Applications of Response Surface-Based Methods to Noise Analysis in the Conceptual Design of Revolutionary Aircraft

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Due to the growing problem of noise in today's air transportation system, there have arisen needs to incorporate noise considerations in the conceptual design of revolutionary aircraft. Through the use of response surfaces, complex noise models may be converted into polynomial equations for rapid and simplified evaluation. This conversion allows many of the commonly used response surface-based trade space exploration methods to be applied to noise analysis. This methodology is demonstrated using a noise model of a notional 300 passenger Blended-Wing-Body (BWB) transport. Response surfaces are created relating source noise levels of the BWB vehicle to its corresponding FAR-36 certification noise levels and the resulting trade space is explored. Methods demonstrated include: single point analysis, parametric study, an optimization technique for inverse analysis, sensitivity studies, and probabilistic analysis. Extended applications of response surface-based methods in noise analysis are also discussed.

I. Introduction

To meet NASA's ambitious long-term goal of reducing transport aircraft noise by a factor of 4 relative to 1997 state of the art, there has been increasing emphasis on bringing noise considerations into the conceptual design phase of revolutionary configurations. In addition, the increasing influences of airframe noise and propulsion-airframe aeroacoustic effects demand that low noise vehicle technologies and design practices no longer be restricted to the powerplant, but expand to encompass the whole vehicle system. Properly characterizing vehicle noise, however, requires knowledge of the relative proportions of each discrete noise source, knowledge that often is not available or carries a high degree of uncertainty in the conceptual design phase.

Traditional aircraft noise analysis consists of two distinct steps. The first is to characterize the engine and airframe as a collection of discrete acoustic sources, each represented by a sound pressure level (SPL) distribution in decibels (dB) that varies with 3rd octave frequency and spherical directivity. The SPL distribution of each source may be obtained by prediction from analytical tools, or from test data. Turbofan engines are usually broken down into five sources: inlet radiated fan noise, exhaust radiated fan noise, combustor or core noise, turbine noise, and jet noise. Distinct sources of a transport airframe include: wing trailing edge, flaps, slats, and landing gear. When all the sources are characterized, the second step in the analysis is to fly them along the vehicle's flight path and propagate the emitted noise to ground observers via ray tracing methods. The propagation analysis can take into account the effects of atmospheric attenuation, ground absorption, and reflection. The noise at the observer may then be converted into a certification or community noise metric that can take into account the human response to frequency, discrete tones, and duration of the noise event.

Due to the logarithmic nature of noise measurement, the total vehicle noise will be dominated by the strongest sources and less influential ones, even by a few decibels, will make very little of a contribution. For example, a noise source with an SPL 10 dB below another will increase the combined noise by less than 1/2 dB. Total vehicle noise prediction and subsequent assessment therefore demands that the relative proportions of the noise levels of all the discrete sources be accurately predicted. It is also important that noise reduction technologies and design concepts be evaluated in the context of the entire system to assess their community noise impact. Failure to do so may lead to misleading conclusions about the influence of a particular source or the effectiveness of a technology or design concept on the vehicle. Such accurate system predictions often do not exist in the conceptual design phase due to uncertainty in source level predictions, and lack of sufficient technology and vehicle definition. For these reasons, it is useful to develop and explore a trade space in which different source level proportionalities may be

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examined, and effects of source level variations may be assessed. This exploration can help a designer or program planner better understand the system and make intelligent decisions despite the lack of concrete information. It is also useful to extend this trade space to encompass effects of aircraft geometry, engine operation, and flight path characteristics on the vehicle noise levels. This trade space exploration is facilitated by the use of response surfaces as they convert complex models into simple polynomial equations that may be rapidly evaluated. This simplicity and speed enables many of the activities common in conceptual design such as rapid point evaluations, parametric studies, optimization, sensitivity studies, and probabilistic analysis.

II. Blended-Wing-Body (BWB) Transport Model

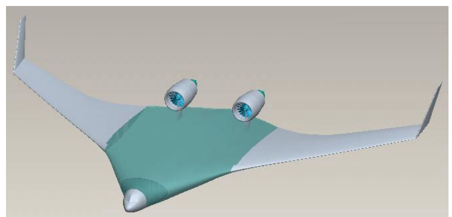

Figure 1. Notional 300 Passenger Blended-Wing-Body Model.

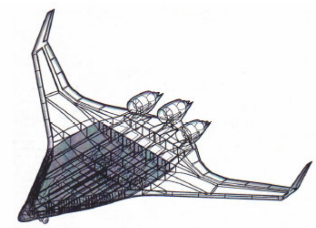

Figure 2. Boeing 450 Passenger Blended-Wing-Body.[1]

Figure 1 shows a notional BWB-like transport. The geometry was created by sizing down the Boeing 450 passenger (pax) version, shown in Fig. 2, to accommodate 300 pax. The three podded engines of the BWB 450 were replaced by 2 General Electric GE-90-like engines. The aircraft sizing and synthesis code FLight OPtimization System (FLOPS) was used to size the 300 pax BWB-like aircraft for a transport mission with a design range of 7,500 Nmi, predict weights, and calculate detailed takeoff and landing flight trajectories. GE-90-like engine state tables were produced through engine cycle and aeromechanical analyses with the Numerical Propulsion System Simulator (NPSS) and the Weight Analysis of Turbine Engines (WATE) codes. Low speed aerodynamic data from wind tunnel tests of the BWB 450-1L model[2] were used for the takeoff and landing flight path predictions.

III. Baseline Noise Prediction

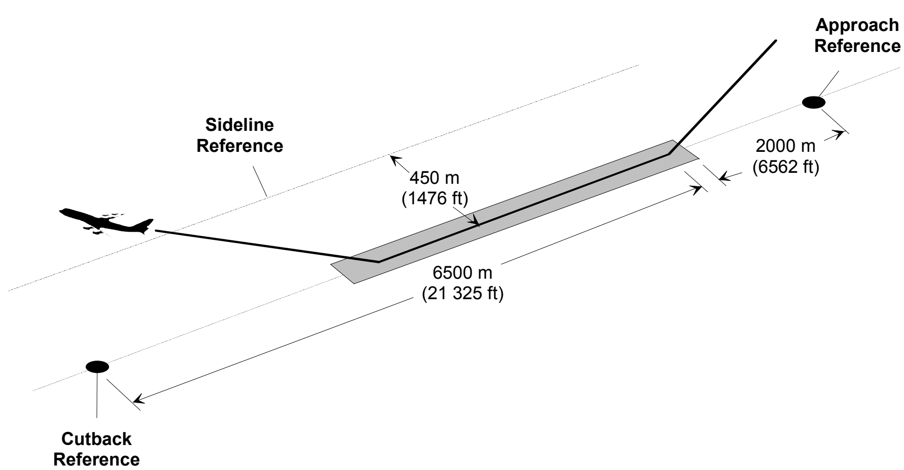

Figure 3. FAR 36 Stage 3 Noise Certification Procedure and Measurement Points.

Aircraft in the U.S. are currently certified under FAR 36 Stage 3 regulations[3]. Figure 3 illustrates the Stage 3 certification procedure and the locations of the measurement reference points. On takeoff, the aircraft must climb at full power and takeoff flaps to an altitude of at least 984 ft (for two engines) at which point it may execute a noise abating cutback maneuver as long as the thrust is sufficient to maintain a 4% climb gradient or an engine-out level climb. On approach, the aircraft must fly along a three degree descent slope at constant speed with gear and flaps down. For both takeoff and landing procedures, the aircraft must be at its maximum weight that it is to be certified for. The Effective Perceived Noise Levels (EPNLs), in EPNdB ,of the takeoff procedure are measured at the cutback and sideline observer points. The EPNL for the landing procedure is measured at the approach point.

NASA's Aircraft NOise Prediction Program (ANOPP) was used both for predicting individual source noise levels and certification EPNLs for the BWB/GE-90-like system. The certification flight trajectories and engine state tables, predicted in FLOPS, NPSS, and WATE, were used in the noise prediction. The engine noise sources considered were inlet radiated fan noise (fan inlet), aft radiated fan noise (fan exhaust), core noise, and jet noise.

Turbine noise was neglected since it usually plays an insignificant role next to the other sources. Fan inlet and exhaust noise were predicted in ANOPP using the General Electric (GE) revised version of the Heidmann Fan Method[4]. Acoustic treatment corrections were applied using the GE method developed by Kontos et al.[4] Core noise was predicted using R.K. Matta's method[4] and jet noise was predicted with Stone's revised method for co-annular jets[4]. All four engine noise sources were then calibrated to publicly available GE-90 EPNL levels as reported by Gliebe[5]. The engine size and flight path from a Boeing 777-like FLOPS model were used for the calibration since the 777 is the normal operating environment for the GE-90. This calibration was necessary in order for the GE-90-like noise model to closely match the noise levels of the real GE-90 engine.

A detailed BWB airframe noise prediction was still in progress at the time of writing so the airframe noise was predicted by ANOPP using Fink's method[4] with the 300 pax BWB geometrical parameters inputted. Sources considered were the wing trailing edge, slats, and landing gear. A small flap source was also added to simulate the noise from the side edges of the elevons. No data existed to calibrate the predictions to so assumptions were made that the airframe noise was 5.1 EPNdB less than the fan exhaust noise at the cutback point, 5.1 EPNdB less than the jet noise at the sideline point, and 0.9 EPNdB less than the fan inlet noise at the approach point. These assumptions are based on the source proportionalities for a notional large quad transport reported in Ref. 6. Although not necessarily reflective of a BWB, this airframe noise model was considered adequate for the purpose of a methods demonstration. Also, in the conceptual design of revolutionary aircraft, such a model is often all there is to work with which underscores the need for trade space exploration. The final calibrated levels of each noise source, before insertion loss corrections, are shown in Fig. 4. The airframe noise levels in Fig. 4 are slightly different than the assumptions described earlier since these assumptions were applied to the values reported in Ref. 5 and the engine size and flight path are different for the BWB.

Since the BWB's engines are mounted above its airframe, forward radiated engine noise is significantly reduced due to shielding effects. Experimental data from Ref. 7 were used to create insertion loss maps for each engine source that correct for the airframe shielding and reflections. No corrections were applied to the airframe noise since the sources are not localized above the airframe as the engine sources are. Figure 5 shows the ANOPP predicted certification EPNLs. Also shown in Fig. 5 are the FAR 36 Stage 3 noise limits for the FLOPS predicted takeoff gross weight of 619,810 lb. Stage 4, to be instituted into the FAR in 2006, will enforce the same noise limits as Stage 3 but will not allow tradeoffs at different points and will further require cumulative noise reductions of 10 EPNdB over all three points, and 2 EPNdB over any two points[3]. Figure 5 thus shows that the BWB/GE-90-like system meets current noise regulations and has a comfortable margin built in for future regulations.

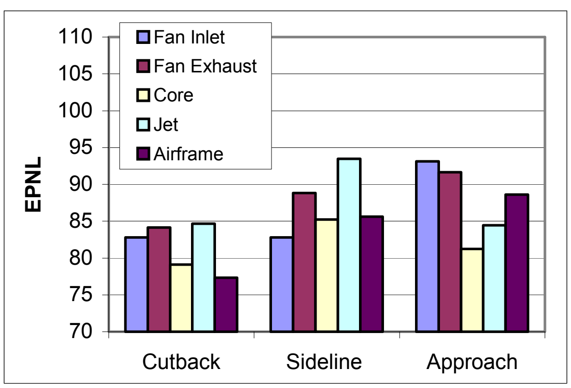

Figure 4. Predicted Source Noise Levels of the 300 pax BWB/GE-90-like System Before Insertion Loss Corrections.

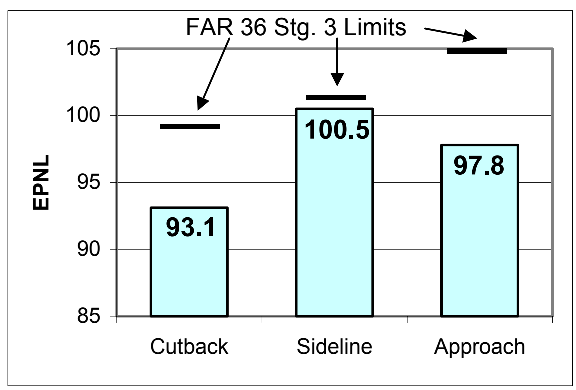

Figure 5. Predicted FAR-36 Certification EPNLs of the 300 pax BWB/GE-90-like System and Stage 3 Noise Limits.

IV. Construction of Noise Response Surfaces

It was desired to create response surfaces of the BWB/GE-90-like system noise model for the purpose of exploring the trade space between the individual source noise levels, and the certification levels of the whole vehicle. The response surfaces effectively convert an ANOPP run into polynomial equations allowing rapid and simplified evaluation. For inputs, artificial suppression factors for the fan inlet, fan exhaust, core, jet, and airframe noise sources were used. Only one factor was assigned to all the airframe noise sources since ANOPP automatically lumps them together. The suppression factors are ANOPP inputs that are applied uniformly to all frequencies and directivities and artificially lower the computed noise levels of a source by a delta dB. They are normally used for calibrations and trade studies. In the present study, manipulation of these inputs allowed the trade space to be created around the levels of the individual sources. The responses consisted of the cutback, sideline, and approach certification EPNLs. The generalized third order response surface equation (RSE) is in the form of Eq. (1):

$$R = b_0 + \sum_{i=1}^{N} b_i S_i + \sum_{i=1}^{N} b_{ii} S_i^2 + \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} b_{ij} S_i S_j + \sum_{i=1}^{N} \sum_{j=i}^{N} \sum_{k=j}^{N} b_{ijk} S_i S_j S_k \tag{1}$$

where R is the cutback, sideline, or approach response, S_i is the ANOPP suppression factor input, and b represents the regression coefficients. The first term on the right hand side, b_0, is the intercept of the RSE, the second term is a summation of the linear terms, the third is a summation of the pure quadratic terms, and the fourth is a summation of the cross product terms. These first four terms are usually sufficient for the equation to properly represent most system models. However, inadequate fits with the noise model prompted the addition of third order terms. These are represented in Eq. (1) by the fifth summation which contains both the pure cubic and cross product terms.

The three RSEs were formed by running ANOPP multiple times in a design of experiments (DOE) framework and regressing the data. The DOE model chosen was a four level, full factorial which is the most accurate of all four point schemes and the most expensive computationally. All five inputs were bounded by a range of ±10 dB around the baseline predicted values. A larger range of ±20 dB was attempted to encompass a larger trade space but this led to inadequate response surface fits. With five input variables, the DOE required 4^5 = 1,024 runs. In addition, an equal number of random cases, within the prescribed input ranges, were run bringing the total number of runs to 2,048. Fortunately, the run time of ANOPP for the BWB/GE-90-like model was only on the order of 90 seconds so the computational expense was not prohibitive. Half of the random cases were used to augment the RSE fits and half were used to check errors. Once formed, the response surfaces were evaluated as to how well they simulated actual ANOPP runs. Figure 6 shows plots comparing the ANOPP predicted noise levels with those predicted by the RSEs.

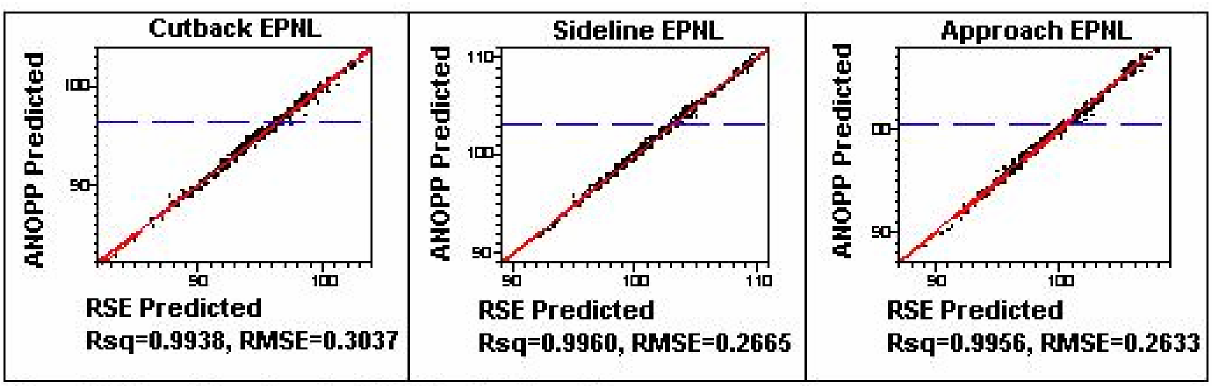

Figure 6. Plots of ANOPP Predicted vs. RSE Predicted for the Three Responses.

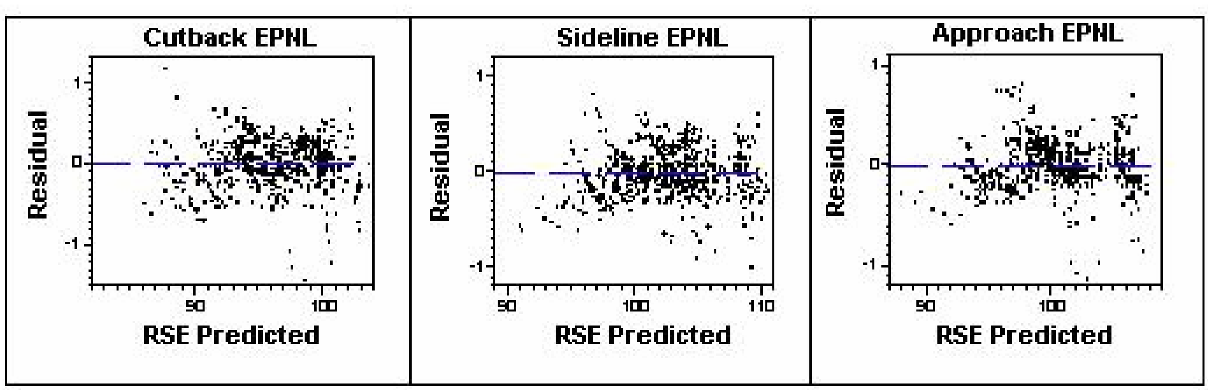

Figure 7. Plots of Residual vs. RSE Predicted for the Three Responses.

A perfect RSE fit would consist of a slope equal to one and an intercept of zero. The R^2 value for the cutback response is 0.9938 which means that the RSE explains 99.38% of the variation in the data. The other two responses have R^2 values of about 0.996 indicating highly accurate fits. All three root mean square errors (RSMEs) are below 0.4 EPNdB which is consistent with the fidelity of the analysis tools. Figure 7 shows plots comparing the residuals (defined as the difference between the ANOPP and RSE predictions) to the RSE predictions. For a good fit, the residuals should be randomly distributed in a "gunshot" pattern. Except for some outliers, this pattern is largely observed in all three of the plots of Fig. 7. The second order response surfaces that were attempted had more organized patterns in the plots, indicating the presence of 3rd order effects, and prompted the inclusion of third order terms in Eq. (1). Further analysis showed the errors of the RSE fits to be uniformly distributed with means close to zero and standard deviations well below one. This check verified that Eq. (1) had been expanded to a high enough order to sufficiently capture all the variable interactions.

As a final evaluation of RSE accuracy, half of the random cases that were run were evaluated with the RSEs and compared with the ANOPP solutions. The error distributions in EPNdB are shown in Fig. 8. These plots give a sense of what uncertainty might be expected in any given RSE calculation. The largest absolute errors are near 0.7 EPNdB. Most errors however lie well below this extreme and the standard deviations are no greater than 0.24 EPNdB. Such high accuracy was desired so that the RSEs could be used with confidence for assessments in which only small changes (on the order of 1/2 EPNdB) in the vehicle noise levels are seen.

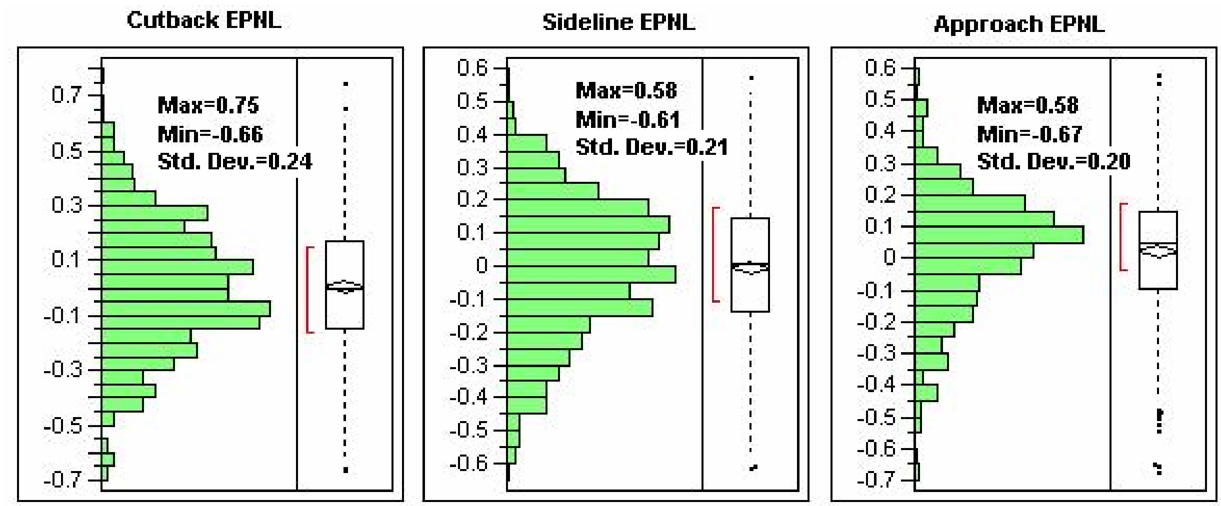

Figure 8. Residual Error Distributions of the 513 Random Cases.

V. Applications

A. Single Point Analysis

The response surfaces may be used to perform trade studies that involve single point perturbations of the baseline noise source levels. This is a common activity in cursory technology assessments where a parameter in a vehicle model is raised or lowered a certain amount to simulate the effect of the technology integration. In aeroacoustics work, noise reduction technologies are often focused on one particular noise source and developers often attempt to quote a technology's noise reduction potential into one overall number for systems studies. Integrating the technology into the system and determining the effect on the noise of the whole vehicle (assuming the technology does not have significant side effects on the weight and performance) is then a simple matter of artificially lowering the noise level of the source in question and recomputing the total noise levels. This can be done through simple queries to the response surfaces.

As an example, the noise benefits of swept and leaned fan stators on the BWB/GE-90-like system approach noise are evaluated. Ref. 8 contains results of acoustic tests of an advanced high-bypass fan engine that incorporates swept and leaned fan stator technology. From the test results, flyover EPNLs of just the fan noise were computed for a notional flight path and airspeed at the cutback and sideline certification points for a range of fan speeds. Reductions of roughly 3 EPNdB, compared to the unswept radial stator baseline, were seen at 50% design fan speed. This throttle setting corresponds roughly to the approach condition. Although the absolute value of an EPNL depends on the flight path and observer locations, a uniform change in the source SPL will often be very close to the change in observer EPNL. It is therefore assumed that the noise effects of the technology integration can be reasonably accounted for by uniformly lowering the BWB/GE-90-like system fan inlet and exhaust source noise by 3 dB. A query of the response surface reveals that the approach noise, considering all sources, is reduced from its originally predicted value of 98.0 to 96.3 EPNdB, a 1.7 EPNdB reduction. This shows that the presence of other sources unaffected by the swept and leaned stators reduces the technology's overall benefit by nearly half.

It may also be desired to evaluate the technology for a number of different source level scenarios. For example, the airframe noise is the next most prominent source on approach and its levels will significantly affect the benefits of the swept and leaned stators. By querying the response surface, a parametric study may be performed that shows how the technology on/off difference varies with airframe noise levels. The results are shown in Fig. 9. Airframe suppression was varied from –5 dB (loudest) to +5 dB (quietest). As expected, the technology noise benefit increases from 0.4 to 2.4 EPNdB as the airframe noise is lowered. This parametric study is helpful since the airframe noise prediction carries a high degree of uncertainty and more insight is gained when the technology benefits are viewed for several different values. It also shows how airframe noise reduction can synergistically improve approach noise by increasing the effectiveness of the swept and leaned stators.

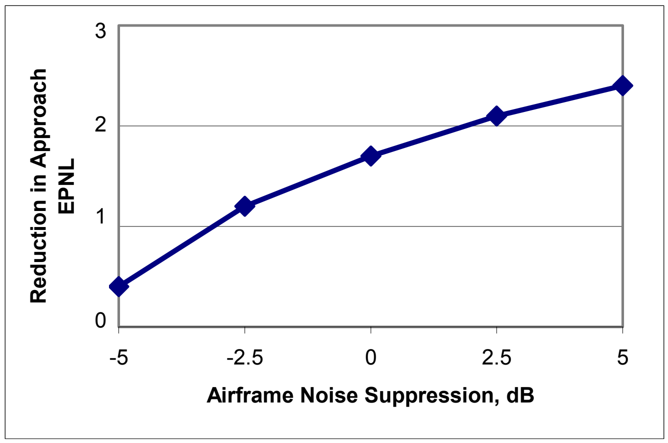

Figure 9. Influence of Airframe Noise Suppression on the Fan Technology Benefit.

Although the above evaluations can be done easily using ANOPP, the response surface approach yields two advantages. First, the processing time is virtually instantaneous since evaluating a polynomial equation is all that is required and it can be programmed into a simple spreadsheet. ANOPP however requires editing an input file and waiting through approximately 90 seconds of computation for the BWB/GE-90-like model. This small convenience is useful when rapid assessments are desired and several unstructured, "what if?", questions, common in conceptual design, can be answered as fast as they are thought of. Having this capability gives a designer increased freedom to think creatively and gives a team the ability to perform assessments in a meeting setting. Secondly, the response surface approach allows non-specialists to perform evaluations. This advantage is useful in a design group where everyone does not necessarily have training and experience using the noise code. As long as one member can create the model and response surfaces, many may use it for their subsequent trade studies.

Although the response surfaces created should not supplant a proper evaluation of a well defined noise technology that would consider the technology's full effects on the noise source spectrum and directivity as well as performance impacts on the vehicle, they can provide a designer with a sense of how the technology affects the noise of the whole system. This sense, even if incomplete, is often necessary in conceptual design since it can help in making design decisions or in assessing if further analysis is worth the effort. The small reductions shown in Fig. 9 illustrate why a noise response surface requires higher order considerations and increased computational expense to drive the error down to the level of fidelity of the noise code.

B. Optimization Technique for Inverse Design

Response surfaces lend themselves to optimization since the evaluations are rapid enough for a large volume of cases to be run quickly. By enabling inverse calculations, optimization problems can be used to develop strategies for vehicle noise reduction and roadmaps for technology investment.

Current NASA vehicle noise research programs are planned by selecting a reference vehicle representing present day state of the art and setting ambitious but reasonably achievable noise goals below the reference vehicle levels. A strategy of investment into a portfolio of technologies is then developed that, when implemented, will enable the reference vehicle to achieve the noise goals. Since noise technologies often concentrate on mitigating one particular noise source, it is thus useful in the program planning stages to have noise reduction goals of all the individual sources so that research investment will be distributed to the technologies that will make the greatest contributions. For developing long term roadmaps for subsonic aircraft where all the noise sources are well balanced and large overall reductions are required, it is not entirely clear what the strategy of investment should be. It therefore becomes of interest to find an efficient means of achieving the overall noise goals through setting well guided goals for each individual source.

This issue may be addressed by setting up an optimization problem and using the response surfaces to run through it. The following objective function is defined in Eq. (2):

$$F(S) = \sum_{i=1}^{5} S_i^{n_i} \tag{2}$$

where S_i are the source suppression factors (normalized with the 20 dB range of the trade space) and n_i are exponents. The three certification noise levels are then defined as constraints and set to their target values and the five suppression factors are defined as design variables. By then directing an optimizer to minimize the objective function, the suppression factors will be varied just enough to meet the constraints. This procedure turns the noise analysis into an inverse problem where desired vehicle noise levels are defined, and sets of suppression factors are found that can meet them. The exponents provide a degree of control over the solutions. For lower powers, particularly straight sums (n_i=1), the optimizer will tend to assign larger suppression values to the more prominent sources since they have more influence in meeting the constraints. For higher powers, the optimizer will tend to assign more level reductions over all five sources since the powers tend to amplify larger values of source suppressions and penalize F(S).

Some practical interpretations may be applied to the parameters in the optimization problem. The objective function F(S), in Eq. (2), may represent the total amount of “effort”, in the form of time, money, resource commitment, etc., that is required to achieve the noise goals specified in the constraints. It may also represent the amount of risk involved in meeting the noise goals. Both these interpretations are consistent with the minimization strategy. The exponents n_i tend to manifest the Law of Diminishing Returns which says that small noise reductions may come easy, but larger reductions will become progressively more difficult. Increasing the value of n_i will increase the severity of these effects since F(S) will be penalized more for large suppression values.

This optimization problem is applied to the BWB/GE-90-like system and the results are summarized in Table 1. Since all source levels were being reduced, half of the trade space was no longer needed for this problem. New response surfaces were thus formed for this specific application by spanning the trade space from 0 to 20 EPNdB suppression. This allowed larger source reductions to be used while keeping the error from the fit at reasonable levels. For this example, individual noise reduction goals of 10 EPNdB at each certification point were established. These values were entered as constraints forcing all input combinations to be such that the total noise was below these targets. The diminishing returns exponents were all set to one value n for simplicity. Inverse solutions were then computed for n=1, n=2, and n=10 and results are shown in Table 1. All three sets of results show the fan exhaust and jet noise sources to be the most significant influences and were subsequently assigned the largest reductions by the optimizer. The target noise goals may be met either by dramatic reductions to these two sources, as shown for n=1, or a more level approach for all sources, as shown for n=2 and n=10. The problem can be further constrained by narrowing the limits on the design variables. For example, referring to the n=1 results, 16.8 dB may be too ambitious of a fan exhaust noise goal so this suppression factor may be constrained to stay below 10 dB. In addition, airframe noise research may show more promise than 3.7 dB, so it may be constrained to stay above 8 dB. The new results from these changes are shown in the “n=1 (mod)” column. Jet noise is now the source requiring the

Table 1. Inverse Design Results.

Objective Function	$F(S) = \sum_{i=1}^{5} S_i^n$					Solutions		
			min	max	n=1	n=2	n=10	n=1 (mod)
Design Variables	Fan Inlet	S1 (dB)	0	20	6.9	6.8	9.0	8.1
	Fan Exhaust	S2 (dB)	0	20,10	16.8	13.6	10.4	10.0
	Core	S3 (dB)	0	20	3.8	7.4	9.4	8.5
	Jet	S4 (dB)	0	20	13.3	11.0	10.6	11.4
	Airframe	S5 (dB)	0,8	20	3.7	4.4	8.3	9.5
Constraints	Δ Cutback EPNL	< -10 EPNdB						
	Δ Sideline EPNL	< -10 EPNdB						
	Δ Approach EPNL	< -10 EPNdB						

most suppression and airframe noise reduction plays a much more prominent role. Given the assumed amounts that the fan exhaust and airframe noise can be reduced, this strategy may be a better one to implement.

The solutions that can be found using this technique do not necessarily represent a “best strategy” for meeting target vehicle noise levels or planning a technology research program. In a real situation, this answer cannot be fully quantified, and it depends on a number of factors such as the projections in the noise technology portfolio, the area of expertise of in-house technical personnel, budgets, and political considerations. The purpose of employing optimization in noise research planning is to provide an analyst with rapid inverse design capability and some control over the solutions so that all peripheral considerations may be, in some measure, reflected in the results. These capabilities, enabled by the response surfaces, can aid in deciding which sources should receive the most attention in further research, and which technologies should be most heavily invested in.

C. Sensitivity Analysis

The influence of each source on the total vehicle noise levels may be assessed with sensitivity studies. A glance of the sensitivities may be obtained with a prediction profiler which is created from the response surfaces in the statistical regression software JMP®. Two sets of profiles are shown in Figs. 10 and 11. Figure 10 shows the sensitivities at zero suppression. The slopes indicate the relative influence of each of the input variables on the three responses. As expected, the slopes generally correspond to the source levels in Fig. 4 with one exception. Fan inlet noise, which is the loudest source on approach, according to Fig. 4, exerts less influence since much of it is shielded by the airframe. Fan exhaust and jet noise show the largest influences which corresponds to earlier results. The logarithmic nature of noise measurement is apparent in the concavity of the curves. As suppression is increased, the slopes become more shallow indicating that the sources lose influence as they drop below the other source levels. This effect is exaggerated in Fig. 11 which shows the sensitivities when fan

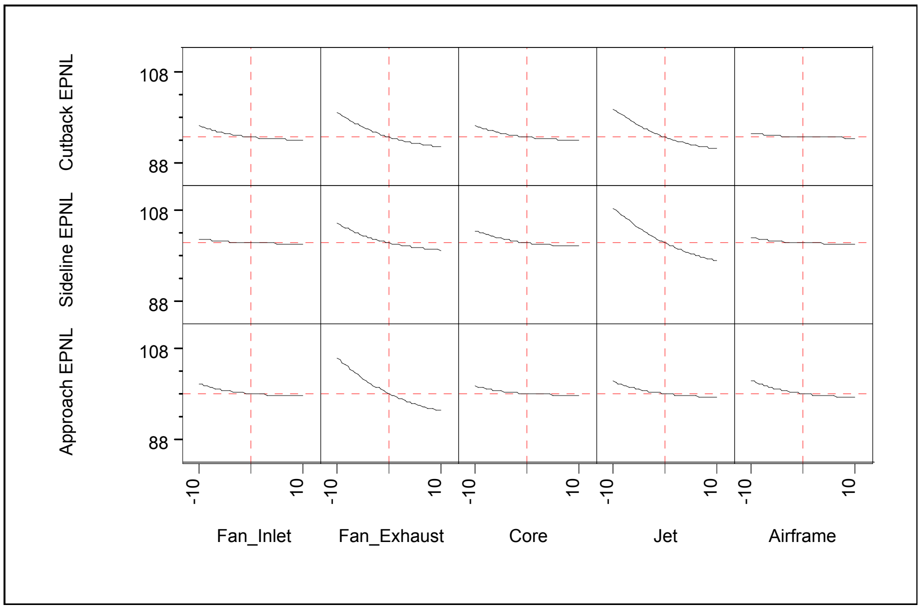

Figure 10. Sensitivities at Baseline Noise Levels.

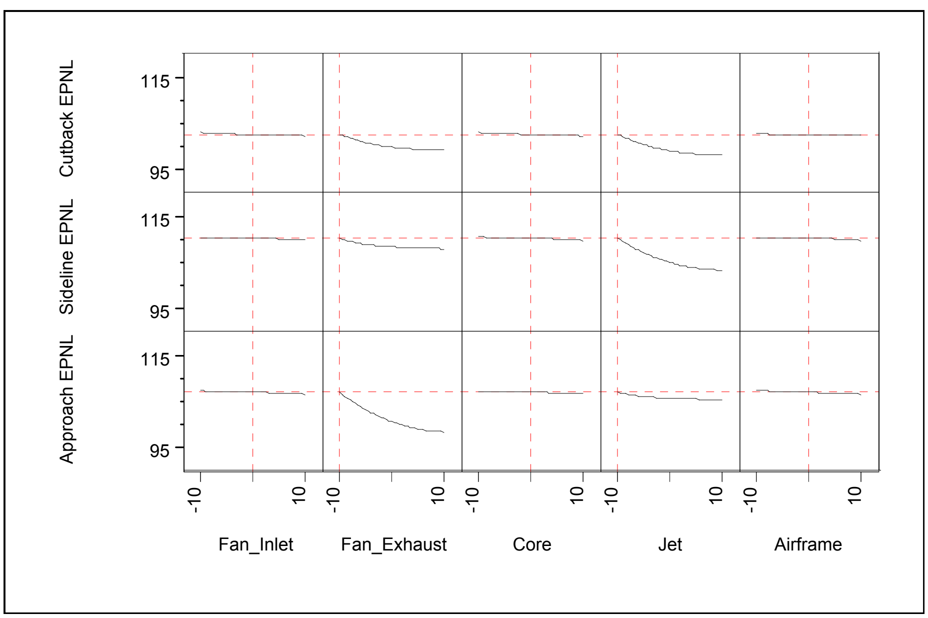

Figure 11. Sensitivities for Dominant Fan Exhaust and Jet Noise Sources.

exhaust and jet noise are set to their loudest levels in the trade space. For this scenario, the remaining sources have nearly zero slope across the curve showing that they have virtually no influence on the noise levels of the vehicle since the fan exhaust and jet noise sources are dominant.

Response surfaces also allow carpet plots to be quickly generated enabling viewing of the trade space between two of the variables. Figure 12 shows the trade space between engine and airframe noise at the approach certification point. This kind of trade study is useful for assessing the effectiveness of airframe noise reduction on the whole system. Engine noise was manipulated by applying uniform suppression to all four of the individual engine sources. Constraint lines were placed at the baseline noise levels (suppression = 0) and at 5 EPNdB below so that the portions of the trade space below these may be easily seen. The carpet plots show engine noise to be the most influential source but the airframe provides significant contributions. Sensitivities may be assessed by examining the slopes of iso-engine or iso-airframe lines. For example, starting at (0,0) on the carpet, it may be seen that reducing airframe noise 10 dB and holding engine noise at 0 dB will decrease the approach EPNL about 1 EPNdB. Decreasing the engine noise 10 dB while holding the airframe noise at 0 dB shows that the approach EPNL decreases about 7 EPNdB. The influence of airframe noise is however greater as engine noise is decreased. If engine noise is 10 dB quieter than the baseline, lowering airframe noise 10 dB will decrease the total approach noise about 3 EPNdB.

Of interest is how airframe noise might be more influential if the fan exhaust and jet noise sources are lowered. This situation could simulate a redesign of the BWB's aft airframe such that the aft radiating sources, which have been shown previously to heavily influence the total noise levels, would be better shielded. Not only would this lower the total noise levels of the BWB, it would provide more opportunity for airframe noise reduction to have an influence. Referring to the ANOPP model, fan inlet noise, which is thoroughly shielded, is reduced approximately 10 EPNdB on approach from the unshielded case. Assuming a modest 4 dB overall reduction for the fan exhaust and jet noise from a redesign of the aft airframe, the approach carpet of Fig. 13 was generated. As Fig. 13 shows, quieting the aft radiating sources tilts the carpet so that airframe noise has more influence. Performing the same previous evaluations, reducing airframe noise 10 dB will lower the approach noise about 1.5 EPNdB for the zero engine suppression case, and about 4 EPNdB for the 10 dB engine suppression case. Although 4 dB reduction from the shielding is only a guess and a modified airframe would significantly alter the flight path and baseline noise levels, this analysis can provide an initial sense of how airframe noise will become more influential if such a modification is made. Due to the rapid generation capability enabled by the use of a response surface, additional carpets may be easily constructed for various guesses of fan exhaust and jet noise reduction.

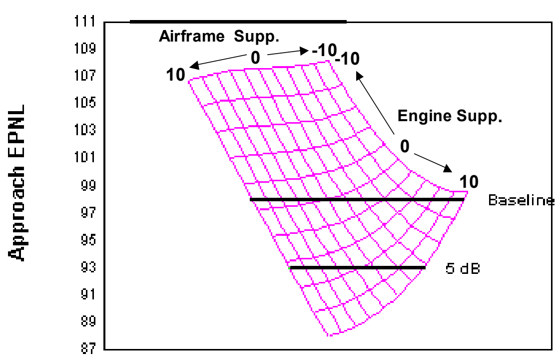

Figure 12. Approach Carpet Plot.

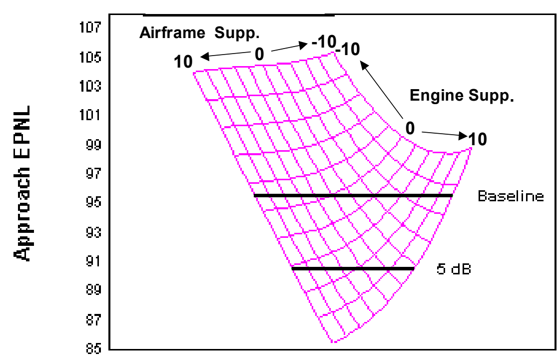

Figure 13. Approach Carpet Plot With Reduced Fan Exhaust and Jet Noise.

D. Probabilistic Analysis

The use of response surfaces is essential if probabilistic analysis is desired due to the large database that must be generated for the statistics involved. Probabilistic analysis is useful to the present study in that it can capture uncertainty in the certification EPNLs given reasonable estimates of the uncertainty in the source noise levels. The analysis is conducted by first assigning a statistical distribution to each input suppression in place of a discrete value. A Monte Carlo simulation is then run which samples the response surface a prescribed number of times, usually in the thousands. The input values chosen for each run are influenced by the input distributions. The calculated responses are then assigned to bins so that probability density functions (PDFs) may be generated.

This procedure is demonstrated with the 300 pax BWB/GE-90-like model. It is desired to estimate uncertainties in the source noise predictions and examine how the certification EPNLs are affected. The distributions are shown in Fig. 14. Triangular distributions were used for all the engine noise sources since these consist of minimum, maximum, and most likely values. Since the baseline values were calibrated to published GE-90 levels on a 777-like engine size and flight path, the main uncertainty is associated with the different engine size and flight path of the BWB as well as the presence of insertion loss corrections. These effects were considered significant enough for a ± 3 dB bound to be placed on the distributions. A –5 dB to 1 dB bound was placed on the jet noise however since much of the radiated noise comes from sources located in the plume rather than at the nozzle exit and the noise is therefore largely unshielded. It is therefore likely that the jet noise was corrected for too much insertion loss which is why the distribution is skewed towards less suppression. Since the airframe noise prediction was made without proper calibration, a uniform distribution spanning the ±10 dB trade space was applied to the source. This indicates that the value for airframe noise has an equal chance of lying anywhere within the trade space. With the input distributions defined, a Monte Carlo simulation of 10,000 runs was executed. This number of runs is usually adequate to produce statistically meaningful results. The necessity of the response surface is realized when it is considered that the runtime of the simulation is only a few minutes whereas running the model through ANOPP in the same manner would take approximately 10 ½ days.

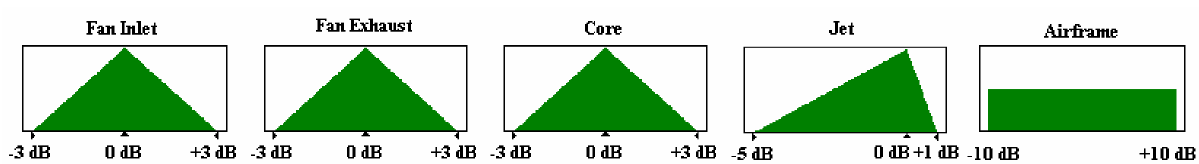

Figure 14. Triangular Input Distributions

The PDFs are shown together in Fig. 15. The distributions are outlines of the bin heights and they provide a bound on the entire range in which the EPNL may be expected to lie and show where the EPNL was most frequently calculated. The mean values, standard deviations, and range widths of all three EPNLs are shown in Fig. 15. For the cutback case, the mean value lies at 94.5 EPNdB and may be considered the most likely value. The range width is 4.9 EPNdB showing that the cutback EPNL has a narrower range of uncertainty than the inputs. Also, the large uncertainty in the airframe noise input does not seem to have an appreciable effect. The approach case however has a much wider range width of 6.9 EPNdB due to the greater influence of the airframe noise input distribution. In all three cases, the mean values are slightly larger than the baseline levels which reflects the influence of the skewed jet noise distribution.

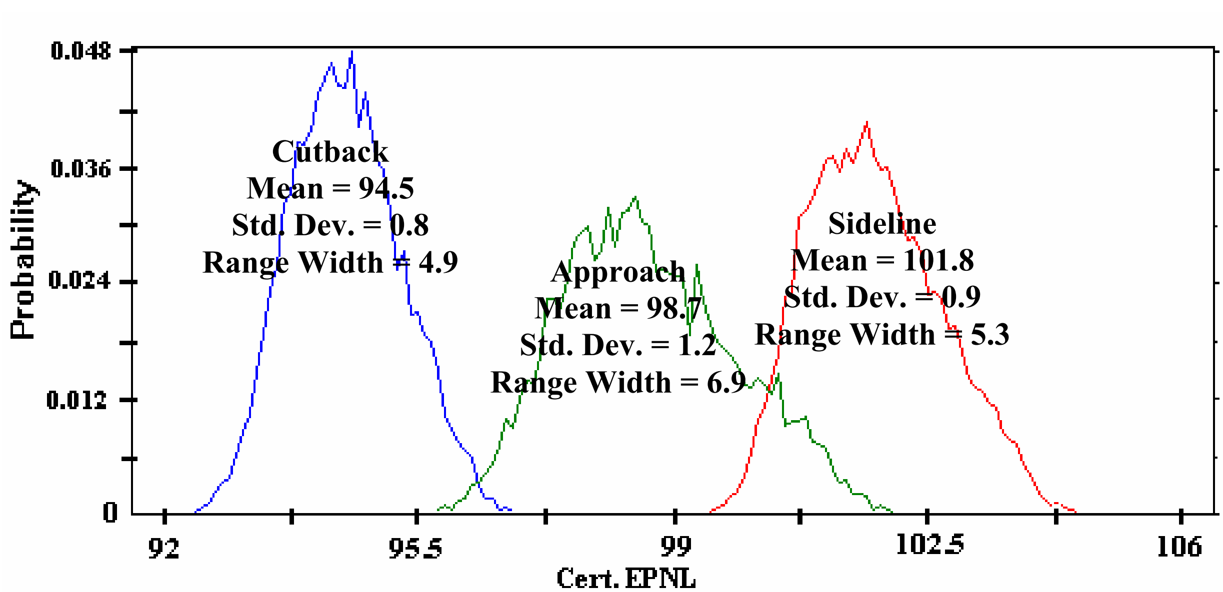

Figure 15. Probability Density Functions of the Certification EPNLs

VI. Extended Applications

As has been demonstrated in the previous sections, a significant amount of useful information may be generated simply by forming a trade space around individual component source noise levels. Response surfaces however, may be created to represent a number of other noise related models. As mentioned previously, applying uniform suppression to a source is only a cursory means of characterizing the effects of a new technology. Some technologies, like the distributed exhaust nozzle[10], are designed to reduce jet noise through shifting the frequency spectrum to a higher range where the noise may be more easily attenuated in the atmosphere. In lieu of test data, this isolated effect may be estimated by adding an additional frequency shifting parameter to the DOE which assumes that the jet noise spectrum is roughly equivalent in shape to that of a round nozzle, but shifted upward in frequency. Airframe shielding effects may be estimated by adding attenuation factors to the DOE at polar and azimuth angles for which there is an airframe component present. This process could be used to obtain a slightly better estimate of the noise effects of an aft airframe redesign on the BWB. As with uniform suppression, neither of these modifications are adequate substitutes for a detailed noise analysis or acoustic test of a technology, but can serve to negotiate the informational void in the conceptual design phase.

RSEs may be created that employ key engine and airframe design variables and thus bring noise considerations into a much broader design framework as has been done in Ref. 11. For example, it may be of interest to study how the BWB's approach noise varies with parameters such as engine and airframe noise levels, slat size, approach speed, angle of attack, and glide slope angle. This trade space exploration would allow a designer to understand the dependence of the approach noise level with his/her choices of approach procedure, and high lift system as well as with the variability of engine and airframe noise. In applications such as these, limits must be placed on the number of input variables since the corresponding number of DOE cases will grow rapidly. Variables may often be eliminated through a screening test where a linear DOE is run and a Pareto analysis is used to determine which inputs significantly affect the variability in the responses[11].

Finally, RSEs are useful for incorporating higher fidelity, computationally intensive analyses into conceptual design. These analyses can include CFD simulations of jet flow or flow around airframe components for use in noise prediction. They can also include higher fidelity reflection/diffraction codes that model airframe shielding effects.

VII. Conclusions

This paper has demonstrated the usefulness of creating and exploring trade spaces of noise parameters in the conceptual design phase. Information regarding the influences and interactions of noise sources and certification EPNLs was produced using many common conceptual design methods. All the methods demonstrated are either enabled or facilitated by the use of response surfaces, in place of the ANOPP model, due to both the speed and simplicity of evaluation that they provide. Although noise sources and vehicle noise levels represent a simple trade space, many more trade spaces may be created using any set of noise, weight, performance, and cost parameters desired depending on the modeling tools available and the limitations of computational resources. Response surface-based methods are thus able to give noise considerations more of role in conceptual design which is necessary for enabling revolutionary, quiet, transport aircraft.

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