ACOUSTIC ANALYSIS OF AN ULTRA-EFFICIENT COMMERCIAL TRANSPORT AIRCRAFT

A Thesis in
Aerospace Engineering

by
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ABSTRACT

In this thesis the noise from an aircraft with future technology is predicted. The aircraft on this project has multiple unique design features which include a transonic truss braced wing design, the use of a slotted natural laminar flow airfoil and N+3 engines. The project to design and test the capabilities of the aircraft is a collaboration between multiple universities and companies. Since the aircraft had a large number of trailing edges, it was thought that airframe noise would be much more significant than what is seen on typical aircraft today. Noise trends from the wing was predicted using the semi-empirical method developed by Brooks, Pope and Marcolini. These trends were used to see which components of noise would contribute most significantly to the wing noise and how flight conditions may affect it. ANOPP was used for full system noise predictions. The aircraft geometry inputs for ANOPP were based on the phase 2 SUGAR High aircraft which is a truss-braced wing design. The engine information was based on an N+3 engine reference. PNLT time histories and EPNL contours were obtained for multiple flight profiles in both takeoff and approach configurations. Noise certification microphone locations were also examined for each flight profile.
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Chapter 1

Introduction

Commercial aviation is one of the largest industries, with over 10 million passengers and tens of millions of tons of cargo transported worldwide per day. According to the International Civil Aviation Organization (ICAO), the demand for aircraft transportation will more than double over the next 20 years. This doubling in demand will lead to significant increases in pollution and noise generated by commercial aircraft. In order to help to reduce the negative side effects of a growing aviation industry, NASA has created a set of goals to help reduce noise and emissions with future technology shown in Table 1-1.

Table 1-1: NASA’s goals for future aircraft technology - adapted from [1].

<table>
<thead>
<tr>
<th>Technology Benefits</th>
<th>Technology Generations (Technology Readiness Level = 5-6)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Near-term 2015-2025</td>
</tr>
<tr>
<td>Noise (cum. below Stage 4)</td>
<td>22 - 32 dB</td>
</tr>
<tr>
<td>LTO NO\textsubscript{X} Emissions (below CAEP6)</td>
<td>70 - 75 %</td>
</tr>
<tr>
<td>Cruise NO\textsubscript{X} Emissions (relative to 2005 best in class)</td>
<td>65-70%</td>
</tr>
<tr>
<td>Aircraft Fuel/Energy Consumption (relative to 2005 best in class)</td>
<td>40 - 50%</td>
</tr>
</tbody>
</table>
The list of goals set by NASA has led to the designs of future aircraft being much different from what can be seen in the skies today. Most aircraft today use high bypass ratio turbofan engines, but advances in technology have created ultra-high bypass ratio engines which help to further reduce fuel burn and reduce engine noise. Some future designs also include hybrid-electric engines to help reduce fuel emissions overall. The designs of fuselages have also changed to help with meeting the goals as well. More unconventional designs such as the double bubble or hybrid wing body design were created with hopes of fitting additional passengers into an aircraft and come with the added benefit of providing shielding to help reduce noise.

ULI Project Overview

This thesis is part of a broader NASA-University Leadership Initiative project seeking to design an aircraft using N+3 technology. N+3 technology is representative of something that would enter into service in the 2030-2040 timeframe. The ULI Project “The Advanced Aerodynamic Design Center for Ultra-Efficient Commercial Vehicles” [2,3] is a five-year project led by the University of Tennessee, Knoxville. The project relies on developing the enabling technology of the slotted, natural laminar flow airfoil [4,5] to help reach strict goals for fuel burn reduction. This project involves numerous universities as well as companies in the aerospace industry. The project was broken down into three major technical subgroups: the Configuration Subgroup which included tasks such as observing boundary layer stability and predicting the benefit of applying winglets to the overall design, Methods and Analysis subgroup which involved tasks such as predicting aeroelastic behavior on the aircraft and performing a theoretical drag decomposition on the aircraft, and the Low-Speed Flight Performance group, which involved tasks such as observing the effects of including a morphing leading edge design and active flow control devices on the main wing of the aircraft.
Project Objectives

The goal of the thesis was to both predict whether the designed aircraft would meet the requirements for certification as well as the aggressive noise reduction goals set forward by NASA while also seeing how N+3 technology would potentially provide benefits to future aircraft designs. This thesis is specifically looks at the aircraft noise while in a low-speed flight condition in the takeoff and approach configurations. The overall aircraft design used an N+3 engine and a new Slotted Natural Laminar Flow (SNLF) airfoil design for the wing to help dramatically increase the aircraft’s fuel efficiency. These advanced technologies allowed the aircraft to meet and exceed some of the goals set for it; however, it was unknown how these newer technologies would affect the noise produced by the aircraft.

Multiple prediction methods were used to calculate the noise. First, the airframe noise was examined as it was believed that the SNLF design of the wing might have significant noise penalties to the overall design. The initial predictions used a semi-empirical method developed by T. Brooks, D. Pope and M. Marcolini to calculate airfoil self-noise [6]. This method was used to get baseline noise levels for the SNLF-design main wing and to help to determine if self-noise would be a significant source of noise. Full system noise was predicted using NASA’s Aircraft Noise Prediction Program (ANOPP) code. ANOPP and ANOPP2 both contain many modules which can be used to predict noise from different aircraft components, such as fan noise and airframe noise while an aircraft is performing maneuvers. Using these codes, takeoff and approach noise were predicted for the aircraft developed in the project as well as a validation case for a Boeing 737-800 aircraft. The validation case was used to determine how to properly run ANOPP and to see how accurate the data would be considering the particular modules and approximations used in this thesis.
Using the previously stated methods, system noise analysis in low-speed flight configurations was possible. The tools were used to provide predictions to see how the noise levels compared to certification requirements as well as the strict guidelines set by NASA on noise reduction for N+3 aircraft. The results generated by the methods were also adjusted as new inputs were obtained from the other tasks and subgroups on the project.

The Vision Vehicle

The aircraft analyzed in this thesis will be referred to as the “vision vehicle” from this point forward. This aircraft has many unique features that are not seen on current aircraft. A concept model of the aircraft can be seen in Figure 1.1. It is an aircraft designed with the same mission in mind as a modern Boeing 737 with a traditional tube-and-wing body. Its defining feature is its unique truss-braced wing design. The vision vehicle has a much larger span than most current aircraft and a high aspect ratio to help reduce drag. This causes the aircraft to need a truss underneath the wing to help support the loads that will be on it during flight. The unique design for the aircraft is based on Boeing’s ongoing Subsonic Ultra Green Aircraft Research (SUGAR) project that began in the early 2000s [8,9]. The reports from that project detail multiple types of aircraft from the more typical tube and wing design that is often seen today to less common hybrid wing-body aircraft which are not currently available as commercial aircraft. The specific design the vision vehicle is based on is the SUGAR high variant, which uses a high truss-braced wing design to help with fuel burn and noise reduction, but has had multiple updates over the course of the ULI project [10]. The wing is also very unique in that it uses a slotted natural-laminar flow airfoil in its design. This allows the wing to maintain laminar flow even at very high Reynolds numbers. The vision vehicle uses engines modeled after an N+3 engine concept design [11]. These engines with future technology help to provide the thrust required for the aircraft while also hoping to reduce
noise. The engines have a very high bypass ratio of over 20, which is much higher than most modern engines and should help to provide noise reductions for this aircraft. Further improvements also include reducing the fan’s pressure ratio by means of an additional gear system and a variable area fan nozzle, which also helps with maintaining performance throughout the flight envelope. Other technology improvements include assumed improvements to the engine’s aerodynamics and better materials to help improve its cooling capabilities.

**Aircraft Noise**

An increase in air traffic in the future will lead to much noisier skies and airports around the world. High aircraft noise levels will lead to problems with community acceptance of the growing field of commercial aviation. It is because of this that studying aircraft acoustics is very important. Aircraft noise can be separated into two large subgroups, those being the airframe noise and the engine noise. Typically, on takeoff the engine noise tends to dominate the spectrum and on approach the airframe noise becomes more important since most of the engine sources become quieter. Looking at aircraft with modern technology, in most cases the fan noise tends to dominate on both takeoff and approach. While fan noise may dominate, on takeoff jet noise can also be a significant contributor to the overall noise of an aircraft and on approach the noise produced by all

![Figure 1.1: Concept artwork showing the SUGAR High design. (Image source: https://www.youtube.com/watch?v=oz3tzG9RxKJ)](https://www.youtube.com/watch?v=oz3tzG9RxKJ)
airframe sources such as the wing, flaps and landing gear may contribute almost as significantly as the fan noise.

The vision vehicle described previously may help to alleviate some of the noise issues of modern aircraft, while also providing a different noise profile compared to what is normally seen. The lower drag of the main wing has allowed for a reduction in the size of the engines used on the aircraft, which should help in providing reductions to takeoff noise. The engines are also designed in such a way to help reduce the fan noise they produce. The high bypass ratio combined with newly-developed fan blade designs should lead to these reductions. The unique SNLF wing design coupled with these newer engines will most likely cause a shift in the key components in the noise spectrum towards the airframe noise sources. This is due to the increase in span of the wing as well as the introduction of additional trailing edges to the design.

When focusing on reducing aircraft noise, it is important to focus on any sources that are producing significantly more noise than anything else. For example, since fan noise is currently so dominant on modern aircraft, future aircraft such as the vision vehicle should attempt to reduce fan noise and other noise sources to contribute about the same as each other. This would mean that each source is optimized to reduce the total aircraft noise as much as possible. At this point, the only way to reduce noise from the aircraft would be to reduce all noise sources together instead of focusing on just a single component.

**Aircraft Noise Certification**

When an aircraft is designed for general or commercial use, it is required to go through a series of tests to determine its airworthiness. One of the tests in the process is to determine how much noise the aircraft produces and make sure it is quieter than a set limit. The process for determining aircraft noise as a form of aircraft certification began in December of 1969 and is
described in the Code of Federal Regulations (CFR) Title 14 Volume 1 Part 36 [12]. The need for noise certification arose from the growing use of jet propulsion aircraft used in commercial aviation. The restrictions for noise production are based on the total weight of the aircraft and the number of engines it has; the more the aircraft weighs and the more engines it has, the more noise it is allowed to produce before it exceeds the restrictions, and these restrictions can be seen in Figure 1.2.


There are three microphone locations used for certification: flyover (cutback), lateral (sideline) and approach. During certification, aircraft must follow a flight path that travels past each of these microphones in both its takeoff and approach configurations. These microphones are then used to produce a time history of the noise from the aircraft flying overhead. The microphone locations can be seen in Figure 1.3. Takeoff has two microphone locations, the first is the flyover microphone and the second is the sideline microphone. The flyover microphone is used to obtain noise from the aircraft along the centerline of its takeoff profile. The sideline microphone locations are an array of microphones and the specific microphone location that is used for sideline noise
measurement is at the location of peak sideline noise on takeoff. The approach microphone is used to obtain the noise along the centerline on the aircraft’s approach profile.

![Certification microphone locations](image)

**Figure 1.3:** Certification microphone locations [13].

Once the SPL is known at these locations, a process is used to calculate tone-corrected perceived noise level (PNLT) specified by the FAA in CFR Title 14 volume 1 part 36. From there, the effective perceived noise level (EPNL) can be calculated at the three locations and summed together. The process for calculating EPNL is also detailed in the same location as the PNLT calculation. This provides a cumulative noise result, which is then compared to the current Stage requirements. As long as the cumulative EPNL is below the Stage requirement, the aircraft will be certified for the noise requirements.

**Thesis Objectives**

The goal of this thesis is to predict the noise from an aircraft design using N+3 technology and quantify any noise benefits that occur as a result. The aircraft design was based on Boeing’s transonic truss-braced wing design from their SUGAR reports [9] with multiple updates occurring over the course of the project. Noise predictions for the SNLF wing are first conducted using the
methods developed by Brooks, Pope and Marcolini [6] to determine how its design will impact its noise characteristics. Full system noise predictions are performed using NASA’s ANOPP code. The system noise predictions are compared to the results of a modern aircraft to determine how significantly the N+3 technology affects the noise and also to quantify any noise benefits. Multiple flight profiles are used for both takeoff and approach to attempt to reduce noise and maximize the aircraft’s performance capabilities.

**Reader’s Guide**

This thesis describes the process for predicting the noise produced by the vision vehicle on this project and presents the results found. General aeroacoustic theory is described as well as the more specific methods used in noise prediction for the aircraft. The method and predictions for noise produced by the wing are then shown. Next, full system noise analysis of the aircraft is described across multiple flight configurations. This is followed by a short analysis on all results as well as a discussion on what could be done to further produce more accurate predictions for the aircraft.

- Chapter 2 provides a foundation for aeroacoustic theory. It describes key components of aircraft noise that are considered when predicting system noise and it provides methods for predicting each noise component.
- Chapter 3 discusses the method used to predict the noise from an SNLF airfoil used on the aircraft. Information on the airfoil and how flow characteristics are acquired is mentioned. Resulting trends for how noise changes from the airfoil are discussed.
- Chapter 4 provides full system noise analysis for the vision vehicle. A demonstration case of the method is used to explain how ANOPP is able to predict system noise. Flight profiles for
the simulations are compared. Noise results from each profile are compared to determine the best profiles for the aircraft. Results are also compared to NASA’s ARMD guidelines for future aircraft.

- Chapter 5 summarizes the results discussed in the thesis. It includes a discussion on future work that would help provide additional details on the noise produced by the aircraft. The chapter also includes suggestions about what could be added to future aircraft designs to help reduce system noise.
Chapter 2

Background of Aircraft System Noise

Aircraft system noise predictions are a vital part of the aircraft design process. System noise predictions generally have less input in guiding the actual aircraft’s design, but they are an important component in determining whether or not the aircraft will be certified once the design is complete. Aircraft system noise can be divided into two broad categories: airframe noise sources and engine noise sources. These can then be subdivided further into components. The airframe noise sources include sources that produce purely aerodynamic noise, such as the wing’s trailing edges, landing gear and flap side-edge noise. Engine noise sources are components produced by the turbomachinery on the aircraft, such as the fan noise, combustion noise and jet noise.

Introduction to Aeroacoustics

Aeroacoustics is a branch of acoustics that involves the study of sound generated in a fluid medium. The development of this branch can largely be attributed to Sir James Lighthill in papers titled “On Sound Generated Aerodynamically” [14,15]. In his papers, he describes a method for predicting noise generated by a fluid volume through the use of what is called an acoustic analogy. The acoustic analogy that Lighthill uses is derived by rearranging the equations for the conservation of mass, momentum and energy for a fluid, which also means the analogy is an exact solution for the noise. In order to represent the noise, the acoustic analogy represents sources as a distribution of equivalent quadrupole sources. In 1955 Curle [16] added to Lighthill’s previous work by also taking into account solid boundaries in a fluid medium. A solid boundary in a fluid medium creates sound by exerting a force on the fluid volume, which Curle represents using a distribution of dipoles. The analogy was then advanced again in 1970 by Ffowcs Williams and Hall [17]. In their
analysis, they looked at the noise from a turbulent flow near a half plane. Their work found that noise produced by the half plane was much more significant than noise produced by a smooth surface found in the prior work by Curle. The noise was found to scale with $U^5$, which can be seen with noise produced from airfoil trailing edges.

**Airframe Noise Sources**

Airframe noise sources can be defined as any non-propulsive component on an aircraft that produces some kind of noise [18,19]. These components of noise are generated by the wing, flaps and slats, landing gear, empennage and any other small components around the aircraft, such as antennae or other small components. The main sources of airframe noise can be seen in Figure 2.1 and an empirical method to predict the noise of each of these components is are described by Fink [20, 21]. For modern aircraft, the most significant sources of airframe noise are the flaps and landing gear, especially in an approach configuration [22, 23]. This becomes especially true with more advanced engine designs that help lead to further reductions in sources such as jet noise. As engine noise sources continue to become quieter, eventually technology will reach a point where the airframe noise sources will set a floor for how quiet an aircraft can be.

![Figure 2.1: Component sources of airframe noise as described by Fink [21].](image)
Trailing Edge Noise

Trailing edge noise is a significant source of noise for components such as the wing and flaps. It becomes more significant when the aircraft has its high lift systems deployed in low-speed configurations. This is especially true in cases where the aircraft is on approach for landing where much of the noise is already set by airframe noise sources. Trailing edge noise itself is caused by an unsteady flow over a sharp edge [7]. Most of the noise produced is radiated downward towards the ground underneath the aircraft. Brooks, Pope and Marcolini [6] developed a semi-empirical method for predicting airfoil self-noise. The method includes predicting five sources of noise from airfoils with three of the sources being the main focus: turbulent-boundary-layer-trailing-edge noise, laminar-boundary-layer-vortex-shedding (LBL-VS) noise and separation-stall noise.

The turbulent-boundary-layer-trailing-edge (TBL-TE) noise component is typically the primary source of noise for airfoils. The mechanism for this source is the turbulent flow over the airfoil passing over the trailing edge. The separation stall noise is also considered a component of the TBL-TE noise and is caused by separated flow on the airfoil when it reaches high angles of attack. The sets of equations developed in Ref. 4 to predict these sources are:

\[ SPL_p = 10 \log \left( \frac{\delta^* M^5 \overline{L D_h}}{r_e^2} \right) + A \left( \frac{St_p}{St_1} \right) + (K_1 - 3) + \Delta K_1 \]  

\[ SPL_s = 10 \log \left( \frac{\delta^* M^5 \overline{L D_h}}{r_e^2} \right) + A \left( \frac{St_s}{St_1} \right) + (K_1 - 3) \]  

\[ SPL_\alpha = 10 \log \left( \frac{\delta^* M^5 \overline{L D_h}}{r_e^2} \right) + B \left( \frac{St_s}{St_2} \right) + K_2 \]  

For each of these equations, the first term is a scaling term based on flow field parameters. Where \( \delta^* \) is the displacement thickness, \( M \) is the flow Mach number, \( L \) is the length of the airfoil, \( \overline{D_h} \) is a directivity function and \( r_e \) is the distance to the observer. The subscripts \( s \) and \( p \) refer to the suction
and pressure side of the airfoil. The second term in each of these equations is a shape function used to form the spectrum for each of the sources of noise. These shape functions are a function of the Strouhal number of the flow field and of the airfoil. The $K$ functions in the equation are amplitude functions that are used to make adjustments based on the Reynolds number and the $\Delta K$ is an adjustment for the pressure side when the airfoil has some angle of attack. These three SPL calculations can then be added together to find the total TBL-TE noise.

The laminar-boundary-layer-vortex-shedding (LBL-VS) noise is another key component of the overall noise spectrum. The mechanism for this source is vortices that are shed from the trailing edge of the airfoil that are created by laminar flow over the surfaces coupled with acoustic excitation of the airfoil itself. The equation for calculating the LBL-VS noise has some similarities to the TBL-TE noise:

$$SPL_{LBL-VS} = 10 \log \left( \frac{\delta_p M^5 L D}{r_e^2} \right) + G_1 \left( \frac{St'}{St'_{peak}} \right) + G_2 \left[ \frac{R_c}{(R_c)_0} \right] + G_3 (\alpha_0)$$

The equation shares a similar scaling term to the TBL-TE formula where the only difference is the scale parameter $\delta$ is the boundary layer thickness instead of the displacement thickness. The next
three $G$ terms are all shape and scaling terms. The $G_1$ term is a shape function similar to the TBL-TE equations that still is dependent on the Strouhal number of the airfoil and the peak Strouhal number of the spectrum. The $G_2$ term is a scaling function that defines the curve shape and is a function of the Reynolds number of the airfoil and a reference Reynolds number that is a function of the angle of attack. The final term, $G_3$ is an additional scaling factor for the previous $G_2$ term that is only based on the angle of attack for the airfoil.

**Flap Side-Edge Noise**

During experiments in the late 70s and early 80s, aircraft jet noise was able to be reduced due to advances in technology such as higher bypass ratio engines. This reduction in jet noise caused other sources to become more significant. One of these sources was flap side-edge noise, especially on approach when high lift systems are fully deployed. Newer aircraft designs also caused flaps to be located in the wake of their jets, which further increased the noise. Early studies in the mechanisms of flap noise were done by Hardin [24] in 1980. He established that the noise was largely produced by vortices being shed along the side edges of flaps. Furthermore, the flap side-edge noise was found to be much more significant than any trailing edge noise produced by the flap itself. More modern methods of predicting flap side-edge noise are more empirical than what was seen in the work by Hardin. Guo [25] provides a method of predicting flap side-edge noise. In his method, the power spectral density is predicted from the following equation:

$$G_{pp} = A_G A_F W(M_\infty) F(f_d, M_\infty) D(\theta, \Phi) \frac{l^2 G_{flap}}{r^2 (1 - M_\infty \cos \theta)^2} \tag{2.5}$$

which is a summation of both the low and high frequency sources found in flap side-edge noise. $A_G$ is an amplitude function based on the geometric properties of the aircraft flap and $A_F$ is an amplitude
function based on the flow parameters. $W(M_\infty)$ is a function used to give a dependence on the Mach number of the flow, $F(f_d, M_\infty)$ is a spectrum function that has a dependence on both the frequency and the flow Mach number and $D(\theta, \Phi)$ is a directivity function. The $l$ term is the characteristic length term which is either the flap chord, $C_{flap}$, when looking at low frequency noise or the flap span, $b_{flap}$, when looking at high frequency noise and the $r$ term is the distance to the observer. The results from this equation also show that the low frequency noise produced by flap side edges have a dependence on the Mach number to the fifth power, similarly to what was seen previously with trailing edge noise. Once the power spectral density is predicted, the function can be integrated to produce the mean squared pressure from flap side edges.

$$\langle p_f^2 \rangle = N_{wing} \int G_{pp}^* df$$ (2.6)

**Landing Gear Noise**

Experimental studies on landing gear noise were conducted by Heller and Dobrzynski in 1976 [25]. In their experiments, they looked at both full- and model-scale aircraft in an attempt to determine significant contributors to landing gear noise and determine the accuracy of prediction methods. They found that the spectra produced by landing gear scaled with the Mach number to the sixth power, which is similar to what was found in earlier research into noise produced by flows interacting with smooth surfaces. The noise produced by the models was only able to show similar trends when compared to full scale tests due to the small intricacies of the full-scale gear not being represented accurately on the models. Fink [20] later built on their work in an attempt to help make their predictions more accurate. He changed the empirical equations to help better account for the noise produced at very high and very low frequencies.
**Engine Noise Sources**

Engine noise is considered the largest source of noise for aircraft in civil aviation. Engine noise itself is considered to be the combination of fan, compressor and turbine noise in the engine which when combined together produce tonal and broadband noise. When separating engine noise into its components, the fan noise is now considered to be the largest contributor. This is followed by jet noise, another significant noise source, and then by all other engine noise sources, which are much less significant.

**Fan Noise**

Aircraft system noise is dominated by engine noise sources on takeoff. Of those engine noise sources, the most significant on modern aircraft are the fan noise and jet noise [27]. An additional factor in determining which source of engine noise will dominate is the bypass ratio of the turbofan engine [19], since it is known that as bypass ratio increases, fan noise becomes more dominant due to decreases in other sources, such as jet noise. Current and future engine designs are expected to use higher bypass ratios (BPR of 20+) than what has been seen previously (BPR of 5-6 or 9-12.5 on geared turbofan engines) in order to gain many benefits for both fuel efficiency and noise. Such an increase in bypass ratio will also make fan noise a much more dominant source of engine noise, which will create a need to develop additional technologies to help further reduce the fan noise on future aircraft.

Fan noise itself is a complex set of interactions that consists of both tonal and broadband components. Tonal noise is produced by interactions between the rotor blades and stator vanes. These interactions create modes at different frequencies that can either be “cut on” and produce noise or “cut off” and decay exponentially before they leave the duct. Fan broadband noise can
occur randomly at many different modes across many different frequencies. In order to predict the broadband noise, empirical methods tend to be used such as those developed by Heidmann [28]. Modern methods of fan noise prediction can be used to predict the noise from the larger engines that are more commonly used on aircraft today [29]. The prediction method takes the form of the following equation:

$$SPL_r(f, \theta) = 20 \log \frac{\Delta T^*}{\Delta T_{\text{ref}}} + 10 \log \frac{\dot{m}^*}{\dot{m}_{\text{ref}}} + F_1(M_d, M_r) + F_2(s^*) + C + D(\theta) + S(\eta)$$ (2.7)

The first two terms in the prediction method represent the mechanical and specific work. $F_1$ and $F_2$ are both source strength functions where $F_1$ is based on the rotor tip Mach number and $F_2$ is based on the rotor-stator spacing. $C$ is a constant that adjusts the amplitude of the noise based on whether or not inlet guide vanes are present, $D(\theta)$ is the directivity function and $S(\eta)$ is a spectrum function where $\eta$ is a frequency function based on Mach number and blade passing frequency.

**Jet Noise**

Jet noise has been a large area of study and concern since the jet engine has been used on aircraft. Jet noise was one of the most significant noise sources for older aircraft, but with the invention of better engines and methods of reducing jet noise, such as chevrons, it has become less of a concern on more modern vehicles. Theories for the prediction of jet noise can be traced back to Lighthill’s acoustic analogy, which provides a basis to understand the mechanics what is occurring. Early research into jet noise prediction began using Lighthill’s method, but failed to capture a completely accurate representation of jet noise. More modern methods of predicting jet noise can be semi-empirical such as Stone’s method [30-32] used in NASA’s ANOPP code. Stone’s method for predicting jet noise was originally developed specifically for ANOPP in 1976, but it
has been adapted and updated to help take into account all types and sizes of engines. The general form of the equation for noise prediction is:

$$SPL(r, f, \theta) = PWL + 10 \log \left( \frac{A_j}{r^2} \right) + 10 \log(D) + 10 \log(F) + SUP$$  \hspace{1cm} (2.8)$$

where $PWL$ is a function for power level, $D$ is a directivity function, $F$ is a spectrum function, $A_j$ is a function based on nozzle area, $r$ is the distance to the observer and $SUP$ is a suppression term.

This equation can be used to predict all sources of jet noise which include the jet mixing noise, plug separation noise and the broadband shock noise. Each source will have its own set of functions for each component in the equation. Each components’ prediction can then be added together to produce the overall SPL of the jet.

**Combustion Noise**

Combustion or core noise is defined as any noise produced by the engine in the combustion process, typically located throughout the turbine and exhaust nozzle. The noise can either be direct meaning it comes straight from the combustion process itself, or it can be indirect which means it comes from the mixing of the products of combustion as they pass through the engine. Combustion noise is generally not considered to be a significant source of noise in configurations such as takeoff, but it can become more significant in configurations that have lower engine power settings [16]. When an aircraft is in an approach configuration or it is taxiing on the runway, the engine power is typically very low which would lead other sources, such as jet noise, to be much lower since they scale with velocity to the eighth power. This is also potentially true for aircraft in cruise. Methods for predicting combustion noise can be empirical in nature [33, 34] and use the equations:

$$SPL = 10 \log(p^2)^* + 20 \log \frac{\rho_\infty c_\infty^2}{p_{ref}}$$  \hspace{1cm} (2.9)$$
Where $\rho_\infty$ is the ambient density of the fluid, $c_\infty$ is the speed of sound through the medium, $p_{ref}$ is a reference pressure and $\langle p^2 \rangle^*$ is the far-field mean-squared acoustic pressure given by:

$$\langle p^2 \rangle^* = \frac{\Pi^* A^*}{4\pi (r_s^*)^2} \frac{D(\theta)S(f)}{(1 - M_\infty \cos \theta)^4}$$

(2.10)

To predict the acoustic pressure, $\Pi^*$ is the acoustic power relating to both the entrance and exit states based on the mass flow rate, area, temperature and a turbine transmission loss factor predicted empirically, $D(\theta)$ is a directivity function and $S(f)$ is a spectrum function.
Chapter 3

SNLF Wing Noise Predictions

When looking at aircraft system noise, certain components of noise will become more significant during specific flight configurations. Generally, fan noise is the most significant noise source in both takeoff and approach configurations. Takeoff noise tends to be dominated sources of engine noise such as fan and jet noise, whereas approach typically is more dependent on the other airframe sources such as flap noise and landing gear noise. For modern aircraft, this is standard, but future aircraft are being designed differently from what aircraft have historically looked like. Some future aircraft designs have more trailing edges and longer trailing edges, such as the aircraft in this project. Other factors such as lower drag have also led to the use of smaller, more efficient engines which is thought to help reduce the noise produced by them as well. The combination of these two factors may suggest that the engine noise from this aircraft will be decreased while the airframe noise will be increased, which may lead to a shift in the most significant sources of noise for the aircraft.

Wing Noise Prediction Method

The unique design of the slotted natural laminar flow airfoil used on this aircraft was a component that was investigated to determine how much it may contribute to the overall noise of the aircraft. In order to predict the noise from this airfoil design, the method developed by Brooks, Pope and Marcolini [6] was used. This method is semi-empirical and uses wind tunnel data obtained from NACA 0012 airfoils to predict airfoil self-noise. The method also includes a way to predict the boundary layer thickness and displacement thickness of the airfoil from an empirical equation, but since the SNLF airfoil’s boundary layer profile would be different from the 0012’s profile,
other estimates were used to predict the noise. Two cases were chosen to see how changes in displacement thickness affected the noise from the airfoil’s fore element. For both cases, the aft element was assumed to be fully turbulent due to its location within the wake of the fore element. Case 1 would be a laminar case for the airfoil with the fore element having much smaller displacement thicknesses to represent that. The second case is a more turbulent case with much thicker displacement thicknesses on the fore element. The two cases and their relative scales can be seen in Figures 3.1 and 3.2. These estimates for boundary and displacement thickness were input

![Figure 3.1: S204 Airfoil with estimated displacement thicknesses – Case 1.](image1)

![Figure 3.2: S204 Airfoil with estimated displacement thicknesses – Case 2.](image2)
directly into the BPM method to get a more accurate prediction of what the noise would be, as opposed to relying on the built-in method for predicting boundary layer and displacement thickness. In order to get reliable estimates for the boundary layer and displacement thicknesses, the airfoil was simulated in multiple CFD codes by other groups on the project. The simulations occurred in both MSES [35,36], a code similar to xFoil [37] but with multi-element capabilities and OVERFLOW [38-40] which is an overset grid Navier-Stokes flow solver code developed by NASA. MSES has the capabilities to give a boundary layer estimate for the airfoil, however it is unable to give an explicit value for the displacement thickness in its simulation.

Wing Noise Trends

Inputs for the method were chosen based on the Phase 2 SUGAR reports for wing span and chord measurements. The Mach number for the aircraft was set to 0.2 as a representative speed for an aircraft during takeoff and the angle of attack of the wing was varied between 0 and 10 degrees. All of the spectra are taken from 150 feet below the trailing edge of the wing. Figure 3.3 shows an example case of the noise spectra from both cases for the airfoil at 0 degrees angle of attack. Each component of self-noise listed is the total for both elements of the airfoil, while the totals for both the fore and aft elements are pictured separate from each other. Also, due to the aft element being located in the wake of the fore element, it was assumed that it was fully turbulent, and thus would not contribute LBL-VS noise. When looking at both of these cases together, it is possible to see that the aft element seems to contribute higher noise levels at its peak than the fore element at its peak. This will become more of a concern at higher angles of attack as the aft element will be
deflected further while it is treated as a flap for the aircraft. In both of these cases, the noise produced from the LBL-VS component is not visible on the graphs as it is too low.

For this aircraft on takeoff, a more representative angle of attack for the wing is around 6 to 7 degrees. Figure 3.4 shows the predicted spectrum for the airfoil at 6 degrees angle of attack.

With the increase in angle of attack, the overall noise from the spectrum increased for both fore and aft element, largely from the separation and LBL-VS noise components. Most of the noise in these spectral plots is coming from the TBL-TE noise components at this point from both cases, and the aft element still has the higher peak between the two elements.
When the angle is increased slightly further to 8 degrees, some important changes seem to occur in the graphs and can be seen in Figure 3.5. One major different to note is that the LBL-VS noise component from the fore element is suddenly contributing significantly to the overall spectrum in both cases, despite the higher TBL-TE noise components in case 2. It also sets the shape of the fore element’s spectrum for a large portion of the lower frequencies between 80 and 600 Hz. Peaks for these spectra seem to reach a maximum of around 70 dB in the frequency range between 100 and 1000 Hz.

**Figure 3.4:** S204 Airfoil noise spectrum comparison between Case 1 and Case 2 at 6 degrees Angle of Attack.
Wing Noise Conclusions

The noise from the wing at first seems very high from looking at the spectra provided, but there are some key pieces of information that must be kept in mind when looking at the results. First, these results are taken from very close to the aircraft, only 150 feet away. During actual flight or certification, the observers will be located much further away than what is seen in these predictions, which will lead to significant reductions in noise. Another key point is that parts of the prediction method and data are out of date. At early stages of the project when these estimates were developed, much of the data was taken from the phase 2 SUGAR reports. As the project developed,
much of that data became out of date and thus was incorrect such as the overall sizing of the wing. CFD predictions of the later updated S207 airfoil also revealed later on that much of the flow around the airfoil is laminar as well. The fore element was found to be completely laminar while large portions of the aft element were also found to be laminar, which would most likely lead to significant decreases in noise due to reductions in the TBL-TE noise components. This method also does not take into account any form of shielding for the fore element of the airfoil. The location of the trailing edge of the fore element above the aft element would cause reductions in noise produced by it. While these predictions are useful for showing the overall trends of the data and what can be expected for the aircraft in flight, the actual airfoil will most likely be much quieter than what has been predicted using this method. All cases using the BPM method for noise prediction can be found in the Appendix.
Chapter 4

Vision Vehicle System Noise Prediction

The vision vehicle used on this project has multiple new and unique features not typically found on modern aircraft. One of the defining features on the aircraft is its truss-braced high wing design that uses a slotted natural-laminar flow airfoil. The wing on its own had two trailing edges producing noise from the design of the airfoil along with a third trailing edge from the truss, so it was thought that airframe noise might play a much more significant part in noise production than what is seen on current aircraft. There are, however other aspects to this aircraft that are unique as well, such as the much more advanced engine design. This advanced engine design was thought to potentially help reduce the engine noise on takeoff since they are much smaller than typical engines and they have additional technology and design features that aid with noise reduction. An important component of airworthiness certification is the check to see how much noise the aircraft produces.

![Vision Vehicle aircraft concept](https://www1.grc.nasa.gov/aeronautics/hep/airplane-concepts/)

**Figure 4.1:** Vision Vehicle aircraft concept, based on Boeing SUGAR concept. Image obtained from: https://www1.grc.nasa.gov/aeronautics/hep/airplane-concepts/
While meeting the requirements set by the FAA is all that is needed for certification, NASA has previously set goals for future aircraft to reach noise reductions below the current stage 5 requirements. A goal set for this aircraft would be to meet those guidelines for noise reduction.

**Demonstration Case Setup**

The tool selected to predict the noise produced by the vision vehicle is ANOPP [41]. A key component of using ANOPP as a tool for noise prediction was to establish how accurately the code could predict noise from a current aircraft. ANOPP’s distribution includes a sample case of a Boeing 737-800 along with a flight profile that can be used as a demonstration for the code’s capabilities. At the time of this input’s creation, this sample case was an accurate representation for a 737-800 and its results were useful for establishing a baseline for ANOPP prediction – without the support of large teams like NASA has.

In order to predict system noise, ANOPP requires multiple input files which can be used to establish an aircraft deck as well as a flight profile for the aircraft to follow. The flight profile input is a simple file which contains coordinates for the aircraft to travel along as well as speeds during the flight. Using this profile, it is also possible to change flap deflection angles, retract or deploy landing gear and change engine power settings to either increase or decrease the engine’s thrust. ANOPP is, however, set up in such a way that the flight profile that is input will occur exactly as the input says it is. This means a user may input a flight profile that is impossible for the aircraft to achieve. Because of this, in order to produce a possible profile for the aircraft, another code must be used that takes in the aircraft’s information and outputs a potential flight path that is possible for it to follow. During the course of this project, this activity was completed by Boeing using data for the project’s engine, which they had available.
The actual input deck for ANOPP is more complicated than the flight profile input since it contains aircraft geometry information, engine state tables as well as general atmospheric information. The order of what is written in the input deck is largely irrelevant, however some of ANOPP’s modules must be established before others. For example, the first thing that should be defined in an input file is the atmospheric conditions. These conditions should be created throughout at least the full altitude that the aircraft’s profile travels. Following the atmospheric data input, any information on atmospheric absorption must then be specified in order to complete ANOPP’s atmosphere model. The atmosphere model is used for calculating atmospheric absorption, which is later used in the propagation module. Next, before any noise prediction modules are run any observers used in the prediction must be specified. With the atmosphere created and observers specified, it is then possible to create any input that a user may want for noise prediction. For use in modules later, it may be useful to establish engine state tables relatively early in the input deck. These state tables provide information on the temperature, pressure, area, fuel-to-air ratio, rotation speed and mass flow rate during different flight conditions for the engine. This allows ANOPP to predict the engine noise at any conditions it may encounter throughout its flight profile. These tables must be established at some point before their respective modules are run in the program in order to allow ANOPP to create arrays of engine conditions along the full flight profile. Once every noise component has had its respective module run for the flight, ANOPP must be told what to do with the resulting prediction. The basic ANOPP output consists of tables sound pressure level across a range of specified frequencies that are picked up by any of the specified observers. The results can have noise suppression applied to them which may help to account for different features that ANOPP may not be able to account for on its own with its inputs. The resulting prediction can also be converted into noise metrics such as overall sound pressure levels, perceived noise levels or effective perceived noise levels.
Demonstration Case Output: No Propagation Effects

An example of ANOPP’s outputs for the 737-800 demonstration case are picture in Figure 4.2. This demo case can be used as a way to help establish what can be expected from running an ANOPP simulation. The results pictured in Figure 4.2 have propagation effects turned off so that it is possible to see exactly how each noise component will act, but there will be no losses as the noise travels towards the observers and there are no additions due to ground effects. At the takeoff,

![Baseline Demonstration PNLT Time Histories](image)

**Figure 4.2:** Baseline 737-800 simulation PNLT time history plots for takeoff and approach without propagation effects, included as a demonstration case.
sideline and approach microphone (observer) locations, it is possible to see that the noise is largely set by fan noise. At the sideline microphone, the jet noise eventually overtakes the fan noise, but towards the end of the flight path the fan noise becomes the dominant source of noise again. For the takeoff profile, the noise is largely set by just the fan and jet noise. Other sources such as the combustion noise and airframe noise sources do not seem to contribute significantly to the total noise. On approach, it is possible to see that the noise is again set by the fan noise, which was seen in the takeoff cases. During this case, however, flap noise and landing gear noise contribute more significantly to the total noise, showing how airframe noise sources may become significant on approach.

**Demonstration Case Output: Propagation Effects**

In order to get a more realistic view of the aircraft noise, it is important to include propagation effects in the prediction of system noise. Using the same demonstration case discussed in the previous section, propagation effects were turned on and the case was run again to get the same output as before. The results of the simulation can be seen in Figure 4.3. The noise has to travel a somewhat significant distance to reach the takeoff microphones which leads to significant reductions in the predicted noise levels for that case. In the approach profile, the noise does not have to travel as far, which leads to less significant reductions. The fan noise is still the most significant contributor for the takeoff and approach microphones, but for sideline the jet noise has become a more significant contributor. This is due to the reductions from atmospheric attenuation affecting the fan noise more significantly than any other noise source. The fan noise is affected most significantly because the noise spectrum is comprised of higher frequencies, which attenuate more than lower frequencies.
Demonstration Case: Comparison to Certification Results

The purpose of running this demonstration case was to address three major goals. The first goal is to learn how to use ANOPP as a tool for system noise prediction. An important part of the overall project is to try to represent the vehicle being used as accurately as possible, and the demonstration cases included with the program help to better understand how to properly create

![Baseline Demonstration PNLT Time Histories](image)

**Figure 4.3:** Baseline 737-800 simulation PNLT time history plots for takeoff and approach with propagation effects turned on, included as a demonstration case.
input decks for aircraft. The second goal is to get a reference for what can be expected from a modern aircraft. While there are some things that would be expected to change with an N+3 aircraft, looking at a modern aircraft’s results will help with finding anything that may be incorrect either in the aircraft’s inputs or outputs. The final goal is to see how accurately ANOPP can predict aircraft system noise compared to certification data, with the level of information available for this study.

ANOPP can predict system noise accurately. The changes I have been making is to acknowledge that we might not have enough information to use ANOPP accurately. That is not ANOPP’s fault. In Table 4-1 are the EPNL predictions for the demonstration case compared to recorded certification data for the same aircraft. With no propagation effects taken into account, the predicted levels are significantly noisier on takeoff than the certification data, which would be expected. Once propagation effects are taken into account, it is possible to see the EPNL results drop significantly for takeoff, which would be expected considering the distance the noise must travel to the microphones. For the takeoff microphone, the predictions are 3.4 EPNdB higher than the certification data. At sideline, the predictions are only 0.4 EPNdB higher than the certification data. The reason for such a large discrepancy on takeoff is most likely due to the fact that this aircraft may not be flying the exact same flight profile used for the aircraft during its certification. The differences between the approach case are 1 EPNdB below certification without propagation effects and 3.6 EPNdB below certification with propagation effects. The cause for the difference between certification and prediction data is most likely the same as with the takeoff case: the flight profile is not exactly the same as what was used during certification. An important aspect to point out, however is the sideline prediction compared to the sideline certification data. Sideline functions differently from the other two certification locations. While takeoff and approach are both specified microphone locations, sideline is instead an array of microphones used to pick up the loudest part of takeoff. Due to this, even if the prediction microphone used and the certification microphone used are in two different locations, they should still yield similar results since they would both be
the loudest point for both cases. It is possible to see from the predictions that the difference between the sideline microphone with propagation effects is only 0.4 EPNdB higher than that of the certification data. This 0.4 EPNdB is encouraging for the overall accuracy of the baseline predictions as a sample case. The results provided also give a small error range, which can be used in assessing the predictions of the N+3 vision vehicle later in the thesis.

**Table 4-1:** Baseline 737-800 EPNL Predictions compared to certification results.

<table>
<thead>
<tr>
<th></th>
<th>Takeoff</th>
<th>Sideline</th>
<th>Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Certification EPNdB:</td>
<td>87.8</td>
<td>93.1</td>
<td>96.8</td>
</tr>
<tr>
<td>Simulation EPNdB (No Propagation Effects):</td>
<td>96.9</td>
<td>98.2</td>
<td>95.8</td>
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<tr>
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<td>93.5</td>
<td>93.2</td>
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<tr>
<td>Difference (No Propagation Effects):</td>
<td>+9.1</td>
<td>+5.1</td>
<td>-1.0</td>
</tr>
<tr>
<td>Difference (Propagation Effects):</td>
<td>+3.4</td>
<td>+0.4</td>
<td>-3.6</td>
</tr>
</tbody>
</table>

**Vision Vehicle Case Setup**

The vision vehicle case input deck was set up based on the provided demonstration inputs for ANOPP. All of the aircraft’s parameters were changed to match those of the vision vehicle. Aircraft geometry information was found in the phase 2 SUGAR papers seen in reference [9] and any updates used during the project were also accounted for from reference [10]. The engine state tables were changed to match those of an N+3 engine [42], which is what would be used in this aircraft’s design. The SNLF wing was modeled by treating the aft element as a large flap and by predicting the trailing edge noise of the fore element. The prediction for the aft element noise was also done using a more modern method for predicting flap noise to help get more accurate results.
The vision vehicle case was run with six different takeoff flight profiles and 3 different approach profiles to get an idea for how the vehicle’s sound would change under different circumstances.

Baseline vs. 2020 Profile

Two different flight profiles were initially used to predict the noise from the vision vehicle, the first being the profile used in the baseline 737-800 predictions discussed previously and the second being a profile designed specifically for the vision vehicle and its capabilities, both of these profiles can be seen in Figure 4.4. Since the baseline profile was designed with a different aircraft in mind, the settings used for the aircraft are not representative of what the full capabilities of the vision vehicle are or what it would actually do during a takeoff maneuver, however it is representative of what a more modern aircraft would do, which can help with determining a difference between what would be expected from a modern profile and from one designed for a future aircraft. Some of the major differences between the two profiles include the vision vehicle’s ability to take off much sooner than what is seen in the baseline case and its ability to get to a higher altitude much faster. These are both qualities that are very beneficial when looking at the case from an acoustics standpoint as they allow the aircraft to be further from any microphones faster than what is seen in the modern (737-800) profile. The flap setting for the baseline case is 30 degrees as opposed to the vision vehicle’s 20-degree flap setting. One thing to keep in mind is that for the vision vehicle, the aft element is what is being treated as a “flap” in this case to help provide a similar benefit. The engine power in the baseline case also changes differently from in the 2020 case. In the 2020 profile, the engine power is set to 54% as the vehicle approaches the cutback microphone and then it throttles back up to full power soon after, only keeping it there for a few thousand feet. The baseline case only cuts its power back to about 68% right before cutback, and maintains that lower power setting over a much longer distance. It then throttles back up to about
80% at a distance of about 28,000 feet and never reaches full throttle again. Another important feature to note is the difference in velocities between the two flight profiles. The 2020 flight profile starts off much slower than the baseline profile, but eventually reaches a much higher speed. This allows the baseline case to spend less time near the sideline and cutback observers than the 2020 profile.

Figure 4.4: Baseline flight profile compared to 2020 flight profile.

Upon examination of the PNLT time histories, it is possible to see that the vision vehicle aircraft benefits from using the 2020 flight profile. The cutback microphone results for the cases without propagation effects can be seen in Figure 4.5. When the vision vehicle’s 2020 flight profile results are compared its baseline flight profile results, it is possible to see a few notable similarities and differences between the cases. The main notable similarity is the fan noise being a large contributing source at cutback for the aircraft in all profiles. However, between the 2020 flight profile and baseline flight profile the important noise sources change. In the baseline profile, the jet noise was the second most significant source across all takeoff cases. In the case of the vision vehicle, however, the next most important source is the flap noise, which even overtakes the fan.
noise at one point during the baseline takeoff profile. This is due to the fact that the vision vehicle uses an SNLF airfoil in its wing design. The aft element component of the wing is 95% of the full wingspan whereas for the demonstration the flaps are a much smaller part overall for the aircraft. The larger aft element on the vision vehicle leads to a much larger source of noise, which makes it more significant than what would be expected from a modern vehicle such as the 737-800. The 2020 takeoff profile shows some benefit for cutback over the baseline profile in the form of its peak only occurring around 77 dB, whereas the baseline profile’s peak occurs at about 87 dB. The baseline profile, however does have a much smaller time range covered by the peak when compared to the 2020 profile’s more consistent noise over the duration of the full maneuver.

![Figure 4.5: Baseline flight profile PNLT time history compared to 2020 flight profile PNLT time history located at the cutback microphone with propagation effects turned off.](image)

With propagation effects included for this case, the results change somewhat significantly. The flap noise is the most significant source of noise in the baseline takeoff profile. In the 2020 profile, the fan noise is competing for the most significant source with both the combustion noise and the flap noise. This has to do with how much each source is affected by atmospheric attenuation and was seen previously in the baseline profile as well. The main difference between what was seen previously and what is seen now is that the noise sources that are contributing the most are still changed due to the vision vehicle’s design. These differences can be seen in Figure 4.6. When
propagation effects are turned on the baseline profile does not seem to get much of a benefit overall due to the flap noise contributing so significantly during that profile. The 2020 profile, however, sees a significant reduction due to the fan noise being reduced throughout the maneuver. While the flap noise and combustion noise do contribute slightly to the total noise as seen in case without propagation effects, they do not contribute enough to be significant noise sources until the fan noise is reduced due to propagation effects. When comparing the two profiles, it is possible to see how much more the 2020 profile benefits from the inclusion of propagation effects. The 2020 profile has its peak noise drop by about 7 dB, but the baseline profile only sees a benefit of about 3 dB. This leads to the peak PNLT for the 2020 profile becoming only about 70 dB with the baseline profile’s peak PNLT staying at about 84 dB. This 14 dB difference in peaks also leads to a significant difference in the predicted EPNL across both cases. For the 2020 profile, the aircraft has a predicted EPNL of about 73 EPNdB, whereas the baseline profile has a much higher predicted EPNL of 82 EPNdB. This shows that while the peak is occurring over a much smaller time range in the baseline profile, it is not enough to cause a significant reduction in the EPNL when compared to the overall lower and more consistent case provided by the 2020 profile.

**Figure 4.6:** Baseline flight profile PNLT time history compared to 2020 flight profile PNLT time history located at the cutback microphone with propagation effects turned on.
The results show a different story when looking at the case using the sideline microphone, shown in Figure 4.7. The 2020 profile was able to realize significant benefits compared to the baseline profile mostly due to it having a much larger distance between the aircraft and the microphone itself on takeoff. For sideline, however, the relative distance to the microphone for both cases is about the same for the duration of the takeoff maneuver. This means differences between the cases will also largely be due to factors such as the shape of the profile during its initial takeoff as well as the speed of the takeoff maneuver. For example, in the baseline profile, the flap noise is significantly higher for the vision vehicle than what is seen in the 2020 takeoff profile. This is caused by multiple factors such as the fact that the baseline profile gets up to a high speed much faster than the 2020 profile and it also has a larger flap deflection setting. The other airframe noise sources such as the landing gear, strut, wing and strut are all more significant than what is seen in the 2020 profile due to the higher takeoff speed. Despite these differences, both profiles seem to be reaching about the same peak when compared to each other. The baseline profile peaks at a PNLT of about 86 dB whereas the 2020 profile peaks at about 85 dB. This is largely due to the fact that the fan noise is dominating both cases when propagation effects are turned off.

With propagation effects turned on, both cases gain benefits because of the reduction in fan noise. In the baseline profile at cutback, not as large of a benefit was seen due to the significance

![Figure 4.7: Baseline flight profile PNLT time history compared to 2020 flight profile PNLT time history located at the sideline microphone with propagation effects turned off.](image)
of the flap noise, however because there is a much larger discrepancy between the two sources in sideline, the benefit is much larger. For both baseline and 2020 takeoff profiles, the peak occurs at around 78 dB, which gives a reduction of about 9 dB for the baseline profile and 8 dB for the 2020 profile. Both profiles also have the same EPNL result at the sideline microphones of 78 EPNdB as well. The major differences between the two cases are due to the airframe noise components, which was stated earlier, as well as the duration of the noise. The baseline profile at this point in its maneuver is traveling much faster, which causes all airframe noise sources to be more significant and it decreases the time that the noise is present. With the 2020 profile being a bit slower at this point in its maneuver, the airframe noise sources contribute much less significantly than what is seen in the baseline profile and it occurs of a much larger duration.

**Figure 4.8:** Baseline flight profile PNLT time history compared to 2020 flight profile PNLT time history located at the sideline microphone with propagation effects turned off.

**Baseline vs. Revised Baseline**

After the 2020 profile was created, it was thought that creating an additional profile to mimic what would be seen in a modern aircraft would be useful if it was tailored specifically to the vision vehicle case. In order to do that, a profile was developed using information about the vision vehicle and the baseline flight profile to attempt to give it more appropriate parameters for its
velocity and positioning as well as power settings and flap deflection angles to better represent what the vision vehicle is capable of. The result was a new revised flight profile based very heavily on the baseline profile that takes the vision vehicle’s capabilities into consideration. Both flight profiles could then be used by the vision vehicle to get a comparison of what is possible if it used a modern flight profile and if it used a profile designed for its capabilities while still maintaining a similar path and velocity. The comparison between the profiles can be seen in Figure 4.9. In the revised variant, the aircraft attempts to maintain its ability to takeoff quickly, which provides noise benefits due to its larger distance to the cutback microphone. It also tries to mimic the baseline profile by getting up to speed faster than what was previously seen in the 2020 profile where the aircraft waited until after cutback to get fully up to speed. The aircraft is also able to capitalize on its more modern technology by further reducing its engine power during cutback, which will allow for reductions to significant engine noise sources.

A comparison of the cutback microphone for the baseline profile and the revised baseline reveals a very similar shape and many similar noise results. This is due in part due to the location

![Takeoff Flight Paths With Velocities](image)

**Figure 4.9:** Baseline flight profile compared to its revised counterpart.
and speed of the aircraft as it passes over the cutback microphone. For both profiles, the aircraft is traveling at about the same speed and has about the same distance between itself and the microphone, so it is possible to see in Figure 4.10 that the airframe noise sources of the flap, wing and strut are all very similar. The landing gear noise is different between the two cases due to it being retracted earlier in the baseline profile compared to the revised takeoff profile. The engine noise sources show slight differences due to the slight reduction in engine power that is able to occur in the revised flight path from the advanced engine technology. Overall, the two profile’s results look similar with peaks occurring at 87 dB for the baseline profile and 85 dB for the revised case. The slight benefit in peak PNLT for the revised profile does not lower the EPNL at cutback since both cases have results of about 86 EPNdB.

When propagation effects are taken into account for both cases, similar results can be seen to what was shown previously in the baseline profile. Since both cases had flap noise competing to be the most significant noise source, there is not a significant reduction that occurs due to propagation effects in the revised takeoff profile. These cases can be seen in Figure 4.11. Overall, the cases are both similar to what was seen previously with the baseline profile for the vision vehicle. The fan noise gets a significant noise reduction due to it mostly being high frequency noise.

**Figure 4.10:** Baseline flight profile PNLT time history compared to revised flight profile PNLT time history located at the cutback microphone with propagation effects turned off.
while all other noise sources do not get as significant of a reduction. Flap noise also becomes the most dominant noise source both cases due to the reduction in fan noise.

![Graph showing baseline and revised baseline takeoff profiles with different noise contributions.](image)

**Figure 4.12**: Baseline flight profile PNLT time history compared to revised baseline flight profile PNLT time history located at the cutback microphone with propagation effects turned on.

The sideline microphones are able to show a slightly different story from what is seen in the results for the cutback microphones. The baseline profile is again what was seen previously, but the revised baseline occurs slightly differently, similar to what was seen in the 2020 takeoff profile. Sideline is occurring at full engine power just like before but revised profile is able to reach the same altitude that the baseline profile does at cutback much faster. This changes the shape of the actual profile as it is passing by the sideline microphone, contributing to the difference in shape.

![Graph showing baseline and revised baseline takeoff profiles with different noise contributions.](image)

**Figure 4.11**: Baseline flight profile PNLT time history compared to revised baseline flight profile PNLT time history located at the sideline microphone with propagation effects turned off.
between the two cases. The revised profile also allows the vision vehicle to perform its takeoff maneuver at a much lower velocity from what was seen in the baseline profile, which also contributes to reductions in the airframe noise sources. The sideline profiles for both of these cases have different shapes, which can be seen in Figure 4.12. The fan noise is contributing most significantly for both cases, and the revised baseline profile is occurring over a much larger time range similarly to what was seen previously, but airframe noise sources tend to be a bit lower in the revised baseline profile. The peak PNLT for the revised case is about 83 dB, which is 1 dB lower than the baseline profile’s 84 dB, but the EPNL results are the same with both at 85 EPNdB.

When propagation effects are taken into account for the sideline microphone, there is again a similar result to what was seen previously in the baseline profile, but with a few noise sources that are shifted. The results can be seen in Figure 4.13. Both cases show reductions in fan noise significant enough to allow other noise sources to compete with it, but the main source competing with the fan noise changes across both profiles. In the baseline profile, it was the flap noise whereas in the revised case it is the gear noise. This is because the lower speed of the revised case allows the flap noise to contribute slightly less than what is seen in the baseline profile, but the landing gear stays out longer, which increases its contribution to the system. The engine sources all seem

![Figure 4.13: Baseline flight profile PNLT time history compared to revised baseline flight profile PNLT time history located at the sideline microphone with propagation effects turned on.](image-url)
to contribute similar amounts to each of these cases, which would be expected as both engine settings at this point in the profile are at maximum. The revised profile also still occurs over a larger time period due to its lower speed during its initial takeoff. Both cases have peak PNLT results occurring very closely together at 78 dB, but the EPNL results are slightly different. For the baseline profile, the EPNL is just under 78 EPNdB whereas the revised case’s EPNL is just over 78 EPNdB, making the baseline profile slightly quieter when looking at EPNL. This slightly quieter takeoff is most likely due to the duration of the sideline microphone’s exposure. With both cases having very similar peaks and numerous sources competing to be the largest contributor, the duration would affect the EPNL sufficiently to cause the overall difference between both cases.

**2020 Profile vs. Variants**

In order to help optimize the 2020 profile to see if better options were available, a few variant profiles were created. These variants were created by attempting to slightly vary the engine power settings and flap settings for the vision vehicle in its takeoff maneuver. Across all cases, the velocities remain similar except for the case with a faster climb out. The flight path for each case also are similar, still with the exception of the faster climb out case. With similar velocities, the airframe noise is expected to remain very similar across all cases and the engine noise should change slightly across all the cases due to the variation in engine power at the cutback location. The four profiles discussed in this section are pictured in Figure 4.14.
While looking at the cutback microphone for the variant cases compared to the 2020 profile, the overall differences can be hard to see. Many of the noise components are almost exactly the same across each case because their overall profiles are very similar and this can be seen in Figure 4.15. Each case peaks at about the same PNLT of about 78 dB at the cutback microphone, but more differences become apparent when looking at the EPNL results for each case. The 2020 flight profile had a resulting EPNL of 82 EPNdB, but each of the variant cases are slightly lower at about 81 EPNdB. This difference comes from slight variations that occur over the flight profiles. The fan noise is the most significant noise source for all cases during takeoff. Slight variations in the fan noise caused by changes in engine power settings and distances to the microphones are what is contributing the most to the differences in noise. Each case’s individual PNLT and EPNL for fan noise are close together, with the largest difference being about 0.3 dB for the PNLT and about 0.8

**Figure 4.14**: 2020 flight profile compared to variant flap deployment profiles.
EPNdB for the EPNL. The 2020 profile has the lowest peak PNLT for its fan noise when compared to each case, however despite this it has the highest EPNL result. This could also be potentially due to the fact that the 2020 profile has the highest engine power setting across cutback, although the difference in power between the cases is not significant. The fact that the 2020 profile has the lowest peak PNLT may also be working against it in how the time range over which the EPNL integration is calculated. A lower peak would cause more points in time to be included in the overall calculation of EPNL since all points may be closer to that peak. Despite all these possibilities, the cases are each very similar to one another in the cutback condition with overall differences in the EPNL and PNLT being small.

Figure 4.15: 2020 profile PNLT time history compared to flap deployment variants located at the cutback microphone with propagation effects turned off.
Comparing the PNLT time histories on top of each other helps to provide a better idea of what is occurring throughout all of the variant flight paths. For the first half of the cutback maneuver, it is possible to see the 2020 flight profile is the loudest case among the variants. This is due to the fan noise contributing so much to the noise. The 2020 profile and subsequent variants all have the engine power dropped at the same location and across the same distance for each case, but the 2020 profile specifically has the highest engine power across the full maneuver, leading to it being the loudest case. Once all the engines are throttled back up to full power for the second half of the maneuver, the totals converge to the same point and then proceed to diverge again. The 2020 profile, 10- and 15-degree flap profiles all reach very similar points at the end of the time history, but the 10-degree flap faster climb profile drops below all other cases. This is due to the faster climb profile beginning its final climb out before any of the other profiles.

![Total Noise PNLT Time Histories](image)

**Figure 4.16:** Total noise PNLT time history of flap deployment variants located at the cutback microphone with propagation effects turned off.

When propagation effects are taken into account, the overall results across the cases change due to the fact that the fan noise is affected so significantly by atmospheric absorption. It is possible to see a larger difference between the initial 2020 profile and the variant counterparts as other noise
sources such as the flap and combustion noise become more significant once propagation effects are included. The results for the PNLT time histories can be seen in Figure 4.17. The fan noise begins to look somewhat different in the 2020 case and the flap variants as it starts off a bit lower for the flap variant cases and then eventually reaches a similar peak to what is in the 2020 case. The location of the landing gear being retracted is slightly different between the 2020 case and the variant cases. This causes a decrease in the total noise at the beginning of the path over the cutback microphone in the 2020 profile, which is not seen in each of the other cases, but this decrease has little effect on the total EPNL for the case as well as the peak PNLT values. Across each of these cases, the PNLT and EPNL are still close together similarly to what was seen in the case without

![Figure 4.17](image)

**Figure 4.17:** 2020 profile PNLT time history compared to flap deployment variants located at the cutback microphone with propagation effects turned on.
propagation effects. The largest difference in peak PNLT between the cases is about 0.8 dB and the largest difference between EPNL across all cases is about 0.4 EPNdB.

When comparing the totals of these four profiles with propagation effects, the differences between them are harder to find. The 2020 profile is the quietest profile for a portion of the first half of the time history due to it also having a slightly less significant flap noise contribution to its total noise. The 2020 profile then goes on to rejoin all other profiles at about the 110 second mark. Similar to the cases without propagation effects, the faster climb case is the quietest case by the end of the maneuver. Overall, when propagation effects are taken into account with these four flight paths the cases seem to converge to very similar time histories at cutback. This leads to them all having very similar EPNL values of about 72 EPNdB.

![Total Noise PNLT Time Histories](image)

**Figure 4.18:** Total noise PNLT time history of flap deployment variants located at the cutback microphone with propagation effects turned on.

The sideline microphone for the 2020 profile and variant cases shows very few differences across all of the cases. Each profile provides almost the exact same PNLT time history both with and without propagation effects turned on. Figure 4.19 shows the totals for each case with propagation effects turned on as an example. The slight differences that occur in these flight profiles include small changes in velocity, aircraft angle of attack and small differences in position at this
point in the profile. Across all cases, the largest difference in the maximum PNLT is 0.2 dB and the largest difference in ENPL is 0.1 EPNdB. When comparing each of these variant cases, there is very little in the way of benefits for noise certification because each profile has a very similar set of results. Despite this, each case is able to provide a distinct noise footprint when looking at EPNL contours for each case. This means that while any one of the variants may not provide a significant benefit over the others from a certification standpoint, they may provide a benefit for matters such as community acceptance if the noise produced around takeoff is not as significant.

![Total Noise PNLT Time Histories](image)

**Figure 4.19**: Total noise PNLT time history of flap deployment variants located at the sideline microphone with propagation effects turned on.

When looking at the EPNL contours, it is possible to see differences between each of the variant cases shown previously. The EPNL contours for the 2020 profile and each of the flap variant cases with propagation effects turned on is shown in Figure 4.20. The profiles begin at break release, starting at 0 feet and travels to the right to a maximum of 60,000 feet. The y axis shows the distance from the centerline, going 10,000 feet in both directions. All four of the cases have a very similar start to their profiles. This similarity leads to the beginning of all of the contours (on the left side of the plot) looking very similar as well. Each of the sets of contours begins to change at around the cutback location (denoted by the white line on the plot). After the cutback position the 10- and
15-degree flap deployment cases both look very similar to each other due to the similarities between their two profiles. The 2020 takeoff profile has a few minor differences from the 10- and 15-degree flap deployment profiles in the form of slight differences to its overall footprint at the cutback location and right after that lead it to be slightly quieter overall. The faster climb profile is shown to have the quietest footprint of all the cases. All cases show that after the cutback location their noise increases again somewhat significantly at around the 40,000-foot point. This significant increase is not present in the faster climb profile since it was designed with the intent of having the aircraft climb out as quickly as possible. The significant increase in distance to the microphones allows it to both slightly benefit more during the cutback certification microphone while also providing a benefit overall to its noise footprint during its takeoff maneuver.
Figure 4.20: EPNL contours for the variant takeoff profiles with propagation effects turned on. Cutback location is marked by the white line.
The vision vehicle has three additional approach profiles that were also run, in addition to the takeoff profiles. Two of the profiles are simple 3-degree and 5-degree approach profiles while the third is a profile that transition from a 5-degree approach into a 3-degree approach. A 3-degree approach is what would be considered standard for most aircraft when they are performing their landing maneuver. A 5-degree approach would be much steeper, but should also allow additional noise benefits due to the aircraft both landing quicker and having it further away from any observers that may be present. The 5-degree approach allows the aircraft to spend less time over the approach observer which will allow for quieter results. The 3- to 5-degree transition profile would have the benefit of starting as a much steeper profile to help with noise production while also finishing its approach as a standard approach. Figure 4.21 is a comparison of the three profiles.

The approach cases perform somewhat differently to what was seen previously in the takeoff cases. The approach results without propagation effects can be seen in Figure 4.22. Between each of the profiles, there are many differences between them. The first profile used for simulations with the aircraft was the transition approach case. This case was thought to be potentially helpful
for reducing noise far from the runway due to it starting at a 5-degree approach and maintaining a high speed on approach. This case uses the highest engine power settings throughout its maneuver. The 5-degree approach case has the lowest engine power settings of all cases while the transition case has the highest engine power to help facilitate its higher landing speed. One thing that must be kept in mind with these cases is that despite the fact that there are much larger differences in engine power than what was seen in the takeoff cases, these cases still only have engine power settings below about 25%, which leads to only slight differences in engine noise. Most of the differences in noise for these cases come from the airframe noise sources, which would be expected from an approach case. The 5-degree approach case is the quietest overall due to its distance from the microphone while also using lower engine power to maintain a lower overall speed compared to the transition case. This helps to additionally keep the airframe noise sources quieter overall during landing. The 3-degree approach is able to maintain a similar speed to the 5-degree approach case, but it must maintain a higher engine power setting to do so. The 3-degree glide slope also results in the aircraft being much closer to the approach microphone, which causes the noise from all of its sources to be higher as well. The 5-degree approach case has an EPNL result of about 84 EPNdB while the transition approach manages to be the loudest case with an EPNL of about 90 EPNdB. The 3-degree case is much closer to the transition case with an EPNL of about 89 EPNdB.

Figure 4.22: 2020 profile PNLT time history comparison for approach cases without propagation effects turned on.
The approach cases with propagation effects turned on, shown in Figure 4.23, provide a similar picture to what was seen with the propagation effects turned off, Figure 4.22. Due to the engine power settings being so low across all of these cases, the fan noise is not affected as significantly as was seen in the takeoff cases. The close proximity to the microphone on approach also impact the role of propagation effects, such as atmospheric attenuation. The EPNL results of the cases with propagation effects are almost identical to cases with the propagation effects turned off.

![Figure 4.23: 2020 profile PNLT time history comparison for approach cases with propagation effects turned on.](image)

The EPNL contours shown in Figure 4.24 also help to show the benefits of each flight profile. Similar to what was seen previously with the PNLT time histories, the approach EPNL contours show that the 5-degree approach has the quietest overall footprint and the transition approach has the loudest footprint. This is largely due to the transition approach having a much higher velocity on approach, which leads to the elevated significance of sources such as the flap and landing gear, coupled with the fact that it is about as far away from the microphones as the 3-degree approach. Since the 5-degree approach case is able to land faster than the other two cases, its EPNL contour shows that the noise becomes significant much later than the other two, i.e., it only reaches 90 dB within the final 10,000 of approach. The other two cases are just as loud for almost twice the distance away from touchdown.
Figure 4.244: EPNL contours for the vision vehicle’s approach profiles with propagation effects.
Certification EPNL Predictions

Flight certification is an important part of finalizing the design of an aircraft, and one of the components of certification is to check the noise levels to be sure they are below regulatory values. The vision vehicle results up until this point have shown EPNL contours across the full set of takeoff and approach profile as well as PNLT time histories to show how the individual noise sources contribute to the overall noise of the system. The results for each takeoff flight profile are shown in Table 4-2. Among all takeoff profiles, the 10-degree flap deployment faster climb case is the quietest case with a total EPNL calculation of 150.3 EPNdB (cutback + sideline) on takeoff and the loudest case is the 737-like profile with a total of 162.3 EPNdB. While the 737-like profile is the fastest case as the aircraft travels over the cutback microphone, it is also the closest case, which causes it to have a significantly louder cutback prediction than all other cases.

Table 4-2: Vision Vehicle takeoff EPNL calculations with propagation effects turned on.

<table>
<thead>
<tr>
<th>Flight Profile</th>
<th>Cutback (EPNdB)</th>
<th>Sideline (EPNdB)</th>
<th>Total (EPNdB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020 Profile</td>
<td>72.7</td>
<td>77.9</td>
<td>150.6</td>
</tr>
<tr>
<td>Revised Baseline Flight Profile</td>
<td>81.2</td>
<td>81.1</td>
<td>162.3</td>
</tr>
<tr>
<td>10 Degree Flap Deployment</td>
<td>72.5</td>
<td>78.0</td>
<td>150.5</td>
</tr>
<tr>
<td>15 Degree Flap Deployment</td>
<td>72.7</td>
<td>78.0</td>
<td>150.7</td>
</tr>
<tr>
<td>10 Degree Flap Deployment Faster Climb</td>
<td>72.3</td>
<td>78.0</td>
<td>150.3</td>
</tr>
</tbody>
</table>
The three approach cases for the vision vehicle are shown in Table 4-3. The loudest case is the transition approach case with the three-degree approach case being slightly quieter. The two profiles look similar as the aircraft reaches the approach microphone, but the transition approach case has the aircraft travelling slightly faster. This in turn increases the significant airframe noise sources slightly, which leads to its slight increase in EPNL. The quietest case was the five-degree approach case due to the aircraft’s steep approach angle, which allows for a much faster and quieter approach.

**Table 4-3:** Vision Vehicle approach EPNL calculations with propagation effects turned on.

<table>
<thead>
<tr>
<th>Flight Profile</th>
<th>EPNL (EPNdB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Degree Approach</td>
<td>88.4</td>
</tr>
<tr>
<td>5 Degree Approach</td>
<td>83.9</td>
</tr>
<tr>
<td>Transition Approach</td>
<td>90.0</td>
</tr>
</tbody>
</table>

**Analysis**

When looking at the results for this aircraft, it is important to look at all flight configurations to see if any have an unusual result or if any of the cases stand out in some unique way. For the vision vehicle in all cases the fan noise is typically either the loudest noise source or it is contributing almost as significantly as the loudest source. This becomes much more apparent when propagation effects are turned on, which help reduce the fan noise across many of the cases. When looking at the cases with propagation effects turned on, the flap noise contributed by the aft element becomes much more significant. This was an expected result since both the aircraft’s design was thought to cause airframe noise sources such as flap noise to contribute more
significantly to the overall noise as well as the 737-800 demonstration case showing that under certain circumstances the flap noise can exceed all other noise sources.

The vision vehicle’s standard flight configuration would most likely be its original set of flight paths, which were the 2020 profile for takeoff and 3-degree approach profile. Using these two profiles together is a useful way to get an estimate for what the potential cumulative EPNL of the aircraft would be for certification. Looking at these two cases, the cumulative EPNL is 238.6 EPNdB, which would put it about 32 EPNdB below Stage 4 requirements with the largest contribution of 88.4 EPNdB coming from approach. The cumulative EPNL requirement for this aircraft does not meet the goals set by NASA for far term aircraft design of 42-52 dB below Stage 4 requirements. A steeper approach angle of 5 degrees instead would reduce the noise from 88.4 EPNdB to 83.9 EPNdB, which would bring the cumulative total down to 234.1 EPNdB. This result brings the aircraft to 36 EPNdB below Stage 4 requirements, which puts it in the mid-term goals category.

Despite being noisier than NASA’s goals, there are some key features of the aircraft and these predictions that must be kept in mind. While ANOPP’s prediction method is a good estimate for many aircraft, there are some things that it is not taking into account. Specific to this aircraft, some of the things it cannot take into account are the slot between the fore and aft element of the wing as well as the large sections of laminar flow. To help with this, the fore element was treated as the main wing while the aft element was treated as a simple flap system, which is how it is intended to operate on the final aircraft design. One of the more significant features of the aircraft is how the wing performs. The wing’s fore element is fully laminar, while the aft element is 71% laminar. This means that noise from the wing and flap would most likely be lower than the predictions. While reductions in noise form the fore element would not be significant in most cases, the reductions this causes to the aft element would be very significant. This is due to the aft element noise being a leading contributor in both the cutback and approach configurations. ANOPP does
not allow for airframe noise predictions to be specified as “laminar” or “turbulent” but rather as “clean” or “dirty”. While this it is still important to specify if the aircraft is in a clean or dirty setup, in the methods used it just shifts the results based on the input. Another significant contributor is the fan noise for all cases. This could potentially see a further reduction for all cases due to the fact that it is most likely being slightly over predicted from the engine not being represented 100% accurately. The overall representation of the engine for this aircraft is close, but there is still little information available on N+3 technology level engines in the form of simulations at varying power settings, Mach number and altitudes. More engine simulations across a large range of power settings and Mach numbers would lead to better predictions, which should lead to quieter engine noise results for this aircraft across all flight configurations. On top of needing better representation for the engine, not every source of noise reduction is taken into account in this simulation. Many of the more significant sources of noise reduction are taken into account such as engine liners, chevrons, and better blade design, but there could still be further advances in technology that help reduce engine noise.
Chapter 5

Conclusions

Noise predictions for a future aircraft design with N+3 level technologies were presented in this thesis. The original design for the aircraft was based on the Phase 2 SUGAR reports [9] and has changed over the course of the project as redesigns helped improve the overall performance. The overall goals of the project were to measure the noise produced by the aircraft using its unique design and N+3 technology and to quantify any benefits it may have because of its design choices. Analysis of the SNLF airfoil design was first conducted using the semi-empirical method produced by Brooks, Pope and Marcolini. Slight changes were made to the method to instead directly put in boundary layer parameters for a more accurate estimate of the noise as opposed to relying on the included method for predicting boundary layer parameters. The primary way of predicting aircraft system noise was using NASA’s ANOPP code to run simulations of the aircraft. The vision vehicle case was run alongside NASA’s included Boeing 737-800 demonstration case to be sure that the predictions were accurate enough with the limited information used in this study. Predictions for each aircraft component across multiple flight paths in both the takeoff and approach configuration were conducted to see, which source would be the most significant and how the N+3 technology and aircraft design would help reduce noise when compared to a modern aircraft.

Research Summary

The main goal of this project was to perform simulations to predict the noise from the vision vehicle while quantifying noise benefits from the N+3 technology used in the design. The cumulative EPNL for the aircraft in its "standard" case was found to be about 239 EPNdB, which puts it 32 dB below Stage 4 noise requirements. This result is quieter than any similarly sized
aircraft currently available. The engine was able to provide noise benefits across all of its component noise sources from the N+3 technology, although fan noise still remains the largest contributor to the noise on both takeoff and approach for this aircraft. Flap noise is also considered to be an important source of noise as well with it being almost as significant as fan noise. The prediction methods used in ANOPP are good for predicting noise on modern aircraft, but many sources of noise could be modeled better using more advanced or up-to-date methods of noise prediction to account for some of the newer technology in sources such as the wing design or the fan. The aircraft does not meet NASA’s goals for far term aircraft being 42-52 dB less than Stage 4 requirements (271 EPNdB), but additional advancements in noise reduction technology will help bring the aircraft closer to the goal.

**Recommendations for Future Work**

Over the course of the project, the overall design for the aircraft changed multiple times. These changes in overall design impacted the aircraft as well as some of the goals. As the design changed, so did the noise analysis of the aircraft to fit any new parameters that came along with it. Many of the changes that occurred on the project came from the unique design of the wing and airfoil. As simulations of the wing and different airfoils used on the project were conducted, the wing became more and more capable than what was previously projected.

**Active Flow Control Noise**

One of the first things to change about the aircraft was the use of active flow control (AFC) devices on the wings to help maintain laminar flow. Part way through the project, it was determined that the airfoil was designed in such a way that AFC devices would be unnecessary as the fore
element would be completely laminar without them. Since they were determined to be unnecessary, they were not included in the noise analysis for the aircraft. While they were ignored, they are still a technology, which may become more common on future aircraft designs if future wing designs rely more on laminar flow such as on this aircraft. The project primarily used ANOPP as a method for noise prediction, and at the time of this project ANOPP is not capable of predicting the noise from AFC devices. In order to determine their contribution, it was thought that they could be approximated as a distribution of dipole sources along the wing with the noise prediction likely being performed in a different program. The contribution could then be added to the ANOPP results to see how significant their overall contribution would be to the system. In future work, this idea could be developed into a noise prediction tool.

**LES Simulations**

Another potential source of noise on the project is from the interaction between the fore and aft elements of the airfoil in the slot between them. There was originally a plan early in the project to run LES simulations of the wing to see what would happen in the slot of the airfoil. These LES calculations could then be used to obtain accurate noise predictions from both the fore and aft element of the wing as well as the slot interactions. The wing was approximated to so that the fore element was treated as the main wing and the aft element was treated as the flap during simulations. While this will still give a good estimate of the noise produced by it, it will still lack any noise generated by sources that cannot be predicted using empirical methods based on contemporary wing designs. The noise predictions will lack full accuracy since many empirical methods assume the flow is mostly turbulent to produce noise, whereas the actual wing is mostly laminar with only a small amount of turbulence overall. The simulation also treats the wing and flap as separate entities in this case as well, which means it will not predict additional noise produced by the
interaction in the slot. Unsteady LES simulations of the wing in a takeoff and approach configuration could help to predict all sources of noise more accurately from the wing, which would help give a more accurate picture of the potential benefits of the system, or drawbacks from more unknown sources such as the slot.

**Recommendation for Future Aircraft Design**

Care must be taken when designing an aircraft to reduce noise. NASA’s ARMD guidelines have set the far term goal for aircraft noise at an optimal 52 dB below Stage 4 requirements. To help reach these goals, key sources of aircraft noise must be reduced such as the fan noise, flap noise and landing gear noise.

Many modern aircraft use engine liners to help reduce sources such as fan noise, but technology exists to help further reduce it. The Advanced Noise Control Fan (ANCF) testbed [42] at NASA was designed to help develop technology that would further reduce fan noise. Some of its initial tests included developing active noise control systems to create destructive interference, and while it would be a useful method to reduce noise it is an extremely complex system that requires microphones and actuators to help monitor and then cancel the noise within the fan duct [43]. An easier way of reducing fan noise is to change the way the blades are designed. One method of doing this is with through the use of Trailing Edge Rotor Blowing (TERB) technology [44,45]. Redesigning the trailing edges of rotor blades to have a serrated or wavy edge can also achieve similar results to a TERB system. Further fan noise reductions can occur from redesigning the stator blades. They can be given a partially porous surface along with internal resonant chambers to help passively reduce noise.

Airframe noise sources are most significant on approach for modern aircraft, making up almost as much noise as engine noise sources. The key sources during landing are the flap and flap
side-edge noise as well as landing gear noise. Multiple advancements in recent years [46-48] have allowed for quieter flap noise while minimally impacting performance. Some of the technologies are simple such as adding specific acoustic liners to the flaps to help reduce noise or changing the skin into a porous surface. A more complicated method of reducing flap side-edge noise is to cover the edge in small fins to help or by connecting a flexible link from the flap side edge to the main wing.

Landing gear noise is the next most significant source of airframe noise after flap noise on approach. It remains a challenging source of noise to reduce due to a lack of concepts caused by design restrictions for aircraft as well as certification requirements [49]. Most of the noise produced by landing gear is bluff body noise produced by the complex undercarriage structures. To help reduce these sources, many of the noise reduction technologies developed for landing gear include fairings and covers to help reduce cove noise caused by the internal structures of the gear. Additionally, there are approaches that include complete redesigns for the landing gear to help reduce the unsteady flow found around the components [47-50], which will lead to significant noise reduction.

Jet noise is regularly considered one of the more important sources of engine noise on takeoff. Jet noise has had technologies created to help reduce it in the past such as the introduction of chevrons, but additional advancements have been made to help further reduce its contribution. To help augment the noise benefits of chevrons, recent studies into the addition of piezoelectric materials to chevrons have been conducted [51]. Piezoelectric materials can allow chevrons to take a more active role in noise reduction through excitation. This kind of a system with chevrons could allow for an additional reduction of up to two dB. Another source of noise reduction currently being considered is the addition of an ejector to the jet flow [52]. The ejector would work to help reduce the speed of the flow coming from the jet, which would help to cause significant noise reductions.
Experiments using this method so far have yet to yield significant results, but successful tests would yield significant noise reductions in jet noise.

One of the best ways to decrease the noise produced by an aircraft while also having no impact on performance is to focus on attenuation. Many developments have been made to help reduce aircraft noise and more will be made in the future, but each involves changing the aircraft in some way such as adding porous structures or changing the shape of a lifting surface, which will have impacts on performance, even if they are only slight. A way to have zero impact on performance while still reducing noise is to have the aircraft itself be further away from any observers. As engine technology improves and takeoffs become shorter and faster, this becomes an easier way to reduce noise by a few decibels without changing anything about the design. Noise abatement procedures can also be developed for any aircraft by slightly altering what the aircraft does during its maneuvers such as changing its speed or changing engine power at key points in the flight path.
Appendix

BPM Additional Cases

The cases that appear in Chapter 3 are used to show more significant trends in the data. The additional cases show slight changes due to a 2-degree incremental increase in angle of attack. The increase in noise from the increase in angle of attack occurs as expected across each of the cases. Each increment shows slight increases in noise due to the separation noise component of the TBL-TE. The aft element is also always the more significant contributor across all cases. The

Figure A.1: S204 Airfoil noise spectrum comparison between Case 1 and Case 2 at 0 degrees Angle of Attack.
LBL-VS noise component from the fore element first occurs at 4 degrees angle of attack. This noise component does not become significant as a source until 8 degrees, which was shown previously.

**Figure A.2**: S204 Airfoil noise spectrum comparison between Case 1 and Case 2 at 2 degrees Angle of Attack.
Figure A.3: S204 Airfoil noise spectrum comparison between Case 1 and Case 2 at 4 degrees Angle of Attack.
Figure A.4: S204 Airfoil noise spectrum comparison between Case 1 and Case 2 at 6 degrees Angle of Attack.
Figure A.5: S204 Airfoil noise spectrum comparison between Case 1 and Case 2 at 8 degrees Angle of Attack.
EPNL values are useful when a single number for noise is required at a specific point, such as a certification microphone during an aircraft’s takeoff or approach. One of the drawbacks is that since EPNL is an integrated result at a single point over some interval of time it is hard to see how the noise changes over time at that point. A way to help with this is by looking at PNLT time histories at specific points. The PNLT results from an aircraft show an instantaneous result for noise, which allows people to see more easily how the sound at one single point changes. Since the

Figure A.6: S204 Airfoil noise spectrum comparison between Case 1 and Case 2 at 10 degrees Angle of Attack.
EPNL is an integrated result based on PNLT, looking at the time histories is also a useful way of validating whether or not the EPNL result is correct. EPNL is a value calculated through a summation of the PNLT results ranging from the peak value to 10 dB below the peak value. This means that if a microphone is unable to capture the noise fully within this range, it is most likely not providing an accurate result for any calculated EPNL value. For most flight profiles, this is not a concern, but in the event the flight profile is very short, such as the transition case used on this project, verifying the EPNL result by looking at the PNLT time histories is useful to get an idea for what noise components may be inaccurate.

The three-degree approach case for the vision vehicle shows an example of what the PNLT time histories should look like for an aircraft on approach in Figure A.7. Close to the runway at 0 feet the key sources include the fan noise from the engine and the flap and gear noise. These results are consistent with what was seen previously. As the aircraft gets further from the runway, it is possible to see that the peak becomes less extreme while the significance of each individual noise source remains the same with fan noise as the most significant source and flap and gear noise competing for the second most significant source. These PNLT time histories do not contain new information that has not been seen before, but they are useful to help validate the accuracy of EPNL values based on the available PNLT time histories.
When looking at the PNLT time histories for the three-degree approach that are spaced 2000 feet from the centerline, the results change slightly as shown in Figure A.8. Since the microphones are now offset from the centerline, different directivities are used for each of the sources and will changes which noise source becomes the most significant. As the aircraft
approaches 0 feet, the landing gear becomes much more significant than the flap noise that was seen in the previous case along the centerline. Another key piece of information to observe is how the time history looks at 0 feet. Unlike the previous case, the 0-foot location is not where the aircraft lands, this case has an offset of 2000 feet to the side of the aircraft. This means that there is some travel time between when the sound is emitted and when it is received, unlike in the previous case.

**Figure A.8:** Vision Vehicle PNLT time histories using the 3-degree approach profile 2000 feet offset from the centerline.
where it would have been nearly instant. This leads to a strange result where the noise suddenly
drops off significantly at the 0-foot microphone instead of being a much more gradual decrease,
which can be seen at every other location. This steep decrease is most likely a byproduct of how
ANOPP calculates the noise from a source at the end of the flight profile. For this specific case, the
end result is not a very significant difference when using the PNLT to calculate EPNL, however in
other cases where the drop is more significant could lead to inaccuracies in the result caused by a
lack of information needed.

When looking at microphones set 5000 feet from the centerline, this type of result becomes
more significant, as the drop in PNLT starts to affect multiple microphones. The overall results are
similar to what is seen in the 2000-foot off centerline case with landing gear noise becoming more
significant than the flap noise, but the sudden drop off in noise is now affecting both the microphone
in line with the runway and the microphone 4000 feet before the runway.

Both of these PNLT time histories can be used to understand how a case should properly
be set up in ANOPP when looking at noise over a large area. Noise directly under the centerline of
an aircraft in a case similar to this should not have inaccuracies or issues since the profile is long
e enough to give the ANOPP simulation enough time to predict the noise travelling to the observers.
As the observers are located further from the centerline, additional time will be needed to get an
accurate prediction of the noise. In the middle of the profile, this will most likely not be an issue,
but closer to the end of the profile, this can lead to issues such as those seen in Figures 0.8 and 0.9
close to 0 feet. A way to help fix this would be to artificially increase the duration of the simulation,
which would give ANOPP additional time to calculate the noise that the points closer to the end of
the profile that the user cares about. This can be done by adding in more distance for the aircraft to
tavel after it has landed. A flight segment where the aircraft is “taxiing” by moving at a slower
speed with less engine power would give the program additional time when predicting PNLT at
microphones that are further away as well as provide more accurate EPNL predictions from the results.

When looking at PNLT time histories, adding additional time for the simulation to continue may not solve the problems. An example of this is looking at the transition approach profile for the vision vehicle shown in Figure A.10. The centerline results close to landing show similar results to what was seen in the three-degree approach case in Figure A.7, but the graph at
−28000 feet shows strange results. The graph begins nearly at a peak and continues to decrease after the 5 second point. While just looking at PNLT time histories, this result is not of much concern, but if the PNLT time history is then used to calculate EPNL, the result would not be fully accurate since it cannot get a full 10 dB down range to calculate from. This problem is caused by the fact that the transition approach profile begins at −29000 feet, while the first microphone is placed at −28000 feet. Since the aircraft begins so close to the microphone, the simulation does not

Figure A.10: Vision Vehicle PNLT time histories using the transition approach profile along the centerline.
have enough time to calculate a full PNLT time history that would accurately predict EPNL. At the
−24000-foot microphone, the PNLT time history predicted would be sufficient for an accurate
EPNL calculation, which shows that the potential maximum distance for accurate EPNL calculation
occurs between −28000 and −24000 feet. This is a problem that is not as easily fixed as the previous
one since extending the flight profile to start further back may not always be an option. In the event
that the flight profile is being simulated externally, it may be best to restart the simulation from
further back to get an accurate profile with a longer travel distance. If a simulation is not possible,
simply extending it may lead to an inaccurate profile for what the aircraft either is capable of or
would do in that situation. Another solution to this problem is to not predict EPNL unless it is
within a region where the results will be accurate. The problem that comes from this solution is
when the results are compared with other cases that are capable of accurately predicting EPNL in
a larger region. A fair comparison between different cases would require the area of EPNL being
predicted to be about the same, which means longer flight profiles will have part of their results cut
out, which may not show the full picture.

Looking at the transition approach case with offset microphones in Figure A.11 shows
similar results to what was seen previously with the three-degree approach case. Landing gear noise
becomes more significant than flap noise as the microphones are further offset and fan noise is still
the most significant source at each microphone. The transition approach case also encounters a
similar noise drop off at the 0-foot microphone similarly to what was seen in the 3-degree approach
case. When looking at the 5000-foot offset case in Figure A.12, the results are more extreme at the
beginning and end of the profile. Similar to what is seen in both previous transition approach cases,
the PNLT contours do not have a full 10 dB down range at −28000 feet, but with the 5000-foot
offset case, this region expands to the −24000-foot microphone as well. This means the observers
that are particularly far away from the aircraft may not predict fully accurate EPNL results when
looking at the contours. When predicting EPNL, the distance to the observers and their ability to get enough noise for a full PNLT calculation should be kept in mind.

Figure A.11: Vision Vehicle PNLT time histories using the transition approach profile offset 2000 feet from the centerline.

The 5-degree approach case travels a much further distance than the transition approach, similar to what was seen in the 3-degree approach. The microphones placed along its centerline can be seen in Figure A.13. Due to the much sharper angle that the aircraft approaches at, the noise is
much quieter for all microphones during this maneuver. The noise sources are of similar importance to what was seen in the previous two cases along the centerline. As the observers get further away from the 0-foot observer the sound drops off much faster than what was seen in any of the previous cases, including the offset microphones. On top of being further away from any of the microphones on approach, the 5-degree approach case also has the lowest engine power setting of all cases.

**Figure A.13:** Vision Vehicle PNLT time histories using the 5-degree approach profile along the centerline.
which helps to provide an additional noise benefit for the fan noise, which was the most significant source in all cases.

The 2000-foot offset case for the 5-degree approach case is similar to both cases seen before. Figure A.14 shows the results, and it is possible to see that similar to both previous cases fan noise is still the most significant source, followed by flap noise until the aircraft gets closer to the runway, at which point the landing gear noise overtakes the flap noise. A major difference between the 5-degree approach case at the 2000-foot offset microphones and the previous cases is that the only significant noise sources are for the fan noise, flap noise and gear noise. No other noise sources are loud enough to appear on the graphs. In both previous 2000-foot offset cases, other noise sources such as the core noise or noise from the wing would appear until the 0-foot microphone, where they would be too quiet. This change in noise is due to the change in directivity as seen in both previous cases combined with the much steeper angle of approach. This steeper angle causes the aircraft to be further from all other observers, which gives atmospheric attenuation additional time to reduce the noise coming from the different sources.
The 5000-foot offset case for the 5-degree approach case seen in Figure A.15 is similar to what was seen previously in both other approach profiles. Fan noise is the most significant noise source until the gear noise attempts to overtake it close to landing at 0 feet. The core noise and wing noise sources appear on the graph, but are not significant enough to make any contributions to the total noise, while other sources do not appear at all. One of the key differences with the core noise

**Figure A.14**: Vision Vehicle PNLT time histories using the 5-degree approach profile 2000 feet offset from the centerline.
in this case is that it is very insignificant compared to other sources. Previously in the transition case in Figure A.12 the core and wing noise were much more significant than they appear in the 5-degree case when the aircraft was still far from the runway. In the 3-degree approach case shown in Figure A.9, the core noise was significant enough to be on the same level as the flap noise while the aircraft was far from the runway as well. This is no longer the case due to the increased distance between the aircraft and the microphones in the 5-degree approach. Atmospheric attenuation is able

**Figure A.15:** Vision Vehicle PNLT time histories using the 5-degree approach profile 5000 feet offset from the centerline.
to affect the noise for a longer time further reducing the amount of noise they produce. In addition to having attenuation act longer, engine noise sources tend to be higher frequency noise sources, whereas airframe noise sources tend to be lower frequency noise sources. This additional factor causes attenuation to be more significant to the engine noise sources than to the airframe noise sources as it affects them more over longer distances. This can be seen in Figure A.5 with how the fan noise changes over time compared to both the flap noise and the gear noise. Fan noise is consistently either the loudest source, or it is almost the loudest source followed by either flap noise or gear noise. Once the gear noise is able to develop fully, it does not change significantly as the aircraft lands, but the fan noise continues to decrease over the course of the rest of the maneuver.

**Takeoff Centerline PNLT Time Histories**

The takeoff cases have additional PNLT time histories along the centerline similar to what was done with the approach cases. Unlike the approach cases, cases that were offset off of the centerline were not calculated. This is due to the nature of the takeoff cases compared to the approach cases. Each takeoff case is longer than the approach cases, which helps with giving observers enough time to accurately predict EPNL. The only microphones that would not have enough time to gather enough PNLT data to predict EPNL completely accurately are microphones that are in line but offset from the aircraft at the start of the runway. This is due to the profiles beginning at break release and a way to fix this would be to create a profile where the aircraft idles for a time before beginning takeoff, however this may not be as easily done in ANOPP due to the way it reads flight profiles. ANOPP reads in and creates profiles using differences in distances and velocities and then calculates the time it takes to do the maneuver itself, which makes creating a profile with an idling aircraft possible, but it could yield strange results.
The 2020 flight profile shown in Figure A.16 helps give an idea for how important noise sources can change over large distances during takeoff. Between the 8000-foot and 24000-foot microphones, the noise behaves similarly to what was seen in previous cases at the cutback microphone for the aircraft when propagation effects are turned on. The fan noise is about as much as the flap noise and core noise is a significant source as well. The more unique cases for this set of microphones occurs after the 24000-foot microphone. From 32000 feet on, the flap noise becomes the most significant contributor, and it is significant enough that other noise sources contribute little to the overall noise of the aircraft. At 64000 and 72000 feet, the noise coming from the aircraft on the graphs is almost exclusively made up of flap noise and wing noise, with almost

**Figure A.16:** Vision Vehicle PNLT time histories using the 2020 flight profile along the centerline.
nothing coming from engine noise sources. This is due to attenuation, similar to what occurred previously in the approach cases when the microphones were far from the aircraft. Since attenuation has a greater effect on sources of high frequency noise, engine noise sources tend to be affected more significantly, causing larger reductions in engine noise at distant observers. Airframe noise sources tend to be lower frequency noise sources, which allows their noise to travel further with less impact from attenuation.

Figure A.17: Vision Vehicle PNLT time histories using the 10-degree flap deployment profile along the centerline.

A similar case is shown in Figure A.17 of the 10-degree flap deployment profile. The overall shape and velocity of this profile and the 2020 profile are very similar, but they have small differences in things such as engine power settings, angle of attack and flap deployment angle. This
similarity in profile causes PNLT time histories for this case and the 2020 case are both very close to each other. It is possible to see similar behavior between the two cases, where the fan noise starts off as being dominant while it slowly transitions to flap noise being most significant as the microphones go further down range.

Figure A.18: Vision Vehicle PNLT time histories using the 15-degree flap deployment profile along the centerline.

The 15-degree flap deployment profile is another profile that is similar to both the 2020 profile and the 10-degree flap deployment profile. It has slight differences in parameters, similar to the differences between the 2020 profile and 10-degree flap deployment profile. Since the differences are only slight, the PNLT time histories shown in Figure A.18 are again similar to what
was seen before. The case follows a similar flight path and speed, which leads to many of the noise sources being close to what was seen at the previous cases’ microphones.

The first profile that is significantly different from the 2020 profile is the 10-degree flap deployment faster climb flight profile and the PNLT time histories for this profile can be seen in Figure A.19. This profile is more unique than the previous three with its faster climb out and slower speed. The beginning of the profile is very similar to what was seen in the past three cases matching both position and speed closely with slight variations to its parameters, but this profile does not get fully up to the same speed as the previous three profiles and it begins its final climb out much faster. One thing to note about this profile is it stops short compared to other profiles, which leads to the
sudden end of the PNLT time history at the 72000-foot microphone. This early stop in the profile is due to the aircraft reaching an altitude of 10000 feet, which is where all other profiles stop as well. These changes in the profile lead to much different results at the microphones that are further out from break release. The beginning of the profile is almost identical to the 10-degree flap deployment case, but the later microphones are quieter than what was seen previously and their time histories have the noise spread out over a larger time range than what was seen in previous cases as well. This spreading of the PNLT time history comes from the increased distance between the aircraft and the observer and can be seen in previous cases such as the 737-800 profile at cutback compared to the 2020 profile.

The last set of PNLT time histories is for the 737-like takeoff profile in Figure A.20. The profile itself is similar to the 737-800 takeoff profile, except it was designed with the capabilities of the vision vehicle in mind. This profile gets up to speed before the previous profiles, but its initial climb is not as significant, which places the aircraft closer to many of the earlier observers. Since the aircraft is closer to many of the observers, the PNLT time histories are also much louder than all previous cases. Many of the key sources are also different from what was seen previously. Fan noise is still a significant contributor for the first two microphones, but jet noise is now also contributing much more than what it did in the other takeoff profiles. Fan noise also drops off significantly by the 24000-foot microphone, which causes the flap noise to be the most significant noise source sooner than other profiles. The later microphones do show some similarities to previous cases with the airframe noise sources contributing most significantly to the total noise with engine noise sources contributing very little overall. Many of the time intervals along the x-axis are shorter to help provide additional details for the 737-like profile. One thing to note because of this is that the PNLT time histories are over shorter spans of time since the aircraft is closer to the microphone for many of them. This is the opposite of what was seen in the faster climb case.
where many of the PNLT time histories were quieter and spanned a much longer time period, which was caused by the increased distance between the aircraft and the microphones.

**Figure A.20:** Vision Vehicle PNLT time histories using the 737-like profile along the centerline.
References


