Equivalent Source Method
Applied to Launch Acoustic Simulations

Jeffrey A. Housman*, Michael F. Barad**, and Cetin C. Kiris*
Corresponding author: jeffrey.a.housman@nasa.gov

* NASA Ames Research Center, Moffett Field, CA, USA.
** Science and Technology Corporation, Moffett Field, CA, USA.

Abstract: Aeroacoustic simulations of the launch environment are described. A hybrid computational fluid dynamics (CFD)/computational aeroacoustic (CAA) approach is developed in order to accurately and efficiently predict the sound pressure level spectrum on the launch vehicle and surrounding structures. The high-fidelity CFD code LAVA (Launch Ascent and Vehicle Analysis), is used to generate pressure time history at select locations in the flow field. A 3D exterior Helmholtz solver is then used to iteratively determine a set of monopole sources which mimic the noise generating mechanisms identified by the CFD solver. The acoustic pressure field generated from the Helmholtz solver is then used to evaluate the sound pressure levels.

Keywords: Launch Acoustics, Equivalent Source Method, Inverse Methods.

1 Introduction and Approach

NASA is currently developing the next generation space launch vehicle, a heavy lift vehicle for both crew and cargo with a total capacity of up to 130 metric tons. Characterization of the launch acoustic environment and ignition overpressure loads is critical to mission success. Details on modeling and simulation of ignition overpressure waves is described in a companion paper, Barad *et. al.* [1]. This work focuses on a method to predict the sound pressure level (SPL) spectrum on the launch vehicle and surrounding structures. In order to generate accurate and efficient SPLs a hybrid CFD/CAA approach is proposed.

High-fidelity simulation of launch acoustics is still a challenging task using modern CFD techniques as demonstrated in Housman *et. al.* [2]. Difficulties including the dissipative and dispersive nature of CFD methods as well as nonlinearity of the governing equations make simulations of acoustic phenomenon computationally expensive for large scale applications. It has been demonstrated that acoustic propagation can often be modeled using simplified linear models such as the wave equation, [3]. In the present hybrid CFD/CAA approach a high-fidelity unsteady CFD simulation is first performed with a small time-step (relative to the frequencies of interest) and highly refined grid in the noise generating regions of the domain. For launch acoustics the noise generating regions include the exhaust plume and its impingement on the trench and platform. Time accurate pressure histories are recorded at N locations of the flow field, located near the noise generating regions, but away from highly nonlinear flow features. Next a linear acoustic model is constructed in the frequency domain such that the pressure history predicted by the model matches the CFD generated results at the N observation locations in a least-squares sense, for each frequency of interest. The acoustic pressure field is then used to estimate the sound pressure levels on the launch vehicle and surrounding structures.

1.1 Linear Acoustic Model

In the linear acoustic model the total acoustic pressure is decomposed into the sum of incident and scattered pressure fields, $P^{tot}(\vec{x},t) = P^{inc}(\vec{x},t) + P^{scat}(\vec{x},t)$. The incident pressure is responsible for representing the noise sources and their radiating pressure field. While the scattered pressure represents the scattering of the incident pressure waves by the launch site geometry. In order to model the noise sources, a set of $M < N$ monopole sources are placed along the path of the exhaust plume and the incident pressure field is given by $P^{inc}(\vec{x},t) = \left[\sum_{m=1}^{M} a_m G(\vec{x},\vec{x}_m)\right] e^{\hat{\imath}\omega t}$, where $G(\vec{x},\vec{x}_m) = \frac{1}{4\pi}\frac{e^{-\hat{\imath}k|\vec{x}-\vec{x}_m|}}{|\vec{x}-\vec{x}_m|}$ is the free-space Green's Function, $k = \omega/c$ is the wave number, ω is the angular frequency, and c is the isentropic sound speed. Once the monopole source amplitudes a_m are known the scattered field is obtained by solving an exterior Helmholtz boundary value problem BVP of the form,

$$\begin{aligned} &\nabla^2 P^{scat} + k^2 P^{scat} = 0, \quad \forall \vec{x} \in \Omega; && \frac{\partial P^{scat}}{\partial n} = -\frac{\partial P^{inc}}{\partial n}, \quad \forall \vec{x} \in \partial\Omega; \\ &\lim_{R=|\vec{x}|\to\infty} \left[R \left(\frac{\partial P^{scat}}{\partial R} + \hat{i} k P^{scat} \right) \right] && \text{Sommerfeld radiation condition.} \end{aligned} \tag{1}$$

The exterior Helmholtz BVP for the scattering field is solved using the equivalent source method as described in Ochmann [4]. In this method, the scattered field is written as a sum of monopole sources $P^{scat}(\vec{x},t) = \left[\sum_{l=1}^{L} b_m G(\vec{x},\vec{x}_l)\right] e^{\hat{i}\omega t}$ where the locations, $\vec{x}_l$, of these sources are placed on the inside of the scattering surfaces. Tessellating the scattering surface into $N_{tri} > L$ triangles, a least-squares problem is formulated for determining the equivalent source amplitudes b_l such that the boundary conditions in Equation 1 are satisfied in a least-squares sense, similar to the procedure outlined in Dunn and Tinetti [5]. The least-squares problem is then solved using a parallel version of the Conjugate-Gradient (CG) algorithm applied to the normal equations. Alternative numerical methods for solving the exterior Helmholtz problem exist, such as the Boundary Element Method [6]. The advantages and disadvantages between the equivalent source method and these alternatives will be discussed in the final paper.

Solution of the forward problem relies on knowing the incident source amplitudes a_m, which are found by generalizing the inverse method described in Nelson and Yoon [7] to include the scattering surface. A similar least-squares problem is formed by setting $P^{inc}(\vec{x}_n,t) = P^{obs}(\vec{x}_n,t) - P^{scat}(\vec{x}_n,t)$ for each $n = 1, \cdots, N$, corresponding to an $N \times M$ linear system which is again solved using CG. The inverse problem is solved iteratively by initially setting the scattered field to zero and then substituting the corrected scattered field after each update until the l^2 norm change in the source amplitudes a_m drops below a user prescribed tolerance.

2 Results and Summary

To demonstrate the feasibility of the method the forward problem is solved with 13 incident monopole sources of unit amplitude and a frequency of 100 Hz being scattered by a simplified launcher geometry, see Figure 1 (a). The scattering surface is discretized into 1.6 million triangles, and the scattered pressure field is predicted using 1000 iterations of CG on 40 Westmere nodes (480 cores) of the Pleiades supercomputer in approximately 20 minutes. Contour plots of the sound pressure level and acoustic pressure on cutting planes are shown in Figures 1 (b) and (c). The acoustic pressure on the launch vehicle, tower, trench, and platform are shown in Figure 1 (d). The fast turnaround time of the forward solver suggests that the inverse problem will be practical for realistic launch site geometries and conditions. Further details and examples of the CFD/CAA coupling will be demonstrated in the final paper.

References

[1] M.F. Barad, J.A. Housman and C. Kiris. Simulation of Ignition Overpressure Waves for NASA's 21st Century Launch Complex. *ICCFD7, July 9-13, Big Island of Hawaii*, submitted, 2012.

[2] J.A. Housman, M.F. Barad and C. Kiris. Space-Time Accuracy Assessment of CFD Simulations for the Launch Environment. *29th AIAA Applied Aerodynamics Conference, Honolulu, Hawaii*, AIAA-2011-3650, 2011.

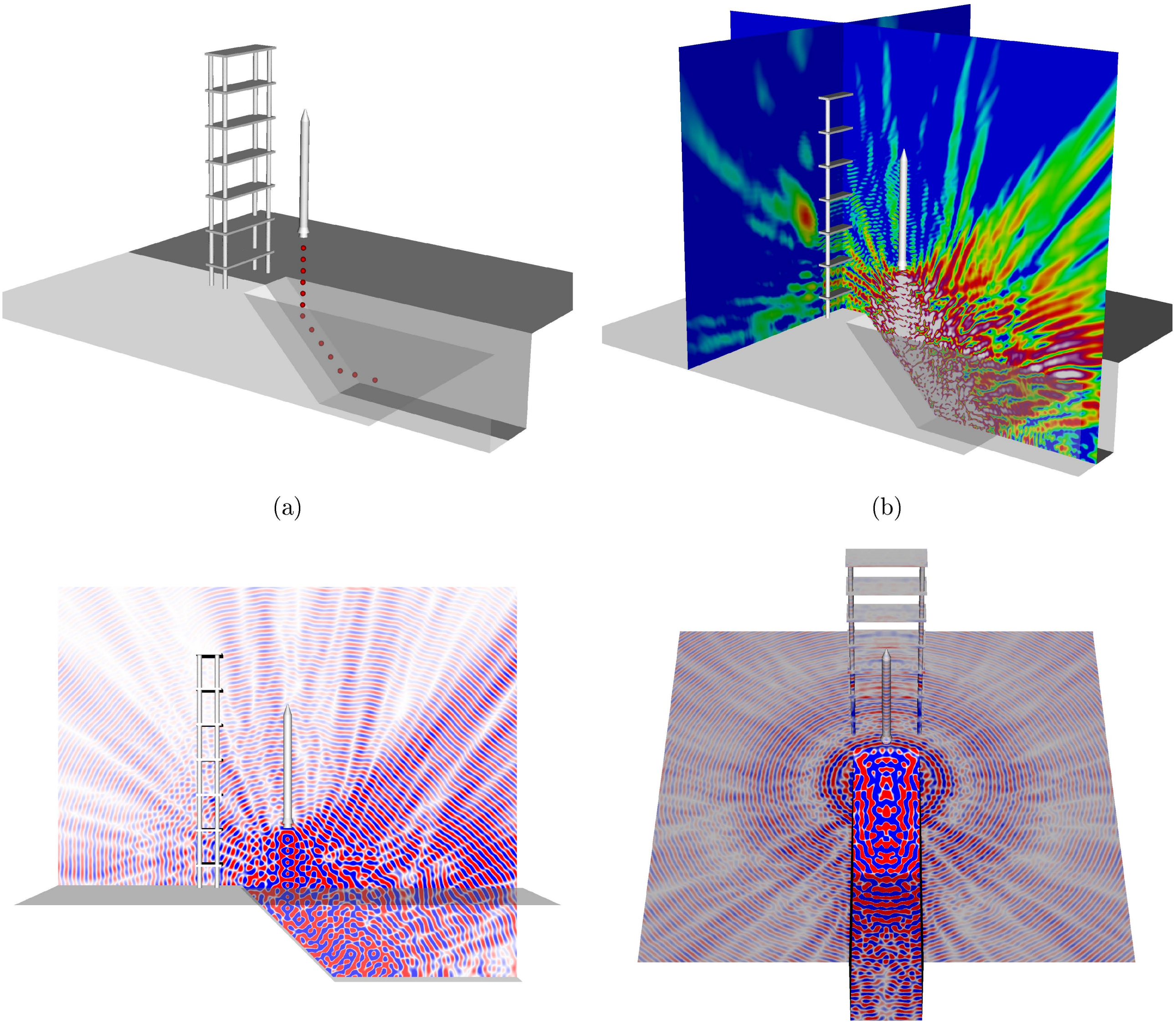
[3] E.M. Salomons. Computational Atmospheric Acoustics. *Kluwer Academic Publishers.* 2001.

[4] M. Ochmann. The Source Simulation Technique for Acoustic Radiation Problems. *Acustica*, Vol. 81, 512-527, 1995.

[5] M.H. Dunn and A.F. Tinetti. Aeroacoustic Scattering Via the Equivalent Source Method. *10th AIAA/CEAS Aeroacoustics Conference , Manchester, Great Britian.*, AIAA-2004-2937, 2004.

[6] Y. Liu. Fast Multipole Boundary Elelment Method. *Cambridge.* 2009.

[7] P.A. Nelson and S.H. Yoon. Estimation of Acoustic Source Strength by Inverse Methods: Part I, Conditioning of the Inverse Problem. *Journal of Sound and Vibration*, 233(4), 634-668, 2000.



(a) (b) (c) (d)

Figure 1: (a) Geometry of the simplified launcher with incident monopole sources shown as red spheres. (b) and (c) Contour of sound pressure level and acoustic pressure on cutting planes. (d) Surface contours of acoustic pressure on the launch site.