A Hybrid Lattice-Boltzmann/FW-H Method to Predict Sources and Propagation of Landing Gear Noise

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A hybrid approach to predict the far-field noise generated by an airplane nose landing gear is presented in this paper. The approach consists of a Lattice-Boltzmann Method (LBM) for the calculation of the flow-field around the fully detailed geometry of the landing gear which provides the input for a Ffowcs Williams – Hawking (FW–H) solver to calculate the far-field noise. Both parts have been validated independently. The method is applied to the nose landing gear of a Gulfstream G550 business jet, for comparison with experimental results obtained in the University of Florida UFAFF wind tunnel. The near-field flow simulation using the LBM method showed good correlation with the PIV measurements of the flow field as well as surface microphone measurements, up to frequencies of about 4kHz. The comparison to experimental far-field results shows good agreement in the mid-frequency range of 1-3kHz. At both low and high frequencies the simulations underpredict the measured results more strongly than the near field and surface measurements would suggest, which may be due to experimental limitations. A comparison between the solid and porous formulation of the FW-H solver shows that both method provide nearly equivalent results. However, inclusion of additional surfaces such as part of the fuselage is critical to achieving good results with the solid formulation. The effects of resolution of the near-field simulations are also investigated and show the expected lower cut-off frequency for lower resolutions for both the near-field and the far-field. No differences between the cases with different resolutions are observed up to 1 kHz in the near-field and up 2-3kHz in the far-field.

Nomenclature

c_i = Lattice Boltzmann discrete velocity vector
f_i = lattice Boltzmann particle distribution function
f_i^eq = lattice Boltzmann equilibrium distribution function
k = turbulent kinetic energy
LES = large eddy simulation
M = Mach number
T = temperature
u = velocity
VLES = very large eddy simulation

\[ \tau = \text{lattice Boltzmann relaxation time} \]
\[ \rho = \text{density} \]
\[ \varepsilon = \text{turbulence dissipation} \]
\[ \nu = \text{kinematic viscosity} \]
\[ y^+ = \text{dimensionless distance, } y u / \nu \]
\[ VR = \text{variable resolution} \]

I. Introduction

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Airframe noise has become one of the leading noise sources during approach and landing of modern aircraft due to the recent improvements made in the reduction of noise from the propulsion systems. The reduction of airframe noise is therefore critical in the development of future aircraft which are required to meet increasingly quieter community noise standards. Traditionally, noise due to the landing gear has been investigated at the end of the design process, in scaled or full-scale wind tunnel testing, or as part of certification flight tests. At this stage in the design process, it is both difficult and expensive for the designer to make modifications to the design if the certification requirements are not met.

Numerical simulations make it possible to address that risk by evaluating the design early in the process. There are, however, a number of challenges that have until now kept the use of Computational Fluid Dynamics (CFD) to predict the far field noise emanating from landing gears out of reach for use in the design process. First, the task of generating a computational mesh that includes all the small geometric details which may contribute to the noise signature of the landing gear is prohibitively expensive for most traditional CFD tools based on the solution of the Navier-Stokes equation. Second, the propagation of noise from the landing gear to an observer in the far-field cannot be addressed by the CFD tool itself and requires a hybrid method that couples the CFD results in the near field to a noise propagation tool, typically based on the algorithms proposed by Ffowcs Williams and Hawkins.

This paper is the second in a series addressing these problems using an alternative approach for the CFD part of the solution. This approach is based on the Lattice Boltzmann method which has been extensively validated in recent years and is fast becoming the method of choice for problems involving unsteady flows over highly complex geometries. The first paper focused on the prediction of surface pressure fluctuations on the surface of both a simplified and a fully-dressed version of the landing gear of the Gulfstream G550 business jet, and provided extensive comparisons to experimental results from two different wind tunnels. The results of this paper are reviewed and summarized here briefly. This paper focuses on the second part of the problem, the propagation of the sound to the far-field. Results are presented for the Partially Dressed Cavity Closed (PDCC-NLG) landing gear. The results are obtained by using PowerFLOW, a Lattice Boltzmann (LBM) based solver, along with a Ffowcs-Williams-Hawkins (FW-H) solver. Results are compared to microphone measurements from in the University of Florida Aeroacoustic Flow Facility (UFAFF), which were obtained as part of an ongoing joint effort between the Gulfstream Corporation, NASA, and Goodrich.

II. Model Geometry

A. Geometry, Computational Method and Computational Setup

The PDCC-NLG geometry was made available for the first AIAA Benchmark problems for Airframe Noise Computation (BANC-1 category 4). This benchmark uses a ¼ scale landing gear based on the actual nose landing gear of a Gulfstream G-550 stripped of any electrical lines, lighting system, steering mechanism and hydraulic pipes. In addition, the fuselage cavity accommodating the landing gear while in flight is closed. The scaled landing gear is mounted on a fairing that mimics the flow acceleration created by the aircraft fuselage. The diameter of the main strut is 0.75 inch and the wheels have a diameter of 5.495 inches. In addition, the model is tilted by 3 degree relatively to the incoming flow to represent the typical angle of attack of the G-550 on final. Figure 1 shows the PDCC-NLG mounted on the fuselage.

An extensive set of aerodynamic measurements was obtained in the NASA Langley Research Center Basic Aerodynamics Research Tunnel (BART) and limited aerodynamic along with acoustic measurement were recorded in the University of Florida’s anechoic wind tunnel (UFAFF). The main difference between the two tunnels is that the UFAFF tunnel is an open jet facility. This paper mainly focuses on the numerical simulations of the UFAFF tunnel. The free stream velocity is set to $M = 0.166$ which results in a Reynolds number of 73,000 based on the main strut diameter. A few results from the BART tunnel are also used to compare the results to the PIV measurements.
Figure 1. Geometry of the partially-dressed nose landing gear as used in simulation.

B. Simulation Method

The results presented in this paper were performed using PowerFLOW, a lattice-Boltzmann-based computational fluid dynamics solver. The lattice Boltzmann Method (LBM) solves a discrete form of the Boltzmann equation:

\[ f_i(\vec{x} + \vec{c}_i \Delta t, t + \Delta t) - f_i(\vec{x}, t) = C_i(\vec{x}, t) \]

with the closing equation expressed by the Bhatnagar-Gross-Krook (BGK) collision form:

\[ C_i(\vec{x}, t) = -\frac{1}{\tau} [f_i(\vec{x}, t) - f_i^{eq}(\vec{x}, t)] \]

where the equilibrium distributions are approximated up to the third order as:

\[ f_i^{eq} = \rho w_i \left[ 1 + \frac{\vec{c}_i \cdot \vec{u}}{T} + \frac{(\vec{c}_i \cdot \vec{u})^2}{2T^2} - \frac{\vec{u}^2}{2T} + \frac{(\vec{c}_i \cdot \vec{u})^3}{6T^3} - \frac{\vec{c}_i \cdot \vec{u} \cdot \vec{u}^2}{2T^2} \right] \]

This scheme has been shown to recover the compressible Navier-Stokes equations for low Mach numbers by applying a Chapman-Enskog expansion. In addition, the direct advection process described by Boltzmann equation results in a natural low numerical dissipation which, along with the inherent transient behavior of the method, makes the LBM a well suited tool for aeroacoustic applications. The resulting system of equations is solved on a Cartesian grid made of cubic cells or voxels.

The direct full resolution of the smallest structures will require a cell size that would lead to a case that would be computationally too expensive to run on the current modern system for the Reynolds numbers encountered in most engineering problem such as the one presented in this paper. To avoid such cost, an additional turbulence model was incorporated directly into the lattice Boltzmann equations to model smallest eddies while resolving the largest ones. The turbulence model is linked to the Boltzmann equation through the relaxation factor \( \tau \) of BGK collision. The final set of equations has been shown to be somewhat equivalent to a full Reynolds stress-like model. The turbulence model used within powerFLOW is a variant of the RNG k-\( \varepsilon \) turbulence model. To further improve the quality of the results, a swirl model was added to the turbulence model to reduce the eddy viscosity in area of high vorticity. This allows resolving the unsteady vortices rather than modeling them wherever the grid is fine enough.
To efficiently predict the far-field noise at any location, an integrated post-processing module was developed. This module uses an acoustic analogy solver based on the Fowcs Williams–Hawkins (FW-H) equation\(^1\) and can handle both moving (e.g. fly-over configuration) and stationary noise sources (e.g. windtunnel testing). The input to the FW-H solver is the time-dependent flow field on a surface mesh, both provided by CFD simulations with the LBM code. This surface mesh can be defined either as a solid (impenetrable) surface, or porous (permeable) data surface, to take into account nonlinearities in the vicinity of the source. A complete description of the formulations, the numerical implementation and the validation of the method are presented in reference 13.

C. Simulation Setup and grid convergence

The grid used for the baseline simulations contains a total of 8 levels of resolution, known as Variable Resolution (VR). The finest level is used only on the main strut. The second finest level is then used on all other components, as well as in the region between the main strut and the trailing components to resolve the unsteady shear layers and eddies that pass from the mains strut and impact the trailing components. Figure 2 shows the Cartesian grid.

Frictionless walls were placed at about 10 meters on each side of the model for the UFAFF setup. This is far enough to avoid any blockage and consider the simulation as a free field setup. The inlet and outlet were at 15 meters upstream and 15 meters downstream of the model, respectively. An acoustic damping zone is implemented in the far field of the setup to avoid any numerical reflection at the inlet and outlet.

![Figure 2. Voxel lattice grid from the baseline simulation (finest voxel size: 0.3mm).](image)

The resulting grid contains about 32.5 million voxels and the runs take about 78 hours on a 128 processors (AMD Opteron 280, 2.4 GHz) cluster using an Infiniband connection.

III. Near-Field Results

A. Simulation Convergence

For both configurations, the first 0.06 seconds of computed data are discarded from any post-processing. This is to insure that the inevitable initial transient is fully excluded from any post-processing results. In addition, to that initial time, the simulations were run long to obtain enough time history to have statistically valid results at the lowest frequency of interest. That is, we ran the simulation for an extra 0.2552 sec of physical time after the initial 0.06 seconds. This allows us to have at least 10 cycles at 40 Hz for the probes. For the surface file, we limited the recording time to 0.18 sec to avoid an excessive amount of data. This allows us to have 10 cycles at 55 Hz for the FW-H calculation.

The figure shows the drag and lift convergence for UFl configuration. A coarse to fine seeding technique was used to reduce the overall convergence time.
The second line on those graphs represents the backward moving average of the force coefficients. This shows that adding more time to the simulation does not affect the lift and the drag anymore. All the mean flow data presented in this paper is obtained by averaging the flow from 0.06 sec to 0.31 sec.

B. Summary of Near-Field Results

Near-field and surface results for both landing gears were published in the previous paper in this series and are summarized here again. The available experimental results included PIV measurements obtained in the BART facility (Basic Aerodynamic Research Tunnel) at NASA Langley Research Center, and surface microphone measurements.

B.1. Comparison to PIV Measurements

Flow field visualizations from PIV measurements are available in different planes of the flow field, allowing a detailed comparison with the simulated flow field. The four experimental PIV planes are shown in Figure 4. The left part of Figure 5 shows the mean stream-wise velocity (U-velocity) in the plane located at the center of the wheels. The simulated flow field agrees very well with the experimental results. The size and location of the separated flow region as well as the velocity levels throughout the measurement plane are very well captured. Z-vorticity in this region, shown in the right part of Figure 5, also shows excellent agreement with the experiment. The higher peak level of vorticity in the shear layer is likely due to the higher sampling resolution available in the simulation.

Figure 3: Drag and Lift convergence for the Track B run

Figure 4: Location of PIV measurement planes. From [1].
Figure 5. Comparison of mean U-velocity and Z-vorticity around the wheel chine for the partially-dressed gear. PIV plane 4.

Figure 6. Comparison of mean U-velocity at the rear of the wheel. PIV plane 3.
The comparisons of U-velocity (Figure 6) and Z-vorticity (Figure 7) in the region behind the wheels show overall good agreement as well, with the simulation predicting a slightly larger wake region than seen in the experiment.

**C.2. Comparison to Surface Microphone Measurements**

A total of 9 probes were used in the experiments to measure unsteady surface pressures. Figure 8 shows the position of those probes on the CAD model along with the corresponding experimental channels.

A comparison of the power spectral density (in psi²/Hz) plots at the probes for the partially-dressed gear is shown in Figure 8. The spectra were obtained by using the 0.3 seconds of unsteady wall pressure fluctuations. A Hanning window with overlapping of 50% and a FFT window width of 16Hz were used to generate the spectra.

In general, the agreement between simulation and experiment is very good. Overall levels are captured accurately up to frequencies of 3-4 kHz, and the shape of the simulation spectra is in good agreement with the experiments. This steeper decay above 4 kHz is mainly due to grid resolution that is not sufficient to support higher-
frequency fluctuations. The probe on the starboard side of the door (channel 3) and the probe on the middle of the door (channel 10) deviate more strongly from the experiment in the lower frequencies.
To investigate some of the potential reasons for differences between simulated and measured spectra, additional analysis is performed for the inner starboard wheel probe. A number of additional probes are placed in the vicinity of this probe in the simulation to investigate the effect of local gradients.

Figure 10 shows that the experimental probe position lies in a region of a strong gradient. A small shift in the location of this probe leads to a much improved match between experimental and simulated PSD (right part of Figure 10). This indicates that the position of the gradient is slightly shifted in the simulation. However, this shift is unlikely to cause a noticeable difference in far-field noise. Here, the shifted probe is only displaced by 4 mm. This illustrates that relying entirely on selected surface microphones for the validation of simulation tools for airframe noise predictions can potentially cause misleading conclusions.

Figure 9: Wall pressure spectra for the partially-dressed landing gear

Figure 10: Influence of a small shift in the position of the probe PSD on the surface of the wheel
The main strut probe (channel 12), which also shows poor agreement between simulation and experiment, is also positioned in an area of strong gradients (Figure 11). A closer look at the flow structures in this area shows that the probe is located in the vicinity of complex flow structures coming from torque arm attachments, indicating that a small shift in the position of the probe could lead to improved predictions.

![Figure 11: Flow structures around the main strut and PSD on the surface (2 kHz 1/3rd octave)](image)

**Figure 11 : Flow structures around the main strut and PSD on the surface (2 kHz 1/3rd octave)**

### IV. Far Field Predictions

Measurements of the far-field sound pressure levels were carried out in the University of Florida’s Aeroacoustic Flow Facility (UFAFF) for the partially nose landing gears. The measurement setup is shown in Figure 12. Two linear arrays of omni-directional free field microphones, located approximately 3.7 feet below the landing gear (flyover rake) and about 2 feet to the side of the gear (sideline rake) were used to measure the noise level spectra along the length of the test section. Standard shear layer corrections were performed to account for the refraction of the sound as it passes through the shear layer of the open jet test facility. A detailed description of the measurements can be found in Reference 3.

![Figure 12: Schematic of linear array configuration for far-field noise measurements](image)

**Figure 12: Schematic of linear array configuration for far-field noise measurements**

Both direct calculations of the noise propagation to the microphone locations with PowerFLOW and the hybrid Lattice-Boltzmann/FW-H calculation are carried out. Direct calculations are possible in this case because of the close proximity of the microphones to the landing gears. For realistic flyover scenarios with observers hundreds of feet away from the landing gear, a direct computation would not be possible. Even for the current case the computational mesh could not be set up in such a way that high frequency fluctuations could be sustained all the way to the microphones. Assuming that at least 6 cells per wavelength are required to properly maintain the fluctuation a cut-off frequency of about 2 kHz is calculated for the current setup. Even with this limitation, the direct computations are useful to support the validation of the hybrid method.

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American Institute of Aeronautics and Astronautics
A. Direct Computation of Farfield Noise

The directly computed sound pressure levels at microphone position 7 of the flyover rake and microphone 6 of the sideline rake are shown in Figure 13. The results are shown for frequencies above 500Hz due to suspected background noise of the UFAFF wind tunnel at lower frequencies. Also, the microphones are placed relatively close to the ground. The acoustic wedges placed on the walls of the wind tunnel are less effective at low frequencies, leading to reflections that are picked up by the microphones.

The agreement between the microphone measurements and the directly computed signal is good in the mid-frequency range (1-3 kHz), in particular for the closer sideline microphone. In this range, the shape of the experimental spectra is generally well matched with an underprediction of 1-2 dB for the sideline microphone and 2-4 dB for the flyover microphone. In the high frequencies, the expected fall-off occurs above 3kHz for the reasons explained above. At frequencies below 1 kHz a stronger underprediction can be observed.

Figure 13: Direct computation of Far-field Noise

It should be noted that the setup differences between experiment and simulation may be the cause of some of the observed deviations. The experiment was carried out in an open jet facility, while the simulation was run with a setup approximating an open-air environment. This is likely to explain the deviations in the lower frequency range, and it may also partially explain the lack of fall-off in the experimental spectra at frequencies above 5 kHz, which is not predicted in the simulation. Further investigations are needed to fully resolve this discrepancy.

B. Hybrid PowerFLOW/FW-H Computation of Farfield Noise (Solid Formulation)

Two options are available for the hybrid computations of the far-field noise: the solid formulation, where the pressure fluctuations on the solid surface of the landing gear are used as input for the FW-H solver, and the porous formulation, where pressure fluctuations, velocities and density on a porous surface in the vicinity of the gear but outside the area disturbed by the flow separation caused by the gear are used as input.

Figure 14 shows the results for the solid formulation using the pressure fluctuations on the landing gear surface only. As expected the fall-off at higher frequencies is avoided in comparison to the direct frequencies, although a strong underprediction in comparison to the experiments above 5kHz is still present. However, the lack of fall-off in the experimental spectra, and in the case of the sideline microphone even an increase at 5kHz, is somewhat surprising and could be due to experimental artifacts, as outlined above.
For frequencies below 5kHz the solid formulation matches the shape of the directly simulated results but underpredicts these by as much as 5dB. As shown in Figure 15, parts of the fuselage and the wall are exposed surfaces in the wind-tunnel experiment, which can potentially contribute to the measured noise. To investigate the effect of these surfaces, additional FW_H calculations are performed using as input not only the pressure fluctuations on the landing gear surface itself but also on the fuselage section and on parts of the windtunnel floor. Details of the input measurement are presented in Figure 15.
Figure 16: PowerFLOW/FW-H computation of Far-field Noise (solid formulation, with fuselage and wall)

The results are shown in Figure 16. Including the additional surfaces improves the results significantly and leads to a prediction that matches the direct simulation in the low and mid frequencies while avoiding the fall-off at frequencies above 2-3 kHz that was observed for the direct calculations. It is indeed important to notice that the direct CFD results intrinsically take into account any reflections that would occur on any of the walls close enough to the microphones. This is not the case for the results obtained by solely considering the surface of the landing gear.

The reduction of levels above 5kHz in comparison to the solid formulation with landing gear surfaces only (blue curve v. green curve in Figure 16) can be explained by the fact that the sampling rate for the additional surfaces was lower (32kHz v. 64kHz on the landing gear).

The results for additional microphone positions for both rakes are shown in Figure 17 and Figure 18 and confirm the findings described above.

Figure 17: Far-field results for additional microphones (flyover rake)
C. Hybrid PowerFLOW/FW-H Computation of Farfield Noise (Porous Formulation)

For the porous FW-H calculations, the required inputs are the pressure, density and velocity fluctuations on a surface in the vicinity of the landing gear. The surface used for the present calculation is shown in Figure 19. This surface lies outside the main wake of separated flow behind the gear although a significant level of pressure fluctuations is still present at the downstream edge of the region.

Results for the porous calculation are shown in Figure 20 and Figure 21. Shape and level of SPL is generally very similar to the results from the solid formulation with fuselage and wall. For the sideline gear the levels are 1-2 dB lower for all frequencies. The reason for this is not well understood at this time. The porous calculation show a stronger fall-off at higher frequencies in comparison to the solid formulation which is likely due to the fact that the resolution of the volume grid is coarsened more and more with increasing distance from the landing gear geometry and that the resulting resolution level at the porous surface is therefore not sufficient to maintain frequency fluctuations at higher frequencies.

Overall it can be concluded that the both the solid formulation – if fuselage and wall are taken into account – and the porous formulation are viable options which enable far-field predictions in good agreement with experimental results in the mid-frequency range.
D. Far-Field Results with Floor Reflections

To further investigate the potential sources of these discrepancies, a numerical experiment is performed to artificially add the contribution of a perfectly reflecting wall below the experimental microphones. The classical method of images and acoustic reciprocity are used to estimate these reflections (see Chap. 6 in Reference 14). As each experimental microphone is mounted on pole at $H = 0.152$ m above a rail, the pressure fluctuations at the corresponding image microphone (i.e., located at $-0.152$ m, below the rail) is computed with the FW-H solver, using the same input source. Then, the pressure histories of both the original and image microphone are summed in the time domain.

The results are presented in Figure 22. Using simple plane wave theory, reinforcement and cancellations can be expected in the spectra. The peak frequencies can be estimated at $c_0/(H/2)$, $c_0/(H)$, etc., where $c_0$ is the speed of sound. In this case, reflections from the bottom floor would lead to peaks at $f_1 \approx 2260$ Hz, $f_2 \approx 1130$ Hz, etc., which is approximately what is observed in the FW-H results (brown curves in Figure 22). While the dB levels are not representative here, since the experimental microphones are obviously not above an infinite and perfectly reflecting wall, it is interesting to note that small peaks are also observed at the same frequencies in the experimental spectra. Additional numerical analysis and experimental testing is needed to fully address this issue. However, this limited study would tend to suggest that some small reflections might be present in the wind-tunnel and could explain some of differences observed in the shape and levels of the spectra.
E. Resolution Dependence

To investigate the dependence of the far-field results on the resolution levels used in the CFD simulation in the near-field, a resolution sweep was performed with the finest voxel size varying from 0.5mm to 0.25mm (see Figure 2 for an illustration of the grid structure). All results presented in previous sections of this paper were computed with a finest voxel size of 0.3mm, which had been determined in previous studies to be the optimum tradeoff between performance and accuracy. Improved accuracy at higher frequencies can be obtained by decreasing the finest voxel size to 0.25mm. However, this increases the simulation cost by a factor of about 2.5. Increasing the finest voxel size to 0.5mm reduces the computational cost by a factor of about 3. Table 1 gives an estimate of the simulation cost and the approximate highest accurate frequency obtained for various finest voxel sizes for a ¼ scale landing gear. These frequencies were estimated using a comparison of the WPF spectra with experiments. The CPUH numbers represent the time, in hours, it would take to run the simulation on one single CPU. Simulations are however generally carried out on clusters with at least 100 processors which can be used by PowerFLOW for the problem sizes required for a typical landing gear without any loss of parallel efficiency.

<table>
<thead>
<tr>
<th>Finest Voxel Size</th>
<th>Approximate simulation cost (CPUH) for 0.25 sec of data</th>
<th>Total number of voxels in millions</th>
<th>Approximate highest accurate frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 mm</td>
<td>2,700</td>
<td>9.2</td>
<td>1,000 Hz</td>
</tr>
<tr>
<td>0.3 mm</td>
<td>10,000</td>
<td>32.5</td>
<td>4,000 Hz</td>
</tr>
<tr>
<td>0.25 mm</td>
<td>25,000</td>
<td>52.4</td>
<td>8,000 Hz</td>
</tr>
</tbody>
</table>

Table 1: Case sizes and CPU-times for different resolutions

Figure 23 shows the effect of finest voxel size on the wall pressure fluctuation spectra for two probes, the mid door probe (channel 12) and the upper arm probe (channel 15). In the low and mid frequencies up to about 1 kHz only very small differences between the differently resolved cases can be observed. However, the finer cells are able to sustain fluctuations of much smaller scale, resulting in a higher frequency cut-off, ranging from about 2kHz to as much as 6-7kHz for the finest resolution.
The results of the FW-H calculation using the near-field data from simulations with different resolutions are shown in Figure 24. The FW-H input data on the fuselage or in the flow field are not available for all resolution and only the results from the solid formulation with input from the landing gear surface itself can be shown here. Generally the same changes with resolution can be observed in the far-field as are seen for the surface microphones. For the lower frequencies there are no significant differences between the differently resolved cases, with the exception of the raised level for low resolution case for the sideline position at about 1,250 Hz, which needs to be further investigated. Some differences between the effects of resolution on the landing gear surface and in the far-field can be observed, however. First, the medium and the fine resolutions provide essentially the same results, even at high frequencies above 5 kHz. Therefore, the significantly higher computational cost of running the finely resolved case does not seem justified. Second, the difference in cut-off frequency between the resolutions is raised to a higher value. While on the surface the fall-off for the coarse case is noticeable starting at 1 kHz, in the far-field the results do not start to diverge until above 2kHz for the flyover position and as high as 5 kHz for the sideline position. These results provide useful guidelines for the choice of resolution depending on the far-field frequency range that needs to be resolved.

V. Conclusions

Near-field and far-field results from a hybrid Lattice-Boltzmann/FW-H simulation method are presented for the partially-dressed version of the Gulfstream G550 landing gear. The near-field results, which had been presented in the first paper of this series, show overall very good agreement with both surface microphone and PIV measurements. For the FW-H calculations, two different approaches are tested: the solid formulation which takes pressure fluctuations on the surface only as input, and the porous formulation, which uses pressure, velocity and
density information at a surface in the fluid close to the landing gear. Results show that the solid formulation requires input from the landing gear surface itself and the surrounding section of the fuselage. Using the landing gear surface only leads to underpredictions in the far-field by about 3-5dB. No significant differences were observed between the solid formulation (using landing gears and fuselage) and the porous formulation. Both lead to good predictions in the mid-frequency range (1-3 kHz) with dB-levels underpredicted by about 1-3dB in comparison to experiments. Stronger underpredictions were observed in both lower and higher frequencies. These may be due to differences between experimental and simulation setups and may be explained in part by wind tunnel limitations (e.g., background noise, small reflections, …) that are not taken into account in the simulations. In particular, a numerical experiment that added the perfect reflections from the floor below the experimental microphone showed peaks in the spectra at the same frequencies than the experimental data. Further investigations are required to resolve this issue. The effect of resolution of the near-field simulations is also investigated. The results show the expected lower cut-off frequency for lower resolutions. The cut-off frequency, which is as low as 1 kHz for the low resolution in the near-field, is moving to higher levels in the far-field, where no significant differences are observed between cases with different resolutions below 2kHz for the flyover position and up to 5kHz for the sideline position.

Acknowledgments

The authors would like to thank Mehdi Khorrami, from NASA/Langley and Lou Cattafesta from the University of Florida, for providing many useful comments about the experimental results, and John Louis from Gulfstream Aerospace Corporation for carrying out the initial nose landing gear simulations.

References