Comparison of Aerodynamic Noise Propagation Techniques

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In this paper the computation of aerodynamic noise via different hybrid noise prediction methods is presented. An unsteady Reynolds-averaged Navier-Stokes (URANS) and a large eddy simulation (LES) solver are coupled to several wave propagation codes such as an in-house two-dimensional Ffowcs Williams and Hawkings (FW-H) acoustic analogy method and several solvers from the commercially available LMS Virtual Lab package. Application examples include the turbulent flows over a cylinder, a NACA 0012 as well as a SD 7003 airfoil. Both the aerodynamic and acoustic results show reasonable agreement with experimental data.

I. Introduction and Motivation

Airframe-generated noise is an important component of the total noise radiated from aircraft, especially during aircraft approach and landing, when engines operate at reduced thrust, and airframe components (such as high-lift devices) are in the deployed state.¹ ³ ⁴ Future Federal Aviation Administration noise regulations, the projected growth in air travel, and the increase in population density near airports will require future aircraft to be substantially quieter than the current ones. Consequently, the attempt to understand and reduce airframe noise has become an important research topic.⁵

A computational obstacle that immediately arises in problems concerning noise is that accurate propagation of the pressure (noise) signatures over a large number of wavelengths can only be obtained with very small computational mesh spacings. This makes all external aerodynamic noise problems, where the computational domain has to cover tens or hundreds of chord lengths, infeasible for even today’s largest computers. A typical approach to tackle noise problems nonetheless is to represent the computational fluid dynamics (CFD) solution on a reasonable computational mesh that does not extend too far from the aircraft. The location of a fixed near-field plane within the computational mesh can then be specified as shown in Figure 1.

This near-field plane or surface serves as an interface between the CFD solution and a wave propagation program based on principles of geometrical acoustics and/or nonlinear wave propagation.⁶ ⁷ ⁸ Such a program is able to model the wave propagation and to calculate the pressure fluctuations at a user specified ground plane which can then be used as a measure of the generated noise. Several prediction methodologies for far-field signals based on near-field flow inputs are currently available and this approach is known as hybrid noise prediction method. The most popular prediction methodologies are the Kirchhoff approach⁹ ¹⁰ and the Ffowcs Williams and Hawkings (FW-H) approach¹¹ which is based on the Lighthill acoustic analogy.¹²

Examples of hybrid predictions using unsteady Reynolds-averaged Navier-Stokes (URANS) solutions as near-field inputs can be found in the literature for a supersonic cavity flow,¹³ radiated sound for a circular

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cylinder,\textsuperscript{14} and for a slat trailing-edge flow.\textsuperscript{15–18} Singer \textit{et al.}\textsuperscript{16} compared two- and three-dimensional hybrid URANS/FW-H solutions for slat far-field noise and demonstrated the usefulness of the two-dimensional results, which gave the correct features of the radiated sound, but overpredicted the amplitude. Choudhari \textit{et al.}\textsuperscript{19} also stated that the two-dimensional approach should be sufficient for the purpose of understanding the basic noise generation mechanisms and determining the effect of Mach number and angle of attack changes. This implies that two-dimensional hybrid URANS/FW-H simulations can be used to find trends, even though they do not represent all of the underlying physics exactly. However, one should really use three-dimensional computations and large eddy simulations (LES) or at least a hybrid URANS/LES methods to be able to capture the near-field physics more accurately.

One needs to be able to calculate the near-field flow fluctuations accurately in order to get good results in some far-field observer location. Over the last century, steady flows over airfoils have been thoroughly studied yielding important experimental and numerical results. On the contrary, unsteady flows around airfoils have not been well characterized due to their higher complexity and it is still a challenge to obtain accurate empirical data. Unsteady flows over airfoils occur in many important engineering applications, such as airplanes, unmanned aerial vehicles (UAVs), helicopter rotors in forward flight, and turbine blades. There are some distinct features of the unsteady flow over an airfoil that draw special attention. These features include the generation of vortices that can strongly interact in the wake of the airfoil as well as potentially large amounts of force and moment hysteresis as well as pressure fluctuations. In most situations, these features can significantly limit the performance.\textsuperscript{20} In order to be able to study unsteady flows numerically and capture all physical phenomena with good resolution, it is crucial to use a numerical scheme that introduces as little dissipation as possible. When the artificial dissipation of the scheme becomes too large, there is significant uncertainty whether the damping observed is due to natural viscosity or numerical dissipation.

In this work both a URANS as well as an LES code are used to generate the near-field input data. NASA’s OVERFLOW\textsuperscript{21} solver is a three-dimensional implicit time-marching URANS code that can also operate in two-dimensional or axisymmetric mode. The code uses structured overset grid systems and only the near-body grids need to be supplied since Cartesian outer grids can be automatically generated. Algebraic, one-equation, and two-equation turbulence models as well as low speed preconditioners are available. The code also supports bodies in relative motion, includes a six-degree-of-freedom (6-DOF) model and allows the use of both MPI and OpenMP for parallel computing applications. Last but not least it allows the user to discretize inviscid fluxes with up to sixth order accurate schemes which helps to keep the artificial

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1}
\caption{Schematic of the propagation of aircraft pressure signatures.}
\end{figure}
dissipation error low. The LES solver uses the high accuracy numerical code FDL3DI\textsuperscript{22} which utilizes an implicit LES (ILES) procedure in which a high-order low-pass filter operator is applied to the dependent variables during the solution process, in contrast to the standard LES addition of sub-grid stress (SGS) and heat flux terms. The resulting filter selectively damps the evolving poorly resolved high-frequency content of the solution.\textsuperscript{23} The code uses a sixth-order compact-differencing scheme\textsuperscript{24} and implicit sub-iterative time marching algorithms.\textsuperscript{22} Application examples can be found in the literature.\textsuperscript{25–28}

The outline of the remainder of this paper is as follows. Section II describes the employed noise propagation approaches. Results of the different hybrid noise prediction methods for different test cases are given in Section III and Section IV concludes this paper.

II. Aerodynamic Noise Propagation Techniques

In the following a brief overview of noise propagation techniques which have been used in this research is given.

II.A. Two-dimensional FW-H Approach

The FW-H equation is analytically superior to the Kirchhoff approach for aeroacoustics because it is based upon the conservation laws of fluid mechanics rather than the wave equation\textsuperscript{29} which means that the FW-H equation is still valid if the near-field surface is located in the nonlinear flow region. The Kirchhoff approach can lead to substantial errors if the near-field surface is not positioned in the linear region.\textsuperscript{29,30} The main difficulty in solving the FW-H equation in two dimensions is the semi-infinite time integral that arises when using the appropriate two-dimensional Green function in the time-domain.\textsuperscript{31} This “tail effect” requires an infinitely long time to account for all contributions of the sources and is thus infeasible. However, the FW-H equation can be transformed into the frequency-domain to avoid this problem\textsuperscript{31,32} and this is the approach taken in this and previous work.\textsuperscript{33,34}

With the unsteady CFD solution in the near-field surface points \( y_s = (y_{s1}, y_{s2}) \) (given by \( f(y_s) = 0 \) such that \( \frac{\partial f}{\partial y_s} = n_i \) is the unit normal vector that points into the fluid) as an input, the FW-H equation after a Galilean transformation can be written as:\textsuperscript{31}

\[
\left\{ \frac{\partial^2}{\partial t^2} + U_i U_j \frac{\partial^2}{\partial y_i \partial y_j} + 2U_j \frac{\partial^2}{\partial y_j \partial t} - a^2 \frac{\partial^2}{\partial y_i^2} \right\} \left[ \rho' H(f) \right] = \frac{\partial}{\partial t} \left[ Q \delta(f) \right] - \frac{\partial}{\partial y_i} \left[ F_i \delta(f) \right] + \frac{\partial^2}{\partial y_j \partial y_{ij}} \left[ T_{ij} H(f) \right] \tag{1}
\]

Here, the monopole term \( Q \), dipole term \( F_i \), and quadrupole term or Lighthill stress tensor \( T_{ij} \) are defined as:

\[
\begin{align*}
Q(y_s, t) &= \rho u_j n_j, \\
F_i(y_s, t) &= [\rho (u_i - 2U_i) u_j + p \delta_{ij} - \tau_{ij}] n_j, \\
T_{ij}(y_s, t) &= \rho (u_i - U_i)(u_j - U_j) + (p - p_\infty) \delta_{ij}
\end{align*}
\tag{2}
\]

where \( \rho = \rho_\infty + \rho', \ u_i = U_i + u'_i \) and \( p = p_\infty + p' \) are the total density, velocity and pressure, respectively. Free-stream quantities are indicated by the subscript \( \infty \), \( U_i \) are the components of the uniform mean velocity, and a prime denotes a perturbation from the mean. The Cartesian coordinates and time are \( y_i \) and \( t \), respectively, \( \delta_{ij} \) is the Kronecker delta, \( H(f) \) is the Heaviside function, and repeated indices follow the usual Einstein summation convention.

After a Fourier transformation of Eq. (1) and some simplifications, the far-field pressure fluctuations in the frequency-domain at an observer position \( y_o = (y_{o1}, y_{o2}) \) for a Mach number less than one can be calculated from:\textsuperscript{31}

\[
\begin{align*}
p'(y_o, \omega) &= - \oint_{f=0} i \omega Q(y_s, \omega) G(y_o, y_s, \omega) \, dl \\
&\quad - \oint_{f=0} F_j(y_s, \omega) \frac{\partial G(y_o, y_s, \omega)}{\partial y_j} \, dl \\
&\quad - \int_{f>0} T_{jk}(y_s, \omega) \frac{\partial^2 G(y_o, y_s, \omega)}{\partial y_j \partial y_k} \, dy
\end{align*}
\tag{3}
\]
with the two-dimensional free-space Green function given by

\[ G(y_o, y_s, \omega) = \frac{i}{4\beta} \exp(i M_{\infty} k r_1 / \beta^2) \cdot H_0^{(2)} \left( \frac{k}{\beta} \sqrt{r_1^2 + \beta^2 r_2^2} \right) \]  

(4)

where

\[ r_1 = (y_{o1} - y_{s1}) \cos \theta + (y_{o2} - y_{s2}) \sin \theta \]
\[ r_2 = -(y_{o1} - y_{s1}) \sin \theta + (y_{o2} - y_{s2}) \cos \theta. \]

The angle \( \theta \) is defined via \( \tan \theta = \frac{y_{o2} - y_{s2}}{y_{o1} - y_{s1}} \).

The starting point is the wave equation which for small fluctuations (<140dB) in a medium reads as follows:

\[ \nabla^2 p - \frac{1}{a^2} \frac{\partial^2 p}{\partial t^2} = 0 \]

(7)

where \( p \) is the pressure and \( a \) is the speed of sound. If one assumes harmonic solutions of the form \( p(x, t) = \tilde{p}(x) e^{i \omega t} \), this can be rewritten as

\[ \nabla^2 \tilde{p} + k^2 \tilde{p} = 0 \]

(8)

which is known as Helmholtz equation where \( k := \omega / a \). Further assuming the solution of a Helmholtz point source to be \( G = \frac{e^{-ikr}}{4\pi r} \), so that \( \nabla^2 G + k^2 G = \delta \), where \( r \) is the distance from source to observer and \( \delta \) is the Dirac delta function which is infinite at the source and zero elsewhere. One can relate the integral over an arbitrary volume, \( V \), to the integral over any bounding surface, \( S \), using Green’s third identity. After simplifications this leads to

\[ \int_S \left( p(y) \frac{\partial G(x, y)}{\partial n} - G(x, y) \frac{\partial p(y)}{\partial n} \right) \, dS = -p(x) \]

(9)

which shows that if \( p \) and its normal gradient are known on \( S \) that \( p \) is known everywhere in \( V \). One can now discretize the surface into elements and assume shape functions of \( p \) and normal velocities, \( v \), on each element and cast it into the form \( [A] \tilde{p} = [B] \tilde{v} \), where \( [A] \), \( [B] \) are non-symmetric, fully populated influence matrices, and \( \tilde{p} \) and \( \tilde{v} \) are vectors of the pressure and normal velocity at the nodes. Once the pressure is known on the surface it can be calculated at any point in the volume using equation (9).

II.B. LMS Virtual Lab

The effect of flow producing a sound field can be modeled in LMS Virtual Lab (VL) using aeroacoustic analogies and unsteady CFD flow data. Direct computational aeroacoustics is very computationally expensive as described in the introduction. There are orders of magnitude between the length scales of the sound producing turbulence and the acoustic field and the energy in the hydrodynamic field and the acoustic field. The approach LMS VL is using is to assume one-way coupling where the unsteady flow produces sound but the flow is unaffected by incident sound waves. That is, CFD results are used to calculate the field. The approach LMS VL is using is to assume one-way coupling where the unsteady flow produces sound but the flow is unaffected by incident sound waves. That is, CFD results are used to calculate the field. The Green function and its derivatives are calculated analytically and the line integrals are computed using the trapezoidal rule. An inverse Fourier transformation can be applied to calculate the pressure fluctuations at the observer position in the time domain.

Boundary Element Method (BEM)

The starting point is the wave equation which for small fluctuations (<140dB) in a medium reads as follows:
**Finite Element Method (FEM)**

The BEM method starts with an exact solution to the Helmholtz equation and adjusts the test functions to match the boundary conditions. FEM in contrast exactly satisfies the boundary conditions and adjusts the solution to match the wave equation. Assuming $p^*$ is an approximate solution to the Helmholtz equation one can define residuals (difference between exact and approximate solution)

$$R_V = \nabla^2 p^* + k^2 p^*, \quad R_v = -\partial_n p^* - i\omega v, \quad R_A = -\partial_n p^* - i\omega A_n p^*$$

and a weighted residual equation given by

$$\int_V W.R_V dV + \int_{S_e} W.R_v dS_v + \int_{S_A} W.R_A dS_A = 0$$

One can then discretize the entire volume with small finite elements and define piecewise polynomial shape functions on each. Equation (11) can then be cast into the form of an “equation of motion” for each node

$$\left(\left[Q\right] + i\omega \left[A\right] - \omega^2 \left[H\right]\right) \bar{p} = -i\omega \bar{F}$$

where $Q$ is compressibility, $A$ is admittance, $H$ is inverse mass, $\bar{p}$ is the vector of pressures at the nodes, and $\bar{F}$ is a vector of excitations at the nodes. This last linear equation can then be solved for $\bar{p}$ for which LMS VL can either use the MUMPS direct solver or a Krylov subspace iterative solver.

**Ray Acoustics**

BEM and FEM both solve the Helmholtz equation through discretization of the surface or volume domains. However BEM and FEM problems quickly grow as the frequency and size increases. The number of nodes or elements increases with $f^2$ for BEM and $f^3$ for FEM and these methods can quickly run out of memory or take impractically long to solve. Ray acoustics applies in the limit that $f^2 L << L$, where $L$ is the size of the body. By treating the sound waves as rays the discretization is no longer frequency dependent.

Ray acoustics uses the Eikonal approximation and can be incoherent with only amplitude propagation, or can be coherent where the phase is influenced by the path length traveled, the wavenumber, and the local complex impedance of the medium. The phase allows constructive and destructive interference. Virtual Lab uses the Green Ray Integral Method (GRIM) and neglects the diffracted wave in regions where the incident wave is visible. It is also limited to first order diffraction only. This means it does not calculate diffractions of reflected waves or reflections of diffracted waves, and it also means it cannot capture creeping waves that diffract around thick objects. Creeping waves can be coarsely simulated by thin artificial panels.

**III. Results**

In the following subsections results for three different application cases are presented, namely the turbulent flows over a cylinder and the NACA 0012 as well as the SD 7003 airfoil. Both FEM and BEM were used in LMS VL and if tuned correctly they yielded pretty similar results. However, since FEM solutions are faster to obtain due to the sparse matrix structure of the underlying equations and FEM also has fewer user options to tune only FEM results are presented here. Ray Acoustics was briefly tried but quickly abandoned due to the poor quality of the results. Also note that the interpolation from the fine CFD mesh to the coarser acoustic mesh has a huge influence on the quality of the results of LMS VL. The key is to use conservative mapping, i.e. every node in the CFD mesh is mapped to the acoustic mesh via a distance weighting. This is in contrast to a non-conservative mapping where every node in the acoustic mesh gets its information from the closest CFD nodes which implies that the information of many CFD nodes will never be used.

**III.A. Flow over Cylinder**

The first test case is the flow around a circular cylinder. In the experiment of Revell et al. \cite{Revell}, circular cylinders with Reynolds numbers between $4.5 \cdot 10^4$ and $4.5 \cdot 10^5$ and Mach numbers between 0.1 and 0.5, were tested to obtain aerodynamic quantities and far-field acoustic spectra. Their smooth circular cylinder with a diameter of $D = 0.019$ m, measured under $Re = 89,000$ and $M = 0.2$ is considered here. The microphone is located $128D$ away from the cylinder, positioned $90^\circ$ from the front stagnation point. Two
different strategies are employed: firstly, 2D URANS calculations are used to propagate the aeroacoustic field to the far-field observer location directly by using a very fine mesh (about 2.3 million nodes). Secondly, only the near-field is finely resolved using 2D URANS on a mesh of about 280,000 nodes and the FW-H and LMS VL FEM approaches described in the previous section are employed to propagate the near-field input data to the far-field observer location. Both meshes utilized are shown in Figure 2.

![Figure 2. Meshes for CFD only (left) and hybrid approaches (right) for flow around a cylinder at Re = 89,000.](image)

Resulting pressure fluctuations at an arbitrary time step employing the SST turbulence model are displayed in Figure 3. The von Karman vortex street is clearly visible.

![Figure 3. Non-dimensionalized pressure contours for flow around a cylinder at Re = 89,000.](image)

Figure 4 shows the resulting lift and drag coefficients versus non-dimensionalized time for both meshes. One can observe that the lift coefficient seems to be grid converged, however, the amplitude of the drag coefficients shows a discrepancy between the 2.3 million nodes (labeled 'Mesh for CFD') and the 280,000 nodes (labeled 'Mesh for FWH') meshes. Nonetheless, mean flow quantities including Strouhal number...
(St_{num} = 0.251) and time-averaged drag coefficient (\bar{C}_{d, num} = 1.19) compare reasonably well with the experimental results of Revell et al. who obtained St_{exp} = 0.209 and \bar{C}_{d, exp} = 1.21.

The numerical data can be shifted in frequency so that the main tone occurs at the same Strouhal number as in the experimental results. According to Curle’s theory, linear frequency scaling also necessitates a small scaling in amplitude. Thus, the frequency and sound pressure level (SPL) predictions (a prime indicates shifted values) are scaled as follows\textsuperscript{37}

\[ f' = \frac{f_{St_{exp}}}{St_{num}} \quad \text{(13)} \]
\[ SPL'(dB) = SPL(dB) + 20\log_{10}\left(\frac{St_{exp}}{St_{num}}\right) \quad \text{(14)} \]

The acoustic spectrum at the given microphone location (calculated from about twenty shedding periods with around 400 time steps per period) is compared with Revell’s experimental spectrum in Figure 5.

Figure 4. Lift (left) and drag (right) coefficients for flow around a cylinder at Re = 89,000.

Figure 5. SPL of flow around a cylinder at Re = 89,000; left shows unaltered computations and right shows results with frequency and amplitude shifts applied.

Clearly the peak frequency is wrong in the left figure since the URANS computed Strouhal number is incorrect. However, if the frequency and amplitude shifts given by equations (13) and (14) are applied with results shown in the right figure the fundamental harmonics agree much better. In order to have a better agreement in the sound pressure levels it may be necessary to run three-dimensional simulations as observed by Lockard:\textsuperscript{31} “The flow structures responsible for generating noise can be pseudo-two-dimensional, with a finite correlation length in the third direction. In such cases, a two-dimensional simulation should give the correct features of the radiated sound, but overpredict the amplitudes. Two-dimensional results can be used to find trends and determine the resolution requirements for three-dimensional calculations...”

In general, there is reasonable agreement among the different noise propagation techniques. LMS VL FEM seems to underpredict the broadband noise levels compared to all other methods. FW-H on the other hand underpredicts the second peak if it is only using cylinder surface pressures without velocity fluctuations from a permeable surface one diameter away from the cylinder surface.
III.B. Flow Around NACA 0012 and SD 7003 Airfoils

These test cases involves the Mach 0.1 flow around a NACA 0012 and a SD 7003 airfoil with a Reynolds number of half a million, angle of attack of four degrees, and a chord of 0.229 m. Both airfoils are shown in Figure 6 for comparison purposes. It can be inferred that the top surface of the SD 7003 airfoil is very similar to the NACA 0012, but overall the SD 7003 airfoil is thinner, asymmetric, and cambered. Pressure contours around the NACA 0012 airfoil from an LES simulation with natural transition (untripped) using FDL3DI on a mesh of about 71 million nodes are displayed in Figure 7. It is shown by Visbal\textsuperscript{38} that the level of resolution on this mesh is of LES-quality.

As an initial verification LES is used directly to propagate the aeroacoustic field of the untripped NACA 0012 to six different observer location which are shown in Figure 8.
These direct LES predictions are compared to the FW-H and LMS VL FEM approaches which are used to propagate the airfoil surface pressure fluctuations from the LES simulation to the same six observer locations. The SPL spectra comparisons in these different stations are shown in Figure 9. These comparison show reasonable agreement which gives confidence that the hybrid methods and the employed wave propagation approaches are implemented and used correctly.

A comparison of noise predictions at an observer location of $1.22\,m$ directly above the trailing edge of the airfoil are given in Figure 10. This location was chosen since a microphone was located in that exact location in the experiments of Brooks et al.\textsuperscript{39} which involved NACA 0012 airfoils with different spans as well as tripped and untripped boundary layers in a variety of flow conditions. The NAF labeled data comes from a semi-empirical aeroacoustic noise prediction code for wind turbines\textsuperscript{39,40} for which a span of $1\,m$ was assumed. NAF was tuned using the experimental data of Brooks et al. and so one can consider the NAF data to be pretty close to actual experimental data.

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Figure 9. SPL predictions from LES and hybrid methods for flow around around NACA 0012 airfoil in observer stations 1-6 (from top left to bottom right).
One can see a decent agreement between LMS VL and FW-H predictions at least up to 3 kHz. Both noise prediction codes use exactly the same input data which are airfoil surface pressure calculations from LES. The peak frequency is slightly overpredicted by LES and consequently by both noise propagation techniques.

Lastly, two potential noise mitigation techniques are briefly investigated. First, the airfoil thickness is reduced and the camber is slightly increased by using the SD 7003 airfoil rather than the NACA 0012. Secondly, the laminar to turbulent transition is sped up by tripping the boundary layer which experiments have shown\(^{39}\) to have beneficial results on the overall noise level. This is accomplished in the LES simulation by a high frequency blowing and suction on the lower surface near the leading edge. Noise results of these strategies in the same observer location (1.22 m directly above the trailing edge of the airfoils) can be seen in Figure 11. Note that the NAF code for the SD 7003 results relies on Xfoil estimates for quantities such as boundary layer heights and then uses some empirical formulae to predict the noise levels. There are presumably considerable uncertainties associated with these results whereas for the NACA 0012 cases NAF can rely on experimental data of Brooks et al.\(^{39}\) which should make those results much more reliable.

A few observations can be made. Firstly, once again the LES/FEM and LES/FW-H hybrid approaches are in reasonable agreement with each other. Secondly, the NAF and hybrid predictions show a vastly different behavior; according to NAF tripping the boundary layer should remove the “hump” at the peak frequency of about 2000 Hz and reduce the overall sound pressure levels considerably whereas slimming and cambering the airfoil will shift the peak frequency but not significantly influence the overall SPL. The hybrid
methods (using LES surface pressure fluctuations), on the other hand, predict that tripping the boundary layer has only a small influence on the peak frequency SPL and overall SPL whereas the SD 7003 airfoil will essentially remove the “hump” around the peak frequency.

In Figures 12 (different scales) and 13 (using the same scale) comparisons of pressure fluctuations in the frequency domain at 2000 Hz for the three different cases are shown.

All three exhibit strong fluctuations in the laminar to turbulent transition region, but they are significantly lower for the tripped NACA 0012 airfoil whereas the SD 7003 and untripped NACA 0012 airfoils are comparable though the fluctuations of the SD 7003 airfoil are over a smaller surface area.

IV. Conclusions

This paper describes the computation of aerodynamic noise via different hybrid noise prediction methods. A URANS solver (OVERFLOW) was coupled to several wave propagation codes and comparisons between experimental and computational results were shown for turbulent flows over a cylinder. In addition, an LES solver (FDL3DI) was also coupled to the same wave propagation codes and aeroacoustic results were presented for the turbulent flow over a NACA 0012 as well as a SD 7003 airfoil. In general, reasonable agreement was found among the different hybrid noise prediction methods. The comparison between directly propagated acoustics via URANS and LES on the one hand and the hybrid methods on the other hand look also very promising. However, comparisons between experimental noise results and the hybrid predictions are less convincing. Given that the verification results look promising the cause of the discrepancy is presumably the quality of the CFD near-field input data. The underlying physical model of URANS may be an issue, however, the arguably much better results based on the LES model do not agree with the experimental data either, though the tendencies seem to be captured correctly. This leads the authors to believe that the differences are most likely stemming from the problem setup, i.e. geometry description, flow conditions, wind tunnel vs CFD boundary conditions, sensitivity of microphones, background noise, incoming turbulence levels, etc. Nonetheless, given that there are orders of magnitude between the length scales of the sound producing turbulence and the acoustic field and the energy in the hydrodynamic field and the acoustic field the presented results are satisfactory and encourage the use of hybrid noise prediction methods at least for preliminary design trade-off studies.

Figure 12. Comparison of pressure fluctuations at 2000 Hz for SD 7003 (left), NACA 0012 untripped (middle), and NACA 0012 tripped (right).

Figure 13. Comparison of pressure fluctuations at 2000 Hz (on the same scale) for SD 7003 (left), NACA 0012 untripped (middle), and NACA 0012 tripped (right).
Acknowledgments

This work was supported by the United States Air Force Research Laboratory (AFRL). The views and conclusions herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or limited, of U.S. Air Force Research Laboratory or the U.S. Government.

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