Large-eddy simulations of multi-bladed VTOL rotors for air vehicle aeroacoustic predictions

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Large-eddy simulations of isolated scaled multi-bladed VTOL rotors are performed to assess the accuracy and computational cost of high-frequency aeroacoustic predictions. Four different scaled rotors with 2, 3, 4 and 5 blades are simulated with the moving-mesh version of the low-Mach flow solver “charLES” for comparison with aeroacoustics measurements conducted at Honda’s wind-tunnel facility. Overall, the noise predictions show good agreement with the experimental data in terms of BPF tone, broadband noise and OASPL. In particular, the simulations capture the experimental trend of increase in high-frequency noise with increase in number of blades. A proof-of-concept simulation of a full-scale eVTOL aircraft with 8 VTOL rotors and 2 propellers is also conducted, to demonstrate the approach and evaluate the potential increase in computational throughput achievable with GPU acceleration.

Nomenclature

\[\begin{align*}
C & \quad \text{Rotor chord} \\
c & \quad \text{Speed of sound} \\
d & \quad \text{Rotor diameter} \\
dt & \quad \text{Time step} \\
f & \quad \text{Frequency} \\
M & \quad \text{Mach number} \\
p & \quad \text{Pressure} \\
Re_C & \quad \text{Reynolds number} \\
s & \quad \text{Entropy} \\
t & \quad \text{Time} \\
u & \quad \text{Fluid velocity vector} \\
x & \quad \text{Cartesian coordinate vector} \\
\sigma & \quad \text{Total viscous stress tensor} \\
\rho & \quad \text{Density}
\end{align*}\]

I. Introduction

Rotor and propeller aeroacoustics has been studied extensively over the last 50 years [1, 2]. Arguably, some of the early work on noise reduction was originally motivated by the need to reduce detectability in military applications such as propeller aircraft and helicopters [3, 4, 5]. While this remains an active area of
research, more stringent community noise regulations and environmental impact concerns are now additional issues pushing the design of rotors towards quieter configurations. In particular, there has been a recent renewed interest in rotors as propulsion device for commercial unmanned air vehicles (UAV) and for Urban Air Mobility [6] such as electric vertical take-off and landing (eVTOL) aircraft (see figure 1). Since such vehicles are envisioned to operate in urban areas in close proximity to humans, minimizing the rotor noise signature will be a key component of the design and certification, in addition to high level of safety.

![Figure 1: Example of Honda’s eVTOL aircraft concepts](images/honda_evtol_concepts.png)

One of the challenges for the design of a quiet rotor is that the geometrical and aerodynamic modifications to achieve noise reduction can affect (and potentially compete with) the overall efficiency, performance or structural integrity of the propulsion system. This leads to a large parameter space to investigate with laboratory and full-scale testing. Numerical tools are therefore desirable to extend the range and success of the design optimization [7].

In terms of modeling capabilities, steady engineering approaches such as Reynolds-averaged Navier-Stokes (RANS) methods, are unsuitable due to the importance of transient phenomena in these flows. In contrast, high-fidelity methods, like Large Eddy Simulation (LES), have shown significant advantages in predicting unsteady turbulent flows and their acoustic fields, in particular for subsonic and supersonic jet noise [8, 9]. Unlike helicopters or propeller aircraft, many of the eVTOL aircraft designs currently considered rely on multiple rotors and propellers. These operating conditions lead to moderate velocities (Mach number less that 0.5) and relatively low Reynolds number (of the order 500,000 based on the tip speed and chord), which are well suited for low-Mach LES solvers. With the advancement in high-performance computing, LES is also becoming a cost-effective computational tool that can ultimately be used to help guide the design optimization. Nevertheless, up to now, the impact of LES has been limited for propeller aeroacoustics predictions, and in general, for simulations of complex geometries relevant to practical engineering applications involving surface motion. The need to generate large (with respect to the number of degrees of freedom), high-quality meshes with careful and efficient resolution of important moving (or stationary) boundaries currently limits the overall time to solution and can have undesirable effects on the solution accuracy.

To address these challenges, Cascade Technologies, now part of Cadence Design Systems, developed a massively-parallel computation framework to perform high-fidelity large eddy simulations of turbulent flow and acoustics, using high-quality, body-fitted, conformal moving meshes. In particular, the approach leverage a mesh generation paradigm based on the computation of 3D Voronoi diagrams, which is ideally suited for surface motion. An overview of the numerical methods is presented in Section II. Then, results of simulations of multi-bladed VTOL rotors conducted in collaboration with Honda are reported in Section III. Finally, a proof-of-concept simulation of a full scale eVTOL aircraft is presented in Section IV, with emphasis on computation cost and GPU acceleration.

### II. Numerical Methods

The moving-mesh low-Mach flow solver charLES is a finite volume LES code that uses low-dissipation numerics within an arbitrary Lagrangian-Eulerian moving mesh framework [10]. The solver is well suited for performing low-speed turbulent flow simulations involving rotating bodies. In the open literature, the static variant of the low-Mach flow solver charLES has been utilized to analyze car aeroacoustics [11, 12], car aerodynamics [13] and building wind loading [14].
A. Low-Mach (Helmholtz) formulation

Incompressible formulations of the Navier-Stokes equations are efficient for the time integration of low Mach number flows by avoiding the time step (or stiffness) associated with the propagation of acoustic waves. The attenuation of all acoustic waves has two immediate consequences. First, as is the case here, it is often desirable to compute the acoustic field in low speed flows. Second, the incompressible equations are a limiting behavior where the speed of sound is infinitely larger than the convective velocity making the governing equations elliptic in nature. This yields a poorly conditioned system of governing equations that are difficult to solve. the low-Mach flow solver charLES addresses these issues by introducing a formulation that preserves a finite speed of sound and admits lower frequency acoustic waves without sacrificing time steps that scale with the convective time-step limit [14]. This is accomplished by approximating the flow as isentropic to yield a coupling between the density and pressure perturbations in a variable density setting. The introduction of a finite sound speed also results in a better conditioned set of governing equations allowing for faster and more scalable solutions.

We admit a two variable expansion of the density, $\rho$, of the fluid in terms of its entropy, $s$, and pressure, $p$

$$d\rho = \frac{\partial \rho}{\partial s} |_{p} \, ds + \frac{\partial \rho}{\partial p} |_{s} \, dp$$

(1)

Assuming the flow is low-Mach, we will admit an approximation that the flow is isentropic. Then integrating Eqn. 1 from a reference state, $(s_{ref}, p_{ref})$ to another thermodynamic state, $(s_{ref}, p)$ yields (dropping the entropy argument)

$$\rho(p) - \rho_{ref} = \int_{p_{ref}}^{p} \frac{1}{c^2} \, dp = \frac{1}{c^2} (p - p_{ref})$$

(2)

where $c = \sqrt{\left| \frac{\partial p}{\partial s} \right|_{s}}$ is the speed of sound.

The continuity and momentum equations for a variable density flow are given by

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_{j}}{\partial x_{j}} = 0$$

(3)

$$\frac{\partial \rho u_{i}}{\partial t} + \frac{\partial \rho u_{i} u_{j}}{\partial x_{j}} = -\frac{\partial p}{\partial x_{i}} + \frac{\partial \sigma_{ij}}{\partial x_{j}}$$

(4)

where $\sigma_{ij}$ represents the total viscous stresses. An LES solution is sought for the fluid state: $\rho$ (equivalently, $p$) and $u_{i}$, so Eqns. 3 and 4 should be interpreted as filtered, where all the variables are grid resolved and the subgrid stresses are included in $\sigma_{ij}$. For this study, the subgrid stresses were modeled using the Vreman subgrid stress model [15].

Eqns. 3 and 4 are time advanced using a second-order backward difference discretization (BDF2) and a fractional step approach:

$$A(\rho u)^* = r^{n}$$

(5)

$$\rho^{n+1}u^{n+1} - (\rho u)^* = -\frac{2}{3} \Delta t Gp$$

(6)

where $A, G$ denote the discrete implicit time advancement and gradient operators, respectively, $(\rho u)^*$ denotes the predicted velocity, and $r^{n}$ includes known terms at the current time step.

Taking the discrete divergence, $D$ of Eqn. 6 and using Eqn. 3 yields

$$-\frac{\partial \rho}{\partial t} |^{n+1} - D(\rho u)^* = -\frac{2}{3} \Delta t DGp$$

(7)

The BDF2 time discretization of the density time derivative in Eqn. 7 is written as

$$\frac{\partial \rho}{\partial t} |^{n+1} = \frac{3}{2} \rho^{n+1} - 2\rho^{n} + \frac{1}{2} \rho^{n-1}$$

(8)
We now use Eqn. 2, assuming a reference pressure of zero, in the above expression and substitute into Eqn. 7 to yield a Helmholtz system for the pressure

$$-rac{3}{2} \frac{1}{c^2} \Delta t p^{n+1} + \frac{2}{3} \Delta t D G p^{n+1} = D p u^* + \frac{2}{3} \rho_{\text{ref}} - 2 \rho^n + \frac{1}{3} \rho^{n-1} \frac{\Delta t}{\Delta t}$$

(9)

The time step is completed using the relations in Eqns. 2 and 6 for $\rho^{n+1}$ and $u^{n+1}$, respectively.

In addition to capturing low-wavenumber (low frequency) acoustics in low Mach number flows, the Helmholtz solver is also more efficient and scalable than an incompressible flow solver. It is well known that the solution of the Poisson equation for the pressure in incompressible fractional step algorithms is the primary bottleneck, which is transformed into a Helmholtz equation when a finite sound speed is introduced.

Without loss of generality, consider the BDF2 Helmholtz equation arising from a one-dimensional problem on the interval $x \in [0, 1]$ (where the problem has been suitably non-dimensionalized by a reference length).

$$\left( \frac{9}{4} \frac{1}{c^2} \Delta t I - \Delta t D G \right) p = f \Leftrightarrow B p = f$$

(10)

With the choice of a simple 3 point discrete Laplacian, $L = DG$, on a uniform mesh ($\Delta x = \frac{1}{N+1}$), the eigenvalues of $B$ are given as

$$\lambda_j(B) = \frac{9}{4} \frac{1}{c^2 \Delta t^2} + 2 \left( 1 - \cos (\pi j \Delta x) \right)$$

(11)

for $j = 1, \cdots, N$. Then, the condition number of the Helmholtz operator is

$$\kappa(B) = \frac{\lambda_{\max}}{\lambda_{\min}} \approx \frac{9}{4} \frac{1}{\pi^2 \Delta x^2} + \frac{4}{\pi^2 \Delta x^2}$$

(12)

For the traditional definition of the Courant–Friedrichs–Lewy number $CFL = \frac{u \Delta t}{\Delta x}$ and Mach number $M = u/c$, let $\theta = CFL/M$ be the acoustic-CFL corresponding to the simulation time step. The condition number can be equivalently expressed as

$$\kappa(B) \approx \frac{9}{4} \theta^{-2} + \frac{4}{\pi^2 \Delta x^4}$$

(13)

Note that the condition number of the discrete Laplacian arising from a Poisson equation is similar to Eqn. 13:

$$\kappa(-L) \approx \frac{4}{\pi^2 \Delta x^2}$$

(14)

which scales with $\frac{1}{\Delta x^2}$.

In the limit when the acoustic-CFL is large ($\theta >> 1$), then the condition number of the Helmholtz operator (Eq. 13) is identical to the Poisson equation (Eq. 14). In the limit when the acoustic-CFL is small ($\theta << 1$), the condition number of the Helmholtz operator approaches unity, making its solution trivial. For the practical applications with $M = O(0.3)$, the Helmholtz operator’s reduced condition number (with respect to the traditional Laplacian operator) greatly reduces the number of required iterations.

### B. Voronoi-diagram based moving-mesh solver

As a way of partitioning, a Voronoi diagram divides space into elements surrounding a given set of forming points with each element defined as the region of space closest to a forming point relative to all other forming points. It enables highly scalable mesh generation, since the global mesh is uniquely defined, yet each individual cell can be constructed with only local information. The mathematical properties of Voronoi diagrams provide computational efficiencies for both robust and flexible mesh generation, as well as for flow solvers. Importantly, the Voronoi paradigm reduces the problem of mesh generation to the much simpler problem of specifying the generating point locations, i.e. the locations where the solution will be sampled. The actual mesh (volumes, faces, topology, neighbor connectivity) is simply a unique mathematical consequence of this choice based on the definition of the Voronoi diagram. This dramatically simplifies the control over local mesh resolution - an important consideration for automation and high-fidelity simulations. Additionally, the discretization of the boundary surface (faceting/triangulation of the surface) is independent from the near-boundary mesh resolution, allowing for arbitrary coarsening or refinement relative to the local surface length scales. The impact of leveraging these benefits in mesh generation is a dramatic reduction
in the time and human interaction required to generate quality meshes for high-fidelity applications. The flexibility and simplicity of the Voronoi meshing approach make it an attractive paradigm for mesh motion. At any given time step, a single, conformal grid (from the collection of deformable Voronoi diagrams) is present that allows for a conservative discretization.

Figure 2: Illustration of 2D Voronoi diagrams given a set of generating points (blue dots). The faces (black edges) are perpendicular bisectors between the generating points. (b) shows the clipped Voronoi diagram for the same generating points, where the bounding surface (red lines) "clips" the exterior cells but has no effect on internal cells whose extents are defined only by generating points. Note that the spatial distribution of the generating points is formally independent of the bounding surface.

For the calculations performed here, the mesh motion is restricted to isolated rotating bodies. This permits two simplifications regarding the mesh motion that allows for substantial speedup: 1) that the interface is effectively “sliding” (a rotating disk for instance) and 2) that there are no appearing or disappearing degrees of freedom (that might be encountered if the total domain volume was a function of time as would be the case for a valve opening). The simplification to “sliding” interfaces is sufficiently general to tackle the problems with rigid body rotations, such as rotating rotor & propeller flows. Under these simplifications, the mesh rebuilding step reduces to performing an update of the Voronoi diagram faces on the moving-stationary interface only. In figure 3, the magenta line segment represents an interface face and the red dot is the cell center in the rotating part next to the face. When the part rotates, the face is cut by different neighbors encountered in the stationary part (blue dots). A one sided operator is constructed for the face in each part and the information between the rotating and stationary parts is exchanged through the interface flux. Away from the interface, the spatial operators in the stationary region are left unchanged while the those of the moving region are linearly transformed.

Figure 3: Rotating interface at two consecutive time steps $t_0$ and $t_1$. 

American Institute of Aeronautics and Astronautics
III. Large-eddy simulations of multi-bladed VTOL rotors

A. Experimental configuration and LES methodology

This present study is part of a larger collaborative effort with Honda R&D to investigate aeroacoustics of rotors and propellers with the moving-mesh low-Mach (Helmholtz) flow solver charLES. Simulations of isolated scaled multi-bladed VTOL rotors with 2, 3, 4 and 5 blades (see figure 4) are performed and compared with experimental measurements conducted at Honda’s wind-tunnel facility. Figure 5 shows pictures of the rig in the anechoic section of the tunnel and of the installed rotor. For this complex configuration with motion, all the details are included in the computational domain and the grids for both stationary and rotating parts are generated using Cascade’s Voronoi-based meshing technology and the moving/stationary interface treatment discussed in the Section II.

(a) 2-bladed rotor  (b) 3-bladed rotor  (c) 4-bladed rotor  (d) 5-bladed rotor

Figure 4: Experimental multi-bladed VTOL rotors

(a) Overview  (b) Installed rotor

Figure 5: Experimental setup in Honda’s wind-tunnel

A schematic of the computational domain is presented in figure 6, highlighting the wind-tunnel walls (in purple), the inlet nozzle (in blue) and the outlet duct (in green), as well as the rig installed in the tunnel. For the present operating conditions, there is no ambient flow (i.e., inflow speed of 0 m/s), and only one rotor is installed on the two-motor rig configuration, on the inlet side of the rig. The different scaled rotors considered have a chord $C$ varying from 51 mm, to 34 mm, 25 mm and 22 mm for the 2, 3, 4 and 5-bladed rotors, respectively. For all the rotors, the rotation speed is set to 5000 rpm, the blade diameter is $d = 395.94$ mm, the blade thickness is $O(6)$ mm, and the tip Mach number is approximately 0.3. The Reynolds number based on chord and tip velocity is therefore in the range $Re_C \approx 150,000$ to 360,000.

The numerical setup is similar to previous work with the low-Mach (Helmholtz) flow solver [11, 12, 13, 14] and is only briefly summarized here. The Vreman [15] sub-grid model is used to account for the physical
effects of the unresolved turbulence on the resolved flow. Non-reflecting sponge treatment is applied away from the rig to minimize acoustic reflections from the walls. Slip-wall boundary conditions are used on all the wind-tunnel surfaces, while the rig is treated as no-slip wall and adiabatic wall-stress modeling based on the equilibrium boundary layer assumption [16, 17] is applied on the rotating blades. The present mesh contains approximately 25 M control volumes (cv) for the stationary part and 4 Mcv for the rotating part, as shown in figures 7 and 8, respectively. Note that the horizontal disk in figure 7 represents the interface between the stationary and rotating parts. The near rotor wake is in a 2 mm resolution region and the blade surface (finest) resolution is 0.125 mm in the wall normal direction and 0.5 mm in the tangential direction (i.e., near-wall cell aspect ratio of 4), with 5 layers over the surface. These choices for the grid resolution leads to modest mesh count of $O(30)$ Mcv with approximately 50 to 100 cv per chord, depending on the rotor. For all the cases, the simulation time step is $dt = 1.25 \times 10^{-6}$, corresponding to $CFL \approx 2.8$. The computational cost for the collection of 0.1 s of data on 1024 cores (AMD EPYC) is approximately 18 KCPUh.

For typical eVTOL aircraft application, the main sound sources corresponding to blade loading and thickness noise at the blade passage frequency (BPF) and harmonics, vortex noise, blade vortex interactions (BVI) and broadband noise are expected in the 1 BPF to 40 BPF frequency range. For the present scaled
rotors, the frequency range of interest is therefore set to between 100 Hz and 17,000 Hz, where the lower and upper bounds are chosen based on the BPF of the 2-bladed rotor (1 × 167 Hz) and 5-bladed rotor (i.e., 40 × 416 Hz) respectively.

The experimental microphone used for comparison with the simulation is positioned 1.515m away from the axis on the rotor plane. Far-field noise predictions at the microphone position are computed using Cascade’s implementation [18] of the frequency-domain permeable formulation [19] of the Ffowcs Williams & Hawkings [20] (FW-H) equations. The FW-H surface enclosed the rotor in the 2mm region and the cutoff frequency is expected to be $f \approx 21,000$ Hz, assuming a minimum of 8 cells per wavelength. The FW-H surface data is sampled at 40,000 Hz for a duration of 0.11 s to 0.24 s, depending on the case (i.e., at least 10 periods of the lowest frequency of interest). Here, it is important to note that the FW-H approach does not take into account the presence of the solid walls outside of the FW-H surface. To estimate the reflections of acoustic waves off the ground of the wind-tunnel and their contributions to the far-field noise measurements, the classical method of images and acoustic reciprocity can be used (see in Chap. 6 in Ref. [21]). The acoustic pressure at the image microphone located at the symmetric position of the original microphone with respect to the rigid floor boundary is computed with the FW-H solver, using the same input source. Then, the complex acoustic pressure of both the original and image microphones are summed in the frequency domain and post-processed to compute PSD in dB/Hz, OASPL in dB and dBA. The resulting acoustic spectra now accounts for both the (perfect) reflections on the floor and the direct propagation from the FW-H surface.

**B. Experimental and numerical results**

Representative flow field results are shown for the 5-bladed rotor in figure 9. For the single isolated rotor installed on the inlet side of the rig, the blade is mounted such that the pressure side is on top and the rotating direction is clockwise (CW) based on the view from the bottom. Therefore, the rotor wake is going up, away from the tunnel ground. In the acoustic pressure field in figure 9(b), strong reflections of acoustic waves off the rig, the motor stand and the ground and these waves are damped in sponge region towards wind-tunnel anechoic walls.

![Figure 9: Flow field visualization for the 5-bladed rotor configuration.](image)

Comparisons of the instantaneous pressure field in the near rotor region are presented in figures 10, with ranges selected to highlight the large-scale vortical structures. Qualitatively, larger, more coherent tip vortex shedding can be observed for the wider 2- and 3-bladed rotors. The tip vortex is convected upward in the rotor wake with limited interactions with the next incoming blade, and multiple instances of the vortex core visible in the wake. In contrast, for the rotors with the higher 4 and 5 count of narrower blades, only a smaller vortex core can be seen near the blade tip, suggesting more blade vortex interactions. Figure 11 shows the instantaneous $y^+$ of the blade suction side for the different rotors, highlighting some of the key flow features and turbulent structures on the blade surface. The range of values $5 \leq y^+ \leq 30$ is appropriate for the present wall modeled approach in the turbulent regions, though additional refinement would likely be needed in the laminar region near the leading edge. Overall, the results are similar for the various rotors, though more spanwise variation can be observed in the region of high $y^+$ at the leading edge toward the blade tip for the 4- and 5-bladed rotors, consistent with increase blade vortex interactions.
Figure 10: Visualization of the pressure field $-400 \leq P - P_0 \leq 400$ Pa in a plane through the axis of rotation for the different rotors. The surface pressure (color contours) is also shown.

Figure 11: Visualization of $5 \leq y^+ \leq 30$ on the suction side for the different rotors.

More quantitative results are presented in figure 12 with the comparisons of the experimental measurements and LES predictions for the noise at the microphone position. The results are reported as a function of frequency in terms of bin-averaged (with 20 Hz bandwidth) power spectral density (PSD), in dB/Hz, and 1/3 octave band sound pressure level (SPL) in dBA, relative to $p_{ref} = 20 \times 10^{-6}$ Pa. As a reference, the narrowband spectra measured with the motor running at 5000 RPM without loading is reported in the figure. Figure 13 also shows the comparison of the 1/3 octave band SPL in dBA for all rotors, with focus on the high-frequency range $1000 \leq f \leq 10,000$ Hz.

Overall, the results show good agreement for both tonal and broadband content. The blade passage frequency (BPF) and harmonics, as well as the tones amplitude are well captured. The BPF tone is the highest for the 2-blade rotor and its amplitude decrease as the number of blade increase. For the frequency range $1000 \leq f \leq 8,000$ Hz, the broadband noise is well predicted, typically within a few dB, and the experimental trend of increase in high-frequency noise with increase number of blade is also observed in the simulations (see details in figure 13). At lower frequencies, the broadband spectra is slightly under-predicted, which is likely related to additional noise sources in the wind-tunnel (i.e., motor noise) and reflections of acoustics waves off the rig and instrumentation which are not fully captured in the LES, with the present FW-H surface in the more refined near-rotor region. For the very high-frequencies $f \geq 10,000$ Hz, the spectra for the different rotors tend to collapse. Additional grid refinement, in particular near the blade leading edge, might be needed to further improve the predictions.

For environmental noise, the simplest and most widely used measure is the A-weighted sound level expressed in dBA (see chapter 13 of Ref. [21]). A-weighting assigns to each frequency a "weight" that is related to the sensitivity of the human ear at that frequency. In practice, the filter tends to slightly increase the noise levels in the 1000 Hz to 5000 Hz frequency range and strongly decrease the lower and higher frequencies. These properties are reflected in the 1/3 octave band SPL reported in dBA in figure 12 and in the overall sound pressure levels (OASPL) reported in both dB and dBA in figure 14. For both experimental and LES data, the OASPL are computed over the frequency range of interest (i.e., $100 \leq f \leq 17,000$ Hz) and show good overall agreement. In particular, the comparison of dB and dBA results highlight the trend
Figure 12: Noise comparisons between the experimental measurements (—•—) and the LES predictions for the 2-bladed rotor (——), 3-bladed rotor (—•—), 4-bladed rotor (——) and 5-bladed rotor (——). As a reference, the narrowband spectra of the motor noise (——) is also shown. The vertical dashed lines represent the BFP and first harmonic.
of increase in high-frequency noise with increase number of blade captured with both approaches. For the 2-bladed rotor, the OASPL in dB is higher that in dBA because the main noise contributions are coming from the strong BPF tone at lower frequencies. As the number of blade is increased, the BPF tone amplitude is reduced and there is more broadband noise in the high frequencies, including in the frequency range further enhanced by the A-weighting. As a results, the trend is reversed for the 5-bladed rotor: the OASPL in dBA is higher that in dB.

![Graph](image1.png)

**Figure 13:** Comparison of the 1/3 octave band spectra in dBA in the high-frequency range between the LES predictions of the 2-bladed rotor ( ), 3-bladed rotor ( ), 4-bladed rotor ( ) and 5-bladed rotor ( ).

**Figure 14:** Overall sound pressure levels in dB and dBA for the experimental measurements ( ) and the LES predictions for the 2-bladed rotor ( ), 3-bladed rotor ( ), 4-bladed rotor ( ) and 5-bladed rotor ( ).

### IV. Simulation of full-scale eVTOL aircraft

As a proof-of-concept demonstration, the method is applied to the simulation of a full-scale air mobility vehicle with 8 VTOL rotors and 2 cruise propellers at different operating conditions. The resolution on the rotors and propellers is similar to the one used for the isolated multi-bladed rotors (in terms of points per chord) and the total mesh size for the initial simulation is 137 Mcv. Figure 15 shows visualization of the instantaneous flow field on and around the vehicle. Preliminary results were collected for the far-field aeroacoustics predictions as well as aerodynamics performance in terms of time-average and rms of forces and torque on the different parts of the vehicle. The predictions and analysis will be presented in future work.
To assess computational cost and performance, a scalability study was also conducted for the full-scale air mobility vehicle on the 137 Mcv grid. The computations were performed without I/O on core count ranging from 1,280 to 32,000 CPUs (AMD 7H12 Rome processors, 128 core/node). As shown in figure 16, the moving-mesh low-Mach charLES solver display good strong scaling and more than 86% scalability at 32,000 CPUs for load as low as approximately 4,000 cv per core. While super-linear scaling is observed in the present case for loads in the $O(10,000)$ cv per core range, this trend is machine dependent and is believed to be related to cache sizes.

While the initial simulations are being performed with the CPU-based version of charLES, reducing time-to-solution and computational costs have been identified as priority to bring full-scale air vehicle aeroacoustics predictions within reach for industrial applications. Recently, Cascade has been developing GPU-accelerated versions of charLES that optimally leverages modern Nvidia and AMD GPU-accelerated high-performance computing (HPC) architectures for predictive, fast, and cost-efficient simulations of turbulent flows.
pared to traditional HPC CPU-based approach, a significant reduction in computational cost (or increase in computational throughput) has been observed [22]. At Honda, collecting $O(0.4)$s of data and statistics for the full-scale eVTOL aircraft takes approximately a day and a half on 2016 CPUs (SGI ICE XA Intel Xeon E5 2697 v4 2.3GHz, 36 core/node). The eVTOL configuration was used to test the performance of the initial prototype of the GPU-accelerated moving-mesh low-Mach solver under development. Preliminary results suggests that the time for the same simulation could be reduced to less than 12 hours on 40 GPUs (AMD Mi210 or equivalent), with additional reduction anticipated with solver and I/O optimization.

V. Conclusions

Large-eddy simulations were performed for aeroacoustic prediction of isolated scaled multi-bladed VTOL rotors, using the moving-mesh low-Mach flow solver “charLES” developed at Cascade Technologies, now part of Cadence Design Systems. Four rotors with 2, 3, 4 and 5 blades are simulated and the LES noise results are compared with microphone measurements conducted at Honda’s wind-tunnel facility. For this complex configuration with motion, all the details of the wind-tunnel are included in the computational domain and the grids for both stationary and rotating parts are generated using Voronoi-based meshing technology. For the present wall-modeled simulations, the grid resolution was chosen to yield modest mesh count of $O(30)$ Mcv with $y^+$ ≈ 30 on the blade surface and approximately 50 to 100 cv per chord, depending on the rotor.

Overall, the noise predictions show good agreement with the experimental data in terms of BPF, harmonics and tone amplitude, as well as the broadband noise and OASPL. In particular, the simulations capture the experimental trend of increase in high-frequency noise with increase in number of blades in the frequency range $1000 \leq f \leq 10,000$ Hz. At higher frequency, the additional grid refinement, in particular near the blade leading edge, might be needed to further improve the predictions.

Based on the results for the isolated rotors, a proof-of-concept simulation of a full-scale eVTOL aircraft with 8 VTOL rotors and 2 propellers was also conducted, to demonstrate the approach for practical applications. The simulation was performed with similar resolution in terms of points per chord, and the total mesh size is approximately 137 Mcv. For this configuration, a scalability study was conducted on up to 32,000 CPUs and the CPU-based solver display nearly ideal strong scaling for load as low as $\approx 4,000$ cv per core. The potential increase in computational throughput achievable with GPU acceleration was also evaluated for this configuration. With the initial prototype of the GPU-accelerated moving-mesh low-Mach solver under development at Cascade, the turn-around time for the collections of data and statistics of a full-scale eVTOL aircraft is expected to be reduced to less than half a day on modest GPU count of $O(40)$ GPU (AMD Mi210 or equivalent).

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References


