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INITIAL DEVELOPMENT AND CALIBRATION OF A DESIGN GUIDE FOR JET NOISE REDUCTION

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ABSTRACT

This paper describes the initial development of a design guide for jet noise reduction, utilizing the NASA/MTC Technologies jet noise prediction capabilities for baseline and complex suppressor geometries. The idea of a noise reduction design guide goes back (at least) to the early 1970s, when the NASA Lewis Research Center advisors suggested that such a product for supersonic jet noise be a deliverable under the Supersonic Transport Noise Reduction Technology Program, conducted by General Electric for the Department of Transportation. The "Design Guide," was a much greater challenge than recognized at that time, and the intended product does not yet exist. This Design Guide idea discussed herein is to be a useful analytical computer tool, not just a compilation of information. It is also intended to be a "living" tool, subject to improvements to be introduced as justified and traceably documented.

INTRODUCTION

NASA has long been involved in aircraft noise research and technology development and has on some occasions carried these activities to the level of engine system and even flight tests. Because of the severe reductions NASA has experienced in its aeronautics budget, its current program is limited to rather basic and fundamental studies with no engine development. Some have come to view NASA sponsorship of engine development as "corporate welfare," and that NASA should focus its limited resources at Technology Readiness Level 6, system/subsystem model or prototype demonstration in relevant environment, or lower. It is our intention that the Design Guide would couple the decades of design experience with recent advances in technology to produce a unified design tool documented by comparisons with experimental data in an "encyclopedic" manner.

We have noise codes for all propulsion noise components for turbojet and turbofan engines, which have been shown to integrate with system design and mission analysis codes. In this paper we focus mainly on jet exhaust noise components: mixing and plug flow separation; shock interaction noise and internally-generated "core" noise are included conceptually, but no examples are included in the present paper. We've demonstrated that our noise tools integrate with other design tools with ease and flexibility.

What is it? - The Design Guide we now envision is a framework whereby our predictive models for engine noise are used to perform design analyses. Such a framework would serve as a vehicle for "knowledge sharing" on engine noise prediction and reduction. This would enable the user to evaluate design concepts and particularly to investigate noise sensitive features. Leverage is highest if design approaches for issues such as noise suppression needs and methods, etc., can be addressed early in the design process. In addition to the noise models, the user could be enabled to access other design tools to get weight and performance (e.g., thrust loss) estimates as well as noise. (These other design tools could include a link to NASA's Numerical Propulsion System Simulator, NPSS[1].) The model would be configured to deal with a wide range of potential design options, whereas current approaches tend to fragmented, i.e. applicable to subsonic or supersonic cruise aircraft but not both. Our approach would enable the assessment of such advanced concepts as blended wing/body aircraft, transonic aircraft such as Boeing's recently-cancelled Sonic Cruiser concept, supersonic business jets, distributed exhaust nozzles, exoskeletal engines featuring vanelsss counter-rotating turbomachinery and inherent jet noise benefits, and a wide range of other concepts not yet defined.

In addition to the predictive models, the system documentation would include quantitative comparisons with the available base of experimental data. Building this up would be a major effort, but would provide the needed credibility for the system. The Guide would also be a powerful tool for qualified research users, who would use the models' capabilities for comparisons with experimental data, to evaluate a concept of interest against the available database and compare with previous analyses of similar configurations, and assess experimental data quality and facility issues.

How would it work? - Research users willing to share the results of their analyses with the system owner/operator (assumedly NASA or a NASA-supported non-profit organization) would receive a

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discount that would be further increased if the owner/operator could publish the results. In this way the research users would aid in the continued development of the database. These research comparisons would span the range from small model tests to full-scale ground and flight tests. Results from continuing research on noise reduction concepts could be incorporated to allow competing concepts to be evaluated against consistent baselines; the benefits of many noise reduction approaches have in the past been overstated due to comparisons with inappropriate baselines.

Initially the system would be assembled from the present models, and validating comparisons made with the most pertinent available data, mainly recent test results; of necessity this would include a critique of each facility and test. A very easy-to-use graphical user interface could be developed to be the system's "window to the world," with the different degrees of access controlled by the owner/operator, depending on the user's approved qualifications.

Annual updates to the predictive models would be made based on the studies performed by the owner/ operator and participating research users. An annual report would be issued, documenting changes and showing typical, representative validating comparisons. This annual report would include a quantification of the demonstrated accuracy of the model for different situations to enable quantitative assessment of the risk of a new product not meeting its noise goal. This quantification of uncertainties should be very valuable to industry; the cost of missing a noise goal is very high.

How does the Noise Reduction Design Guide relate to ANOPP/AVATAR? - The Design Guide would not be a competitor to the Aircraft Noise Prediction Program (ANOPP)[2] or the proposed Advanced Vehicle Analysis Tool for Acoustics Research (AVATAR) programs. Most, if not all of the noise predictive models that would be in the initial design guide are also available in ANOPP or intended to be added. Some of the jet noise models already go beyond the ANOPP paradigm by breaking down the mixing noise problem into different regimes and taking into account source distribution. This breakdown is intended to facilitate the future evolution to even more fundamentally based models for AVATAR. A strong point of our approach is the methodology for breaking down engine noise into its components for further analysis, a necessary step in improving/evolving the component noise models.

What are the benefits to NASA and industry? - Knowledge Sharing: The approach suggested herein would build and grow a database and support the continuous improvement of predictive models. This base would include the experiences of the past in a manner facilitating their application to new problems in a meaningful way. This process of knowledge sharing would be enhanced by interaction of both design and research users with the system's development and maintenance team. A common basis for comparisons would be provided; use of the same predictive tools by proponents of competing concepts would provide a level playing field and allow true differences to be emphasized and investigated. Traceable technology evolution would be fostered; the predictive models are formulated on basic physical principles, with necessary empiricism introduced to yield computational efficiency and include real-world effects not readily amenable to theoretical analysis. Thus the models include scaling effects and are applicable throughout the project cycle, from small scale model tests to full-scale engines, even including flight effects. Controls would be developed to assure the industrial partners/participants that their own proprietary methods and data are protected.

BACKGROUND

This capability has been developed by MTC Technologies (MTCT), mainly with the support of the NASA Glenn (GRC) and Langley (LaRC) Research Centers, much of it as a subcontractor to General Electric (GE). The initial work was directed toward two-dimensional mixer ejector (2DME) nozzles under the High Speed Research Program.[3] Similar methods were then applied to internal mixer nozzles in a brief study not yet reported. Next earlier separate models for conventional and inverted-velocity-profile coannular jets were coupled together,[4] and along with the 2DME code, were utilized to investigate suppression requirements and approaches for a supersonic business jet.[5] With temporarily declining interest in supersonic aircraft, the emphasis switched to high-bypass ratio coannular nozzles, including the effects of nozzle exit chevrons.[6] More recently we have extended these relations to higher jet velocities and lower bypass ratios and generalized the suppression relations to include other inner and/or outer stream suppression devices on a dual stream nozzle; this also includes the effects of convergent and convergent-divergent nozzle terminations and plug tip geometry on shock noise. In the final reported step, we have shown that these dual-stream relations limit properly and agree with the experimental data for single-stream nozzles.[7] The philosophy and evolution of our modeling approach along with extensive references are included in this recent paper.[8] Throughout these studies data quality and flight simulation issues have been investigated in considerable detail.

With these tools in hand, we can deal with a wide spectrum of aircraft and engine types in a consistent manner. Of course for practical application we must show that the set of procedures does agree with data for all of these configurations, and we are doing this. Some sample comparisons are shown in this paper with experimental data from several configurations and test facilities.

APPROACH

This FOOTPR framework[8] has been used by MTCT in developing noise prediction models for NASA and the industry throughout these studies. The approach MTCT has employed in these tasks is to use an initial prediction model based on analogy to simple circular jet theory.[9-12] We assume that even for complex geometries subsonic jet noise will correlate in a manner analogous to the classical model, if the proper characteristic velocity and characteristic length can be established. These initial models are used to estimate the relative contributions of each noise component at each frequency and angle, and the resulting corrections are applied to the experimental data, yielding what we refer to as "experimental/extracted" spectra at each angle. These experimental/extracted results are then correlated empirically to yield more accurate models than those originally used. Repeating this process starting with the already improved models further improves the ultimate accuracy of the final predictive model; sometimes several iterations are worthwhile.

FEATURES OF MODEL

Any jet mixing noise source region is treated as a round jet of appropriate nozzle exit area at the appropriate conditions. For a general mixing region the overall level, uncorrected for refraction, UOL, is given by the following:

$$UOL = C + 10 \log [(\rho_{amb}/\rho_{ISA})^2 (c_{amb}/c_{ISA})^4] + 10 \log (A/R^2) + 10\, \omega \log (\rho/\rho_{amb}) + N \log (V_e/c_{amb}) - 5\, k \log [(1 + M_c \cos \theta_{cor})^2 + \alpha^2 M_c^2] \quad (1)$$

Where C is the coefficient and N the velocity slope, both determined experimentally and then correlated, A is the appropriate nozzle exit area, and ρ is the fully-expanded jet density for that region. The convection coefficient k has been taken as 3 in our past work; our current model uses k = 4. In our earlier work[4-5] we have assumed $\alpha = 0.2$, but it now appears that $\alpha = 0.3$, and this is incorporated in the model. The effective velocity for noise generation, V_e, is in most cases calculated as follows:

$$V_e = V [1 - M_f (c_{amb}/V)]^{1/2} \quad (1a)$$

Where V is the characteristic velocity for this region.

The convective Mach number, Mc, is calculated from the following relation:

$$M_c = n_c [(V/c_{amb}) - M_f] \quad (1b)$$

Until our more recent work[6-7], n_c was assumed constant at 0.62, as has been assumed in many early models. We found that using a variable n_c was quite helpful. Such variations could be related to flow-acoustic interaction, or "flow shielding." These considerations are explored more thoroughly by Gliebe, et al.[13]

The effect of refraction is incorporated in the spectral directivity relations in an empirical manner, but crudely in the direction suggested by theory. The relative sound pressure level, SPL – UOL, is correlated as a function of the effective directivity angle, θ', and the logarithmic Strouhal number, log S, where the Strouhal number is calculated as follows:

$$S = (f\, D/V_e)\, (T/T_{amb})^{0.4\,(1 + \cos \theta')} \quad (2)$$

Where D is the characteristic diameter, typically $(4A/\pi)^{0.5}$ and T is the region total temperature. The effective angle, to account for refraction effects, is calculated as follows:

$$\theta' = \theta_{cor}\, (V/c_{amb})^{0.1} \quad (2b)$$

It is by use of this effective directivity angle that in a very simple and approximate way refraction is accounted for. It is assumed that the spectra for widely differing jet velocities are similar at this adjusted angle rather than at the same geometric angle. This approach, in conjunction with the analytically modeled convection effect in Eq. (1), correlates the variation of SPL with frequency and angle rather well, as shown earlier[3-7].

When comparisons are made with experimental data, it must be accounted for that noise measurements are typically made at a distance far enough from the engine/model to be in the far field of any individual noise source region, but not far enough away to treat the entire exhaust plume as a point source at the center of the nozzle exit plane, as is usually assumed in determining the directivity angle. The prediction procedures must take this difference into account. The relationship of the actual (corrected) source-to-observer distance, R_{cor}, to its apparent value, R, for a source at distance, X_s, downstream of the exit plane is as follows:

$$(R_{cor}/R)^2 = 1 + (X_s/R)^2 + 2\, (X_s/R) \cos \theta \quad (3)$$

The prediction is made at the corrected angle, θ_{cor}, with the corrected distance, R_{cor}.

In reality the noise received at any point in the far field comes from multiple locations within the source region as a function of frequency, but reasonably accurate predictions can be made with a simple model wherein the source location variation with frequency is assumed to be less important than the variation with angle. These corrections differ for each component, because the source positions are different. The simplification of assuming no change in source location as a function of frequency at each far field angle is

generally adequate because each component contributes only over a limited frequency range; however, it is quite feasible to introduce frequency dependence if needed, as it might very well be to deal with airframe installation effects. These source locations must be accounted for in the correction for free jet shear layer effects, as shown by Stone, et al.[6-7]. The magnitude of the corrections is not widely appreciated, but for the large scale mixing noise, corrections of 1.0 dB and 10 deg are typical for both model and engine test facilities.

SAMPLE EXTRACTION

A sample of the component noise extraction procedure for a very high bypass (BPR = 13) case[12] in Fig. 1 for nondimensionalized mixed jet velocity V_{mix}/c_{amb} = 0.766 at static conditions (M_f = 0.0). Component noise separation is shown at a directivity angle, θ = 90 deg. The measured noise spectra (SPL_{exp}) are shown by the heavy solid curve; the large scale (merged) mixing noise spectra ($SPL_{L,EE}$) are indicated by the ○ symbols connected by the dashed curve; the small scale mixing noise spectra ($SPL_{S,EE}$) are indicated by the □ symbols connected by the dotted curve; the transitional/intermediate/premerged mixing noise spectra ($SPL_{T,EE}$) are indicated by the ◇ symbols connected by the dot-dash curve; and the plug separation noise spectra ($SPL_{P,EE}$) are indicated by the Δ symbols connected by the dash-double-dot curve. Data are not usually plotted if $SPL_{compnent,EE} - SPL_{exp} \leq -10.0$ dB, since such data are not meaningful; where such low values are shown, it is simply to show that the particular component does not contribute significantly at that angle. It should be noted that regardless of whether or not component levels are plotted, using this method of extraction, the antilogarithmic sum of the components always equals the total SPL, whether experimental or predicted. The large scale mixing dominates low and middle frequencies, while small scale and transitional contributions are significant in the middle to high frequency range, and plug separation noise is very strong at high frequency.

Comparison of these extracted component levels with the corresponding predicted levels is shown in Figure 2 for this same case. The agreement is quite good for all components. Since increasing BPR is one approach to noise reduction, it is important to demonstrate that the predictive model works well here. Such extractions have been performed over a wide range of geometric and aero/ thermodynamic conditions, and the resulting component levels and spectral directivities are correlated.[6-7] We intend to continue such analyses for all noise components as the Design Guide evolves.

NOZZLE/FACILITY COMPARISONS

One part of the Design Guide development process is to make comparisons of baseline and suppressor nozzle data from specific test facilities with the predictive model. For example very similar nozzles were tested in both GRC[14] (Fig. 3) and LaRC[15] (Fig. 4) free-jet flight simulation facilities. It was shown[6-7] that a relatively high jet velocity, the experimentally determined coefficients for the various noise components were essentially the same, except for plug separation noise, which was significantly more evident in the GRC facility. On the other hand, the experimental data remained consistent to considerably lower jet velocities in the GRC facility. This underscores the fact that there are no perfect test facilities, and it is only by quantitative comparisons between them on an absolute basis are necessary to make test results meaningful, especially for suppressor nozzles. Even if two facilities show good agreement for baseline nozzles, it is conceivable that the facility background noises may become exposed for effective suppressor nozzles, and they may be different for the two facilities.

MOVING TOWARD GENERALITY

In our recent work we have begun to unify the empirical approaches for different type nozzles, and have done so for single-stream and dual-stream baseline and suppressor nozzles of approximately (except suppressor elements) axisymmetric geometry. In our most recent previous publication we showed that the relation for large scale mixing noise for these nozzles was very similar to that of the much more complicated 2DME systems.[7] What remained to bring this all together was to replace the "delta" approach for suppressor nozzles with a relation for "effective velocity" for these devices instead. We expect that in order to incorporate ejector effects, the mixing area ratio will also be a factor. The preliminary relation developed for dual-stream suppressors is given by the following:

$$V_L/V_{mix} = PR_I^{-0.24}\, PR_O^{-0.0725}\, SAR^{-0.093} \qquad (5)$$

Where V_L is the effective (reduced) mixed jet velocity for the suppressor, PR_I is the perimeter ratio (suppressed/unsuppressed) for the inner stream, PR_O is the perimeter ratio for the outer stream, SAR is the product of the suppressor area ratio of the two streams. This formulation appears, based on limited tests to actually do a better job of predicting the noise level reduction than the previous "delta" approach, and it also correctly predicts the fairly slight change in spectral directivity characteristics that the previous model neglected. Comparisons at θ = 90 and 150 deg for a BPR = 5 nozzle with core and fan stream chevrons are shown in Figure 5 to demonstrate these points.

SAMPLE APPLICATION

At NASA GRC, an assessment was made of the baseline noise characteristics of a reference airplane against which to evaluate the potential benefit of various noise suppression technology developments under the Quiet Aircraft Technology Project and the Vehicle Systems Program. The reference airplane is the B777-200 with GE90-85B engines. These analyses were conducted with a specific set of noise tools included in NASA's ANOPP[1] system for noise including our jet noise model. A non-proprietary NASA simulation of the GE90-85B reference turbofan engine was developed using the NPSS[2] engine cycle code and the Weight Analysis of Turbine Engine (WATE)[16] aeromechanical analytical code.

The appropriate NPSS case files, functions, and viewers were developed so that NPSS could generate the so-called "engine state tables" appropriate for use in ANOPP. Using the NPSS-generated engine state tables, ANOPP component source noise models were developed for the following sources of the B777-200/GE90-85B system: fan inlet and exhaust (revised Heidmann method, broadband and interaction tones); jet (revised Stone method for coannular jets); core (Emmerling GECOR method); turbine (Smith and Bushell method); and airframe (Fink method). Lossless SPL spectra are computed for each aircraft noise source at various yaw angles and power settings based on thermodynamic, aeromechanical, and aircraft data.

These lossless spectra are shown in Fig. 6 for maximum sideline takeoff power at $\theta = 50$ and 120 deg; fan inlet noise is dominant in the forward quadrant at $\theta = 50$ deg (Fig. 6 (a)), while jet noise and aft fan noise are dominant in the rear quadrant at $\theta = 120$ deg (Fig. 6 (b)); but any suppression of those components would expose core noise, which is of comparable magnitude in the middle frequency range. Noise spectra are analytically "flown" over the three-point listening references on the ground, and propagation effects are calculated. Tone-corrected Perceived Noise Level (PNLT) versus yaw angle distributions, and PNLT-time histories were also computed, as shown in Figs. 7 and 8, respectively. The spectra and PNLT vs. angle plots are shown on a lossless 150-ft radius basis. The time history includes source-to-observer propagation effects and is adjusted for the proper number of engines. (Of course, per the EPNL definition, only PNLTs within the 10 PNdB-down region are used, but I show PNLTs much lower just to show all of the sources and their relative magnitudes.)

Noise footprints were also calculated based on a conventional takeoff and landing, vertical-plane trajectory. The trajectory is an analytical "touch and go" operation so that a continuous footprint before and after the runway may be computed. Engine throttle settings used throughout the trajectory are as follows: ground roll through sideline to cutback: 100% low-pressure spool speed (N1); community cutback (from 18,000 ft through 28,000 ft from brake release): 85% N1; maximum continuous climb: 95% N1; approach to touchdown: 50% N1.

Footprints were calculated for Effective Perceived Noise Level (EPNL), A-weighted SPLs and Sound Exposure Levels (SELs). Analytical observers are located on a square grid every 500 ft, and EPNLs are computed at each point, and contours of constant EPNL are then interpolated. Fig. 9 shows an airport planview plot of the certification EPNLs near the airport. The contour levels shown are 80, 90, and 100 EPNdB. A 12000-ft runway is shown by the heavy line, the approach and takeoff observers are marked on the extended centerline, and the sideline is marked with a dashed line. The effects of throttle changes and trajectory can be seen. The areas of these footprints are 21.1, 4.2, and 0.9 mi^2, respectively. A larger grid than that shown in the figure is of course necessary to resolve the footprint areas of the two lower levels.

If the noise reduction design guide were available for all the engine noise components, results such as this would be backed up by statistical properties of the predictive models and reference to experimental versus prediction comparisons for each noise component for as nearly as possible similar conditions. The level of test for which these validations are given, whether small-scale model, full-scale engine, or intermediate technology testbed would allow the designer to assess the level of confidence in the predictions.

CONCLUDING REMARKS

The concept of a noise reduction design guide is discussed herein, with particular emphasis on jet noise, since it is that component on which most of our efforts have been devoted, and where we have the greatest confidence in the approach proposed. The prediction models for jet noise have been the subject of continuous improvement over the last few years, and we have pointed out areas where the model can be generalized further. A general model, applicable to any type exhaust nozzle is clearly quite feasible now, but would still require work.

We have also shown how the noise models can be incorporated into an inter-disciplinary design tool. The envisioned design guide would include these features, so that the total impact of alternative noise reduction approaches could be evaluated. The procedures presented and discussed herein lays the groundwork for a comprehensive jet noise design guide, hopefully to be developed in the future and possibly including design correlations for the aerodynamic performance also.

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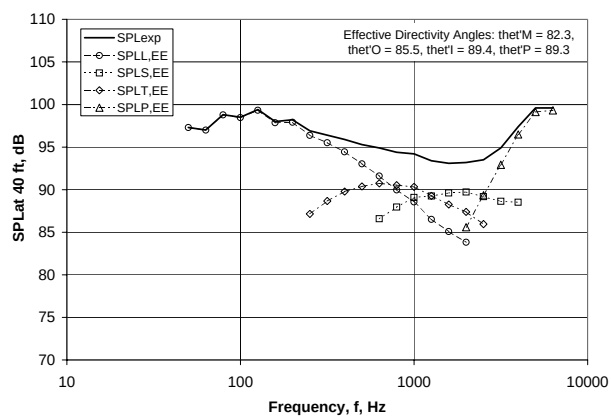


Figure 1 –Component Spectral Extraction for High-Bypass Nozzle with V_{mix}/c_{amb} = 0.766 and M_f = 0.00 at Directivity Angle, θ = 90 deg

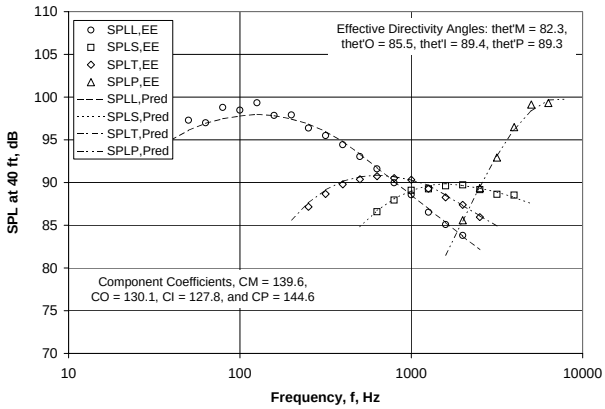
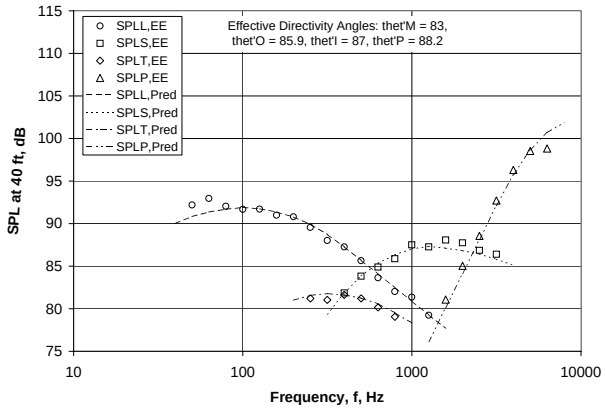
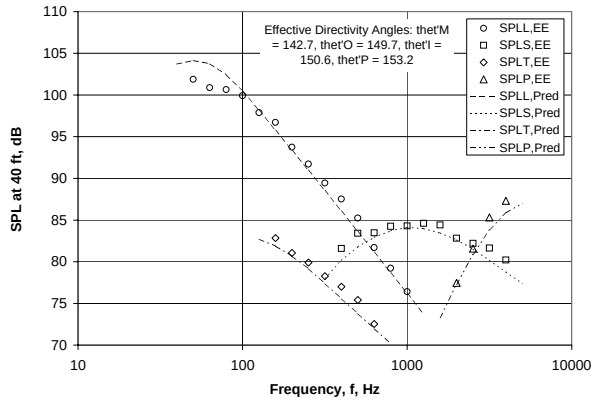


Figure 2 – Comparison of Extracted and Predicted Spectra for High-Bypass Nozzle with V_{mix}/c_{amb} = 1.92 and M_f = 0.00 at θ = 90 deg

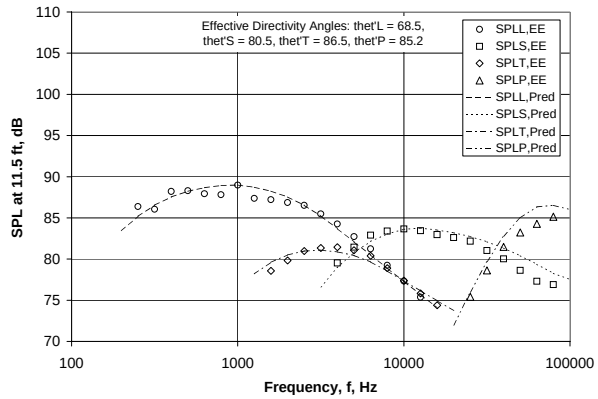


(a) Directivity Angle, θ = 90 deg

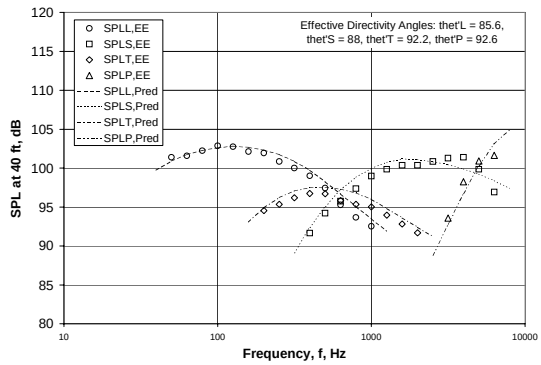


(b) Directivity Angle, θ = 155 deg

Figure 3 – Comparison of Extracted and Predicted Spectra for GRC Facility: BPR ~ 8 Coannular Plug Nozzle, V_{mix}/c_{amb} = 0.798, M_f = 0.28

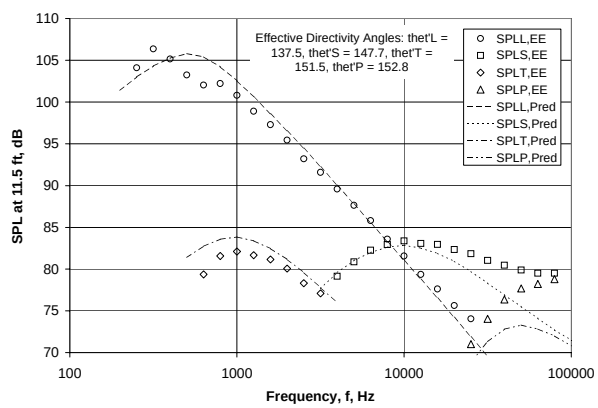


(a) Directivity Angle, θ = 90 deg



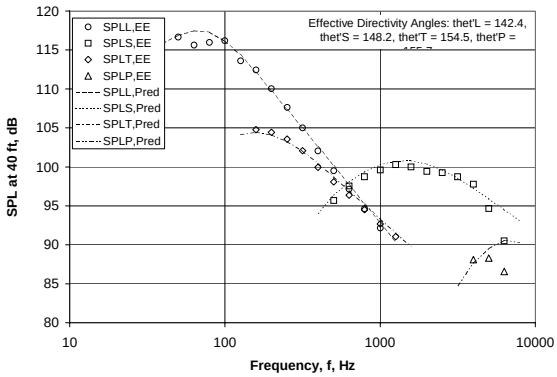
(b) Directivity Angle, θ = 154 deg

Figure 4 – Comparison of Extracted and Predicted Spectra for LaRC Facility: BPR ~ 8 Coannular Plug Nozzle, V_{mix}/c_{amb} = 0.810, M_f = 0.20



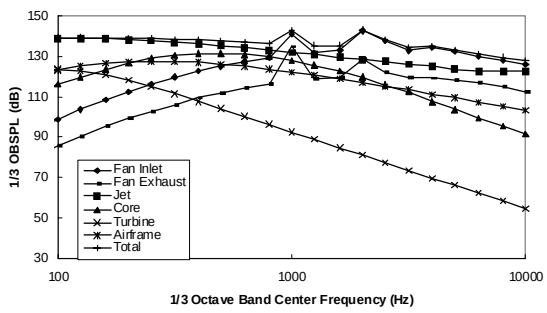
(a) Directivity Angle, θ = 90 deg

Figure 5 – Comparison of Extracted and Predicted Spectra for BPR = 5 Inner and Outer Stream Chevron Nozzle at V_{mix}/c_{amb} = 1.09 and M_f = 0.28

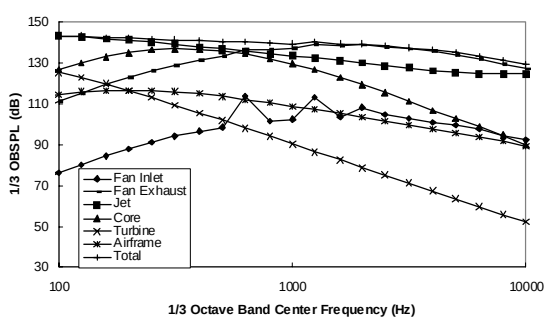


(b) Directivity Angle, θ = 150 deg

Figure 5 – Comparison of Extracted and Predicted Spectra for BPR = 5 Inner and Outer Stream Chevron Nozzle at V_{mix}/c_{amb} = 1.09 and M_f = 0.28



(a) Spectra at θ = 50 deg



(b) Spectra at θ = 120 deg

Figure 6 – Predicted Lossless Component Noise Spectra for Baseline Airplane (B777-200/GE90-85B) at Takeoff (Sideline) Power

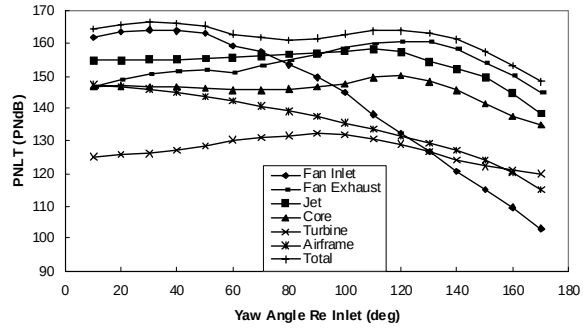
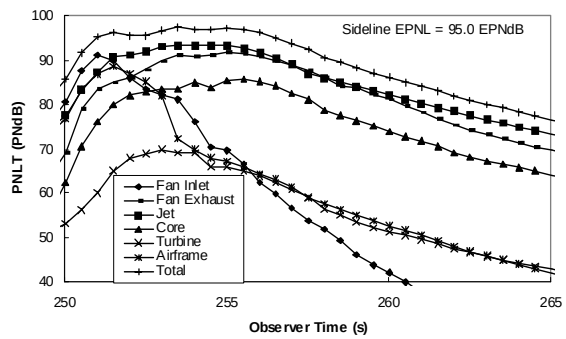


Figure 7 –PNLT Versus Angle for Baseline Airplane (B777-200/GE90-85B) at Takeoff



(Sideline) Power

Figure 8 – PNLT Time History for Baseline Airplane (B777-200/GE90-85B) at Takeoff (Sideline) Power

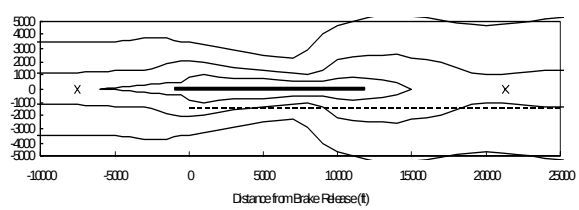


Figure 9 – Baseline Airplane (B777-200/GE90-85B) EPNL Footprints