Project 043 Noise Power Distance Re-Evaluation

Georgia Institute of Technology

Project Lead Investigator

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Investigation Team

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Project Overview

The standard technique for evaluating noise from flight procedures is through Noise Power Distance (NPD) relationships. Noise calculations in the Aviation Environmental Design Tool (AEDT) rely on NPD curves derived from aircraft certification data. This dataset reflects representative aircraft families at set power levels and aircraft configurations. Noise levels are obtained as a function of observer distance via spherical spreading through a standard atmosphere. Other correction factors are applied to obtain the desired sound field metrics at the location of the receiver. The current NPD model does not take into account the aircraft configuration (e.g., flap settings) or alternative flight procedures being implemented. This is important as the noise characteristics of an aircraft depend on thrust, aircraft speed and airframe configuration, among other contributing factors such as ambient conditions. The outcome of this research will be a suggested NPD + configuration (NPDC) format that enables more accurate noise prediction due to aircraft configuration and speed changes.

Georgia Tech will leverage domain expertise in aircraft and engine design and analysis to evaluate gaps in the current NPD curve generation and subsequent prediction process as it relates to fleet noise prediction changes from aircraft configuration and approach speed. The team will use EDS physics based modeling capabilities to conduct a sensitivity analysis to identify additional parameters to be included in the NPDC (NPD + Configuration) curve format. The team will also seek out airport noise measurements to assess the increased accuracy of the developed NPDC format.

Task 1: Perform Sensitivity Study on NPD Curve Generation and Prediction

Objectives

The first task involves the identification of parameters for possible inclusion into the NPDC curves that will be generated in Task 2. Georgia Tech will apply its prior expertise in conducting statistical analyses of the impact of vehicle design and operations on fleet noise and NPDs to determine the number of additional dimensions required to sufficiently capture the impact of aircraft configuration and operational changes on vehicle noise. Sensitivities will be performed both at the NPD and SEL contour area levels to properly frame the problem at the fleet/AEDT analysis level.

Research Approach

In order to accomplish these tasks, the research will be broken down into three distinct research phases. The first phase of research is the generation of aircraft Noise-Power-Distance (NPD) curves. At first, these curves will be generated for a single vehicle with various input parameters. The NPD curves for this aircraft will then be analyzed to determine the sensitivity of the magnitudes of the NPD tables to various configuration parameters. The sensitivity analysis will also provide insight on if (and how) interpolation/regression can be used to minimize the number of required NPD generation runs for each vehicle class being investigated. The final research phase of this task is to generate NPD supersets for each vehicle class that can be used in subsequent tasks.

ANOPP NPD Generation

The first phase of research for this task is to generate the vehicle-level NPD curves using non-standard configurations for various vehicle class models. Georgia Tech used the Environmental Design Space (EDS) to generate the aircraft vehicle models. Georgia Tech utilized NASA's Aircraft Noise Prediction Program (ANOPP) to simulate the noise generated and observed by the aircraft. ANOPP has the capability to generate NPD tables (which can be plotted to produce NPD curves) for a specific aircraft model. NPD tables include four noise metrics (as a function of power setting and altitude): sound exposure level (SEL); effective perceived noise level (EPNL); maximum A-weighted sound pressure level (max SPL); and maximum tone-corrected perceived noise level (max PNLT). The input variables in the NPD prediction method include airframe geometry, engine geometry and performance, aerodynamic performance, flight path and configuration parameters.

In this study, Georgia Tech is tasked with assessing configuration specific NPD curves. Due to the fact that AEDT/INM currently requires specific standard settings for NPD generation, ANOPP's NPD prediction module has corresponding pre-set defaults for many of the flight path and configuration parameters. It is necessary to alter ANOPP to account for non-standard configuration settings. This includes flap deployment angle, slat deployment angle, landing gear setting, and flight velocity. Flap/slat deployment angles and landing gear settings are classified as configuration parameters while aircraft flight velocity is a flight path parameter. However, for the sake of simplicity, flight velocity will also be referred to as a configuration parameter in this report. This is required because as the flight velocity changes, the source noise levels will also change drastically—not only at the flight points in the NPD prediction module. Once the parameters to be altered are identified in the ANOPP model, a new set of flight path library files must be generated for each configuration (using a separate ANOPP module). These flight path library files are then leveraged by source prediction and propagation modules that comprise the rest of the ANOPP model to generate NPD curves for the aircraft. This process is repeated for each distinct configuration of the aircraft model used in the sensitivity analysis. The results of the sensitivity analysis will then determine the number of executions of ANOPP are necessary for the NPD superset generation for each vehicle class being assessed.

NPD Sensitivity Analysis

Sensitivity analysis is performed to determine the effect that each configuration parameter has on the sound exposure level (SEL) generated by the vehicle at a given distance. Future revisions will include sensitivity studies of EPNL, Max A-Weighted SPL, and Max PNLT metrics. To perform the sensitivity analysis, ANOPP is used to generate NPD curves for the

150 passenger class (150pax) vehicle model by sweeping through a range of flap angles, slat angles and speeds for both the gear up and gear down configurations. The 150pax model is used as the baseline vehicle to indicate sensitivity to these factors because the model has gone through extensive calibration and verification in previous studies to emulate the performance a Boeing 737-800. It is important to note that a sensitivity analysis of each vehicle can be time consuming due to program set up and run times; however, the trends are expected to be similar across different vehicle size classes. These results will be used to infer sensitivity of SEL to configuration parameters for other vehicle size classes.

Ultimately, ANOPP data will be used to interpolate noise level with respect to configuration parameters. To avoid extrapolation, the maximum possible ranges of each configuration parameter are considered.

Variable	Min	Baseline	Max	Units
Flap angle	0	15	30	deg
Slat angle	0	10	30	deg
Speed	130	160	200	kts

Table 1. Variable ranges for sensitivity analysis

Table 1 shows the ranges of values considered for each configuration parameter. It is important to note that the flap and slat angle values tested in this study correspond to the actual angles of the devices on the vehicle, not the flap setting that a pilot sets. The mapping of flap setting set by the pilot to the actual flap and slat angle of the vehicle is vehicle dependent and not relevant to the goal of this study, but could be included in future work. Each variable sweep is performed individually with other remaining parameters held fixed at their baseline values. Flap angles are modified in 5 degree increments while speed is varied in ~12 knot increments.

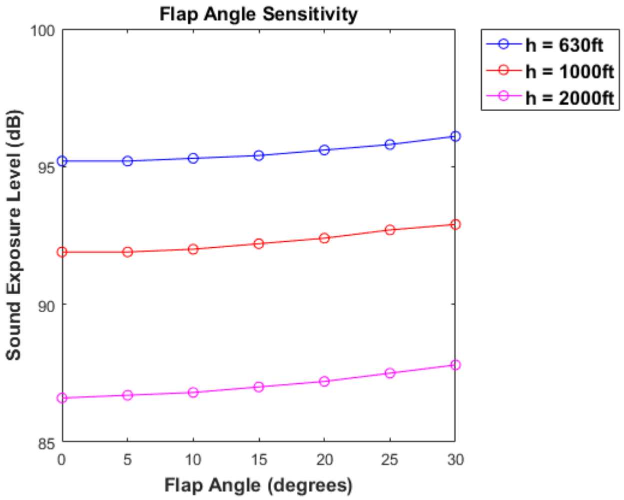

Figure 1. Sound Exposure Level vs. flap angle

Figure 1 shows a sweep of SEL vs. flap angle at various aircraft heights, *h*. Ten different height settings are examined to evaluate the sensitivity of SEL to flap angle (only three were selected for clarity). Flap angle has a significant impact on SEL. Figure 1 shows a portion of the flight envelope at lower altitudes. The sensitivity approaches a 4 dB difference as the flight conditions change to higher altitudes and different thrust settings.

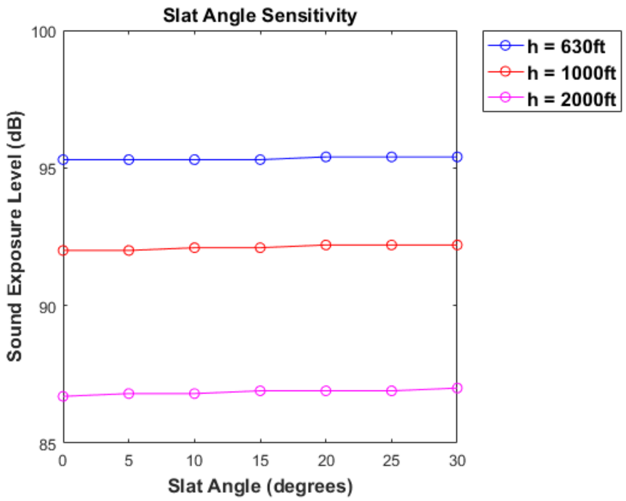

Figure 2. Sound Exposure Level vs. slat angle

Figure 2 shows a sweep of SEL versus slat angles at various aircraft heights. It is observed that slat angle has negligible impact on SEL. The change in SEL over the entire range of flap angles tested is on the order of 0.5 dB, which is likely within modeling uncertainties. The insignificant contribution of slat angle to noise level provides an opportunity to reduce the dimensionality of the problem by removing it as an independent variable. Instead, it is possible to tie the slat angle setting to the flap angle setting. This is also practical because pilots generally do not set slat angles independently of flap angles; they are both tied to flap setting based on a predetermined schedule that is different for each vehicle type. In this study, slat angles are dependent on flap settings. This reduces the number of dimensions that must be interpolated within AEDT while also reducing the number of grid point evaluations needed to accurately obtain the final results.

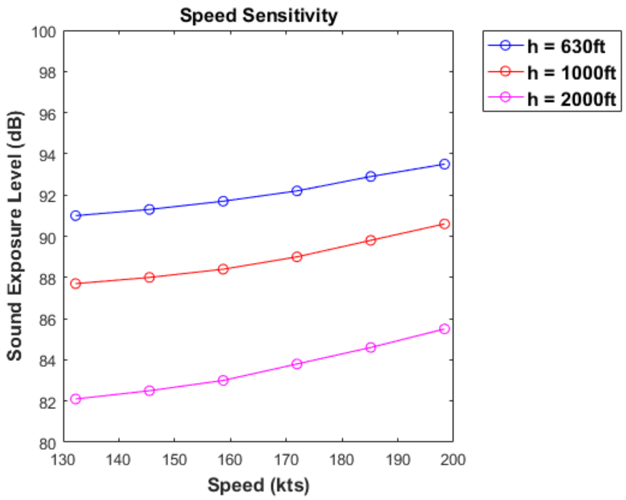

Figure 3. Sound Exposure Level vs. speed

Figure 3 shows the sweeps of SEL vs. speed at various heights. Speed also has a significant effect on SEL, changing it by ~3 dB over the examined ranges. From these sensitivity studies, it is clear that flap angle and speed have significant effects on SEL while slat angle does not. Thus, an interpolation scheme must be developed to include these variables.

NPD Superset Generation

When performing analysis in AEDT, a superset of NPD curves will be imported that includes NPD tables for a range of vehicle configurations. Each vehicle configuration has its own NPD curve that can be used to interpolate noise level based on distance and thrust setting. By considering configuration, multiple dimensions are being added to the noise model, and AEDT must be able to interpolate noise with respect to each of these dimensions. The solution to this problem is to generate a grid of NPD curves, or superset, which contains enough points needed to interpolate with respect to each dimension. These curve fits are then evaluated to interpolate noise level along each dimension. A study is performed to determine the appropriate order of interpolation in each dimension and the appropriate number of points needed to produce these curves.

Since slat angle is tied to flap angle and gear setting is a categorical variable, only flap angle and speed must be analyzed to determine the appropriate interpolation scheme. Due to the run time of each test and the complexity of creating the grid in AEDT, it is desirable to have the fewest number of curves possible in this superset. First, data from the sensitivity analysis will be used to generate polynomial fits at each height. All available data points will be used to generate polynomials curves from first through fourth order based on the least squares method. The R^2 value will be computed at each height to evaluate the quality of the fit. The lowest order that has a good representation of the training data is selected. With the order of the polynomial selected, the number of points used to generate the polynomial is then varied to determine the appropriate grid density. The RMS error at each point is evaluated to determine the quality of each fit. The smallest number of points with which the last additional point provided significant improvement will be selected. Repeating this for both flap angle and speed determines the appropriate density of the superset and the nature of the interpolation scheme in AEDT.

	1st Order	**2nd Order**	**3rd Order**	**4th Order**
R^2	0.9241	0.9805	0.9896	0.9931

Table 2. Correlation coefficient for flap angle curve fits

Table 2 shows the R^2 value of each order curve fit for flap angle. It is shown that significant model improvement occurs from 1st order to 2nd order, but improvement becomes less significant beyond that. For this reason, a second order curve is selected to fit SEL vs flap angle.

Number of Points	**3**	**4**	**5**	**6**	**7**
RMS Error (dB)	0.0545	0.0449	0.0406	0.0405	0.0403

Table 3. RMS Error for flap angle curve fits

Table 3 shows the RMS error at each point when fitting flap angle with a 2nd order polynomial at each height. In every case, the RMSE is small enough to be indistinguishable for all practical purposes. As a result, it is possible to fit the 2nd order curves using 3 points, which results in a closed form solution. This eliminates the complexity of having to perform a least squares regression since a closed form solution is available.

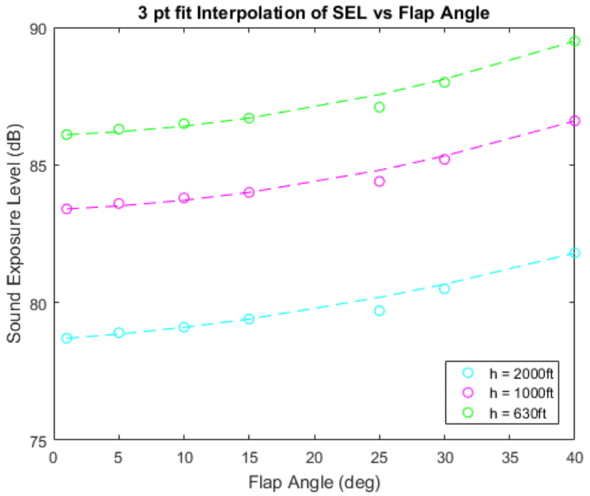

Figure 4. SEL vs. flap angle with 2nd order fit

Figure 4 shows the results of this study at a few example heights. The quality of each fit should be adequate for the purposes of the analysis in AEDT as each fit captures the behavior of SEL with flap angle fairly well.

	1st Order	2nd Order	3rd Order	4th Order
R^2	0.9813	0.999	0.9997	0.9999

Table 4. Correlation coefficient for speed curve fits

Table 4 shows the R^2 value of each order curve fit for flap angle. It is shown that a linear interpolation does an adequate job of capturing the behavior of the data. Consequently, a linear approximation will be used to fit SEL with respect to speed.

	2	3	4	5	6
RMSE (dB)	0.068	0.0453	0.0424	0.0416	0.0416

Table 5. RMS Error for speed curve fits

Table 5 shows RMS error at each point when speed with a linear regression at each height. In every case, the RMSE is small enough to be indistinguishable for all practical purposes. As a result, it is possible to fit the linear approximations using the 2 end points, which results in a closed from solution. This eliminates the complexity of having to perform a least squares regression since a closed form solution is available.

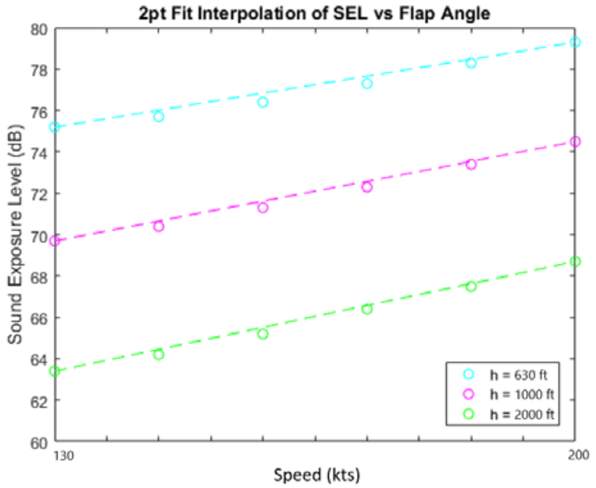

Figure 5. SEL vs. speed with linear approximations

Figure 5 shows the results of this study at a few example distances. The quality of each fit should be adequate for the purposes of the analysis in AEDT as each fit captures the behavior of SEL with flap angle fairly well. Once all relevant NPD data is generated for a given vehicle, it must be compiled into a single XML document to be imported into AEDT. The XML document is generated by EDS and contains relevant data fields and attributes for each vehicle type. Once the new grid of NPD data is incorporated into the XML file, analysis can be performed in AEDT on the full data superset.

In conclusion, dimensions for configuration parameters are to be accounted for in AEDT analysis by importing a superset of NPD relationships that vary in each new dimension. Flap angle is accounted for by importing 3 sets of NPD curves at 3 flap settings at each set of parameters and interpolating between them using parabolic fits. Speed is accounted for by importing two NPD curves for each set of parameters and linearly interpolating between them. Each case will also need to be run for gear up and gear down cases. The result is 12 NPD curves (3 flap settings x 2 speed settings x 2 gear settings) that must be imported into AEDT to fully map the space of configuration parameters.

Run	Gear	Speed (kts)	Flap (deg)
1	Up	130	0
2	Up	130	15
3	Up	130	40
4	Up	190	0
5	Up	190	15
6	Up	190	40
7	Down	130	0
8	Down	130	15
9	Down	130	40
10	Down	190	0
11	Down	190	15
12	Down	190	40

Table 6. NPD superset values for 150 passenger class

Table 6 shows a breakdown of the 12 cases that must be run and imported for this study. It is important to note that while particular values and ranges may change from vehicle to vehicle, it is expected that the same interpolation method should be valid for each vehicle in the fleet. The 150pax class model provides a valuable case study due to the availability of calibration and verification data from previous studies that can be used to validate the method. Now that the method has been validated, the next step is to apply it to all other vehicles in the fleet.

Milestones

- ANOPP NPD Generation – Completed November 2016
- NPD Sensitivity Analysis – Completed December 2016
- NPD Superset Generation for 150pax Class – Completed December 2016
- NPD Superset Generation for 50pax Class – In Progress
- NPD Superset Generation for 100pax Class – In Progress
- NPD Superset Generation for 210pax Class – In Progress
- NPD Superset Generation for 300pax Class – In Progress
- NPD Superset Generation for 400pax Class – In Progress

Major Accomplishments

- Determined the input parameters to change in the ANOPP model to simulate changes in vehicle configurations and vehicle flight velocity
- Developed an automated method for implementing changes to the desired input parameters to significantly reduce model simulation preparation time
- Generated baseline/reference ANOPP NPD input files for all vehicle classes
- Completed NPD generation set of runs for the 150pax NPD sensitivity study
- Completed analysis of NPD sensitivity study for the 150pax model
- Determined appropriate interpolation methods for SEL for each input parameter
- Generated NPD superset for 150pax model to be used in subsequent tasks

Task 2: NPDC Generation and Sensitivity Study

Objectives

Georgia Tech will use EDS to generate NPDC curves for different aircraft size classes that represent a large portion of the existing fleet. Table 7 lists the EDS vehicles that will be used in the analysis. NPDC curves will be generated for vehicles in each size class to ensure the resulting format is appropriate and representative across the fleet. GT and the FAA will coordinate on the appropriate vehicles of interest to carry forward in the research. EDS and ANOPP will be used to parametrically vary vehicle low-speed configuration, speed, and ambient conditions. The outcome of this parametric study will be a series of NPD curves that represent varying configurations, speeds, and ambient conditions. A sensitivity study will be performed to identify the quantitative impact of changing vehicle characteristics on both the resulting NPD and on the resulting fleet noise. Finally, the results of the sensitivity study will be used to recommend a format for the NPDC tables. The format will include both the additional parameters that should be included (i.e., flap angle, vehicle speed), and the number of additional conditions at which NPD data must be provided (e.g., 3 flap angles and 2 flight speeds). The outcome of Task 2 is a detailed comparison of differences in predicted noise when using the AEDT database NPDs, EDS baseline vehicle NPDs, and the NPDC curves generated in this task.

AIRCRAFT SIZE	EDS REPRESENTATIVE AIRCRAFT
50 pax	CRJ900
100 pax	737-700
150 pax	737-800
210 pax	767-300ER
300 pax	777-200ER
400 pax	747-400

Table 7: Existing EDS baseline vehicles

Research Approach

Including the vehicle's varying low-speed configuration and reference velocity for the complete flight envelope will yield differences in predicted noise. In order to assess these results, representative NPDC curves are required. These curves are acquired through an interpolation of the NPD supersets, which are described in more detail in section 6 of the report.

For the first iteration, each superset describes the noise evolution for a combination of the three following parameters: flap and slat setting (1°, 15°, & 40°); aircraft airspeed (133.35 knots & 200 knots); and gear setting (up & down). Furthermore, each individual NPD superset, from the 12 simulated in ANOPP, is composed of 10 NPD curves. A curve describes the uncorrected noise metric for a specified slant distance for increasing thrust settings. Figure 6 depicts a notional NPD supersets library produced in-house.

For the computation of a noise metric, AEDT currently uses a fixed reference speed of 160 knots and flight trajectory information that is discretized into segments. The segment's data can be expanded to include instantaneous reference speed and the vehicle's configuration. By increasing the data used in the acoustic computation algorithm, an interpolated NPD (NPDC) is obtained corresponding to a higher fidelity description of the segmented vehicle parameters. This description is to be propagated in AEDT to appropriately obtain the noise characteristics for the complete flight envelope.

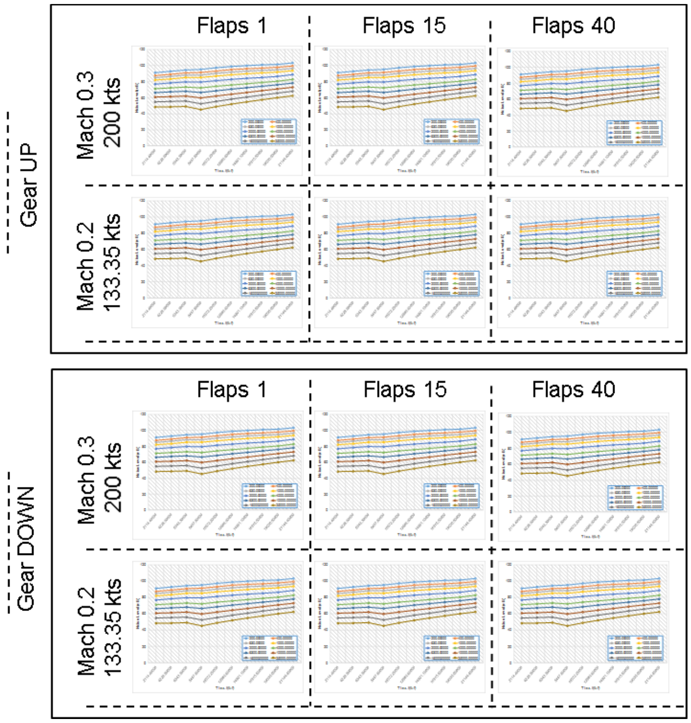

Figure 6. In-house developed NPD supersets library

Potential NPDC Integration Approaches with AEDT

In order to integrate the newly generated noise sources for a given flight profile and configuration, three approaches were initially studied. The first option considered involved running each NPD from the superset one-at-a-time through the AEDT algorithm in order to extract the custom noise metric results describing the flight procedure. This method was discarded due to the prohibitive computational expense incurred for a fleet of vehicles. A normal procedure result is computed on the order of minutes. An analysis including 12 different combinations of a vehicle configuration and reference speed amounts for several hours. Furthermore, by following this process, a more intensive modification of the source code would be required because segment-to-segment information would need to be post-processed. The parameters required to properly assess the noise adjustments would complicate the procedure as each computation would include its native configurations and reference velocities.

A variation to this approach requiring the analysis of all the NPD supersets was deliberated as well. In this case, the custom SEL grid was to be used in the ANGIM tool available to ASDL in order to superimpose the necessary segmented grids to portray the mission. This methodology suffered from the same weaknesses as the aforementioned practice. Figure 7 further portrays the discarded methods. It is important to note that Figure 7 does not reflect the NPD's currently used. Slat angle and flap angle were found to be correlated in the algorithm and are considered in the same vehicle configuration.

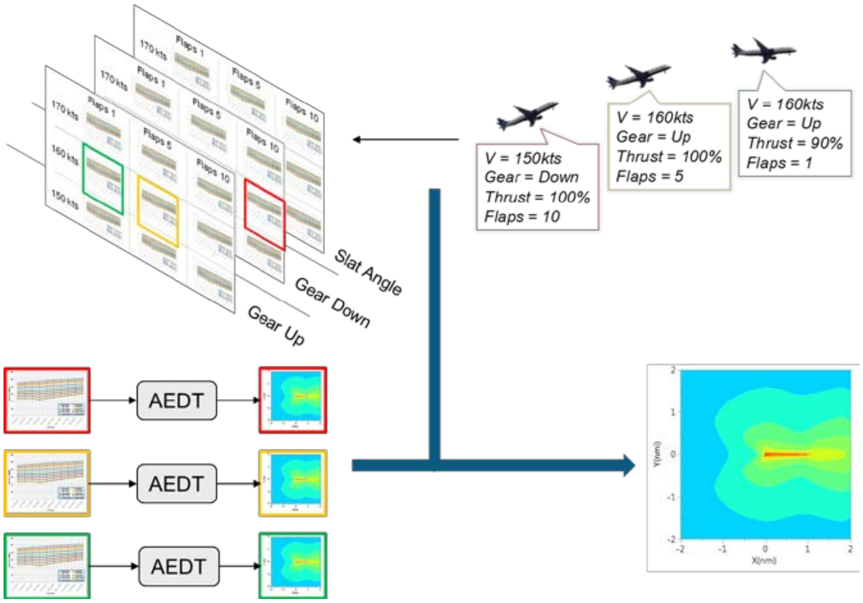

Figure 7. Discarded methods for the integration of the NPD library

The third, and subsequently selected, approach was to assemble a custom NPDC representing the flight procedure input to AEDT. This is performed by obtaining the segment information required to iterate between the NPD sets to create the NPDC curves (Noise-Power-Distance-Configuration). The vehicle object is expanded to include the library of NPD supersets considering flap, slat, and gear configurations. Each of the sets also includes the flap-slat setting, gear setting, and reference velocity data with which the ANOPP simulation was performed. The segment-to-segment part of the acoustic computation process is then expanded to contain an interpolation algorithm for each specific point required within the 12 NPD supersets with 10 NPD curves. The detailed process is explained in section 7.2.3. Using this approach does not increase the computational expense as significantly as the two other solutions considered. The required alterations to AEDT's source code are thought to be minimal due to the potential inclusion of the interpolation algorithm within the segmented information. The parameters describing the mission profile will also be available.

Required AEDT Modifications (Noise Corrections)

Georgia Tech has developed a wrapper (AEDTTester) around the AEDT source code that allows for the automation of reading aircraft definition and flight procedures input files with minimal user interaction. Our focus lies in researching the sensitivity of the acoustic analysis to the expanded data. It is of importance to do so with the least modifications to the AEDT source code as possible, in order to provide the FAA with a relatively simple implementation of the methodology.

As stated in the previous section, the modification to the NPDC curve accounts for both the aircraft configuration in terms of the noise produced due to the different drag characteristics and the speed. The acoustic computation process does not consider the configuration the vehicle is flying in as long as the NPDC curves portray this information; however, this is not the case with regards to the dissimilar reference velocity that was previously used for the creation of the NPD supersets.

The acoustic computation process in AEDT contains two correction algorithms referring to the reference velocity of 160 knots. First, the noise fraction adjustment includes a hard coded number that is 171.92 feet for a sound exposure level (SEL) value or 1,719.2 ft. for an effective perceived noise level (EPNL). The formulation below shows the equations used for the specified adjustment factors. For an arbitrary segment,

$$NF_{ADJ}(dB) = 10 * \log_{10}[F] \qquad F = \left(\frac{1}{\pi}\right)\left[\frac{\alpha_2}{1+\alpha_2^2} + \tan^{-1}\alpha_2 - \frac{\alpha_1}{1+\alpha_1^2} - \tan^{-1}\alpha_1\right]$$

$$\alpha_1 = -\frac{q}{S_L} \qquad \alpha_2 = -\frac{q+L}{S_L}$$

$$S_L = S_0 * 10\hat{}((L_{E,P,d} - L_{Smx,P,d})/10)$$

Where:

- q = relative distance (ft) from segment start point to point P_S
- L = length of segment
- s_0= 171.92 ft for L_{SEL} or 1,719.2 ft. for L_{EPNL}
- $L_{E,P,d}$ = unadjusted interpolated NPD noise exposure level (dB) at 160 knots. This value will reference the NPD interpolated value for the implemented modified velocity.
- $L_{Smx,P,d}$ = unadjusted interpolated NPD maximum noise level (dB) (L_{Amax}, L_{PNTmax})

The s_0 in the AEDT source code is hard coded; nevertheless, after researching the nature of this factor, it was discovered that it comprises the reference velocity utilized in the creation of the NPD. S_0 is to be modified to its physical expression,

$$S_0 = \frac{2}{\pi} V_{ref} t_{ref}.$$

The second correction algorithm that is affected by the alteration of the reference velocity is the duration adjustment. The duration adjustment accounts for the effect of time-varying aircraft speed, with both acceleration and deceleration. The segment aircraft speed is first computed as follows:

$$AS_{seg} = AS_{p1} + \frac{\delta AS}{2}$$

- AS_{p1} : speed (kts) at the start of the flight segment
- δAS: change in speed along the flight segment

The aircraft speed for the segment AS_{seg}, (at the closest point of approach) is included with AS_{ref}, the vehicle's reference speed at which the NPDC was sampled in order to calculate the duration adjustment factor:

$$DUR_{ADJ} = 10 * \log_{10} \left[\frac{AS_{ref}}{AS_{seg}} \right].$$

The flowchart in Figure 8 illustrates the complete acoustic computation process for a single flight segment. It provides an understanding of where these revised correction factors will influence the noise results.

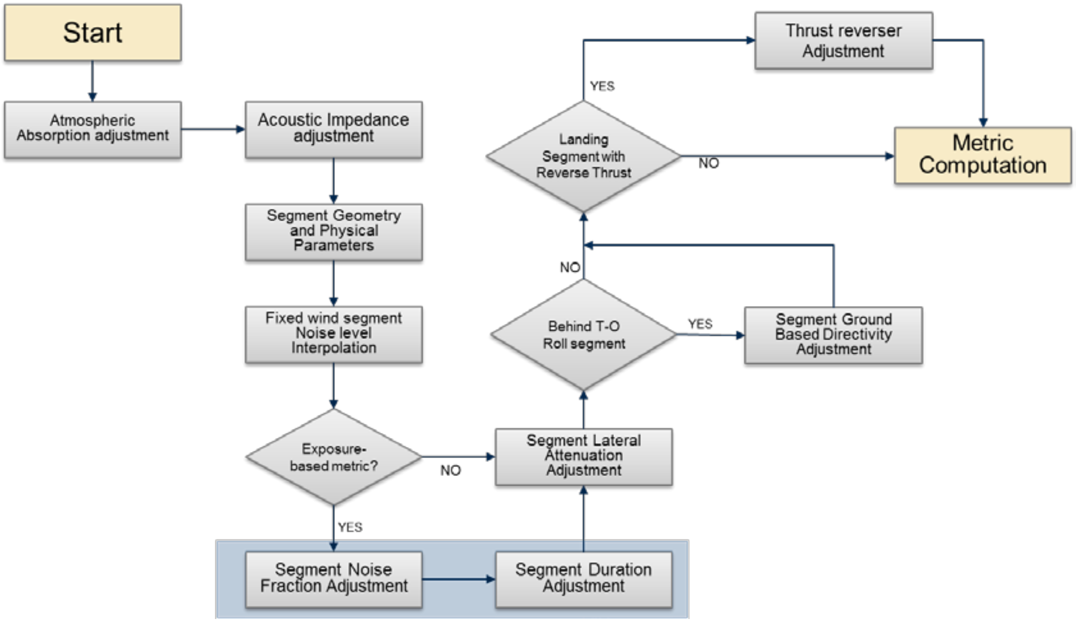

Figure 8. Acoustic computation process in AEDT with the revised noise adjustment factors

Implementation Roadmap

The flight parameters described for each of the NPD curves, including the varying vehicle configuration and speed, are associated with the segment-to-segment information in order to find the appropriate NPDC interpolated values. Consequently, the development of the NPDC is a crucial step in our research efforts. Figure 9 depicts the algorithm procedure and is taken as the baseline to demonstrate the logic behind the NPDC development process.

The first option to include the family of NPD supersets was to directly input the data in the methodology once the algorithm has reached the "Segment Geometry and Physical Parameters" section as seen in Figure 9. All of the required input data from the aircraft and flight procedure readers were obtained at the start of the computation process. It was concluded that an expansion of the vehicle object was preferred as it requires the fewest modifications to the source code. The AEDTTester would otherwise need to be re-called for an appropriate reading of the NPD family superset. This step then leads into modifications in the segment-to-segment calculation, within the main container source algorithm, for the expansion of the object instances and the inclusion of further rules to read the vehicle's parameters.

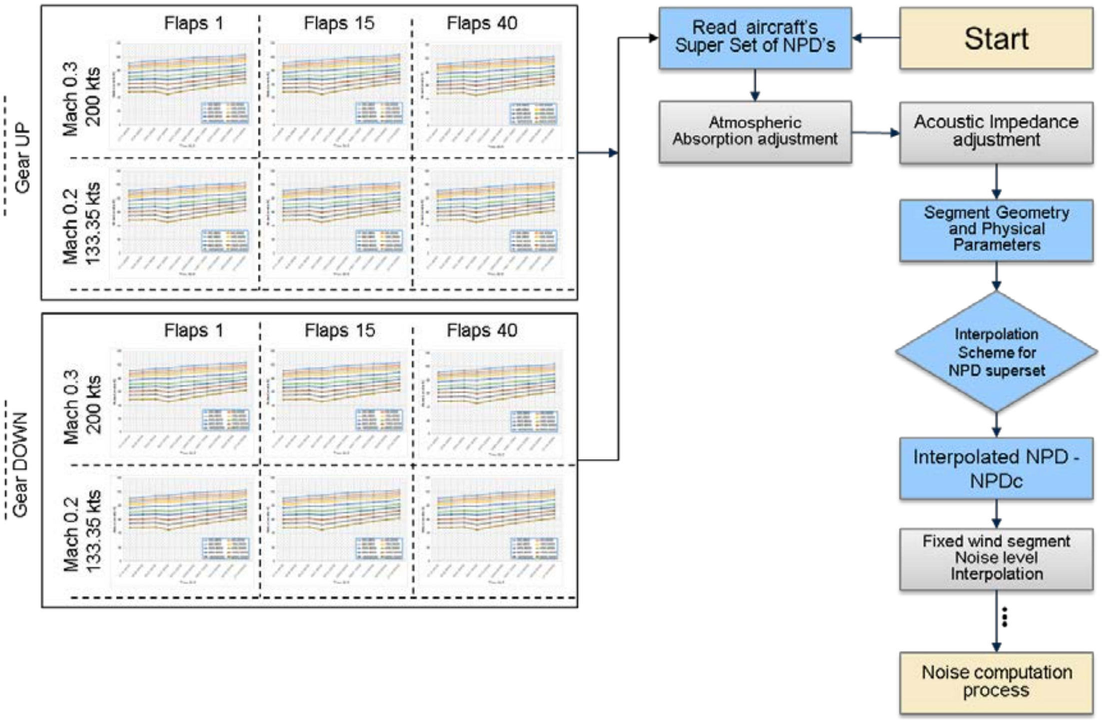

Figure 9. NPDC development process – 1

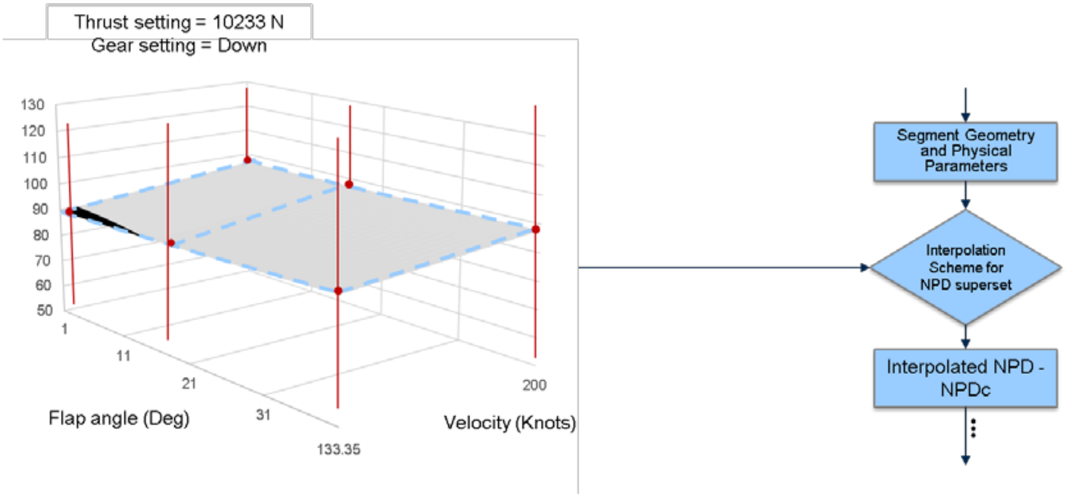

Figure 10. NPDC development process - 2

Major Accomplishments

- Modified the input XML file into the AEDTTester to include 12 NoiseGroup elements with the NPD superset family information
- Modified the schema to accommodate the new format of the input file
- Developed a new class of the noise parameters for the C# method to be able to include noise groups
- Modified the airplane interface for it to include the expanded format
- Modified the Fleet3xAccessAircraftWithLinqObjectsCache for the source code of the AEDT to handle the modifications
- Modified the aircraft XML reader to use the combined noise parameters
- Created a new class including the combined NPD curve long record
- Used it to obtain the reference speed and configuration
- Created a new class for the aircraft combined NPD data to accept the reference values
- In the XML reader, modified the method obtaining the Noise Power Distance Curves to accept the combined NPD curve long records
- Modified the method obtaining the Noise Power Distance Curves to include the combined NPD aircraft data including the three reference velocities
- Changed the airplane interface to account for the combined noise parameters
- Included the references in the noise power distance curve interface
- Modified the thrust interface to make the corrected thrust value available throughout the project
- Developed the interpolation algorithm. Still not applied to the segment-to-segment information

Publications

None, as this project has just started.

Outreach Efforts

None, as this project has just started.

Awards

None.

Student Involvement

Kenneth Decker and Arturo Santa-Ruiz are intimately involved in the day-to-day activities on this research. Kenneth is working on Task 1 and Arturo works on Task 2.