Figs. 2 and 3. No phase differences were taken into account in these plots.

Inlet acoustic field is obtained using the full Eu-
ler solver, while the exhaust acoustic field is obtained using the linearized Euler solver. Figure 4 shows the instantaneous acoustic pressure field of the generic engine as created by the (6,0) and (6,1) modes. The upper half of this figure is for the hard-wall case and the lower half is for the lined-wall case with a specific impedance value of $Z/p_{\infty}c_{\infty} = 2.17 - 1.98i$. The liner lengths and locations are shown in Fig. 4. Differences created by the liner in the acoustic field are evident. Forward-arc farfield radiation results shown in Fig. 5 were obtained by Kirchhoff integration on the surface enclosing the inlet mouth as shown in Fig. 1. Fig. 6 shows the farfield SPL for the exhaust radiation as computed by Kirchhoff integration on the surface enclosing the fan exhaust (Fig. 1). The attenuation effects of the liner are evident in both fore and aft farfield SPL results. Most fore radiation occurred in a direction about 42° angle from the inlet axis, while most aft radiation occurred in a direction about 35° and 77° from the exhaust axis. The latter indicates two significant lobes for the aft radiation. The one that is closer to the exhaust axis is due to the (6,0) mode, while the other is due to the (6,1) mode. This will be clearer when we consider only the (6,0) mode. Total attenuation by the liner was predicted as approximately 3 dB in both the fore and aft peak radiation directions.

The (6,0) mode was run also alone to see the differences the (6,1) mode made in the results discussed above. Acoustic pressure contours are not shown, but the predicted farfield SPLs are shown in Fig. 7 and 8 for the inlet and exhaust radiation, respectively. It is clear that the fore radiation lobe is now narrower and in the exhaust radiation pattern there is only one significant lobe which is at about 35° from the exhaust axis. This and the previous results clearly indicate that the (6,1) mode radiates to farfield at a higher angle from the engine axis. Again the attenuation effects of the liner are evident in the SPL results.

4 Conclusions

A general framework for predicting fore and aft radiation from turbofans has been described and simulations for a generic engine have been carried out. Fore radiation simulations were performed using a full Euler solver, and aft radiation simulations were performed using a linearized Euler solver. Use of a linearized Euler solver was necessary for the aft radiation calculations since difficulties were experienced with the exhaust fan-face source conditions coupled to the full Euler equations. In the full Euler approach a mean flowfield is obtained first and then acoustic excitation is started at the fan-face to compute the acoustic field. This in turn requires that the fan-face boundary conditions used for both steady and time-accurate computations of the exhaust field be consistent. Although for exhaust acoustic calculations the 3-D characteristics based boundary conditions given in the paper were most appropriate, they did not work for mean flow calculations with the full Euler solver. However, the difficulties experienced in acoustic calculations were overcome when a simpler, 1-D characteristics based condition was employed for the mean flow computations with the full Euler solver and the 3-D characteristics based boundary conditions were employed for the acoustic computations with the linearized Euler solver.

References


Figure 1: Generic engine mesh and mean Mach number contours: \( M_\infty = 0.2, \dot{m} = 17.8 \text{ kg/s}, \text{BPR}=4.0, \text{FCR}=1.1. \)

Figure 2: Inlet fan-face acoustic source modal shape.

Figure 3: Exhaust fan-face acoustic source modal shape.

Figure 4: Acoustic pressure contours. Source (6,0)+(6,1) modes with 45-deg phase, \( M_\infty = 0.2, \dot{m} = 17.8 \text{ kg/s}, \text{BPR}=4.0, \text{FCR}=1.1, \text{2BPF}=3120 \text{ Hz}. \)
Figure 5: Forward-arc farfield SPL, Source (6,0)+(6,1) modes with 45-deg phase difference, $M_\infty = 0.2$, $\dot{m} = 17.8$ kg/s, BPR=4.0, FCR=1.1, 2BPF=3120 Hz.

Figure 7: Forward-arc farfield SPL, Source (6,0) mode, $M_\infty = 0.2$, $\dot{m} = 17.8$ kg/s, BPR=4.0, FCR=1.1, 2BPF=3120 Hz.

Figure 6: Aft-arc farfield SPL, Source (6,0)+(6,1) modes with 45-deg phase difference, $M_\infty = 0.2$, $\dot{m} = 17.8$ kg/s, BPR=4.0, FCR=1.1, 2BPF=3120 Hz.

Figure 8: Aft-arc farfield SPL, Source (6,0) mode, $M_\infty = 0.2$, $\dot{m} = 17.8$ kg/s, BPR=4.0, FCR=1.1, 2BPF=3120 Hz.