

Quantifying Uncertainty of Landing and Takeoff Noise for Commercial Supersonic Aircraft

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Of the many challenges faced by manufacturers attempting to offer supersonic travel to the public, the uncertainty in predicting the noise of these aircraft in airport operations has an immediate impact. No noise regulation exists in FAA or ICAO for certifying such aircraft, as these organization require solid data, usually from existing aircraft. Manufacturers are taking large risks to design a vehicle not knowing whether it will be allowed to fly. A partial solution to this conundrum is to use physics-based simulations to provide the “data” used to calibrate system-level prediction methods, carefully documenting the uncertainty of the method for application to supersonic aircraft. A close look at the accuracy of empirical prediction methods points to areas where improvements need to be made if noise studies of supersonic aircraft are to be useful. As NASA embarks on a focused research program to improve predictions of noise from the noise-dominant propulsion noise of commercial supersonic aircraft, this paper documents the work done to baseline the uncertainties found in today’s noise prediction methods. A relatively simplistic method was developed, summarizing the error of the empirical methods on a component basis and following their impact on the total aircraft during landing and takeoff operations using Monte Carlo analysis. By this method it is found that current empirical noise prediction methods have an uncertainty of 1.5 EPNdB cumulative for propulsion noise of a representative conventional subsonic passenger aircraft. When applied to likely near-term supersonic commercial aircraft, the uncertainty is 7.6 EPNdB cumulative, a difference that must be reduced if the prediction methods are to guide decision makers.

I. Motivation

As of 2022, there are no noise regulations to which a manufacturer of a civilian aircraft can apply for type certification. This is in addition to the general restriction from flying at supersonic speeds over land for much of the world, a limitation being addressed by NASA in the Quesst Mission using the X-59 vehicle. A new landing and takeoff (LTO) noise standard is needed to provide regulatory certainty for manufacturers of new supersonic civil airplanes under development. In 2020, the FAA produced a Notice of Proposed Rule Making (NPRM) that sought to establish maximum noise limits and set recommended practices for certifying small supersonic aircraft[1]. It marks the first time that aircraft noise standards have been proposed based on predictions alone, rather than on actual aircraft noise measurements. This NRPM was largely established from studies done by NASA and other independent research groups, working with industry to identify likely configurations. One such study, commissioned by the ICAO Working Group 1, is commonly referred to as the Supersonic Technology Concept Aeroplane (STCA)[2]. This study aircraft was designed with input from manufacturers to represent a potential near-term entrant into the supersonic market using current technologies, and had enough definition of flight

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characteristics and engine performance over the flight envelope to allow extensive studies using empirical prediction tools.

While the STCA studies provided a transparent model for the international community to evaluate the potential economic and environmental impacts of such aircraft, the more difficult question of how accurate the results were invited a closer study. One attempt to quantify the uncertainties was made[3],[4], but the inputs for the component uncertainties were not based on documented data. At the same time, an effort to reduce the uncertainties was initiated that needed a baseline quantification of the prediction uncertainties, using a methodology that could be used to measure progress of the effort. This paper documents the methodology developed and the findings of uncertainty in LTO noise for conventional subsonic aircraft and commercial supersonic aircraft. Our studies show that propulsion noise is clearly dominant for the supersonic aircraft we are focusing on; therefore only propulsion noise components are included in the analysis.

II. Background

Prior collective work of the NASA acoustic community to quantify the accuracy of noise prediction methods for aircraft has been documented[4]. In particular, Ref [4] contains a summary of the ANOPP noise prediction method used for system-level prediction of aircraft noise. The present work is influenced by this earlier work, but a potentially more consistent method of evaluating the disparity between prediction and experimental data is applied here. While much more advanced noise prediction methods can be employed, they are not suitable for system-level studies as they require very significant resources and higher fidelity of flow surfaces than are generally available at an early stage in aircraft development. The aim of the current work is a carefully bookkeeping of uncertainties in the prediction of the current conventional certification metric, specifically Effective Perceived Noise Level or EPNL as are measured for noise certification for landing and takeoff. As such we prioritize attention on those noise components which dominate the metric, which are fan and jet noise for supersonic aircraft.

Assessing uncertainty starts with identifying the sources of the uncertainty. Here we are primarily interested in the epistemic uncertainty of low-fidelity models that require only a few input variables. Within the epistemic uncertainty we consider two distinct types: *model uncertainty* and *completeness uncertainty*. The former can be understood as “How well does the model fit data when the variables of the model completely describe the system?” This is often given by goodness-of-fit metrics when a model is created from data. The latter uncertainty is “How well does the model fit the data when the system depends on variables not included in the model?” Alternatively, this can be viewed as the likely range of errors in assuming that the details not captured in the model don’t make an impact on the predicted result. It is a “completeness” uncertainty in that it comes from the list of important variables in the model being incomplete. Of course, when assessing a model against data there is additional experimental uncertainty included, as the data here is obtained experimentally. Experimental uncertainty in the facilities from which data used here was obtained is much smaller than the model and completeness uncertainties found in this study. Also, in this work, our data comes from model-scale rig tests and the relationship between the data acquired from rigs and from full-scale flight is set aside as a separate entity. One such study comparing results of ANOPP to flight certification data for conventional subsonic aircraft is found in [5].

For conventional aircraft for which our noise prediction models have been developed, the biggest source of uncertainty is model uncertainty, and it is relatively small. For supersonic aircraft, several aspects of their design differ significantly from conventional aircraft. These

aspects are not covered in the models and could impact the noise, leading to completeness uncertainty. Specifically, while conventional propulsion features single-stage fans behind cylindrical inlets positioned well ahead of the airframe, supersonic propulsion systems will likely have multi-stage fans behind inlets incorporating centerbodies, auxiliary openings, unconventionally-placed acoustic treatment, and close integration with the airframe. The acoustic impact of distorted flow interacting with multiple rotor-stator combinations is likely to be significant. For the jet, supersonic propulsion is likely to feature internally mixed exhaust systems with external plugs to minimize boattail drag. This is a configuration rarely seen in the literature, but recently documented as having noise sources louder than conventional jet mixing noise [6].

The difficulty in establishing completeness uncertainty is that without data demonstrating the impact of the variables not modeled, the disparities of the model cannot be measured. For our assessment we have found a very limited set of data which are relevant to supersonic configurations. To estimate the impact of multistage fans on fan noise, data from a two-stage fan noise test in NASA's 9x15 wind tunnel were used. Details of this test can be found in Reference [7]. While the fan design is not reflective of current design practice, and hence are not directly relevant to estimates of potential near-term supersonic aircraft, it does offer the same type of variability not covered by fan models used in systems studies. Thus it is an example of how wrong current fan models could be if applied to today's multi-stage fans. For the jet component, a recent test program produced a limited set of data for an internally mixed exhaust system with external plug operating over flow conditions given by system studies such as the STCA study[6].

Uncertainty Analysis Recipe

A "recipe" for quantifying the uncertainty of the noise prediction of an aircraft was developed and was applied to both a conventional and supersonic aircraft. The steps were

1. Identify representative aircraft and acoustic rig datasets with similar geometric features and flow conditions.
2. Use noise prediction tools to predict noise as documented in rig datasets.
3. Compute discrepancies between predictions and rig data to generate population of discrepancies.
4. Statistically summarize discrepancies in the population to generate a quantitative description of uncertainty for each noise component.
5. Use a Monte Carlo method to evaluate how distributions of noise component discrepancies propagate through to a total discrepancy for the overall noise of the aircraft.

The choice of representative aircraft was driven by the analytical models and experimental datasets available. At NASA, fan and jet rig tests have been conducted over the decades for each new generation of propulsion, and system models with different levels of fidelity have been created for many existing aircraft for use in various studies. The system models are composites of NASA tools such as Numerical Propulsion System Simulation (NPSS)[8] for propulsion performance, with the noise prediction being handled by NASA's Aircraft Noise Prediction Program (ANOPP)[9]. As shown below, for most conventional and supersonic aircraft the fan and jet propulsion noise components were the dominant sources, with the airframe being a close third in the case of the conventional aircraft.

Existing test data acquired on NASA propulsion rigs were identified that closely matched the geometric and flow conditions of the fan and jet during landing and takeoff operations. The

ANOPP modules for fan and jet noise were employed using the flow and geometric conditions of the rig test points as inputs. Prediction and data were directly compared, producing measures of discrepancy or error for each test data point.

While it was very illuminating to compare spectral directivity across frequency and polar angle, ultimately it was the ability of the prediction module to predict noise at frequencies and angles that impact EPNL that mattered. Rather than devise a filter to select frequencies and angles that had the most impact on the EPNL metric (such as frequencies above human annoyance or extreme angles where distance and atmospheric attenuation reduce the annoyance) we simply transformed the acoustic data to the application scale and “flew” it to produce input for an EPNL calculation. The differences between component EPNL predicted and measured became the input for the statistical analysis of uncertainty.

The sample population of differences in EPNL predicted and measured varied over flow conditions around the three cycle points of certification flight and over variations in geometry which represent alternative viable designs for the aircraft system. For instance, in a fan noise test, wind tunnel data existed for several blade designs, all matching the bypass and pressure ratios of the targeted conventional aircraft, at roughly a dozen cycle points over the range of flight conditions from approach through takeoff. As the blade design was not a variable in the prediction method, these variations represent completeness uncertainty in the model. Each point contributed a sample to the population of EPNL discrepancies between predicted and measured noise. The population of discrepancies was summarized by conventional average and standard deviation metrics, referred to as “component uncertainties”. Conceptually, the average discrepancy represents a bias in the prediction method while the standard deviation is better described as the uncertainty. We note that the component uncertainties include experimental uncertainties from the experimental data. The experimental uncertainties are generally unrelated to the model and completeness uncertainties, and are similar across configurations.

Because different noise components weigh in to the cumulative EPNL differently at the three certification points, a Monte Carlo method of evaluating the impacts of the various component uncertainties was used to determine the uncertainty of the total aircraft noise, much as was done in Reference [2]. The system model for a nominal aircraft design produces one deterministic value for each noise component when evaluated at the expected design point. Subsequently, these variables were replaced by random values with normal distribution having the same offset and standard deviation as the component uncertainties found in the comparisons of the models with experimental data. As multitudes of evaluations were made with the combinations of the variations on the component noise at each certification condition, the distribution of total aircraft noise results were built up, producing distributions of EPNL at each certification condition and for the cumulative EPNL. The standard deviation of this distribution of final cumulative EPNL is our prediction uncertainty for LTO noise.

Study Aircraft

As the objective of this work was to compare uncertainty in noise prediction of conventional aircraft with that of supersonic aircraft, two aircraft designs were studied, one representing conventional subsonic transports (“Conventional”) and one representing near-term commercial supersonic aircraft (“Supersonic”).

Conventional—For the Conventional study aircraft, a 737-800 with CFM56-7B27 engines was chosen. NASA has developed a detailed system model of this aircraft that validates well against published data for weights, flight characteristics, and noise[10]. The single-stage fan design is of

roughly the same vintage as fans tested in the NASA 9x15 Low-Speed Wind Tunnel, for which there is extensive documentation and acoustic data[11]. The exhaust system is a separate flow nozzle very similar to that tested at NASA's Aero-Acoustic Propulsion Lab in 1997. The system model for this was described, and predictions of airport noise corroborated in Reference [12].

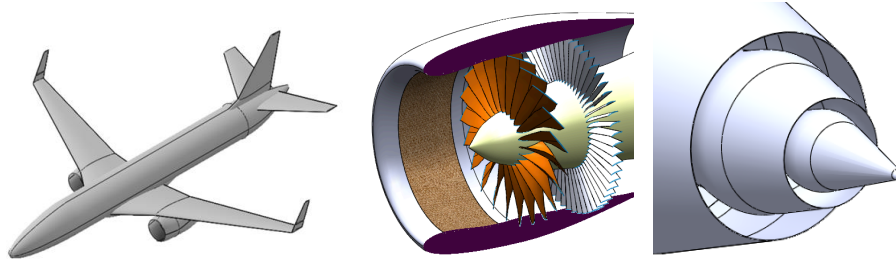


Figure 1 Conventional aircraft. Single-stage fan rig and separate flow nozzle.

Supersonic—The representative Supersonic aircraft was based on the study vehicle created for the FAA/ICAO studies, known here as the 55-tonne Supersonic Technology Concept Aeroplane, or STCA55t, documented in [2]. Two main differences exist between the STCA55t and the study vehicle used in this report: (i) the original outboard rear-fuselage-mounted engines were mounted under the wing in our vehicle, avoiding uncertainties in noise due to shielding by the wing, and (ii) the fan in our study is a 2.5-stage fan design.

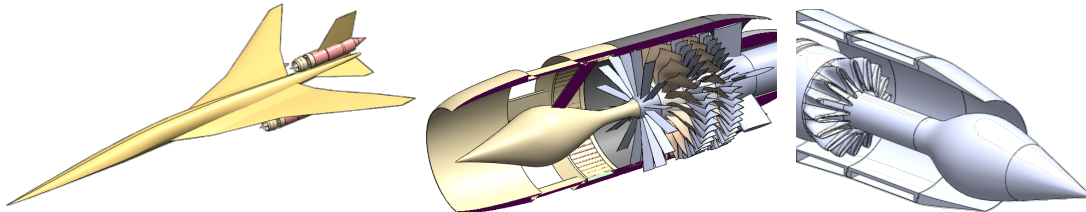


Figure 2 Supersonic aircraft. 2.5-stage fan rig and internally mixed, external plug nozzle.

Noise Prediction Methods

As documented in [9] and [13], within the ANOPP code are modules for predicting noise sources for fans and jet flows. For the fan noise component, there are four empirical models based on the framework provided by Heidmann[14]. The models predict five sources: Inlet blade-passing and multiple pure tones, inlet broadband noise, aft blade-passing tones, and aft broadband noise. The original Heidmann model is available in ANOPP but was based on data that was contaminated with inflow distortion. The second option is based on a noise database from small engines[15], the third option is for large engines[16] and the fourth option is for the NASA Source Diagnostic Test wind tunnel model[17]. A user starting to model fan noise has to pick the model that best describes the fan being studied. The primary factors to consider are likely the engine size and pressure ratio, although experience and judgement is required. The use of these models for a supersonic application was considered in [18] where the four models were compared to wind tunnel data for a specific high speed fan model. As shown in the first table of that paper, only a few parameters go into the model such as basic geometric and aerodynamic quantities. Details about blade geometry or flow physics are not considered. For example, there is a flag for the presence or absence of inlet guide vanes (IGVs) but no details about the IGVs are considered. IGV to rotor spacing, turning angles, lean, sweep, etc, are beyond the scope of the model.

For the jet component, ANOPP contains six methods, but of these the second Stone method[19] and SAE ARP876 mixing noise method[20] are most applicable to the present problem. The

SAE876 method available in ANOPP is suitable for a single-stream jet only, but the Stone method contains options to account for two streams and to model the acoustic impact of an external plug.

Conventional— For the Conventional aircraft exercise, the choice of ANOPP fan model was obvious, as the large engine model [16] was created in 1996 to represent fans such as on the CFM56-7B27, being designed at that time.

The choice of Stone’s method as the jet noise model was dictated by the fact that it was created at the time when nozzles of the type used on the CFM56-7B27 were being developed, and thus the model was most appropriate for the Conventional study aircraft.

Supersonic— For the Supersonic aircraft exercise, none of the Heidmann-based fan models in ANOPP were meant for multi-stage fans. Various assumptions in assigning pressure rise over the different stages could be made, with noise sources modeled by adding the noise of different stages, but these would be gross assumptions. One prediction code, contained in the HSRNOISE code[21] and created to fit data from a single test of a two-stage fan, is available, but has no ability to adjust fan pressure ratio. This makes it inappropriate for general design work.

As for jet noise from the Supersonic aircraft, none of the noise models in ANOPP address internally mixed exhaust systems, and certainly not in combination with an external plug. A common assumption used is that the internal mixing emits no noise itself and the exhaust flow at the nozzle is completely mixed. This would justify prediction of noise based on an equivalent single-stream jet, where both SAE876 and Stone methods would apply. This assumption was made for the present study, and while both methods were explored, only the SAE876 jet noise method was used for the Supersonic study aircraft.

Experimental Datasets

Conventional— The fan design of the Conventional aircraft resembled the General Electric High Speed Fan tested at GRC’s 9x15 LSWT in 1999[11], shown in Figure 3. That model system had variations in fan blade sweep and chord, and in vane sweep and lean. These design variables are not included in the fan noise models and are sources of completeness uncertainty for the noise models. Data from six of these configurations were used, with acoustic data acquired over an operating range representative of fan pressure ratios of the 737-800/CFM56. Specifically, the “wide chord” fan model (linear scale factor 2.8) tested in the 9x15 is similar to the fan used in the CFM56-7B27 for the 737-800. The aerodynamic conditions were similar as shown in Table 1. Noise measurements were made with a traversing microphone on a sideline, following the procedures of Reference [22].

A significant effort was made as part of the present study to isolate the various components of fan noise from the combined sideline microphone measurement. For some cases, a barrier wall was installed to shield aft noise from the microphone. For other cases, the inlet noise was quantified by only using emission angles upstream of 90°. An example spectrum is shown in Figure 4. The sideline data were processed into narrowband maps of blade rate tones and broadband. These were used to compute simulated flyovers.



Figure 3 Inlet view of GE High Speed Fan model in GRC 9x15 LSWT

Table 1 Aerodynamic variables of high speed fan measured in experiment.

	High Speed Fan Experiment, wide chord fan		737-800/CFM56 model	
% Speed	Pressure ratio	Temperature ratio	Pressure ratio	Temperature ratio
50	1.140	1.047		
Approach 61.8	1.226	1.071	1.238	1.0702
70	1.303	1.092		
80	1.426	1.125		
Flyover 84.5	1.494	1.145	1.493	1.1341
90	1.588	1.165		
Lateral 96.9	1.721	1.198	1.708	1.1793
100	1.766	1.212		
102.15	1.799	1.226		

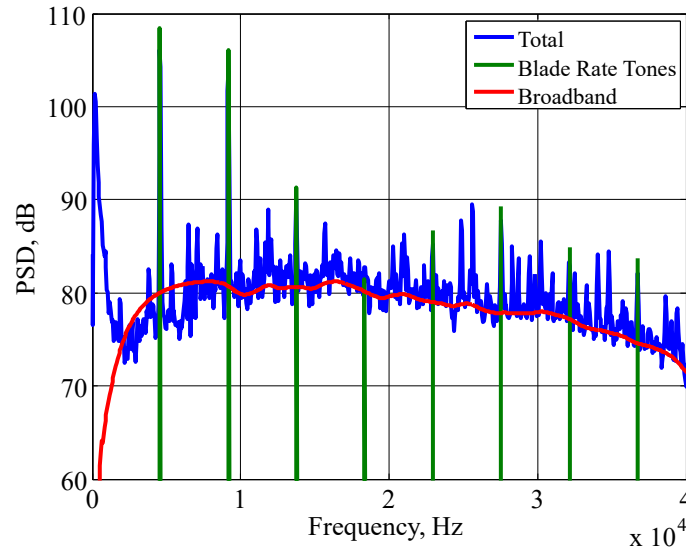


Figure 4 Example of tone and broadband noise separation for fan data.

For the jet noise, the nozzle design and bypass ratio of the Conventional aircraft closely match the axisymmetric separate flow nozzles tested in the NASA Aero-Acoustic Propulsion Lab in 1997, documented in [12]. Far-field acoustic data exist for a range of conditions that bracket the operating points of the CFM56 engine during LTO operations, as shown in Figure 5.

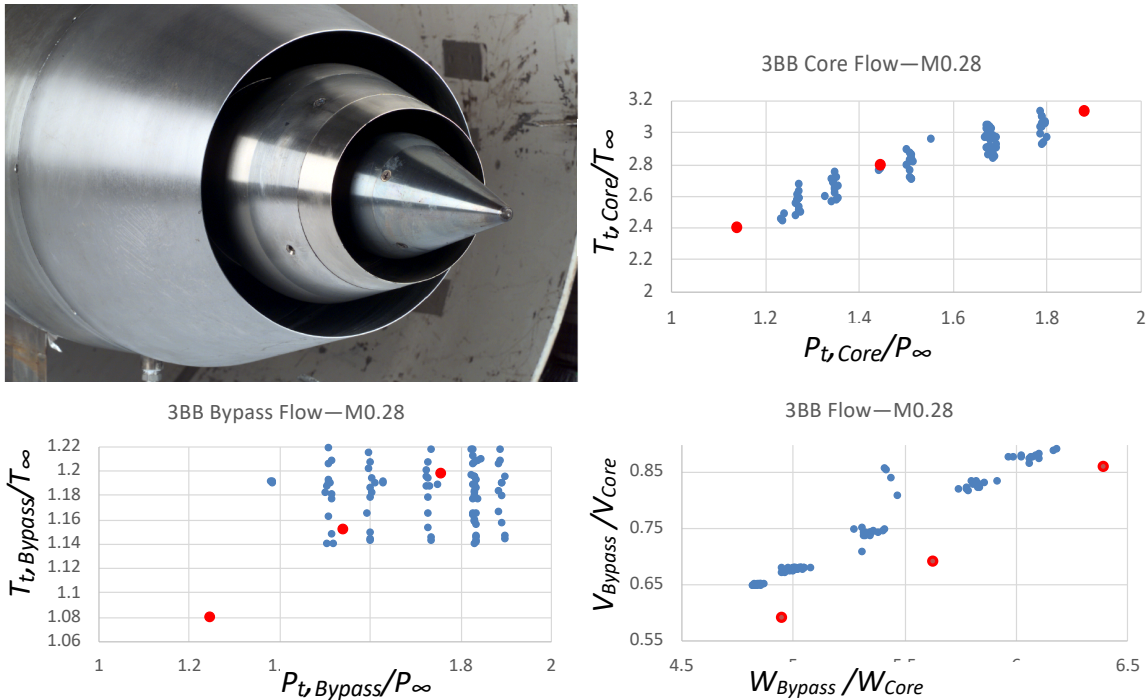


Figure 5 3BB nozzle and flow conditions as tested in GRC Aero-Acoustic Propulsion Lab. Blue dots denote the flow conditions tested while the red dots represent the flow conditions of the exhaust plume of the Conventional study aircraft at LTO certification points.

Supersonic—For the Supersonic study aircraft, there is very little experimental fan noise data for a multi-stage design. In a test conducted the GRC 9x15 LSWT in 2003, the Quiet Supersonic Platform (QSP) fan, a two-stage fan was tested with inlet guide vanes. This fan was designed by Pratt & Whitney for the NASA High-Speed Research Program in the 1990's and was tested after the Program terminated in 1999[7], [18]. Although the fan blade design does not represent what a manufacturer would use in a near-term commercial supersonic engine today, it does have multiple fan stages and was tested over fan pressure ratios similar to those for the Supersonic study aircraft. The test did incorporate variations in inlet guide vane count and angle, spacing between the IGW and the first fan and between the first fan and the first stator. None of these variations are captured in current empirical fan noise models and these variations represent the types of completion uncertainties that dominate the problem of predicting the noise of proposed supersonic aircraft. The dataset was exclusively focused on inlet radiated noise, so exhaust fan noise is out of scope for the present effort also. Finally, note that in the QSP fan test the inlet is of a conventional subsonic-style, and does not represent that of a supersonic propulsion system with centerbody structure and variable (“auxiliary”) inlet areas (with attending gross flow distortions) which would be required for actual operation at LTO conditions. This complexity is completely missing from both prediction models and test data.

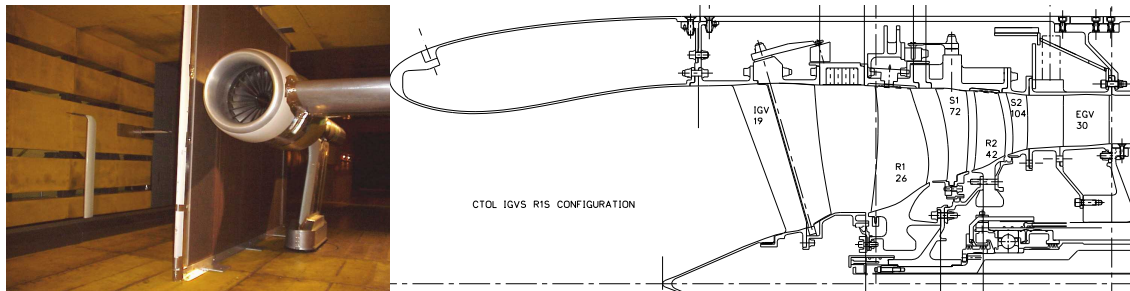


Figure 6 (a) QSP fan being tested in GRC 9x15 LSWT, (b) QSP cross section, in low noise configuration.

More representative data was available for the jet noise of the Supersonic aircraft. Likely variations in plug and mixer designs were used in a test campaign (“Plug20” test) in which the impact of various external plugs on an internally mixed nozzle was documented[6]. Historically, the noise of an internally mixed nozzle system has been found dependent upon the internal mixer design[23]–[25], with a perfect mixer apparently being the lowest noise producer. Thus, along with the aforementioned Plug20 dataset, single-flow conditions acquired as a baseline for tests described in [26], denoted as “GE11ref”, were also included in the evaluation. Figure 7 shows one of the Plug20 nozzles tested along with plots of the flow conditions tested and the Supersonic study aircraft flow conditions at LTO certification. Figure 8 shows similar plots for the GE11ref dataset where the single-stream, fully mixed jet flow conditions represent the flow of a perfect mixer design.

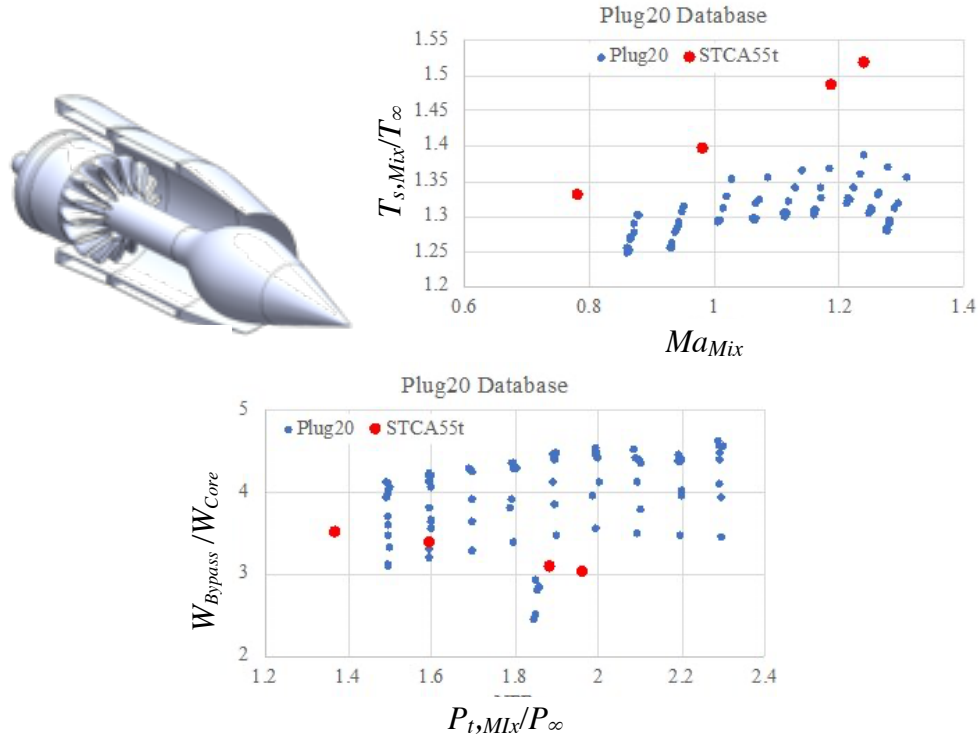


Figure 7 Representative Plug20 nozzle and flow conditions as tested. Blue dots denote the flow conditions tested while the red dots represent the flow conditions of the exhaust plume of the Supersonic study aircraft at LTO certification points.

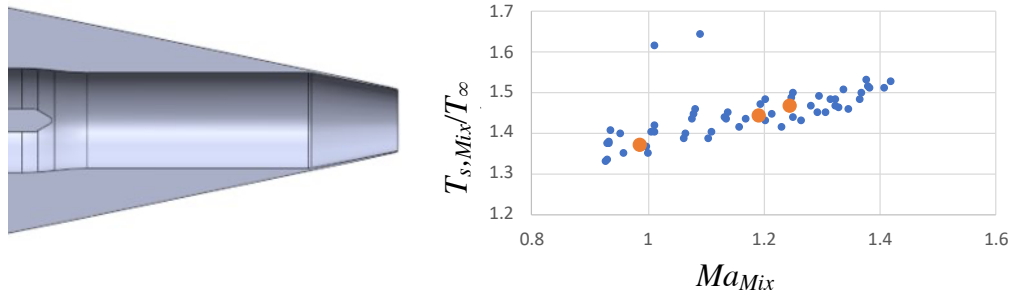


Figure 8 GE11ref nozzle and flow conditions as tested. Blue dots denote the flow conditions tested while the orange dots represent the flow conditions of the exhaust plume of the Supersonic study aircraft at LTO certification points.

Returning to the topic of categorizing types of uncertainty, it was noted above that experimental uncertainty was included in the assessments of component uncertainty, along with model and completeness uncertainty. Looking at the sources of data being used to quantify the component uncertainty we note that all fan data come from the same facility as do all the jet data. This opens the possibility that the experimental uncertainty contains undetected bias error, which can be addressed best by comparisons with flight data. It also simplifies the estimation of the contribution of experimental error to the standard deviation of the component uncertainty as it is the same for all configurations. Repeatability of common configurations across years of testing give estimates of experimental uncertainty to be less 0.3 EPNdB for jet noise and less than 1 EPNdB for fan noise. This will be seen to be much smaller than the component uncertainties In the following analysis no attempt is made to remove the experimental uncertainty from the component uncertainties. In the end, when comparing the overall uncertainty in predicting noise of conventional subsonic

aircraft to that of predicting noise of future commercial supersonic aircraft, the experimental uncertainty is common to both.

III. Results

The experimental datasets described above were assembled, along with the variables describing their exact flow conditions and geometries as used in the noise prediction calculations. The data were rescaled to the study vehicles and transformed to a simple flyover scenario for which the spectral directivity was produced. Similarly, the noise prediction models were exercised on the exact test conditions and geometries of the data to predict tone directivities or broadband spectral directivities at the same transformed conditions.

Some interesting observations were made in the comparisons of spectral directivities of noise power spectral density (PSD) and examples are given in figures below. However, the final uncertainty analysis required single values of discrepancies for each data point. As the metric of interest in aircraft noise certification is the Effective Perceived Noise Level (EPNL), this was the metric to which the data and prediction were reduced to for the discrepancy database. The direct difference between the EPNL from prediction and from data, denoted as dEPNL, was compiled from all the comparisons and was the population of data whose summary statistics became the measure of prediction uncertainty.

Conventional—Fan noise comparison were made on both broadband and tone components but were restricted to the inlet radiated component. As an example, the inlet radiated broadband noise for the High Speed Fan test with the wide chord fan and radial swept stator set at approach speed is shown in Figure 9. The fan speed scaled to full size was 3379 RPM, with a mass flow of 472 lbm/s and a temperature rise of 37.8 °F. Predicted and measured source maps are given in Figure 9, including (a) the GE large engine model[16] and (b) the experimental measurement.

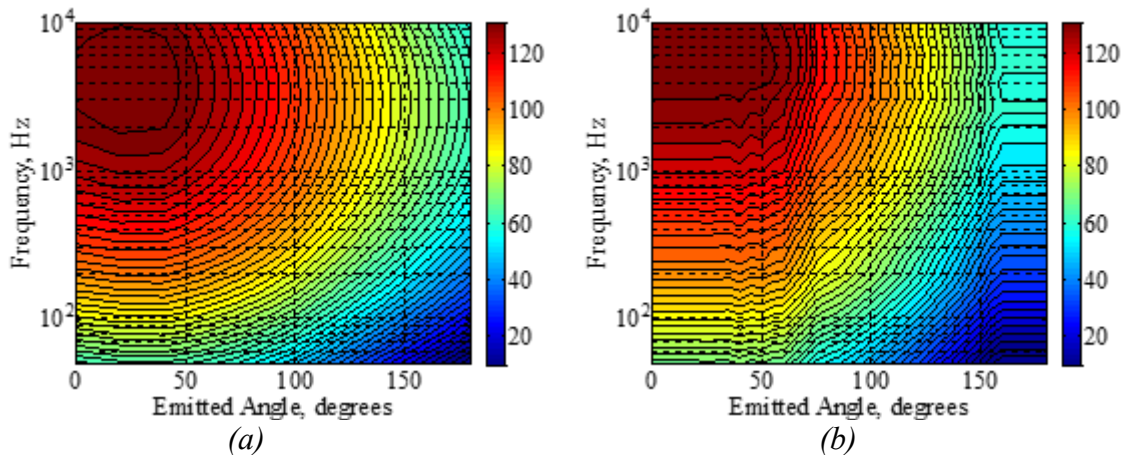


Figure 9 Inlet radiated broadband flyover source maps for approach speed, High Speed Fan test, wide chord fan with baseline radial swept stator set. (a) Prediction by Heidmann fan model option 3, (b) experimental data.

The source maps were used to conduct simulated flyovers, as shown in Figure 10. For this example, the PNL trace is used to calculate the EPNL, which was 81.8 dB for the model and 78.6 for the experiment. This gives a difference of 3.2 dEPNL, meaning the model is louder than the data.

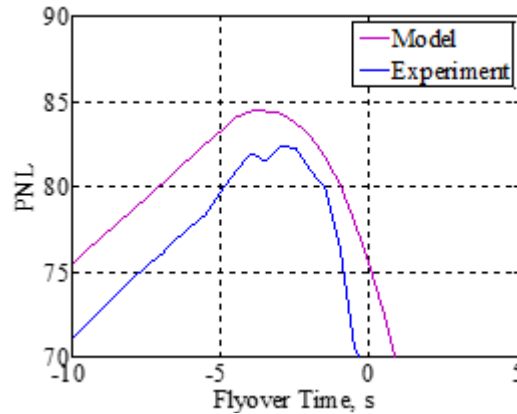


Figure 10 Simulated flyover for inlet broadband noise, conventional fan at approach speed of 61.8%.

This process was repeated for all six configurations and 12 fan speeds of the available data set. The combined result is shown in Figure 11. The spread in dEPNL is smallest for speeds above 80% of design speed as the fan models are closer to their design speed. It seems the off-design noise is more dependent on the fan and stator design details.

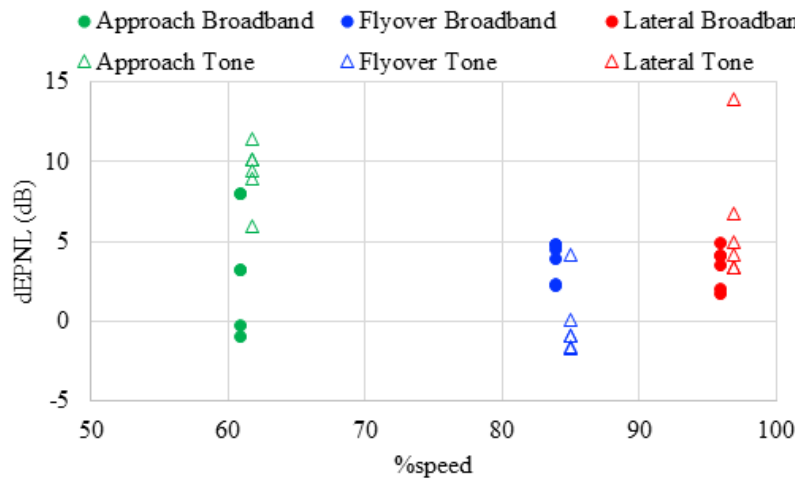


Figure 11 Summarized broadband (circle) and tone (triangle) dEPNL between model and test data for three fan speeds (% of design speed) and single stage subsonic fan. Markers offset slightly from actual speed for visualization purposes.

The process was repeated for inlet radiated tones at multiples of the blade passing frequency. Results for both noise sources at the three rating conditions are summarized in Table 2. Note that the offset values are to be added to the model prediction to get the rig data. The fans studied here did not exhibit multiple pure tones (MPTs) which are the third type of inlet noise available for prediction by the fan models. We believe this is due to precision manufacturing and care taken for typical wind tunnel models. Whether a full-sized engine made with modern methods would exhibit MPTs is not clear.

Table 2 GE HSF dEPNL summary. Average subtracted from model matches experiment.

Variable	Std.Dev.[dB]	Average [dB]
Fan inlet tone (lateral)	4.05	6.08
Fan inlet tone (flyover)	2.21	-0.16
Fan inlet tone (approach)	1.87	9.38
Fan inlet BB (lateral)	1.28	3.33
Fan inlet BB (flyover)	1.18	3.71
Fan inlet BB (approach)	3.85	3.49

Comparison of predicted and measured jet noise for the Conventional aircraft often saw that, on average over frequencies and polar angles, the prediction did a good job of matching the data. However, the deviations could be significant, with overpredictions at some frequencies being compensated for by underprediction at other frequencies. For example, in Figure 12a, the direct comparison of noise in model-scale over frequency and polar angle is shown by the color mapping of the deviation of the power spectral density (PSD) on the surface of the spectral directivity. Averaged over the entire surface, the difference is less than 1dB. But there are regions of red and blue where the discrepancy is 5dB or greater. Because the EPNL metric weighs frequencies by human response, it was insightful to look at the spectral directivity of Perceived Noisiness [27] (Figure 12b), where the power spectral directivity has been weighted and polar angles converted to duration of the flyover at fullscale. Integration of perceived noisiness over frequency and duration is essentially the EPNL. In this view we see those regions where the spectral discrepancies make the most impact on the prediction of EPNL. So the large overprediction at polar angles greater than 150° and frequencies greater than 10kHz in Figure 12a are seen to have no impact on the full-scale perceived noisiness and hence on EPNL.

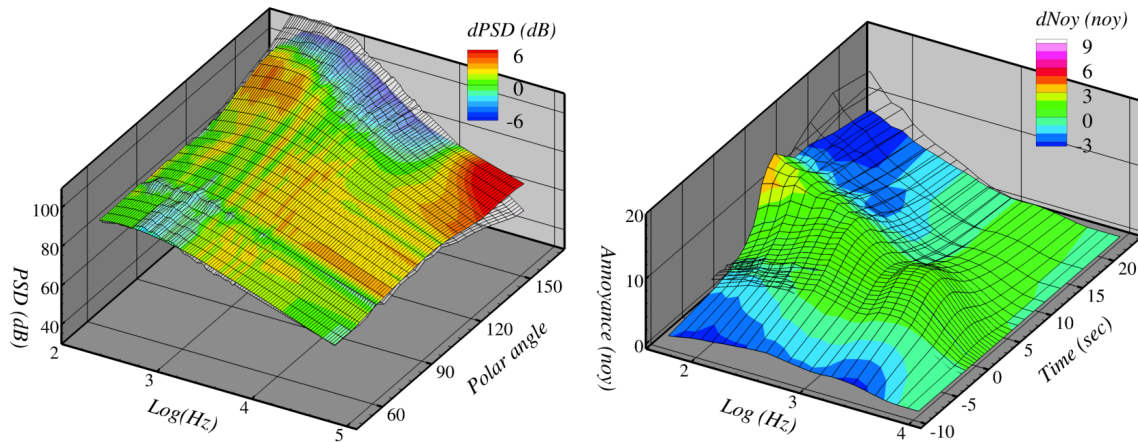


Figure 12 Comparisons of rig data and prediction for jet noise of Conventional aircraft. (a) Carpet plot of difference in PSD at 1-foot, lossless, modelscale; (b) Carpet plot of difference in perceived noisiness (integrand of EPNL) for fullscale flyover. Transparent mesh is NATR data.

Differences in fullscale EPNL for experiments and predictions were computed for all relevant conditions of the experimental 3BB database and are shown in Figure 13 as a function of the core nozzle pressure ratio. The data points are grouped by flow conditions near the three certification points (Approach, Flyover, and Lateral), and the populations of dEPNL in each group are further summarized in

Table 3 by their average and standard deviation. These statistics represent the uncertainty in predicting the jet noise component for the Conventional aircraft at the three certification points.

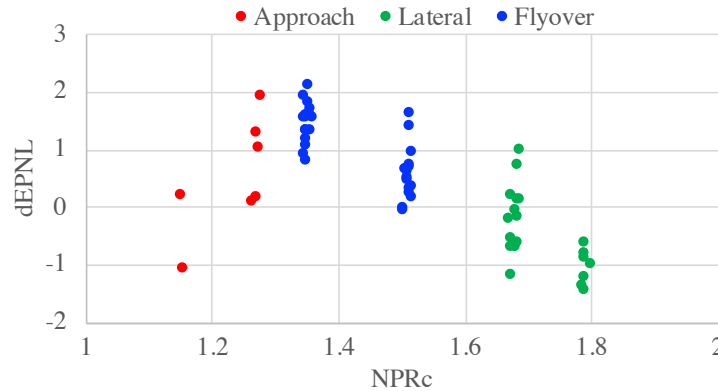


Figure 13 Distributions of dEPNL for Conventional aircraft database, plotted against core NPR.

Table 3 Conventional jet dEPNL summary. Average subtracted from model matches experiment.

Variable	Std.Dev.[dB]	Average [dB]
Jet (lateral)	0.69	-0.01
Jet (flyover)	0.63	1.74
Jet (approach)	0.81	1.07

Supersonic— For the fan noise analysis the process was analogous. Since the QSP fan was only operated with a barrier wall, the noise decomposition routine was simpler. It was assumed the wall completely blocked noise from the aft source and the inlet/aft routine was simplified to return only inlet radiated noise. There were seven hardware configurations used in this data set and 11 fan speeds. Following the recommendation of [18] the inlet broadband noise was modeled using the GE Large Fan Model while the inlet tone noise was modeled using the AlliedSignal Small Fan Model[15]. The differences in geometry can be expected to be responsible for some noise differences, but it was useful to investigate the noise prediction deficiency when the available prediction tools were used. In the QSP fan model, the stages are extremely compact and there is no instrumentation between the stages. For the Heidmann fan model, the entire temperature rise was used for the source amplitude term. The rotor tip and rotational speed, mass flow, blade counts, rotor-stator spacing were all from the front stage. In short, the model was used to predict noise from the front stage as intended, but with the work (temperature rise) from both fan stages. This exercise was not an attempt to find the best way to use the Heidmann model to predict noise of a two-stage fan, which would require a separate activity.

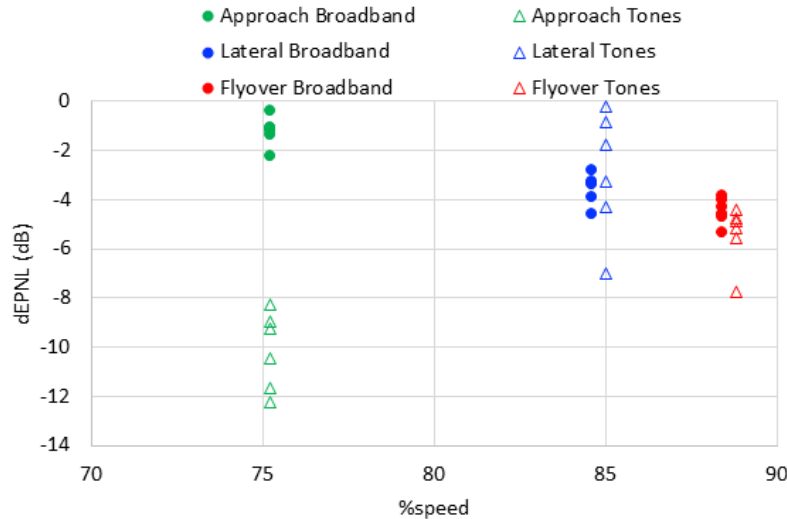


Figure 14 Summarized broadband (circle) and tone (triangle) dEPNL between model and test data for three fan speeds and two stage supersonic fan. Markers offset slightly from actual speed for visualization purposes.

Results are summarized in Table 4. Two main observations are immediately obvious. First, the model significantly underpredicts the noise level from the two-stage fan, and second, the variation in the differences is large, as the model does not include parameters to account for spacing between inlet guide vanes and the first rotor, or for variable inlet guide vane angles, or for other geometric designs incorporated in the QSP model. This led to a very large offset as tone levels especially were significantly underpredicted. The standard deviation is relatively low, by comparison. Mathematically, this could occur because the model predicts the data well, but in this case we know that it does not. The standard deviation is small because the configuration changes made a small difference to the radiated sound. An interesting observation is that the fan inlet broadband noise at approach was predicted quite closely, but this appears to be a case of statistical serendipity.

Table 4 Supersonic fan dEPNL summary. Average subtracted from model matches experiment.

Variable	Std.Dev.[dB]	Average [dB]
Fan inlet tone (lateral)	2.80	-6.12
Fan inlet tone (flyover)	2.35	-2.68
Fan inlet tone (approach)	1.47	-8.60
Fan inlet BB (lateral)	0.38	-5.60
Fan inlet BB (flyover)	0.72	-3.71
Fan inlet BB (approach)	1.25	-0.93

A combined result from the GE HSF and QSP fan model was determined to be a reasonable method for an overall prediction uncertainty, since perhaps either a single or two-stage fan might be chosen as the final design for an efficient and quiet supersonic aircraft engine. To get these values, the six subsonic and seven supersonic fan model dEPNL numbers were combined. Since the single stage fan was overpredicted while the two-stage fan was underpredicted, the combined prediction “offset” is relatively small. The standard deviation, on the other hand, is large. This represents a large uncertainty in the prediction of sound from an engine that might be single or two-stage, and might have geometric or operational features not captured in existing empirical noise model.

Table 5 QSP and GEHSF combined dEPNL summary. Average subtracted from model matches experiment.

Variable	Std.Dev.[dB]	Average [dB]
Fan inlet tone (lateral)	7.13	-0.49
Fan inlet tone (flyover)	2.55	-1.52
Fan inlet tone (approach)	9.46	-0.30
Fan inlet BB (lateral)	4.71	-1.48
Fan inlet BB (flyover)	3.96	-0.28
Fan inlet BB (approach)	3.50	1.11

Looking at the detailed comparisons between data and predictions of jet noise for the Supersonic aircraft, the discrepancies are more egregious than for the Conventional aircraft. This is especially true for the Plug20 configurations that had a real internal mixer. Figure 15 shows how the SAE prediction method over-predicted the noise at peak frequencies while not capturing the high frequency noise attributed to the internal mixer. These errors were found in the perceived noisiness as well. Fortunately, the integral over frequency and duration allowed the two regions of error to mostly cancel and the resulting error in EPNL was not as large as the ± 10 dB errors in the raw spectral directivity. It was, however, generally larger than the Subsonic cases, which can be seen by comparing the population of dEPNL for the Supersonic test cases in Figure 16 with those of the Conventional test cases in Figure 13.

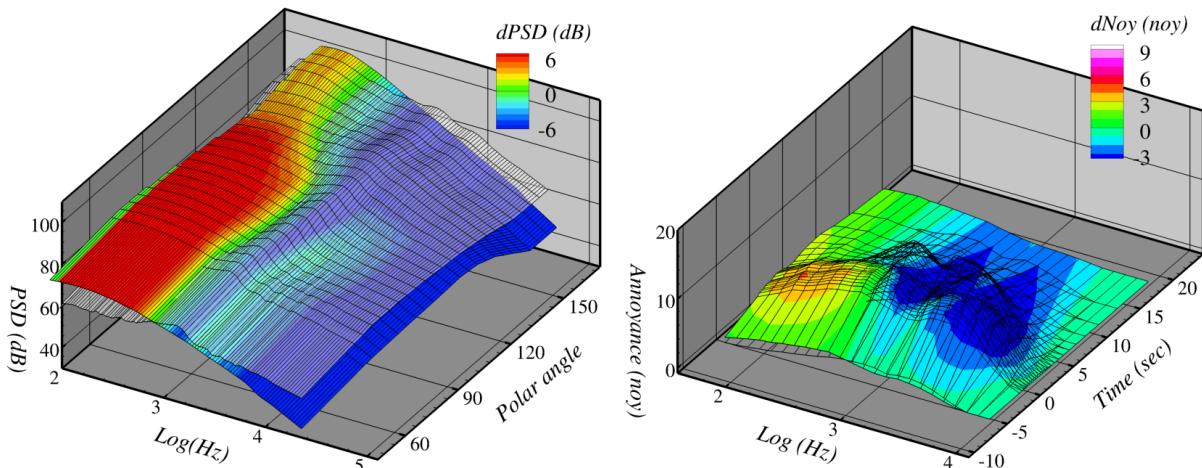


Figure 15 Discrepancies between prediction and experiment for noise of internally mixed Plug20 nozzle at NPRn=1.8, NTRn=1.52, Mflight=0.3. Spectral directivity of (a) PSD, (b) perceived noisiness.

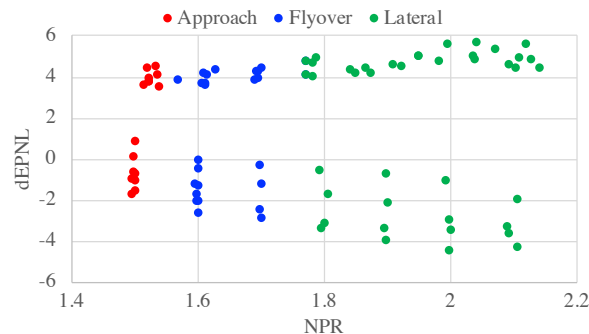


Figure 16 Distributions of dEPNL for Supersonic aircraft database, plotted against nozzle NPR.

The wide-spread distribution of dEPNL in Figure 16 can be seen as a result of an assumption about how much noise is created by the internal mixer/external plug feature. The tight band of positive dEPNL is the discrepancy one would have if the internal mixer perfectly mixed the core and bypass flows without making any noise. This is likely to be an unrealizable design goal for a mixer. The increased spread of dEPNL below zero are the results from different combinations of mixer and plug designs, and represent the discrepancy for realistic, if non-optimized, exhaust systems. In the process of development an actual exhaust system would probably land somewhere in between these. However, the spread does represent the range of possible designs that could be fielded. Although the distributions of dEPNL are not at all Gaussian, the average and standard deviation (Table 6) are being used to summarize the populations of dEPNL for each certification point.

Table 6 Supersonic jet dEPNL summary. Offsets to be subtracted from model to match experiment.

Variable	Std.Dev.[dB]	Average[dB]
Jet (lateral)	3.85	1.68
Jet (flyover)	2.92	1.47
Jet (approach)	1.74	1.61

IV. System-level Aircraft Predictions—Monte Carlo analysis

The inputs of aircraft trajectory, engine settings, etc. required by ANOPP were determined from the various system-level models of the study aircraft. With these inputs ANOPP predicts the benchmark EPNL values for the three certification points. Component EPNL values can also be computed to understand the relative contributions of each noise component to the total EPNL.

Having extracted distributions of dEPNL for the noise components of the Conventional and Supersonic aircraft, we need to see how these components impact the prediction of total aircraft noise, taking into account their relative weights in the total noise. For this a Monte Carlo experiment was implemented, where distributions of random numbers were generated for each noise component with the same average and standard deviation as was found in the above analysis. (Gaussian distributions were used in this study for simplicity.) For each of thousands of evaluations, samples from the distributions of deviations were applied to the benchmark values for each component, a delta-dB at the spectral level. The modified component spectra were combined and propagated to the observer where the EPNL was computed. This process was repeated, building up a population of output EPNL values, until the statistics of the output histograms converged. In these two studies this required 10,000 evaluations each for the Conventional and Supersonic study aircraft.

Conventional—Component and total EPNL values for the Conventional aircraft are given in Figure 17. From the figure we see that the jet component dominates the Lateral and Flyover certification points while the fan component dominates the Approach. Based on this one would expect the uncertainties of the jet component would dominate the total uncertainties. Taking the input component uncertainties shown in Table 7, obtained from the populations of dEPNL computed above, the histogram of cumulative EPNL was found to have a standard deviation of 1.5 EPNdB. This metric is taken as our measure of uncertainty in predicting the LTO noise for a Conventional aircraft using ANOPP.

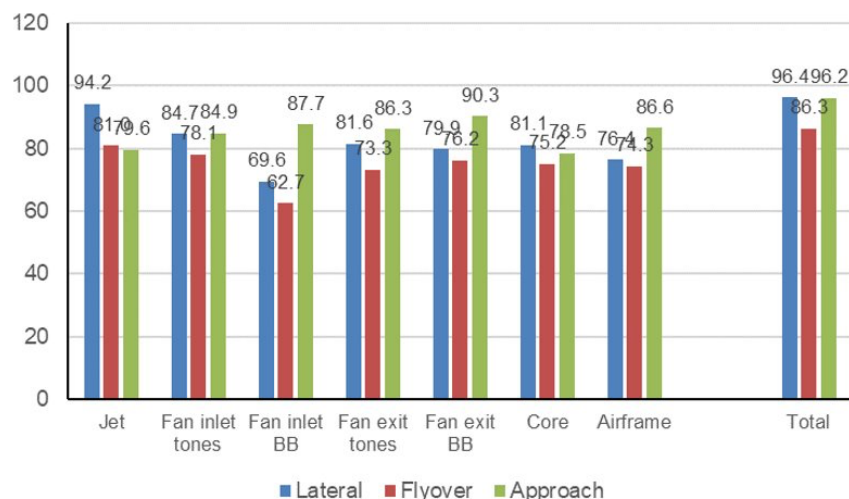


Figure 17 Benchmark component and total EPNL for Conventional study aircraft as predicted by ANOPP.

Table 7 Component uncertainties for Conventional study aircraft at three certification points. Values to be added to ANOPP prediction of component levels.

Variable	Std. Dev. [dB]	Offset [dB]
Jet noise (lateral)	0.63	0.01
Jet noise (flyover)	0.69	-1.74
Jet noise (approach)	0.81	-1.07
Fan inlet tone (lateral)	4.05	-6.08
Fan inlet tone (flyover)	2.21	0.16
Fan inlet tone (approach)	1.87	-9.38
Fan inlet bb (lateral)	1.28	-3.33
Fan inlet bb (flyover)	1.18	-3.71
Fan inlet bb (approach)	3.85	-3.49

Supersonic—Component and total EPNL values for the Supersonic aircraft are given in Figure 18. From the figure we see that the jet component dominates other components at the Lateral and Flyover certification points while the fan inlet tones are comparable to the jet at Approach. One would expect that the uncertainties of the jet component would dominate the total uncertainty of the aircraft. Taking the input component uncertainties shown in Table 8, obtained from the populations of dEPNL computed above, the distribution of cumulative EPNL was found to have a standard deviation of 7.8 EPNdB.

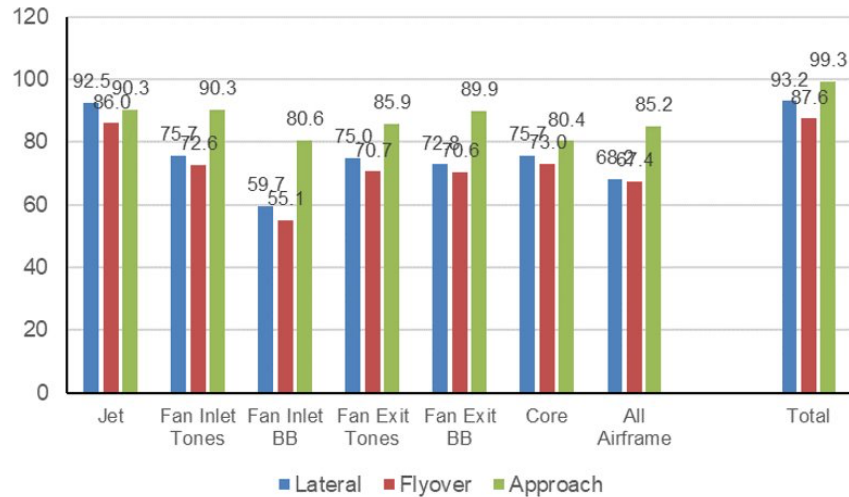


Figure 18 Benchmark component and total EPNL for Supersonic study aircraft as predicted by ANOPP.

Table 8 Component uncertainties for Supersonic study aircraft at three certification points. Offsets to be added to ANOPP prediction of component levels.

Variable	Std. Dev. [dB]	Offset [dB]
Jet noise (lateral)	3.85	-1.68
Jet noise (flyover)	2.92	-1.47
Jet noise (approach)	1.74	-1.61
Fan inlet tone (lateral)	7.13	0.49
Fan inlet tone (flyover)	2.55	1.52
Fan inlet tone (approach)	9.46	0.30
Fan inlet bb (lateral)	4.71	1.48
Fan inlet bb (flyover)	3.96	0.28
Fan inlet bb (approach)	3.50	-1.11

By this measure of uncertainty in predicting the LTO noise for the Conventional and Supersonic aircraft using ANOPP, the *uncertainty* in prediction of LTO noise is *five times greater* for Supersonic aircraft than Conventional. Most of this uncertainty comes from the prediction of jet noise, and the root of that uncertainty is the poor prediction of the noise which comes from internally mixed exhaust systems. However, the component uncertainties of fan noise components in Table 8 are very large, and given the strength of the fan noise at Approach (Figure 18), this uncertainty must be addressed with equal urgency. In both cases, it is the unique characteristics of the propulsion system, required for supersonic flight, that produce the heightened uncertainties as little data exists upon which to base an empirical noise model.

It must be noted that today the missing noise data for unique propulsion configurations may be best acquired using validated physics-based simulations. For jets, large eddy simulations are showing high accuracy, and their resource requirements are comparable to what is required to build and operate physical noise rigs. High-fidelity fan noise simulations, either of the unsteady RANS or full multi-scale simulations, are showing promise and may soon demonstrate enough accuracy to compete with the extremely expensive scale-model fan noise testing methods which have long been used. While physical testing will be required as propulsion system development reaches a

certain maturity, properly validated numerical methods are well situated to produce not only the databases needed for enhanced system models, but also the diagnostic insights in the noise mechanisms that often lead to new noise reduction concepts.

V. Summary

The ability to predict the landing and takeoff noise of proposed aircraft is critical in their developmental phase, especially when the vehicle is not a conventional subsonic transport, such as unmanned multirotor or commercial supersonic aircraft. Inherently, noise prediction methods are much more accurate for conventional subsonic aircraft where historical data exist than on configurations that have unique features producing noise. The increased uncertainty of the noise prediction at landing and takeoff (LTO) conditions is a detriment to not only to manufacturers but also to regulators who set noise standards based on solid, transparent data describing the impact of the proposed aircraft on the community.

NASA has embarked on an effort to reduce the uncertainty in prediction of airport noise for near-term commercial supersonic aircraft, where the aircraft technology has significant differences from conventional aircraft but is still fairly well known. Initial efforts reported herein have created a baseline assessment of the relative uncertainty in noise prediction between Conventional and Supersonic aircraft. The method of quantification starts by identifying relevant aircraft designs for which enough information exists to determine trajectories and engine conditions for landing and takeoff operation. This information is required to predict the noise as measured using current certification metrics. The prediction methods most appropriate for these configurations were identified and model-scale experimental far-field noise data of comparable propulsion elements were found. The discrepancies between the experimental data and predictions of noise were collected to build a distribution representing the uncertainty in the ability to predict the noise. This distribution was then fed through the noise prediction system to quantify the uncertainty in predicting the noise of the total aircraft in certification flights.

For the baseline activity described here, data were obtained from previous rig tests at NASA, but in the future this data may come from physical rig tests or from validated physics-based simulations. Going forward, the methodology employed in the paper will be used to quantify progress in the research effort to reduce the uncertainty in noise prediction of supersonic aircraft.

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