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AN OVERVIEW OF VIRTUAL ACOUSTIC SIMULATION OF AIRCRAFT FLYOVER NOISE

Stephen A. Rizzi

NASA Langley Research Center
Hampton, Virginia 23681 USA
Email: stephen.a.rizzi@nasa.gov

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EXTENDED ABSTRACT

Methods for testing human subject response to aircraft flyover noise have greatly advanced in recent years as a result of advances in simulation technology. In the past, subjective acoustic experiments took place in the field or under controlled laboratory conditions subjects, where subjects would be asked to rate live or recorded aircraft flyover sounds according to various scoring methodologies. Field tests using real aircraft flying over the subjects are challenging because it is not known precisely what each listener is hearing, the same flyover can never be reproduced exactly, and flight tests are expensive. Therefore, subjective testing is routinely performed through presentation of flyover recordings in laboratory listening situations, where signals can be exactly replayed and the same sound can be presented at different levels [1-4]. What is typically lost in such settings is the spatial sense and interactivity that come with an actual outdoor listening environment.

In an attempt to retain a controllable test environment, yet more closely recreate conditions in the field, capabilities have been developed which allow subjects to be immersed both visually and aurally in a three-dimensional virtual environment [5-9]. Two types of aural display are generally available; headphones and loudspeaker arrays. With a headphone display, head tracking (real-time measurement of a listener's head orientation), three-dimensional (3D) real-time graphics rendering, and binaural simulation [10, 11] allow the sense of presence to be maintained as the subject interacts with the test environment. Visualization may be rendered on a head-mounted display (HMD) or on a (multi)screen display [12]. For a 3D loudspeaker display, sounds are played back using a spatial audio method, e.g. vector-base amplitude panning (VBAP) [13], with visualization on an HMD or screen. The Exterior Effects Room (EER) at the NASA Langley Research Center is a specially designed laboratory for this purpose [14-17], and utilizes a 31-element loudspeaker array and a single-screen 3D visual display.

The use of recorded aircraft flyover noise in these environments greatly simplifies the simulation because the recordings contain the time varying characteristics associated with the source itself and the propagation from the source to the observer. Under ideal recording conditions, such simulations are likely the best that can be achieved in the laboratory, as they most closely resemble the sounds that listeners are exposed to on a daily basis. From a practical standpoint, however, such simulations are limited in value by the existence of extraneous noise in the recordings (natural or artificial), the finite number of fixed recording positions and the cost of conducting the flight tests. Perhaps the greatest limitation is the inability to examine proposed aircraft, engines, flight procedures, and other conditions or

configurations for which, obviously, recorded data are not available. Synthesis of aircraft flyover noise as an alternative to recordings is therefore desirable as it allows the flexibility and freedom to study sounds from aircraft not yet flown.

Early efforts at the National Aeronautics and Space Administration (NASA) to synthesize aircraft flyover noise were limited to simplified flight paths and component noise sources [18], making results unsuitable for studies of low noise flight operations and advanced configurations. Over the last decade, substantial effort has been undertaken at NASA [7, 19-27] and elsewhere [8, 9, 28-31] to completely simulate aircraft flyover noise in a more versatile fashion. The approach taken by NASA for flyover noise auralization is an engineering-based one, and entails prediction-based source noise synthesis, physics-based propagation path modeling, and empirically-based receiver modeling. This source-path-receiver paradigm allows complete control over all aspects of flyover auralization, but requires added effort to make the simulated event both realistic to the observer and consistent with system noise prediction methodologies such as those found in the NASA Aircraft Noise Prediction Program (ANOPP) [32] and its successor ANOPP2 [33].

In the approach taken by NASA, pressure time histories of each component noise source are synthesized local to the source. The synthesis occurs at the instantaneous emission angle as determined by the straight or curved [25] propagation path between the source and the receiver. As the noise source moves relative to the observer, the source noise characteristics change with emission angle. The synthesis must be performed in such a way that the sound continually evolves with a changing emission angle. The methodology employed depends on the nature of the source.

For broadband sources such as jet noise, the source directivity is usually expressed in 1/3-octave bands, see for example [34]. For these types of sources, a subtractive synthesis technique is used where short snippets of synthesized waveform obtained from filtered white noise are overlapped and added to generate a long duration waveform with time-varying spectral characteristics [19, 21, 22]. The filter is derived from the 1/3-octave band spectrum at the emission position. For tonal sources such as fan noise, the source directivity is usually expressed as tonal amplitudes at blade passage frequencies, see for example [35]. For these types of sources, an additive synthesis technique is used to generate each tone based upon its instantaneous amplitude and frequency [23, 24]. For sources whose predictions provide pressure time histories directly, e.g. rotor and propeller noise [26], a method has been developed to curve-fit and interpolate the waveform over time and space [23].

Semi-empirical prediction methods, such as those indicated above, lack temporal fluctuations found in real data. The lack of temporal fluctuations makes the resulting synthesized noise sound clinical. Consequently, evaluation of time-varying characteristics in isolated source noise data is required such that it may be introduced during synthesis. A limited number of studies have been performed to evaluate temporal fluctuations in jet noise [36] and fan noise [24]. Efforts are presently underway to evaluate fluctuations in rotor noise. It has been shown through psychoacoustic testing that source noise synthesized with temporal fluctuations compares more favorably with real recordings than noise synthesized without fluctuations [37, 38].

At the end of the synthesis process is a pressure time history for each source noise component. For a real aircraft, these include engine sources such as fan, core, turbine and jet noise in the case of a turbofan engine, and airframe sources such as landing gear, slats, flaps, and trailing edge noise [27]. Each must be propagated to the observer in a fashion consistent with the medium. For a uniform atmosphere, the straight line propagation path is determined at incremental points along the trajectory, and the time delay, atmospheric absorption, spreading loss, and ground plane effects are applied. In the NASA approach, these effects are applied by signal processing in the time domain. Application of a time-dependent fractional delay line directly simulates the Doppler effect, while a time-dependent gain simulates the spreading loss. Atmospheric absorption accumulated along the slant range is expressed as a range and elevation angle dependent finite impulse response (FIR) filter, which operates on the time-delayed signal. The procedure for doing so is fully described in [22]. Similarly, an angle dependent FIR filter is developed to simulate the ground plane reflection, based on specular reflection of a plane wave from an impedance boundary, e.g. as described by the Delany-Bazley model [39]. A spherical wave correction is required for grazing incidence [40]. For non-uniform atmospheres, a curved propagation path is determined by finding the so-called eigenray [25]. Depending on the particular conditions, multiple paths may be possible and this directly affects the source noise synthesis. The eigenray calculation is computationally intensive, but recent advances have been made to speed up the calculation using a graphics processing unit (GPU) [41].

Propagation path processing results in a pressure time history at a designated observer location. Sometimes dubbed a pseudo-recording, this data is analogous to what a microphone would record at the observer location and has been shown to generate flyover noise metrics, e.g. the A-weighted sound exposure level (SEL_A) and effective perceived noise level (EPNL), comparable to those obtained by ANOPP at both the component and integrated aircraft levels. At present, the synthesis and propagation processes are not well integrated with the source noise prediction. Efforts are underway to more closely couple the auralization with ANOPP2 via a new auralization application programming interface (API), through which prediction-based synthesis and propagation are more readily performed [42].

A final (optional) step in auralizing aircraft flyover noise is to render it in the immersive environment. The process for simulating flyover noise using a pseudo-recording or an actual recording is the same. In the NASA Community Noise Test Environment (CNoTE) [7] or the NLR derivative Virtual Community Noise Simulator (VCNS) [9], trajectories of the emission position are loaded in an event list [5] on a real-time audio server [11] to position the source in 3D space using binaural simulation or VBAP. A visualization application generates the graphics scene based on listener tracking data and synchronizes that with the audio server. For psychoacoustic testing, subject responses are solicited and acquired via a tablet computer.

In summary, advances in system noise prediction methods coupled with auralization methods have only recently made virtual acoustic simulation of aircraft flyover noise for realistic aircraft under realistic operating conditions possible [27]. As a validated tool chain, auralization can be used with confidence to more effectively communicate the societal benefit of low noise concepts to stakeholders than can tabulated metrics alone. Further, auralization provides a feedback mechanism to the technologists developing noise reduction concepts. With this capability, it is now possible to assess human response to flyover noise by systematically evaluating source noise reductions within the context of a system level simulation. Examples of source noise and movie clips representative of an immersive aircraft flyover environment can be downloaded from the Internet [43].

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