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Noise Certification Predictions for FJX–2–Powered Aircraft Using Analytic Methods

Jeffrey J. Berton
Lewis Research Center, Cleveland, Ohio

February 1999

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Williams International Co. is currently developing the 700-pound thrust class FJX-2 turbofan engine for the General Aviation Propulsion Program's Turbine Engine Element. As part of the 1996 NASA-Williams cooperative working agreement, NASA agreed to analytically calculate the noise certification levels of the FJX-2-powered V-Jet II test bed aircraft. Although the V-Jet II is a demonstration aircraft that is unlikely to be produced and certified, the noise results presented here may be considered to be representative of the noise levels of small, general aviation jet aircraft that the FJX-2 would power. A single engine variant of the V-Jet II, the V-Jet I concept airplane, is also considered. Reported in this paper are the analytically predicted FJX-2/V-Jet noise levels appropriate for Federal Aviation Regulation certification. Also reported are FJX-2/V-Jet noise levels using noise metrics appropriate for the propeller-driven aircraft that will be its major market competition, as well as a sensitivity analysis of the certification noise levels to major system uncertainties.

Introduction

As part of the General Aviation Propulsion (GAP) Program, NASA has joined with the general aviation industry and the Federal Aviation Administration to address the propulsion technology needs of future general aviation aircraft. The GAP Program's Turbine Engine Element is focusing on the development of a lightweight, low cost, high bypass turbofan engine for application to light general aviation aircraft of six seats or less. Williams International Co., LLC, and its partners have teamed with NASA to develop, manufacture, and flight demonstrate the FJX-2: a 700-pound sea level static thrust class turbofan engine capable of throttled cruise speeds of greater than 300 knots. The FJX-2 will be demonstrated on a twin-engine flying test bed aircraft designed by Williams International and developed and manufactured by Scaled Composites, Inc. This aircraft, dubbed the V-Jet II (see Figure 1), is a six-seat, 3800-pound gross weight class airplane and is scheduled to be demonstrated with FJX-2 engines at the EEA AirVenture 2000 Oshkosh air show. The V-Jet I (see Figure 2), a single-engine variant of the V-Jet II, is a concept aircraft used for program advocacy purposes and is not intended for development.

As part of their internal evaluation of the FJX-2 engine, Williams International performed their own analytical noise certification calculations using the semi-empirical noise prediction software described in Reference 1. NASA's own semi-empirical noise prediction software (Ref. 2) uses many of the same theoretical source noise prediction and propagation models as those used by the Williams program. However, an important revision has recently been made to NASA's fan noise model which applies to the case at hand. The original Heidmann fan noise prediction method (Ref. 3) was calibrated to an acoustic database of large hardwall fans with flow rates up to 950 pounds per second. This model is not very accurate in predicting the noise of small, modern geometry, high bypass ratio fans, and it significantly overpredicts the multiple pure tones that occur at supersonic relative tip speeds. AlliedSignal Inc., using hardwall acoustic measurements of three of their fans as a database, recalibrated the original Heidmann theory to be accurate in predicting the noise of smaller fans (Ref. 4). This model has been programmed into the current NASA noise prediction methods and is considered to be accurate for fan sizes with flow rates from 100 to

220 pounds per second. Although the small FJX-2's fan flow rates are lower still, this code upgrade represents the best currently available analytic tool for small hardwall fan noise prediction and it provides a compelling reason to re-evaluate Williams' original noise certification study. Therefore, under the 1996 cooperative working agreement with Williams, NASA agreed to analytically calculate the noise certification levels of the FJX-2-powered V-Jet II and conceptual V-Jet I aircraft using the new fan method. Although the V-Jet II is a demonstration aircraft that is unlikely to be produced and certified, the noise results presented here may be considered to be representative of the noise levels of small, general aviation jet aircraft that the FJX-2 would power. Better certification noise predictions will be possible later by using actual noise levels measured from FJX-2 acoustic tests to be made in 1999.

Reported in this paper are the analytically predicted FJX-2/V-Jet noise levels appropriate for Federal Aviation Regulation certification. Also reported are FJX-2/V-Jet noise levels using noise metrics appropriate for the propeller-driven aircraft that will be its major market competition, as well as a sensitivity analysis of the certification noise levels to major system uncertainties.

Method of Analysis

Detailed takeoff trajectories were calculated by Williams for the V-Jets using engine performance data, aircraft physical characteristics, and low speed aerodynamics using the methods described in References 5 and 6. The V-Jet altitude and speed trajectories are shown in Figures 3 and 4, respectively. The arrangement of the Effective Perceived Noise Level (EPNL) measurement points used in Part 36 certification is shown in Figure 5. No throttle derate was assumed from brake release through the final segment climb. The sideline observer therefore is subject to the noise produced by maximum takeoff rated power. And although regulations allow a noise abatement throttle cutback under Part 36 above the community observer, no such cutback was performed, and the community observer is subject to maximum takeoff power engine noise as well. Williams also calculated an approach power setting based on predicted approach aerodynamics, aircraft weight, and a standard three degree glide slope. A threshold distance of 956 feet is assumed in these calculations, giving an aircraft on a three degree slope an altitude of 394 feet as it passes over the approach observer.

Williams also provided the necessary thermodynamic and aeromechanical engine performance data of the FJX-2 based on their late 1997 analytic cycle predictions. Because of their proprietary nature, the data are not reproduced here.

The noise of each emitting source was calculated on the basis of one-third octave band sound pressure levels ranging from center frequencies of 50 to 10000 Hz and summed at the aircraft as a point source (Ref. 2). The aircraft source was analytically "flown" through its trajectory and spectra were calculated at half-second intervals. The individual source noise calculation procedures used were the AlliedSignal small fan hardwall noise model (Ref. 4), the Stone coannular jet noise model (Ref. 7), the Emmerling core noise model (Ref. 8), and the Fink airframe noise model (Ref. 9). Turbine source noise was not calculated in this study because the existing NASA methods are known to be significantly inaccurate in both absolute level and in spectral distribution (Ref. 10). Thankfully, turbine noise is likely to be dominated by other engine noise sources (Ref. 11), and its omission from this study may not be a bad assumption.

Noise propagation effects considered include spherical spreading, Doppler shift, atmospheric attenuation (Ref. 12), ground reflections (Ref. 13) based on data for grass-covered ground (Ref. 14), and extra ground attenuation (Ref. 15).

Results and Discussion

Fan Noise Model Benchmarking

Although the AlliedSignal small fan noise model had been validated and verified with respect to the fans used in its development, a system noise prediction applying this model to small jet aircraft had not been performed by NASA using its in-house methods. For this reason, the new fan model was used first to analytically predict the certification noise of an existing small jet aircraft and compare it to its measured, published noise certification data. The Cessna 525 CitationJet, equipped with twin Williams International FJ44-1A turbofan engines, was chosen for this benchmarking exercise. Of the three certification EPNLs, the sideline EPNL is the least dependent on the aircraft's performance. Since detailed trajectory data from the CitationJet certification tests were not immediately available, the sideline noise condition was chosen as the noise metric most appropriate to match. Unlike the community and approach EPNLs, which are highly dependent on aircraft altitude and engine throttle setting, the sideline EPNL is dominated by maximum takeoff power engine source noise at an altitude at which ground attenuation begins to vanish. And since the sideline EPNL is defined as the maximum EPNL along the entire sideline reference, the actual aircraft trajectory becomes much less critical to analytically model with precision. The remaining aircraft-dependent variables of importance in predicting the sideline EPNL are the aircraft orientation and velocity, which affect source noise directivity, forward jet effects, fan noise flight cleanup effects, Doppler effects, and the EPNL duration component. If reasonable values can be chosen for aircraft orientation and velocity, the predicted sideline EPNL can be a good metric to use for comparison to actual sideline certification data.

As in the case of the FJX-2, Williams provided appropriate thermodynamic and aeromechanical FJ44 cycle data to use in predicting engine source noise. The source noise levels of the twin FJ44s were calculated and "flown" past an array of sideline observers at 125 knots, and at flight path and attack angles of six and seven degrees, respectively. The calculated and measured certification sideline noise levels are shown in Table 1.

	Predicted	Measured
EPNL (EPNdB)	85.5	83.7
Peak dBA	71.6	71.4

Table 1: CitationJet/FJ44 Sideline Noise Levels

Although not used as a certification parameter for jet transport aircraft, the FAA also measures peak A-weighted sound pressure levels during certification testing. This result compares even more favorably than the EPNL because the dBA metric is simpler, without additional, complicating, tone and duration components. Based on this benchmarking study, the accuracy of the new fan noise model was considered acceptable for use in this preliminary study.

V-Jet/FJX-2 Certification Noise

Using the methods described above, the source noise spectra of each component were calculated at the maximum takeoff power sideline condition. Lossless, freefield spectra at constant radii from a single FJX-2 engine source were calculated for various yaw angles relative to the inlet zero angle reference. Spectra for the fore engine quadrant at 50° are shown in Figure 6. Shown in the figure are data calculated for the V-Jet I sideline condition at an altitude of 1000 feet and an airspeed of 135 knots. Data for the V-Jet II sideline condition at an altitude of 1000 feet and an airspeed of 170 knots are very similar and are not shown. Also shown in Figure 6 is the zero roll (horizontal) airframe noise spectrum, calculated for the V-Jet I geometry with gear and flaps extended at 135 knots. Fan inlet noise dominates at this angle. Note that the discrete fan tones at the higher-order harmonics are not even audible at this power setting, and, at the relatively high blade passing frequency of nearly 7000 Hz, even the fundamental interaction tone may be significantly attenuated by the atmosphere. With a relative tip Mach number of 1.2, some multiple pure tones are predicted by the fan inlet noise model at multiple fractions of the blade passing frequency. At these low levels, however, the pure tones do not significantly contribute to the EPNL.

Spectra for the aft engine quadrant at 140° are shown in Figure 7 for the V-Jet I sideline condition. Fan discharge and broadband jet noise dominate at this angle. The V-Jet II sideline aft spectra are similar and are not shown.

Shown in Figure 8 are the sideline Perceived Noise Levels (PNLTs) of the V-Jet I as a function of yaw angle from the inlet. The PNLT noise metric is calculated as a weighted summation of the spectral sound pressure levels with an additional tone component penalty. V-Jet II sideline PNLTs are similar and are not shown.

The PNLT traces for several V-Jet I sideline observers are shown in Figure 9. Propagation effects were considered for these calculations. EPNLs were computed from these traces. The maximum EPNL (in this case, for a sideline observer at a distance of 4500 feet from brake release) is the sideline certification EPNL. Although the noise data shown in the figure span nearly 40 PNdB, the regulations described in Reference 6 permit noise data within 10 PNdB of the maximum PNLT to be used for EPNL calculations. The V-Jet II traces are similar and are not shown.

Lossless fore spectra, aft spectra, and PNLT levels for the V-Jet I community configuration are shown in Figures 10, 11, and 12, respectively. Shown in the figures are data at fixed radii calculated for the V-Jet I community condition at an altitude of 2000 feet and an airspeed of 135 knots. Data for the V-Jet II community condition at an altitude of 3100 feet and an airspeed of 170 knots are very similar and are not shown. Indeed, since the community condition throttle setting is at full power, its spectra are nearly identical to the spectra at the sideline condition. Shown in Figure 13 is the V-Jet I PNLT trace for the community observer. The community EPNL calculation method is similar to that at the sideline, except that the geometry and propagation calculations differ, and the airframe noise is reduced due to the retraction of the gear and flaps. The regulations of Reference 6 permit a throttle reduction maneuver at a minimum altitude of 984 feet for an aircraft having less than three engines. A throttle cutback to a level that would maintain a minimum four percent aircraft climb gradient would further reduce these community noise levels.

Lossless fore spectra, aft spectra, and PNLT levels for the V-Jet I approach configuration are shown in Figures 14, 15, and 16, respectively. Shown in the figures are data at fixed radii calculated for the V-Jet I approach condition at an altitude of 400 feet and an airspeed of 70 knots. Data for the V-Jet II approach condition at an altitude of 400 feet and an airspeed of 85 knots are very similar and are not shown. The effects of the reduced throttle setting used for approach are apparent. With relative tip speeds now subsonic, the multiple pure tones are gone. Indeed, the tip speeds are so low, the fundamental is clearly cut off and the tone at the second harmonic is barely visible. The fan spectra are dominated by broadband noise. Core and airframe noise are no longer insignificant contributors to the overall noise signature. In fact, since the core noise model used here is based on acoustic data measured from relatively large combustors, the approach core noise for the small FJX-2 combustor calculated here may be overpredicted. Shown in Figure 17 is the V-Jet I PNLT trace for the approach observer.

Shown in Tables 2 and 3 are the predicted EPNLs for the V-Jet aircraft. The maximum allowable EPNLs for stage 3 jet transports with gross weights under 77200 pounds are also shown.

The noise level of each individual source component is shown. They were calculated simply by running each source model separately so that their relative magnitudes may be compared. Note that the relative proportions of each noise source shown in the tables may not intuitively match with the relative proportions of the PNLT noise sources shown in Figures 8, 12, and 16. This is due to EPNL trajectory dependencies and propagation effects, which alter the characteristics of the spectra. Note that the community EPNL of the V-Jet II is actually lower than that of the V-Jet I due to differences in flyover altitudes. Although the V-Jet II's twin engines produce more source noise, the V-Jet II climbs much more rapidly than the V-Jet I and has a lower community EPNL. At all three conditions, the V-Jets are significantly quieter than regulations permit. In certification parlance, the V-Jet I and II are a remarkable 66 and 64 cumulative EPNdB under the stage 3 rule!

	Sideline	Community	Approach
Fan	62.1	63.5	62.8
Jet	71.5	70.9	42.6
Core	65.1	65.7	64.0
Airframe	41.1	54.2	39.3
Total	73.5	73.6	67.9
Rule	94.0	89.0	98.0
Variance	-20.5	-15.4	-30.1

Table 2: EPNL Predictions for the V-Jet I

	Sideline	Community	Approach
Fan	65.3	59.2	65.9
Jet	72.0	68.8	48.3
Core	67.6	64.6	66.5
Airframe	46.5	55.6	39.3
Total	74.9	71.5	70.7
Rule	94.0	89.0	98.0
Variance	-19.1	-17.5	-27.3

Table 3: EPNL Predictions for the V-Jet II

Level Flyover Noise Predictions

Jet transport and small propeller-driven aircraft are subject to different noise regulations under Part 36. The noise metrics used are different as well, with EPNLs used for jet aircraft certification and peak A-weighted sound pressure levels used for small propeller aircraft certification. The spectral noise signatures of jet and propeller aircraft are also significantly different. Nevertheless, although they would not be subject to the noise regulations of propeller general aviation aircraft, any FJX-2-driven airplane would be competing with exactly that aviation market segment. For this reason, noise certification analyses that are commensurate with small propeller aircraft regulations were performed for the V-Jet I and II.

Some discussion of the noise certification regulations of Reference 6 is necessary to explain the approach used in this study. For general aviation propeller-driven airplanes certified prior to 1988, level flyover tests over a microphone were required to satisfy Part 36, Appendix F, of the Federal Aviation Regulations. The flyovers were conducted at the highest throttle setting of the normal engine operating range, in a cruise configuration, at a steady speed, and at a constant altitude of 1000 feet. The peak A-weighted sound pressure level limit varies with maximum airplane gross weight, beginning with 68 dBA for gross weights to 1320 pounds, and increases at 1 dBA per 165 pounds to a maximum, constant, 80 dBA limit at 3300 pounds and more.

For aircraft certifying since 1988 under Part 36 Appendix G, a bona fide takeoff procedure is used. A microphone is placed at 8200 feet from the point of brake release and peak A-weighted sound pressure levels are measured as the airplane flies overhead at whatever altitude it can achieve. Unlike the earlier regulation, which is mostly dependent on engine and propeller noise, the current regulation is very dependent upon the airplane's thrust, weight, aerodynamics, and takeoff procedures that determine its flyover altitude.

Since the V-Jet II is only intended to be a demonstration airplane, its weight and aerodynamics may not be exactly representative of the weights and aerodynamics of the actual certifiable airplanes that the FJX-2 will eventually power. Therefore, a level flyover, pre-1988, Appendix F regulation analysis, which is a better *engine* noise certifying regulation, is used in this study.

A flyover noise analysis was performed for the V-Jets, this time calculating peak A-weighted sound pressure levels rather than EPNLs. Shown in Tables 4 and 5 are the measured peak noise levels of selected single- and twin-engine small aircraft, the predicted peak noise levels of the V-Jets, and the maximum allowable peak noise level specified under the Part 36 noise rule.

	Level	Rule
Beech Bonanza F33A	78.3	80.0
Beech Bonanza A36	78.8	80.0
V-Jet I	68.6	77.6

Table 4: Peak A-Weighted Noise - Singles

	Level	Rule
Beech Baron 58	82.0	80.0
V-Jet II	71.9	80.0

Table 5: Peak A-Weighted Noise - Twins

The noise levels shown for the existing airplanes is the actual measured peak sound before the rate of climb adjustment credit allowed under Appendix F is taken, and may not be the final reported certification noise level. The Baron 58, for example, had a climb rate credit of 3.1 dBA, which brought the airplane under the 80 dBA limit rule and allowed it to certify.

The Beech F33A uses a Teledyne Continental IO-520-BB engine, a McCauley 80-inch, three-bladed propeller, and has a gross weight of 3400 pounds. The Beech A36 uses a Teledyne Continental IO-520-B engine, a McCauley 80-inch, three-bladed propeller, and has a gross weight of 3600 pounds. The V-Jet I is assumed to have a gross weight of 2900 pounds.

The Beech Baron 58 uses twin Teledyne Continental IO-550-Cs, Hartzell 78-inch, 2-bladed propellers, and has a gross weight of 5400 pounds. The V-Jet II is assumed to have a gross weight of 3600 pounds.

The results shown above indicate that FJX-2-powered aircraft will be about 10 dBA quieter than the selected comparable propeller aircraft listed. This roughly translates to one-half the noise of the listed aircraft using a perception-based standard. The FJX-2 fares very well using this noise metric.

Sensitivity Studies

Several noise sensitivity studies were performed for variable effects that can change the certification EPNLs. Shown in Figure 18 is the influence of the change in flyover altitude on the V-Jet community EPNLs. This is one of the most significant sensitivities calculated, since aircraft weight, aerodynamics, and takeoff procedures are all important in determining the community flyover altitude.

Another significant aircraft-dependent effect is the throttle setting required to maintain a three degree approach glide slope. Shown in Figure 19 is the effect of approach thrust, measured as a function of the low spool shaft speed, on the V-Jet approach EPNLs.

A sensitivity that may affect the community and approach centerline observer EPNLs is the amount of fuselage and tail shielding of fan inlet noise that occurs due to the single engine mounting location on the V-Jet I. This sensitivity is calculated using a simple suppression level applied to the fan inlet results. No Fresnel source diffraction calculations are made. Shown in Figure 20 are the community and approach EPNLs of the V-Jet I with varying amounts of fan inlet noise shielding.

Another sensitivity study performed were calculations for the amount of fan inlet and fan discharge noise suppression that may be expected if acoustic lining material were added to the fan inlet and exhaust ducts. The suppression model used in these calculations is described in Reference 16. Shown in Figure 21 is the change in certification EPNL of the V-Jet I calculated for various amounts of liner material. This suppression model does not predict the noise reduction of multiple pure tones. But, since acoustic lining is somewhat effective at suppressing these tones, calculations were made where the tones were neglected, thus providing a lower bound for this sensitivity. Since the FJX-2 is already extraordinarily quiet, and since the suppression benefit seems small, it appears that the addition of acoustic lining material is unnecessary to reduce certification noise. Some inlet lining, however, may prove to be necessary if multiple pure tones are annoying to cabin occupants.

The final sensitivity study performed was the influence of engine size on the V-Jet II EPNLs. If future engine component testing demonstrates performance levels different than current Williams analytical studies indicate, the final size of the FJX-2 may change in order to maintain the thrust levels necessary for a 700-pound thrust class engine. Flow rates and engine dimensions only were changed. Spool speeds were modified to maintain constant fan tip speeds. The influence of engine size on the V-Jet II EPNLs as a function of relative engine airflow is shown in Figure 22.

Conclusions

The analytical results of this study indicate that future certifiable small production aircraft powered by Williams International FJX-2 engines may be expected to be extraordinarily quiet. The predicted certification EPNLs of the FJX-2-powered V-Jet I and V-Jet II concept and demonstration aircraft are a remarkable 66 and 64 cumulative EPNdB under the Part 36 stage 3 rule. This confirms the expectations of industry and NASA.

A comparison of the V-Jets to several small, propeller-driven, general aviation aircraft was made for rough noise market competition comparisons. Using pre-1988 flyover certification noise level metrics for these aircraft, the V-Jets were predicted to be approximately 10 dBA quieter than the selected comparable competing aircraft.

The sensitivity calculations performed in this study may be used to roughly estimate the effects of several aircraft-dependent system uncertainties on the predicted certification noise levels. The results of one of these studies indicate that minimal suppression levels may be expected from fan duct acoustic lining. Lining material for the FJX-2 turbofan is not recommended unless multiple pure tone suppression is necessary for the comfort of cabin occupants.

Acknowledgments

Thanks to Pete Morris of Williams International for providing the thermodynamic and aeromechanical engine cycle data used for the source noise calculations. Thanks also to Paul Meyer of Williams for providing the V-Jet takeoff flight profiles used in the system noise calculations. And thanks to Tom Bengal of Williams, who performed the original noise assessment of the V-Jet aircraft.

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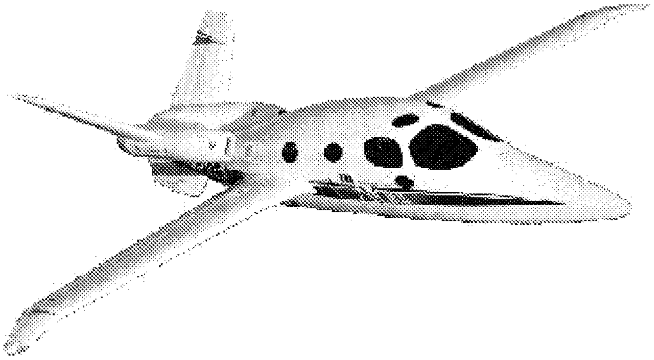

Figure 1: V-Jet II General Arrangement

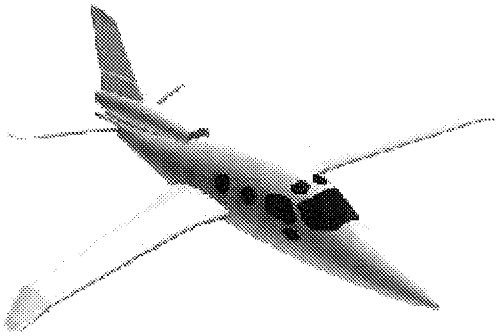

Figure 2: V-Jet I General Arrangement

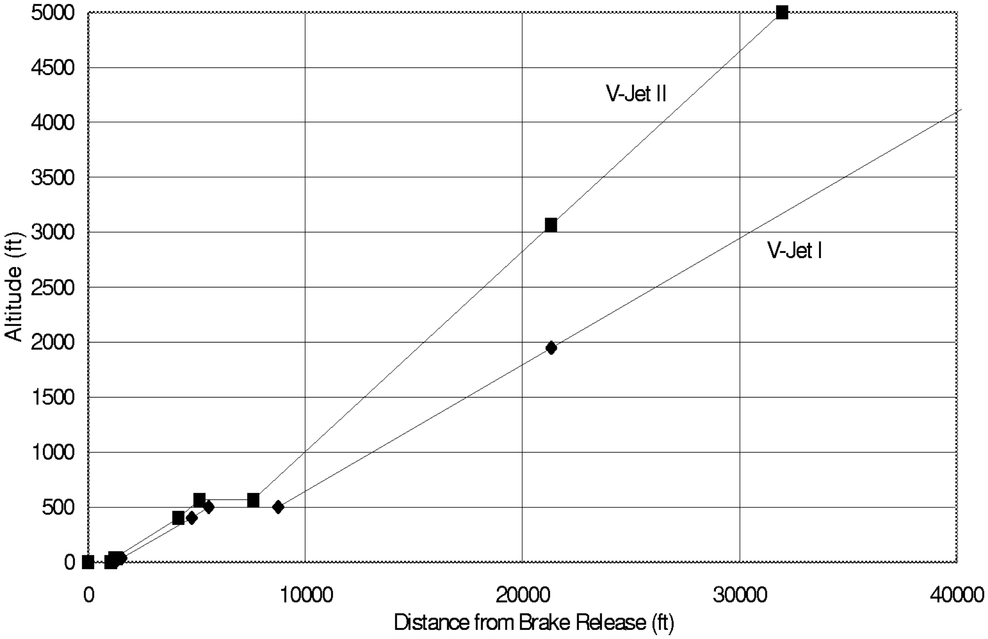

Figure 3: V-Jet Trajectories

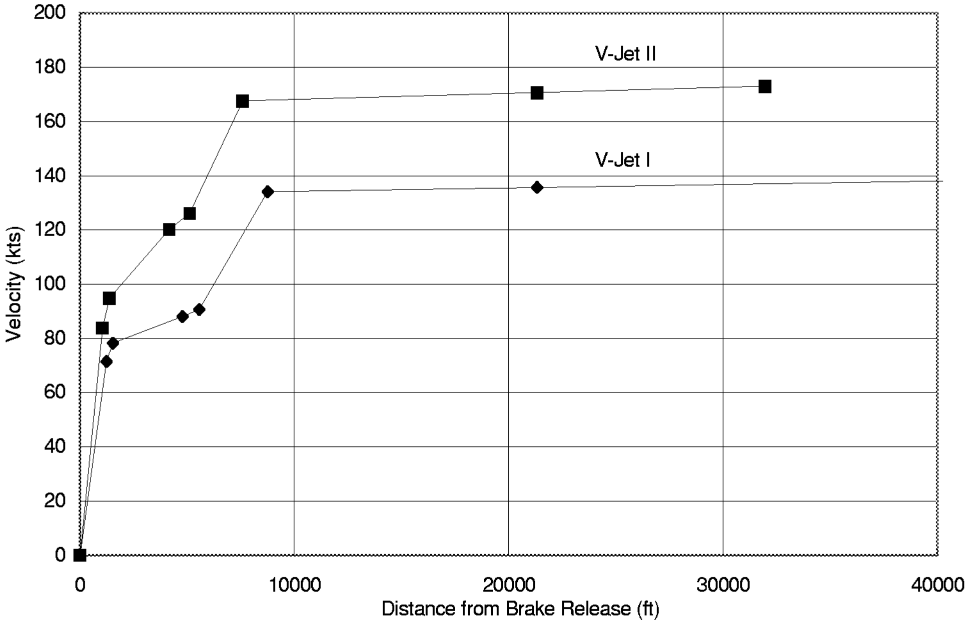

Figure 4: V-Jet Speeds

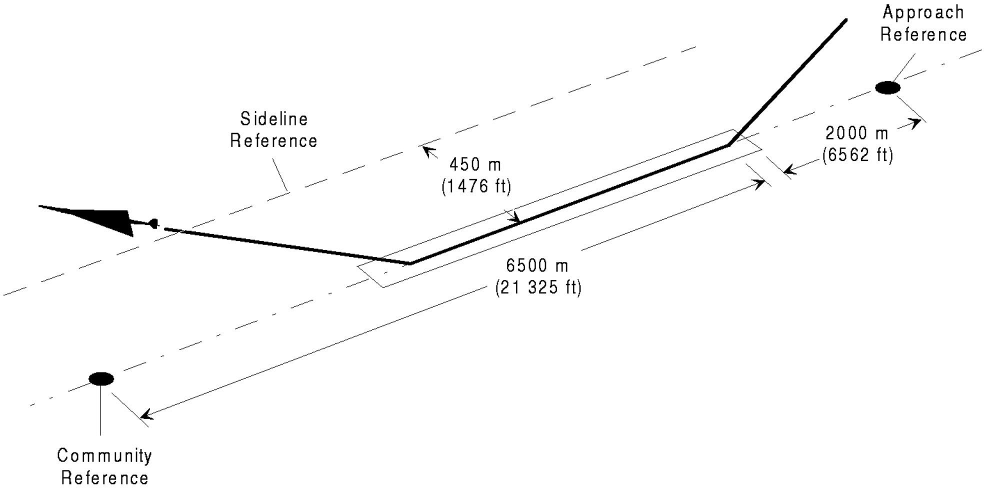

Figure 5: Part 36 Noise Certification Observer Locations

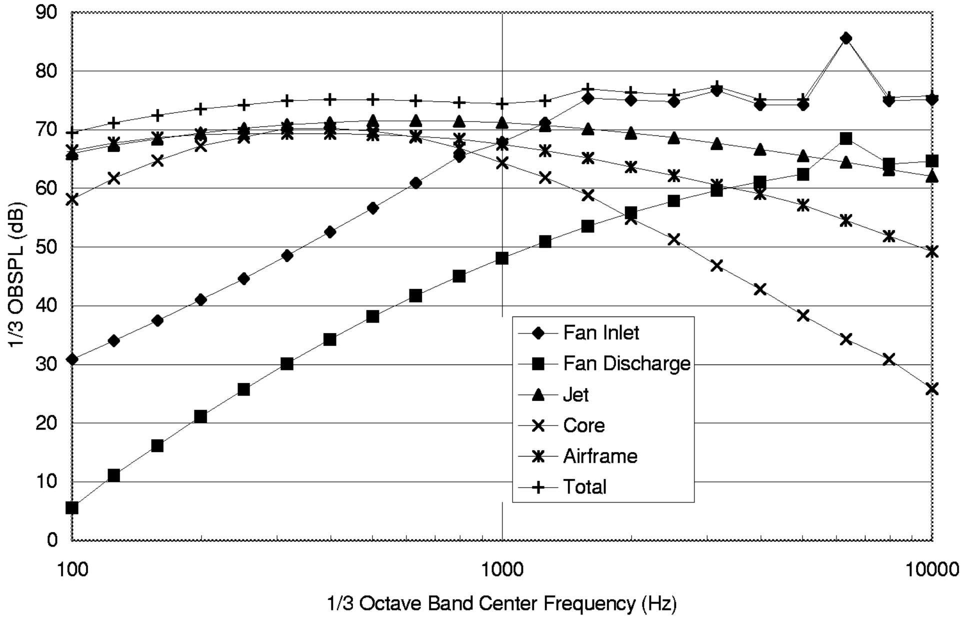

Figure 6: FJX-2 Source Spectra, Sideline Power Setting, Fore Quadrant

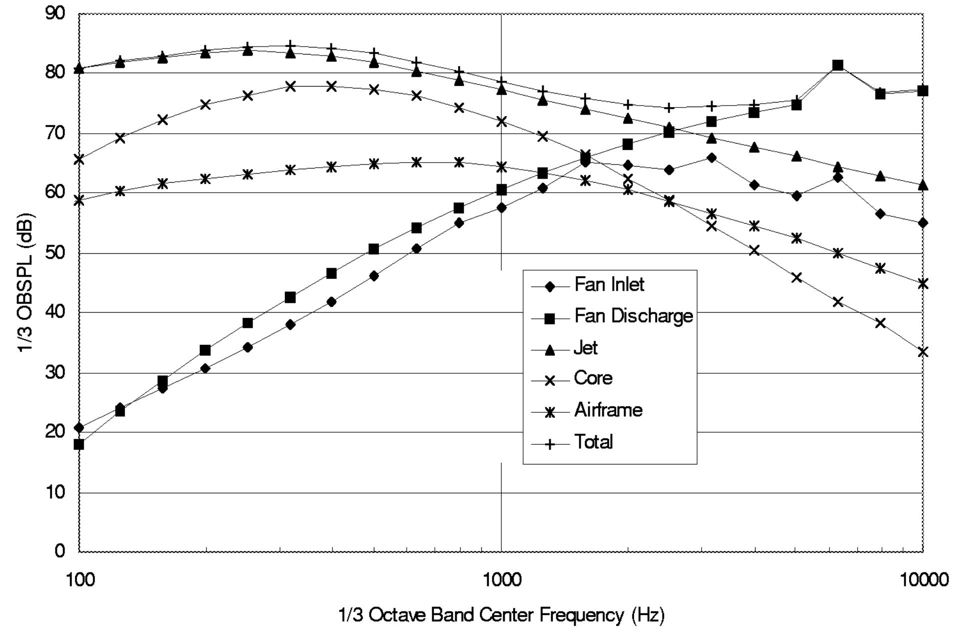

Figure 7: FJX-2 Source Spectra, Sideline Power Setting, Aft Quadrant

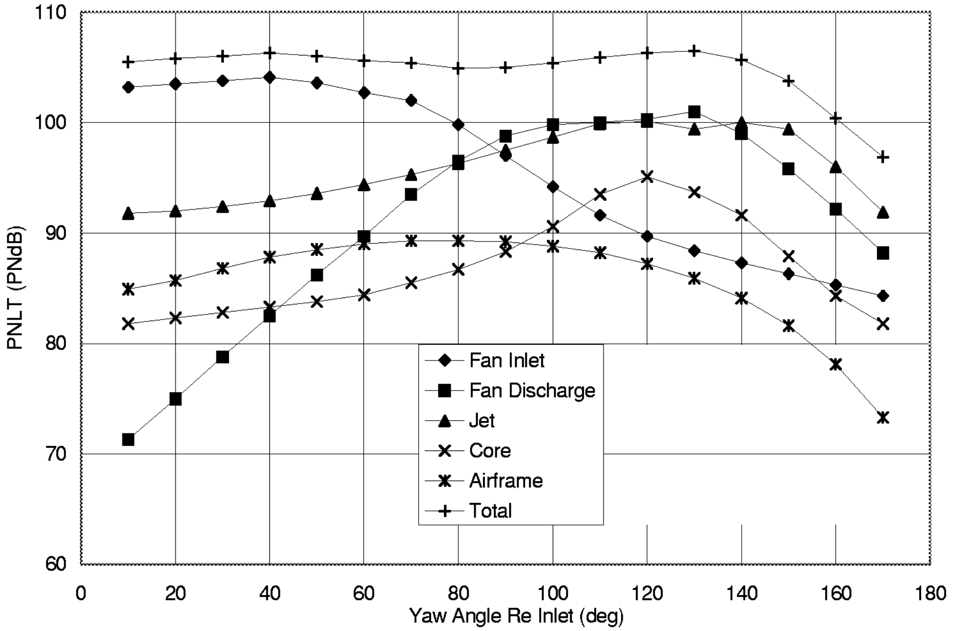

Figure 8: FJX-2 Source PNLT, Sideline Power Setting

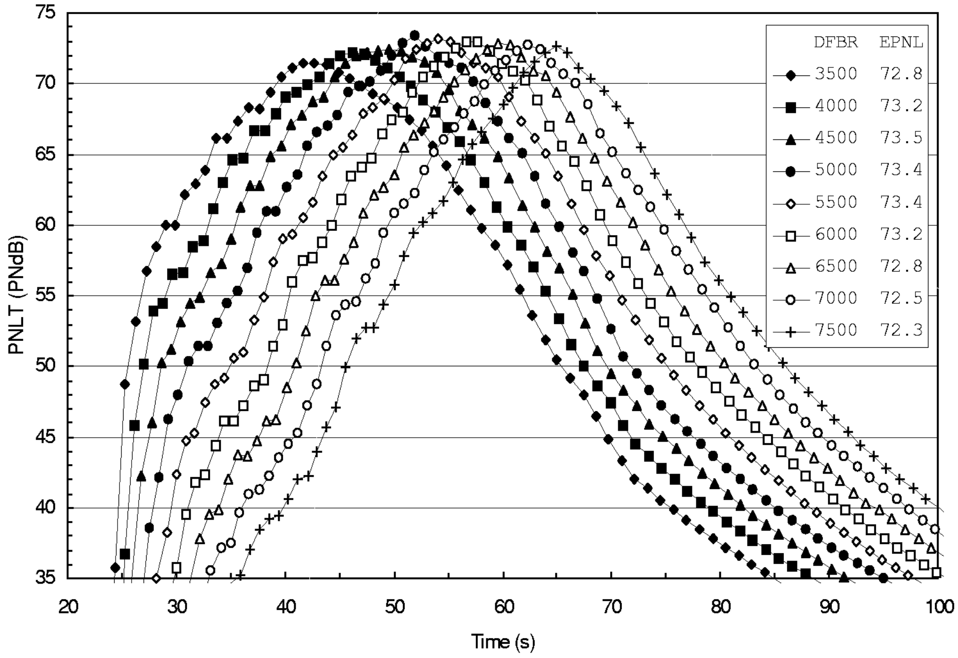

Figure 9: V-Jet I Sideline PNLT Histories

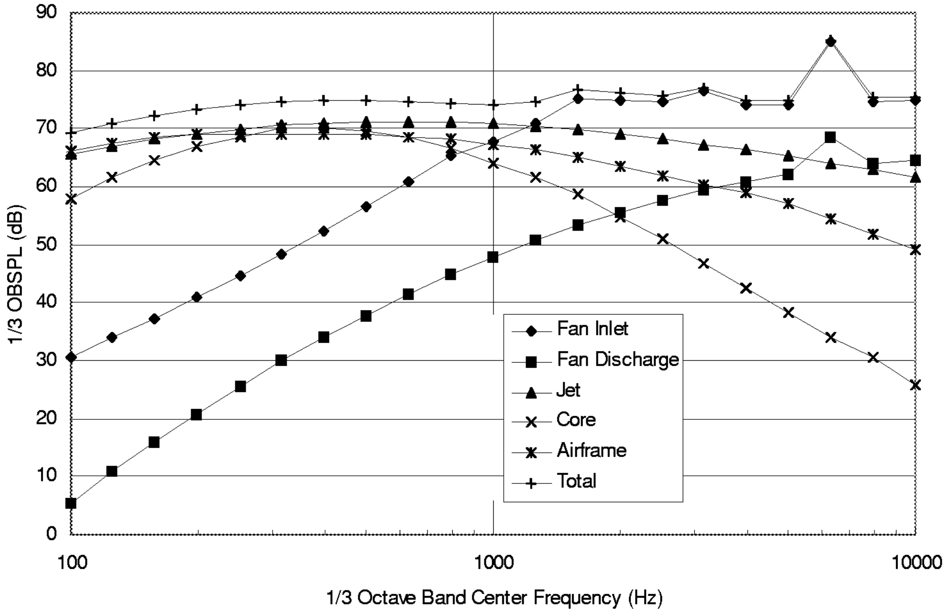

Figure 10: FJX-2 Source Spectra, Community Power Setting, Fore Quadrant

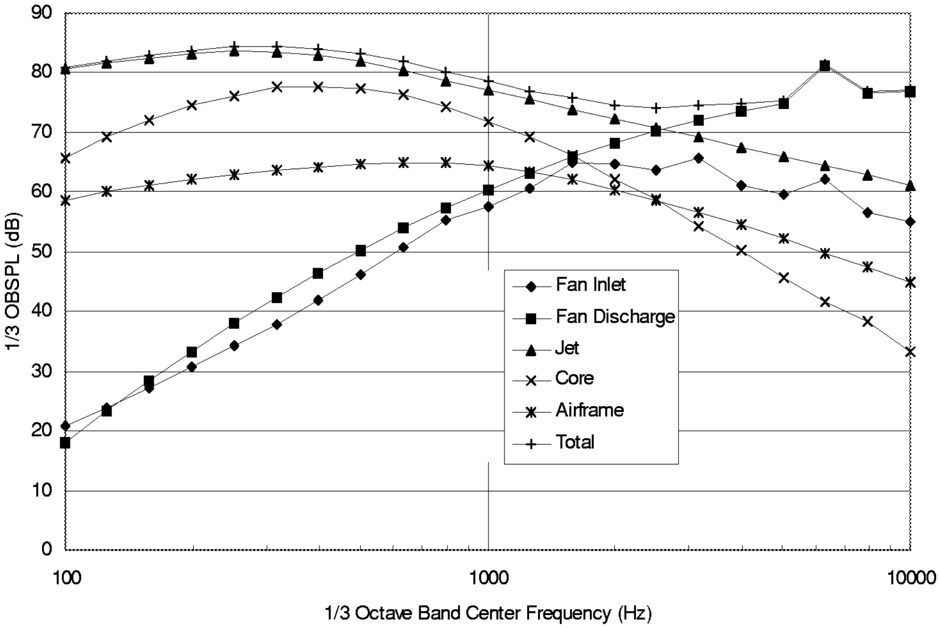

Figure 11: FJX-2 Source Spectra, Community Power Setting, Aft Quadrant

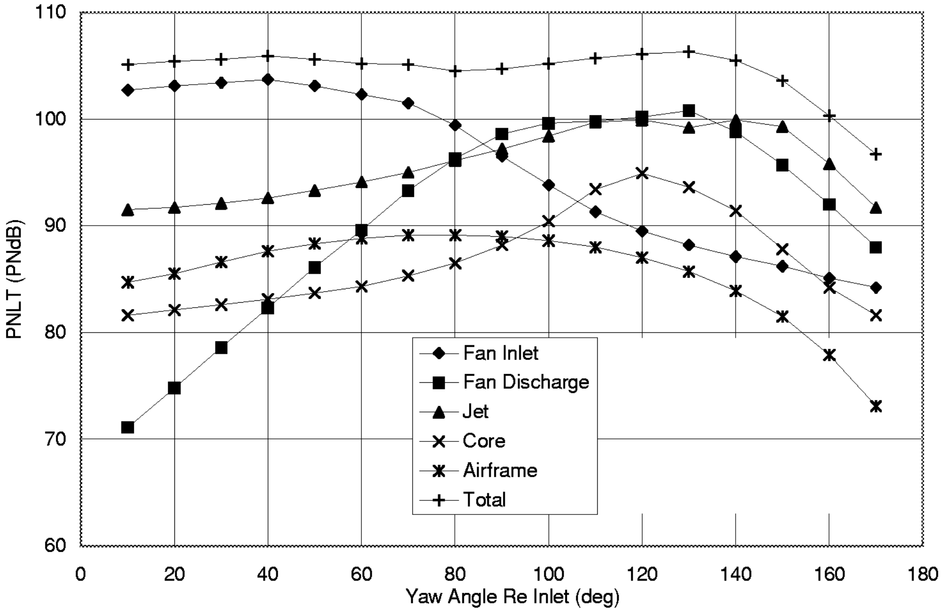

Figure 12: FJX-2 Source PNLT, Community Power Setting

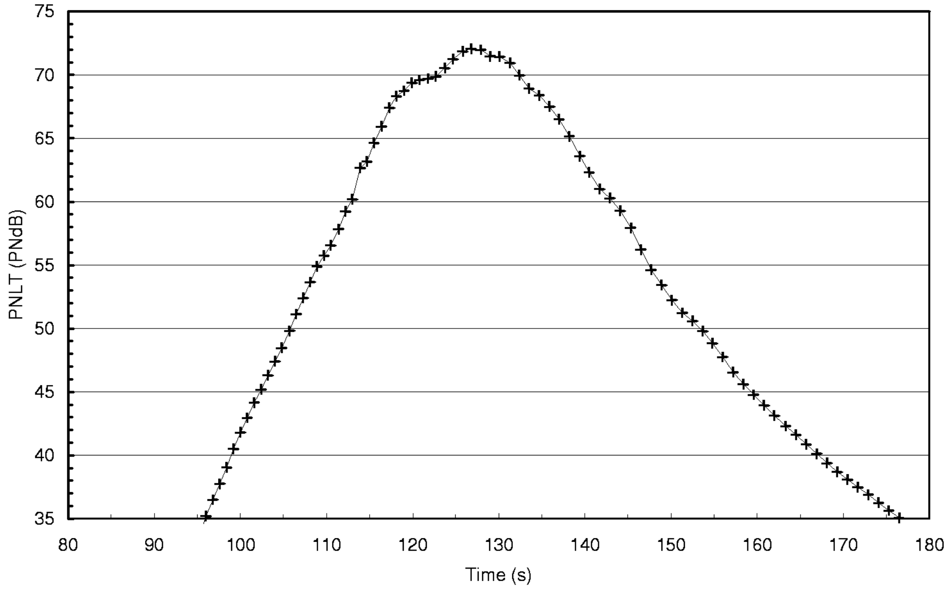

Figure 13: V-Jet I Community PNLT History

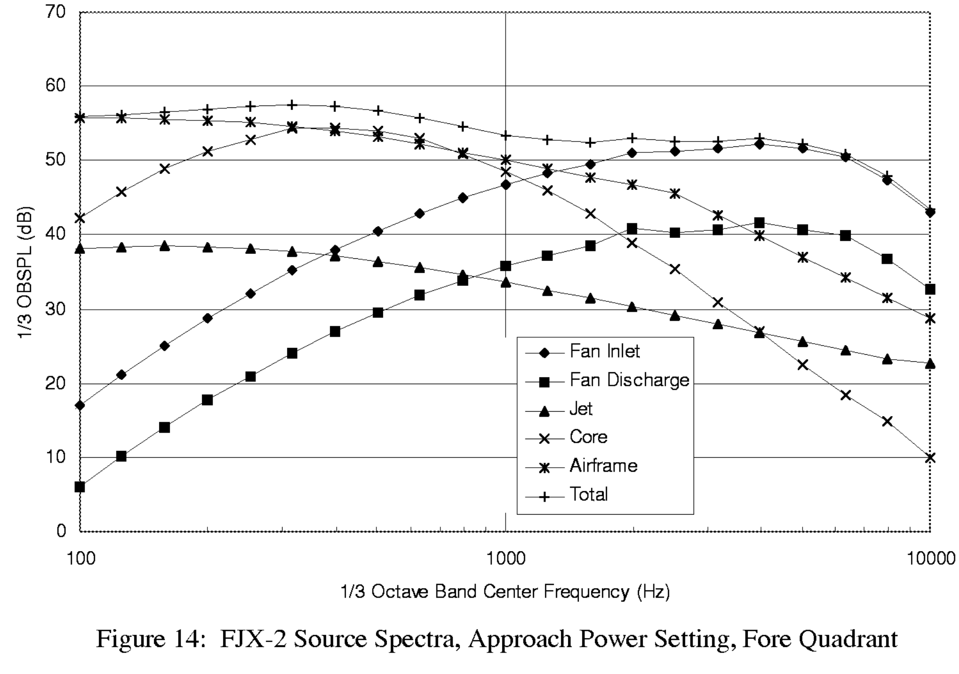

Figure 14: FJX-2 Source Spectra, Approach Power Setting, Fore Quadrant

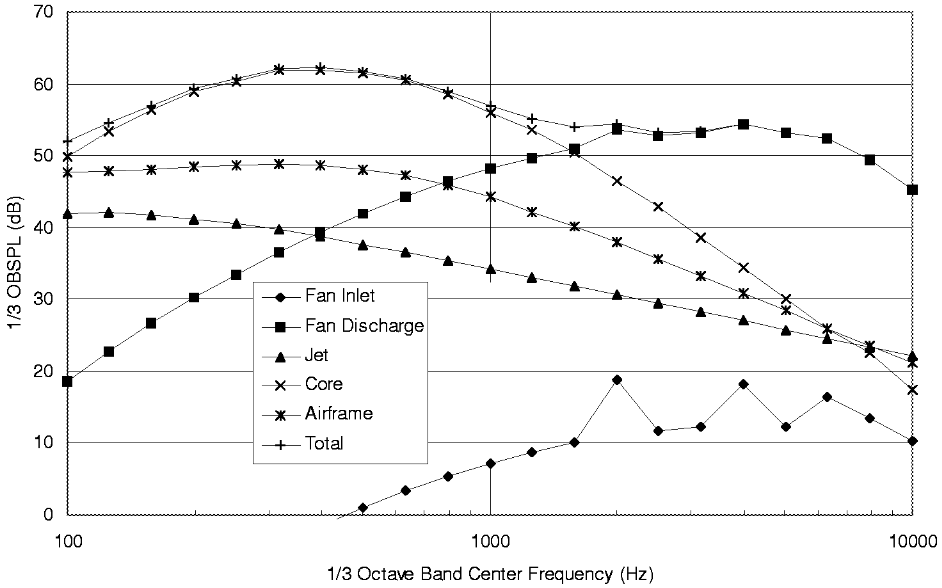

Figure 15: FJX-2 Source Spectra, Approach Power Setting, Aft Quadrant

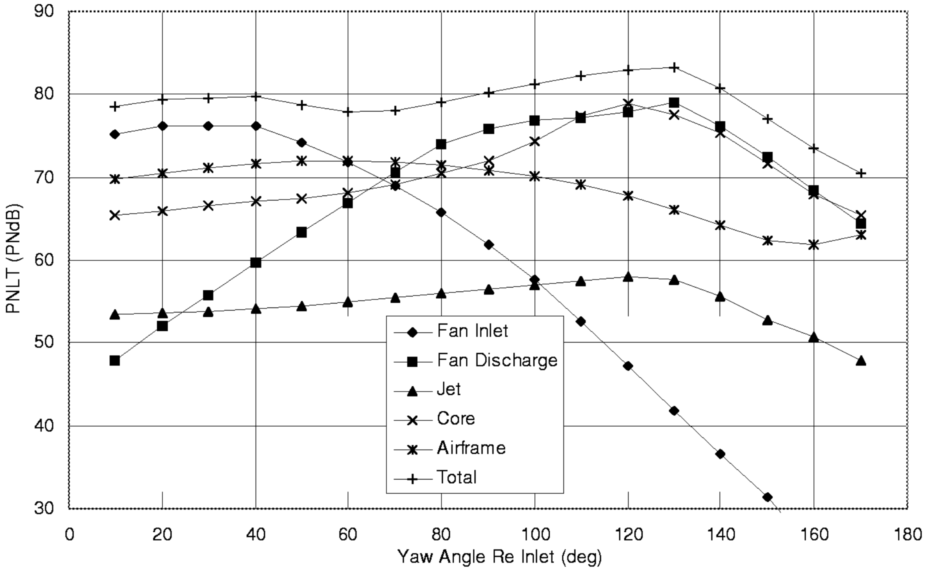

Figure 16: FJX-2 Source PNLT, Approach Power Setting

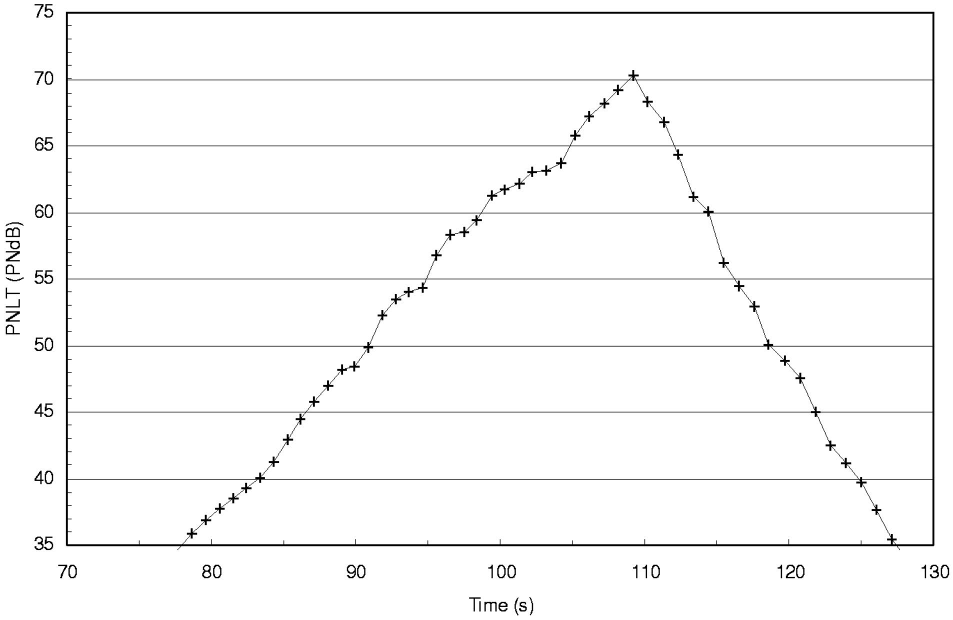

Figure 17: V-Jet I Approach PNLT History

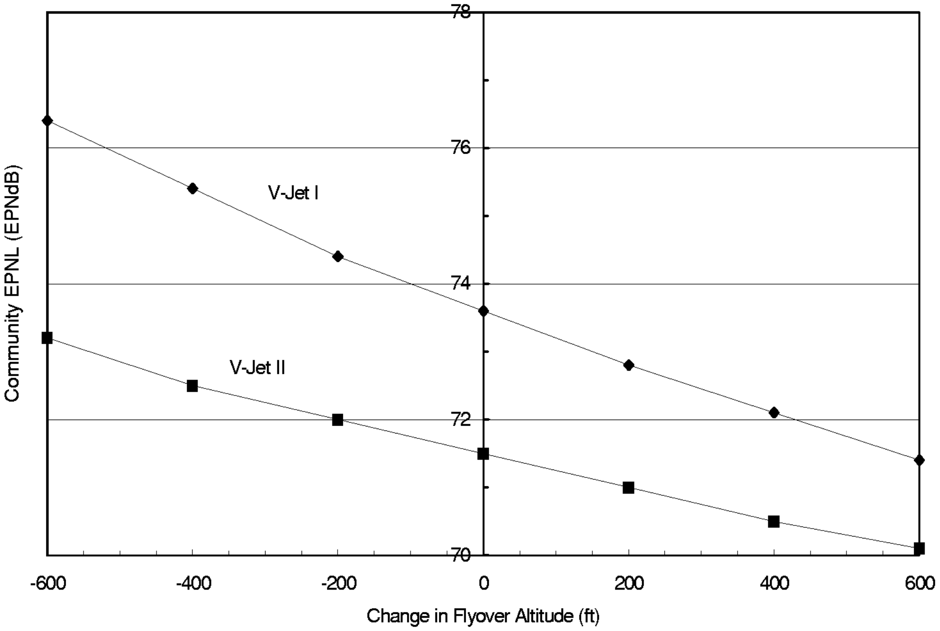

Figure 18: Influence of Flyover Altitude on Community EPNLs

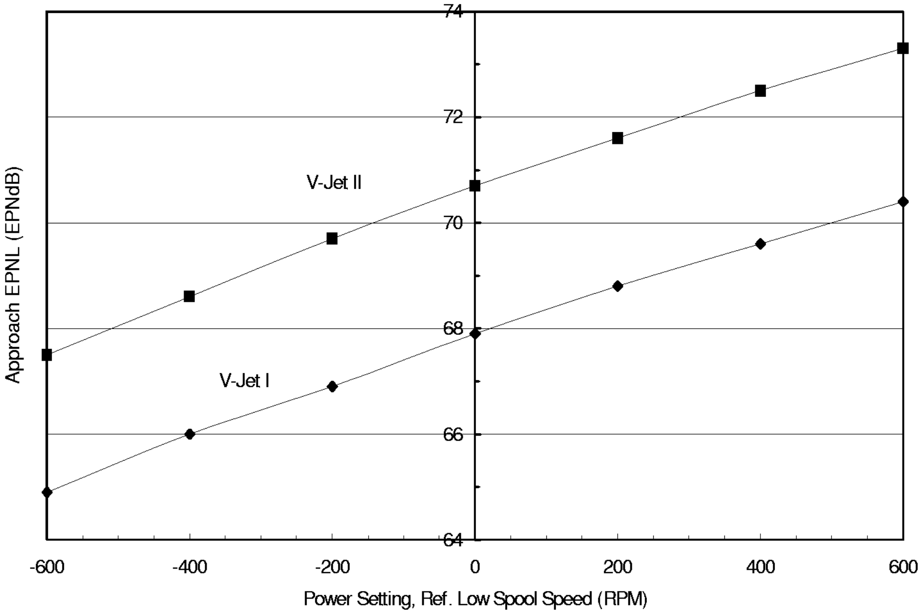

Figure 19: Influence of Approach Power Setting on Approach EPNLs

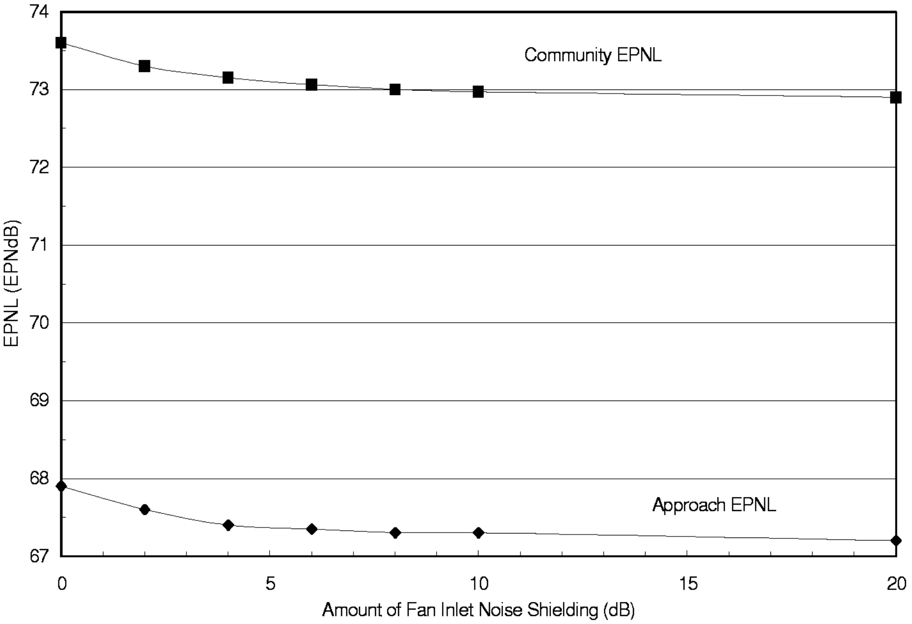

Figure 20: Influence of Fan Inlet Shielding on V-Jet I Flyover EPNLs

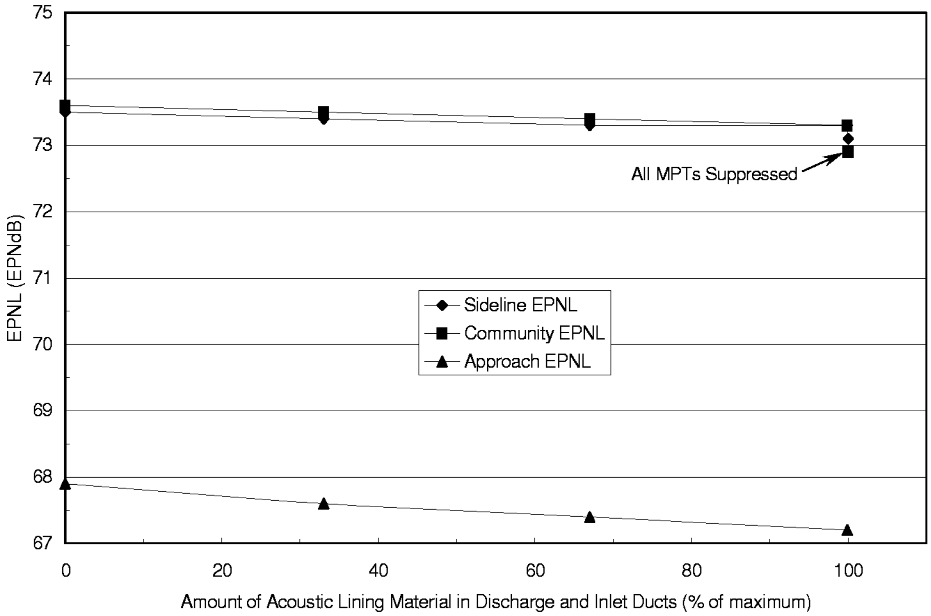

Figure 21: Influence of Acoustic Lining Suppression on V-Jet I EPNLs

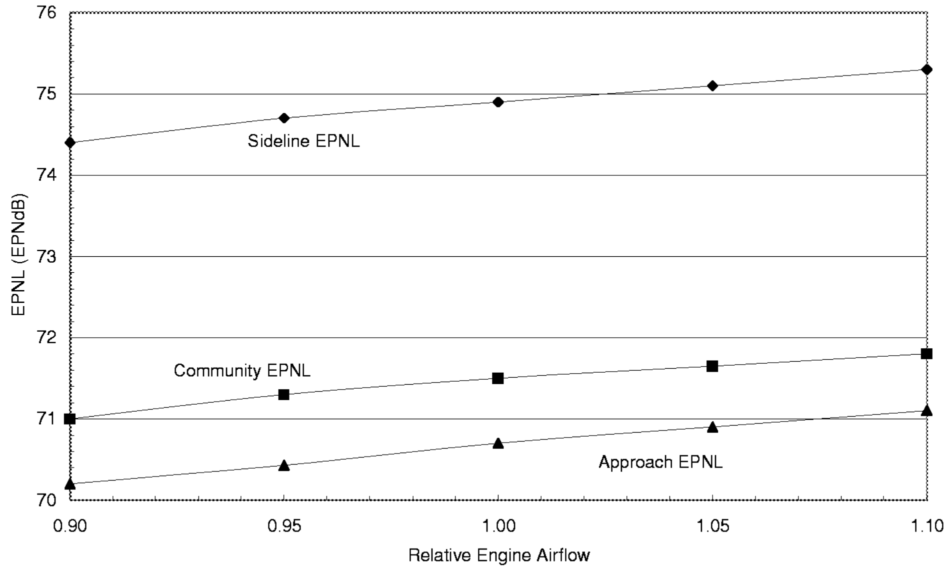

Figure 22: Influence of Engine Size on V-Jet II EPNLs

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13. ABSTRACT *(Maximum 200 words)*

Williams International Co. is currently developing the 700-pound thrust class FJX-2 turbofan engine for the general Aviation Propulsion Program’s Turbine Engine Element. As part of the 1996 NASA-Williams cooperative working agreement, NASA agreed to analytically calculate the noise certification levels of the FJX-2-powered V-Jet II test bed aircraft. Although the V-Jet II is a demonstration aircraft that is unlikely to be produced and certified, the noise results presented here may be considered to be representative of the noise levels of small, general aviation jet aircraft that the FJX-2 would power. A single engine variant of the V-Jet II, the V-Jet I concept airplane, is also considered. Reported in this paper are the analytically predicted FJX-2/V-Jet noise levels appropriate for Federal Aviation Regulation certification. Also reported are FJX-2/V-Jet noise levels using noise metrics appropriate for the propeller-driven aircraft that will be its major market competition, as well as a sensitivity analysis of the certification noise levels to major system uncertainties.

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