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Measurement and Prediction of Noise Propagation from a High-Power Jet Aircraft

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Static engine run-up noise measurements have been made on the F-22 Raptor at low and high power settings. At afterburner, the propagation measurements reveal significant evidence of nonlinearity in that there is much greater high-frequency energy than is predicted by linear theory. The measurements have been compared against the results of a nonlinear numerical model based on the generalized Mendousse-Burgers equation. Although the model simplifies the propagation environment in that it neglects ground effects and atmospheric variability, agreement between the measured and nonlinearly predicted spectra is quite favorable. This comparison demonstrates that nonlinear effects can play a significant role in the propagation of high-amplitude noise and that prediction of these effects is possible with this type of numerical model.

I. Introduction

THE prediction of high-amplitude noise propagation has been the subject of a number of previous studies[1-3] that have utilized the generalized Mendousse-Burgers equation (GMBE)[4] to model the propagation. Pestorius and Blackstock[1] experimentally and numerically investigated the propagation of finite-amplitude noise in a one-dimensional duct. They developed an algorithm that Blackstock later used to propagate an actual T-38 noise recording[5]. Although that study predicted a nonlinear evolution of the jet noise waveform, measurements were not made at greater distances, which prevented a direct comparison of the prediction and measurement. Howell and Morfey[2] and Crighton and Bashforth[3] devised methods by which power spectra could be directly evolved nonlinearly via an ensemble-averaged version of the GMBE, but both of these methods have fundamental difficulties in that they neglect phase, an essential part of nonlinear propagation physics.

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Recently, Gee *et al.*[6,7] built upon Pestorius and Blackstock's original work and compared the results of numerical propagation of F/A-18E waveforms via their algorithm against measurements that showed evidence of nonlinear propagation[8,9]. Although there were distinct similarities in the high-frequency roll-off trends for comparisons at 74 and 150 m there were also notable differences between predicted and measured spectra. These differences were qualitatively confirmed in a similar comparison by Brouwer[10] that employed a different solution technique of the GMBE. Although the reasons for the discrepancies between the nonlinear model and the F/A-18 measurement are still not fully understood, it is believed that environmental effects contributed to the differences. The numerical model assumes free-field propagation through a quiescent atmosphere, whereas in the actual experiment, there were notable variations in terrain topography and composition, which can lead to complicated multipath interference effects, and wind and temperature gradients that likely caused refractive effects.

The previous F/A-18E comparisons showed the nonlinear model's promise in predicting high-amplitude noise propagation, but the limitations in the experimental setup and measurement environment precluded a more conclusive comparison. Lessons learned from those measurements were incorporated into the test plan for static engine run-up measurements of the F-22 Raptor. Specifically, the Raptor measurements were of greater bandwidth and the propagation environment was better understood. After a description of the measurement setup and a presentation of third-octave spectral results at low and high power settings, measured and predicted spectra are compared and discussed.

II. Measurement Description

The F-22 static engine run-up tests were conducted by Wyle Laboratories and Penn State during the early morning on 15 September 2004 at Edwards Air Force Base (EAFB). A measurement array, consisting of Bruel and Kjaer (Types 4938, 4939 and 4190) and GRAS (Type 40BF) condenser microphones were located at various distances along five different radials, all at a height of approximately 1.8 m. The microphone layout is shown in Fig. 1 relative to the orientation of the jet; angles are measured relative to the jet inlet. The origin for the measurement array was located approximately 5.5 m (roughly 7-8 jet diameters) downstream from the jet nozzles in an attempt to place the origin near the dominant aeroacoustic source region. Note that this is only a rough approximation, because the dominant source region varies both as a function of frequency and angle. During the tests, the engine farthest from the measurement array was held at idle while the other engine's condition was varied for the run-up tests. Acquisition of the pressure waveforms was carried out using National Instruments 24-bit PXI-4472 DAQ cards with a 96-kHz sampling rate.

The time of the tests was selected to be early morning with the hope of minimizing atmospheric effects that are common during the day at EAFB, namely a significant temperature lapse and moderate winds. The run-up measurements took place between 6:30-8:00 a.m. Pacific Daylight Time (PDT), during which time atmospheric conditions were generally conducive to making propagation measurements. A meteorological station, which consisted of three temperature sensors, two relative humidity sensors, and wind speed and direction gauges, was used to track the local meteorology near the ground throughout the measurements. The particular measurements highlighted in this paper occurred when there was little or no wind and little temperature gradient.

III. Measurement Results

Measurement results for two engine conditions, idle and afterburner (AB), are presented in this section. The results are presented as one-third octave band spectra. The low-amplitude idle measurement and the high-amplitude AB measurement represent the two extremes of the run-up tests. The focus of this paper is the results along the peak emission angle of 125º.

A. Idle

The first measurement to discuss is for both engines at idle. This test represents the lowest overall levels encountered in the run-up measurements. Displayed in Fig. 2 are the measured spectra at idle along the 125º radial. Because of system noise floor issues, particularly for the 152 and 305-m measurements, the upper one-third octave band shown has been limited to 4 kHz. Despite these noise floor issues, some useful information may be extracted from an examination of linear extrapolations of the measured spectra out to 305 m, which are shown in Fig. 3. The free-field linear predictions, which include spherical spreading and atmospheric absorption, of the idle spectra out to 305 m demonstrate fairly good agreement out to 4 kHz. Two differences, however, are readily noticeable. First of all, the levels of the 305-m measured spectra at low frequencies are a few dB higher than the predicted spectra, all of which collapse very well between 20-200 Hz. A similar discrepancy is also seen in the afterburner measurement, shown subsequently, that was made less than one minute after the idle run. The fact that it is also seen in a low-amplitude idle measurement likely indicates that its cause is a linear, rather than nonlinear, propagation phenomenon. The second major discrepancy between the linearly predicted and measured spectral levels occurs between 500 Hz and 3 kHz, and is likely due to variation in ground interference nulls as a function of range. Similar ground effects are seen in measurements of higher acoustic amplitudes.

B. Afterburner

Measured spectra at the highest engine setting, AB, are now discussed. Shown in Figs. 4 and 5 are the measured and linearly extrapolated spectra out to 305 m along 125º. The OASPL at a given measurement location has increased dramatically from the idle measurement, by an average of about 45 dB. Evident in Fig. 4 are similar ground effects as were present in the idle measurement (e.g., at 700-800 Hz, the 23-m prediction has the lowest amplitude whereas the 61-m prediction has the highest amplitude). Figure 5 also reveals much less roll-off at high frequencies than what would be expected due to atmospheric absorption. The anticipated decrease in high-frequency energy due to linear propagation is seen in Fig. 5, where each of the linearly predicted spectra demonstrates a significant loss of power at high frequencies. For example, the 23-305-m linearly predicted and 305-m measured spectra differ by about 150 dB for the 20 kHz one-third octave band. This apparent transfer of energy to higher frequencies may be attributable to nonlinear steepening of the time waveform as it propagates.

IV. Numerical Model Comparisons

A. Idle

The hypothesis that the anomalously low absorption at high frequencies is caused by nonlinear propagation is tested by comparing the measured results against those of the nonlinear and linear propagation models. Before consideration of the AB test, the idle test is first used to show the agreement between the measurement and models when radiated sound levels are low. Displayed in Fig. 6 are the measured, nonlinearly predicted, and linearly predicted spectra for idle. The nonlinearly predicted spectrum is generated from the 23-m waveform that is used as an input to the model. The linearly predicted spectrum is the same linear extrapolation from Fig. 3. There is very little difference between the nonlinear and linear model results out to the maximum one-third octave band of 4 kHz; however, agreement between the models and the measured spectra is not outstanding. Note that this discrepancy between predicted and measured spectra is not unexpected because Fig. 3 showed that there is a rather monotonic increase in level at low frequencies (50-100 Hz) as a function of range relative to the assumption of spherical spreading. Because the aeroacoustic source region is likely to be rather compact for this low-amplitude test, the cause of this discrepancy at low frequencies is thought to be the propagation environment. Because agreement between the model and the linear prediction is better over shorter ranges (e.g., see the 152-305-m extrapolation in Fig. 3), atmospheric refractive effects are suspected. The results of this test have been shown in order to provide a direct comparison against the AB test.

B. Afterburner

In Fig. 7, the 305-m measured and predicted spectra are shown, where again the predicted spectra are calculated from the measurement at 23 m. For the sake of comparison against the idle results in Fig. 6, the maximum one-third octave band shown in Fig. 7 is 4 kHz, where there is a difference of about 10 dB between the measured and linearly predicted spectra. On the other hand, the nonlinear prediction follows the measured spectrum much more closely at high frequencies. This greatly strengthens the assertion that the cause of the excess high-frequency energy is nonlinearity. The measured levels at and below the peak frequencies are 2-4 dB greater than predicted, similar to the measured spectral behavior at idle. As discussed previously, it is suspected that because very similar behavior is observed in the idle measurement, the cause of the low-frequency discrepancy is not nonlinear propagation. The preceding idle measurement is important, because without it, the results in Fig. 7 may lead to the conclusion that there is a nonlinear transfer of energy to low frequencies possibly due to shock coalescence. However, the idle measurement results tend to negate that conclusion and suggest that the cause of excess energy is a linear rather than nonlinear effect.

Figure 8 shows the same AB comparison as Fig. 7, but on an expanded scale out to the 20 kHz one-third octave band. The agreement of the nonlinear model is better shown on this scale, because at 20 kHz the linear extrapolation is approximately 150 dB less than the measured spectrum. On the other hand, the difference between the nonlinear and measured spectra is only 4 dB at 20 kHz. In Fig. 9, the 152-m AB waveform has been used as an input to the nonlinear model and shows similar high-frequency agreement at 305 m as the 23-m input waveform did. Over the shorter range calculation, however, agreement at low frequencies is better, as it was for the idle measurement in Fig. 3.

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V. Conclusion

These comparisons of F-22 run-up measurements against the predictions of a generalized Mendousse-Burgers equation-based numerical model show clearly what the previous F/A-18E comparisons did not. For both engines at idle, there is little difference between nonlinear and linear predictions and the results of the models match the measured spectrum fairly well, within expected discrepancies due to ground reflections and atmospheric effects. For one engine at afterburner (AB), there is an excess of high-frequency energy in the 305-m AB measurements relative to a linear propagation prediction. This excess is largely predicted by the nonlinear propagation model. One question that remains to be more fully explored, however, is the role of shock coalescence in nonlinear jet noise propagation. These comparisons suggest that the apparent excess of energy at low frequencies and large distances is a linear effect, however additional comparisons with the F-22 Raptor data set and correlation with the meteorological measurements could help answer that question.

Acknowledgments

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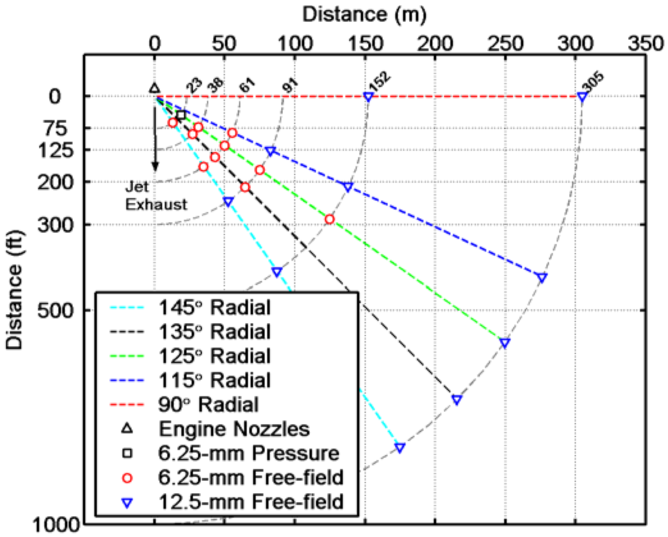

Figure 1. Microphone layout for the static engine run-up tests. All microphones were located approximately 1.8 m above the ground.

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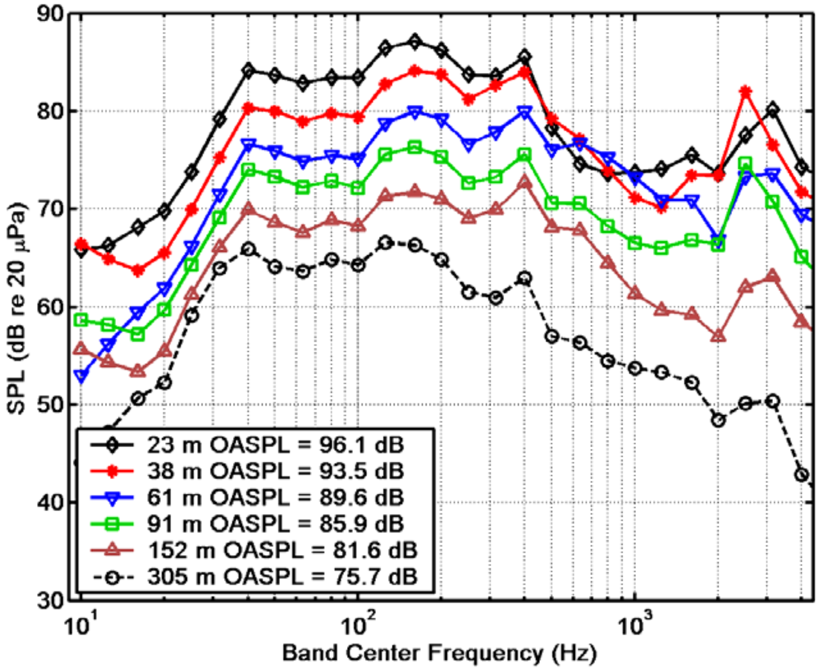

Figure 2. Measured one-third octave band spectra at idle along 125°. The upper frequency limit is 4 kHz because of system noise floor issues at higher frequencies. Also visible is the noise floor below 20 Hz for 38, 91, and 152 m.

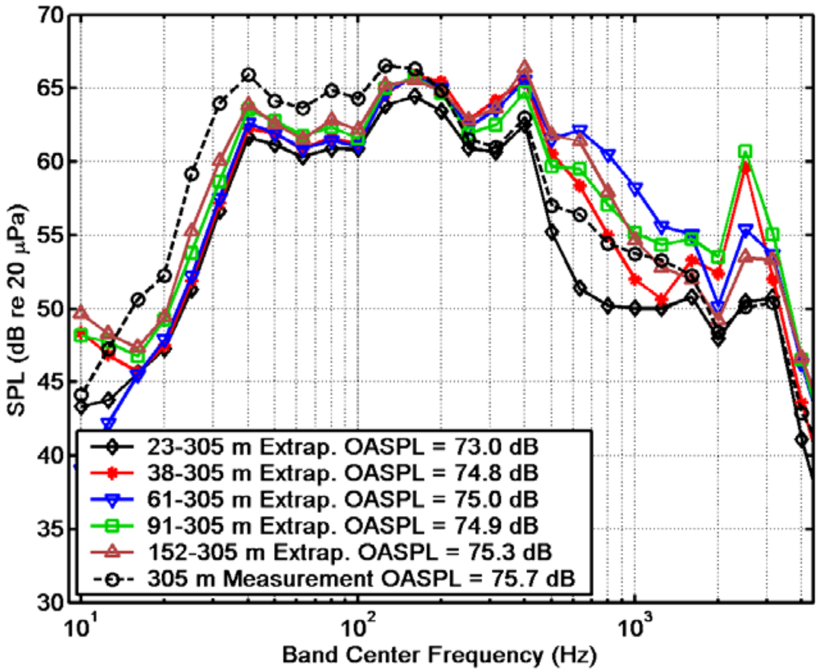

Figure 3. Linear extrapolations of the measured idle one-third octave band spectra out to 305 m.

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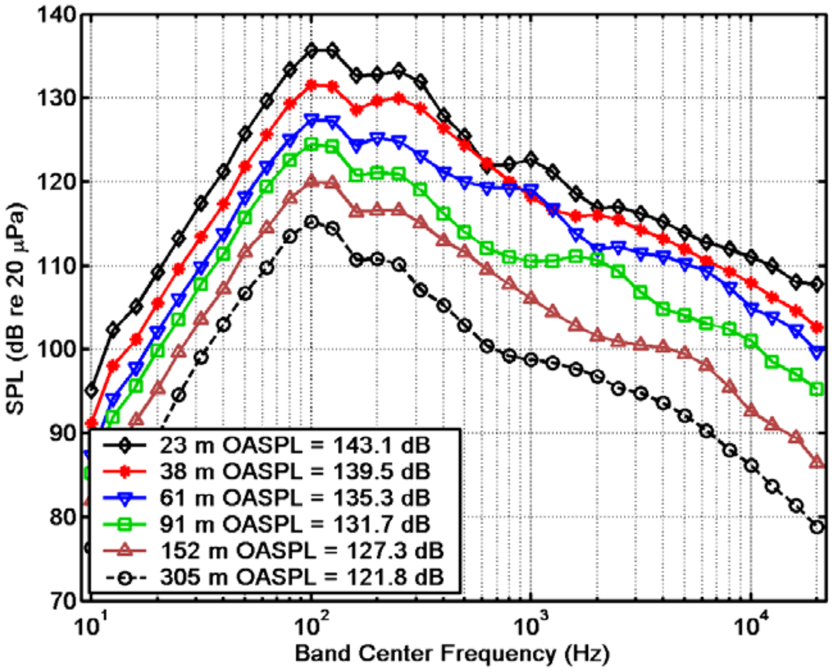

Figure 4. Measured one-third octave band spectra for one engine at afterburner along 125°.

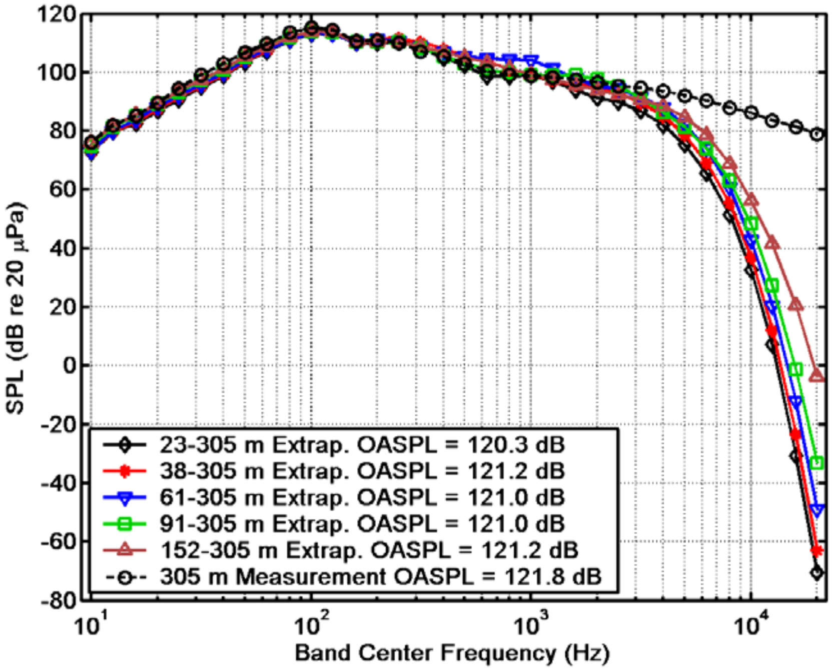

Figure 5. Linear extrapolations of the measured afterburner one-third octave band spectra out to 305 m.

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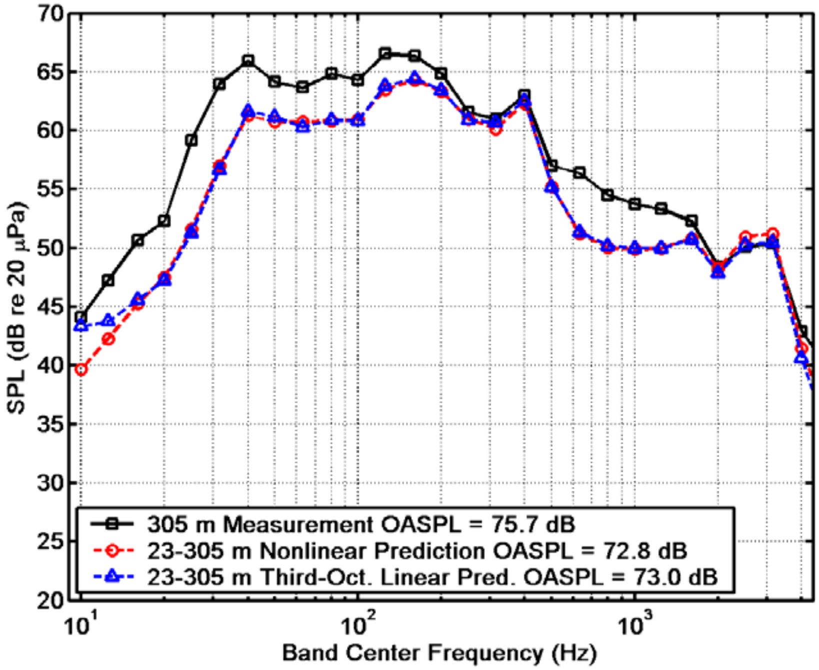

Figure 6. Comparison between the measured and predicted one-third octave band spectra for idle at 305 m.

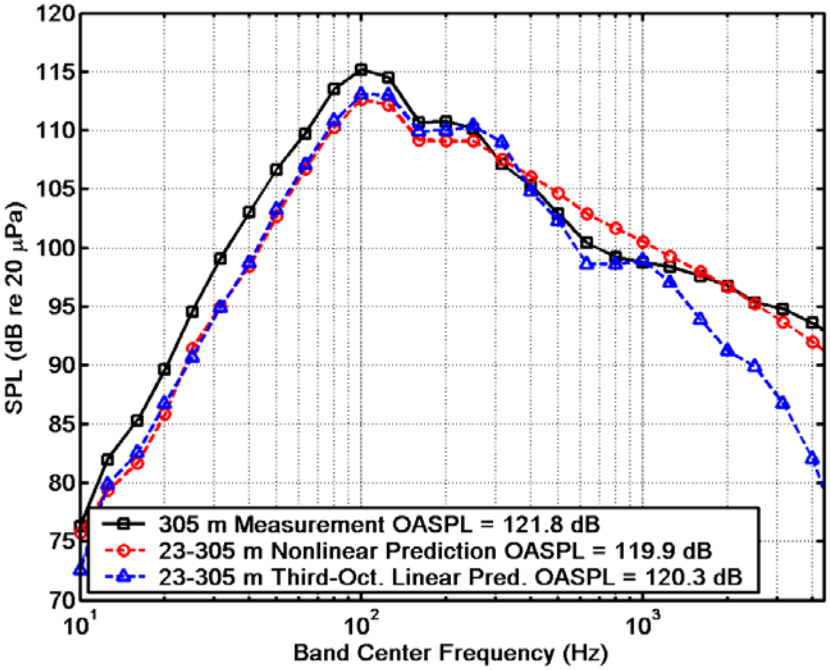

Figure 7. Comparison between the measured and predicted afterburner one-third octave band spectra at 305 m. The maximum third-octave band shown is 4 kHz in order to directly compare with the idle measurement at high frequencies.

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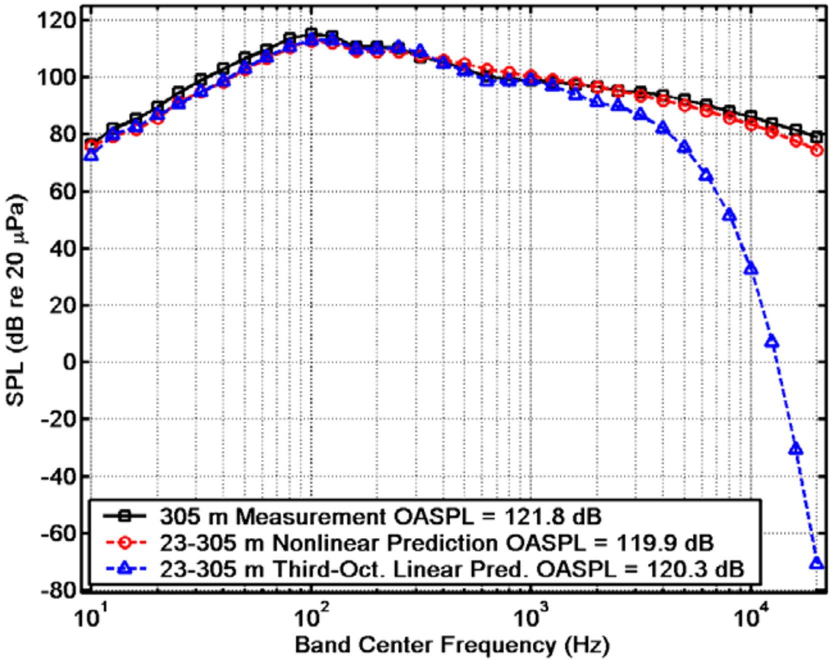

Figure 8. Comparison of measured and predicted spectra for the afterburner case in Fig. 7. The frequency range has been extended in this plot out to the 20-kHz one-third octave band in order to show the extreme differences between the measurement and linear prediction at high frequencies.

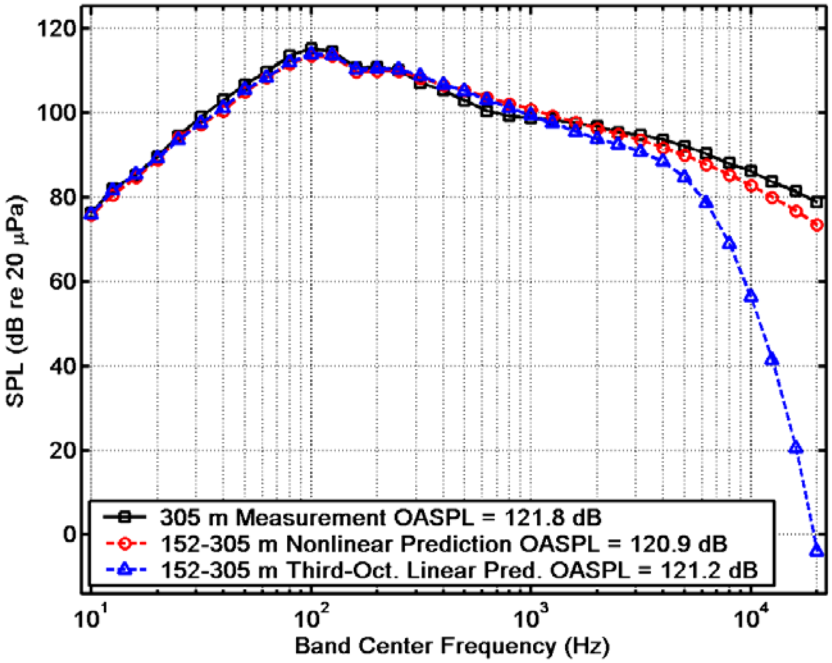

Figure 9. Comparison of measured and predicted spectra for the same afterburner test as in Fig. 8, but for an input distance of 152 m.