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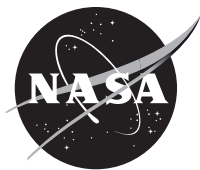
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## **Abstract**

Two novel fan noise reduction concepts were tested using the Source Diagnostic Test fan stage model in the NASA Glenn Research Center 9- by 15-Foot Low-Speed Wind Tunnel (9×15 LSWT). One, referred to as over the rotor treatment, consisted of a number of different casing treatments some of which contained acoustic treatment. The other, known as soft vane, consisted of fan exit guide vanes whose interior volume contained acoustic treatment that was exposed to the vane suction side surface through a perforate.

## **Introduction**

The use of novel noise reduction concepts has a greater importance with the trend toward shorter turbofan engine inlets which have less usable area for the application of conventional acoustic liners. Two novel concepts have been recently investigated at NASA Glenn Research Center, over the rotor (OTR) treatment and soft vane (SV). The OTR treatment is designed to reduce rotor noise by functioning as an acoustic liner as well as by mitigating the large pressure pulses that occur at the fan tip gap. SV relies on reducing the level of fluctuating pressure on the vane surface leading to reduced response of the vane to the incident rotor-induced flow perturbations. Previous tests of OTR treatment at NASA Glenn have shown encouraging noise reduction benefits on a low-speed fan rig and on a low bypass ratio turbofan engine (Refs. 1 and 2). In other wind tunnel tests at NASA Glenn, different OTR treatment and SV designs applied to a high bypass ratio fan model have shown mixed results (Ref. 3). This paper will summarize results of new generation of OTR treatment and SV designs on a high bypass ratio engine model in the NASA Glenn Research Center 9×15 LSWT.

## **Test Hardware**

The NASA Glenn Universal Propulsion Simulator (UPS) was used as the drive system of the turbofan model. Turbines within the drive rig are fed by a 450 psi air source, which turns the fan. The turbofan model used in this test was the Source Diagnostic Test (SDT) fan rig using the R4 fan (Ref. 4). The hardware models a turbofan's bypass system and includes the nacelle, fan, outlet guide vanes, inlet, and nozzle. The fan has 22 blades and the outlet guide vane has 26 vanes. The R4 rotor has a design tip speed of 370 m/s (1215 ft/s) and a design stage pressure ratio of 1.47.

The OTR treatments were designed to be modular allowing different configurations to be tested. An underlying composite base of two 180-degree arc sections was used for all configurations. This base not only extended over the rotor, but also somewhat upstream of it. The base contains oval shaped slots of variable depth. By using different inserts, the slots of the base could be covered in different ways. The

cover inserts were made of nickel-plated composite. An insert consisting of a flat hardwall was used as a baseline. For all other configurations tested, grooves were designed into the inserts. Grooves have traditionally been used to increase fan stall margin, but in this test they also resulted in the reduction of the large pressure pulses at the fan tip before they reached the acoustic treatment underneath the grooves. Using different covers allows different area sizes of the underlying treatment to be exposed to the incident sound field. A wire mesh was used above the grooves upstream of the rotor and between the grooves and treatment over the rotor. In all, six different configurations of rotor casing treatment were designed and tested. These were hardwall (HW), baseline grooved casing (BG), inlet treatment only, OTR treatment only, fully treated small openings (FTSO), and fully treated large openings (FTLO). Figure 1 and Figure 2 show the casing treatment hardware including the composite base and cover inserts for the OTR treatment.

For the SV tests, a solid vane pack was used as the baseline. The SV pack was tested with the hardwall nacelle as well as with the casing treatment. SV features internal cavities that are exposed to the suction side flow starting near the leading edge of the vane and extending to its mid-chord. Figure 3 shows a view of the soft vanes before installation in the SDT model.

## **Test Matrix**

Due to the interchangeability of the casing treatments, the six treatment configurations, namely, HW, BG, inlet treatment only, OTR treatment only, FTSO, and FTLO were tested with the solid vane pack. The SV hardware was tested with both the hardwall and FTSO treatment, which at the time was considered the best treatment acoustically. The tests were conducted at a wind tunnel free stream flow of Mach 0.1. The rotor shaft speeds tested ranged from corrected RPMs of 6328 to 10758.

## **Test Facility**

The test was conducted in the NASA Glenn Research Center 9×15 LSWT. The 9×15 LSWT has acoustically treated walls using Kevlar batting. Information about the 9×15 LSWT can be found in References 5 to 7.

Sideline acoustic measurements were obtained using a traversing microphone on a track parallel to the fan axis and 89 in. away from it. Data were taken at 48 positions on the traverse at 2.5-degree intervals ranging from 27 to 135 degrees relative to the fan stacking axis with zero angle being at upstream infinity. At a free stream Mach Number of 0.1 the corresponding emitted angle range of the traversing microphone is from 25 to 131 degrees. Three additional microphones were placed on the floor of the test section between the traversing microphone and the model at an axial position of the aft most traverse stop. These three microphones give additional angular measurement coverage of 140, 150, and 160 degrees. The corresponding emitted angles for a free stream Mach Number of 0.1 for the fixed floor microphones are 136, 147, and 158 degrees. The microphones used were 1/4-in. in diameter and nose cones were installed for in-flow measurements. The nose cones used in this test are based on the flow induced tone eliminator (FITE) design that was developed at the NASA Ames Research Center (ARC). Data were taken at a sampling rate of 200 kHz in order to ensure a reliable frequency upper limit of at least 60 kHz. This would permit scaling this data to full-scale for system noise analysis purposes. Corrections to the data have been made for the microphone response, bullet nose receptivity, atmospheric attenuation, and spherical spreading. All far-field data shown are corrected to 1-ft lossless distance. The accuracy of the data system is  $\pm 1$  dB (Ref. 8). A photograph of the test section containing the model and microphones in the acoustic configuration is shown in Figure 4. It should be noted that the traversing microphone starts in the aft position and moves forward during the test.

## Results

### Sideline Acoustic Results

#### Over the Rotor Treatment

Figure 5 shows overall power levels versus the corrected RPM (RPMc) for the six casing treatments tested. The power levels were calculated using data from the 48 traverse microphone stops as well as the three floor microphones. The frequency range for the calculations was set to 1 to 50 kHz. The results indicated that, for the lower shaft speeds, up to 8000 RPMc, the baseline grooved casing treatment adds 1 dB or more to the overall acoustic power level (OAPWL). The inlet treatment only reduces the grooves noise penalty by about half. Unfortunately, not all of the configurations containing OTR treatment help with the noise increase due to the grooves. In fact, OTR treatment adds another 0.5 dB to the OAPWL. Most of the configurations have the same noise signature as the hardwall in the mid speed range with the inlet treatment only and OTR treatment being upwards of 1 dB higher at the peak levels at 8860 RPMc. This is near the operating condition where the fan tip speed becomes transonic. At the higher speeds the acoustic performances of the treatments start to diverge greatly. Above 9400 RPMc, the baseline noise level of grooved casing approaches hardwall level while the treatment configurations increase in level by as much as 2 dB. Below transonic operating condition, OTR only, FTLO, and inlet treatment only show noise level increases relative to hardwall of approximately 1, 0.5, and 0.5 dB, respectively. The power spectral density (PSD) plots, shown in Figure 6 to Figure 14, help interpret the OAPWL results. Figure 6 shows the spectra for 6961 RPMc and 46 degrees emitted angle. In the top plot it is apparent that the baseline grooved and inlet treatment only configurations have higher broadband levels in the 7 to 19 kHz range than does the hardwall configuration. The OTR treatment has similar broadband levels as the hardwall, but these are negated by additional tonal content appearing at BPF and its higher harmonics. The FTLO configuration is also hampered by the increase in BPF harmonic tones while the FTSO configuration does not add as much tonal content while having a lower broadband than hardwall above 15 kHz. The major downfall for the OTR treatment and FTLO is the addition of tonal content, which appears at all speeds and emitted angles. Both the FTSO and FTLO configurations have lower broadband noise levels relative to the hardwall configuration in the frequency range below 10 kHz. At 6961 RPMc and 90 degrees emitted angle as shown in Figure 7, the broadband noise level increases for the baseline grooved and inlet treatment only configurations are not as large. The additional tonal content of the OTR treatment is still present. The added tonal content of the FTLO configuration is still great while that for the FTSO configuration is somewhat less while showing acceptable broadband levels. The results for 6961 RPMc at 131 degrees emitted angle, shown in Figure 8, are very similar to the 46 degree results, with the broadband differences not as great. At the shaft speed of 8860 RPMc and at an angle of 46 degrees, shown in Figure 9, the broadband noise level differences are not as large as the 6961 RPMc case. The tones induced by the OTR treatment are still present. These tones can also be seen in the FTLO configuration while the hardwall configuration has a higher low-frequency broadband noise level relative to both the FTSO and FTLO configurations. The broadband noise levels for the FTSO configuration are lower over the entire range relative to the hardwall configuration. At 8860 RPMc and 90 degrees, shown in Figure 10, broadband noise levels are 1 to 2 dB higher for almost all treatment configurations relative to the hardwall configuration from 15 kHz on up. The exceptions are inlet treatment only, which merges back with hardwall levels above 25 kHz, and the FTSO which doesn't vary much from hardwall. Except for the FTSO configuration, the broadband noise levels from 15 to 40 kHz are higher for all configurations relative to the hardwall configuration, while the FTLO configuration remains higher even past 40 kHz for the 131 degrees emitted angle at 8860 RPMc. This is shown in Figure 11. The FTSO

configuration, while showing higher broadband levels relative to hardwall, is still the best compared to the other configurations.

At higher speeds, such as 10126 RPMc shown in Figure 12 to Figure 14, the tonal content is great for all configurations. Even the hardwall configuration contains more tonal content than at the lower speeds. It should also be noted that these tones are interspersed between the BPF harmonics in the spectra. The configurations that were noisy due to tonal excitation are now even more so. Interestingly the baseline grooved configuration does not have as large a broadband noise penalty relative to the hardwall as at lower speeds. This coupled with the fact that there is a slight increase in tonal energy for the hardwall now reduces the penalty of the grooves. In addition to the increase in tonal content, the high frequency broadband levels of the over the rotor, FTLO, and FTSO treatments are much higher than broadband, especially at 90 and 131 degrees emitted angle.

### **Soft Vanes**

The OAPWL's plotted in Figure 15 show the performance of SV, both alone and in conjunction with the FTSO treatment, relative to the hardwall configuration. Except at the highest speeds, SV reduces the overall power levels from approximately 0.5 dB to as much as 2 dB over the rest of the shaft speed range. The greatest reduction is found at the 8860 speed when the fan tip speed becomes transonic for which the reduction is approximately 2 dB. When used in conjunction with the FTSO treatment, the low and high shaft speed penalties of the treatment are still seen, negating any soft vane benefits. At transonic tip speed, the FTSO treatment does show an advantage relative to hardwall of around 1 dB while it actually outperforms the SV alone by almost 0.5 dB from 7000 to 8000 RPMc. Figure 16 to Figure 18 show spectra comparing the three configurations of Figure 15 for the shaft speeds of 6328, 8860, and 10126 RPMc, respectively. Each Figure shows the spectra at three emitted angles of 46, 90, and 131 degrees. At 6328 RPMc shown in Figure 16, the SV alone tends to show broadband reductions in the higher frequency range without the increased tonal energy that is introduced by the OTR casing treatments. While not as detrimental as some of the other casing treatments, once again the FTSO treatment introduces additional tonal energy. At 8860 RPMc shown in Figure 17, the SV alone shows reduced broadband noise levels at high frequencies, providing even better attenuation than the FTSO treatment at 90 and 131 degrees emitted angles. The increased reduction in the aft angles is to be expected since SV removes rotor-stator interaction noise that is propagating downstream. While the addition of the FTSO treatment with SV once again has higher tonal energy, it does show lower broadband noise levels at low frequencies at both 6328 and 8860 RPMc. Lastly Figure 18 shows the spectra at the three emitted angles for 10126 RPMc. As before SV does well at reducing high frequency broadband noise relative to the hardwall configuration. The addition of the FTSO treatment introduces BPF tone harmonics as well as high-frequency broadband noise at the 90 and 131 degree emitted angles.

### **Conclusions**

The application of different casing treatments to the SDT fan showed mixed results. The use of a grooved casing treatment adds additional broadband noise at all speeds and frequencies relative to a hardwall configuration. Since all of the casing treatments used this grooved design, the noise floor is higher for all of these configurations. The inlet treatment only configuration shows a tendency to reduce broadband noise compared to the baseline grooved casing, but, unfortunately, the penalty of the grooves does not allow the inlet treatment only benefits to approach the hardwall levels. A negative aspect of the various OTR treatments was the tendency to introduce additional BPF tonal harmonic energy. This was particularly evident in the OTR alone and FTLO treatments. The FTLO and especially the FTSO

treatments showed low-frequency broadband noise reduction in the inlet relative to hardwall, but unfortunately the higher noise floor of the grooves and the introduction of tonal energy negated any of these benefits when comparing the overall power levels. In fact, when looking at OAPWL metrics over the entire speed range, there is no noise benefit for these OTR treatments. In low and mid shaft speed conditions, the FTSO treatment also shows some high frequency noise reduction relative to the hardwall, particularly in the inlet quadrant.

Except for the highest shaft speed, SV show OAPWL noise reductions from just under 1 dB to as much as 3 dB over the entire speed range. The majority of the SV noise reduction is in high frequency broadband noise relative to hardwall casing. This noise reduction was present over the entire shaft speed and emitted angle ranges. The combination of SV with FTSO casing treatment does not show any benefit compared to SV alone on the basis of OAPWL. The FTSO treatment does introduce additional tonal energy, and this negates any broadband benefit seen in the lower frequencies in the inlet for low and mid shaft speeds. Lastly, the FTSO treatment increases high frequency broadband noise levels relative to hardwall and SV alone for mid and aft emitted angles at the higher shaft speeds.

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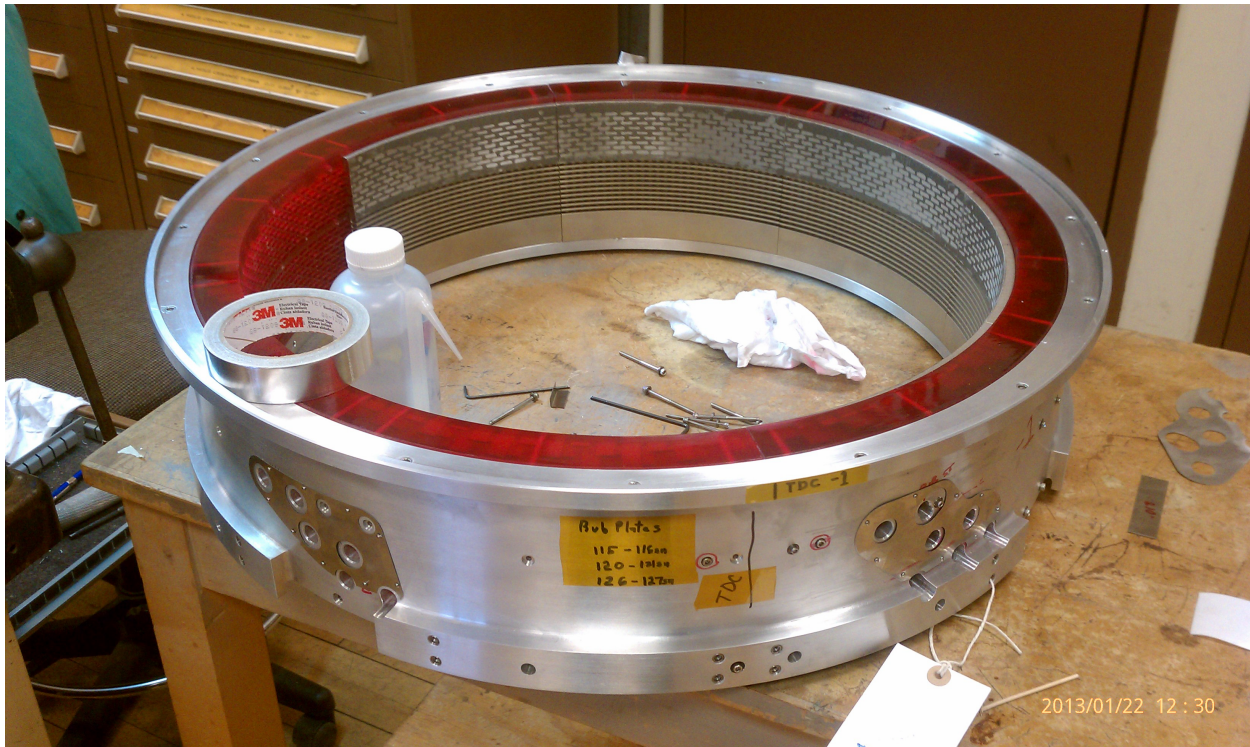


Figure 1.—Over the Rotor casing treatment showing composite base containing variable depth treatment and interchangeable top pieces with grooves.

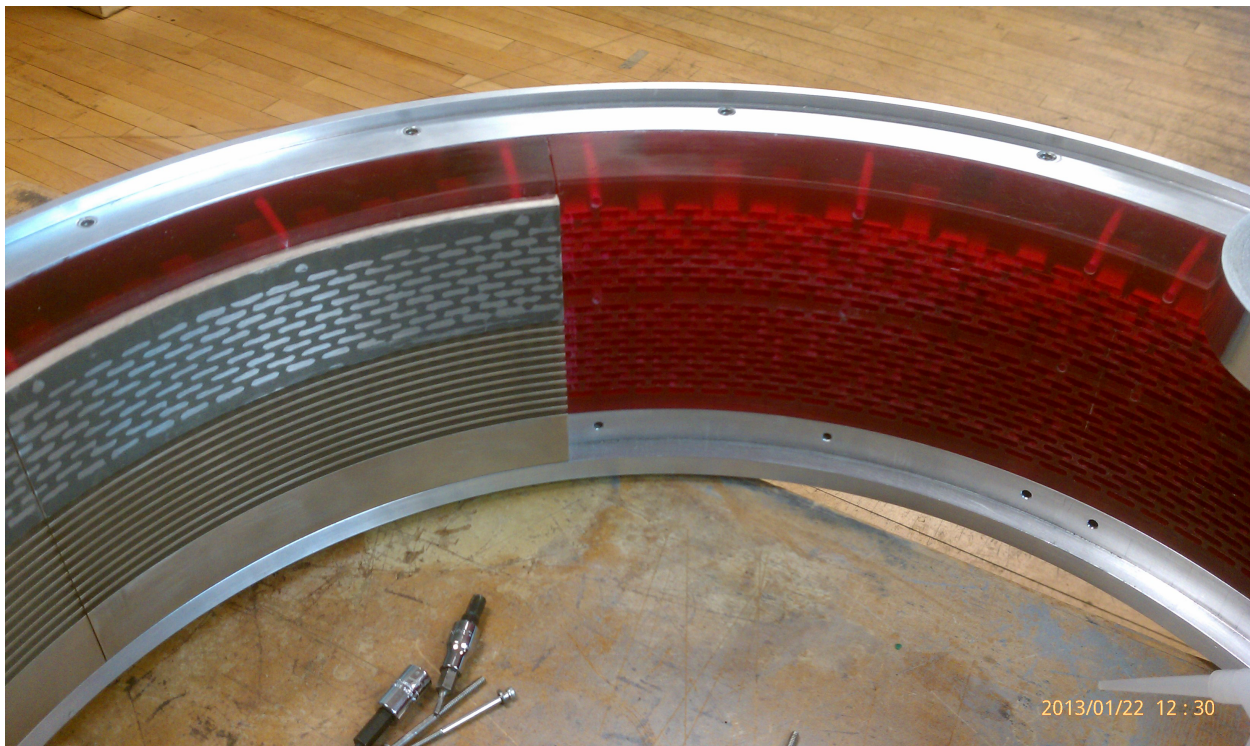


Figure 2.—Close up of Over the Rotor casing treatment showing composite base containing variable depth treatment and interchangeable top pieces with grooves.

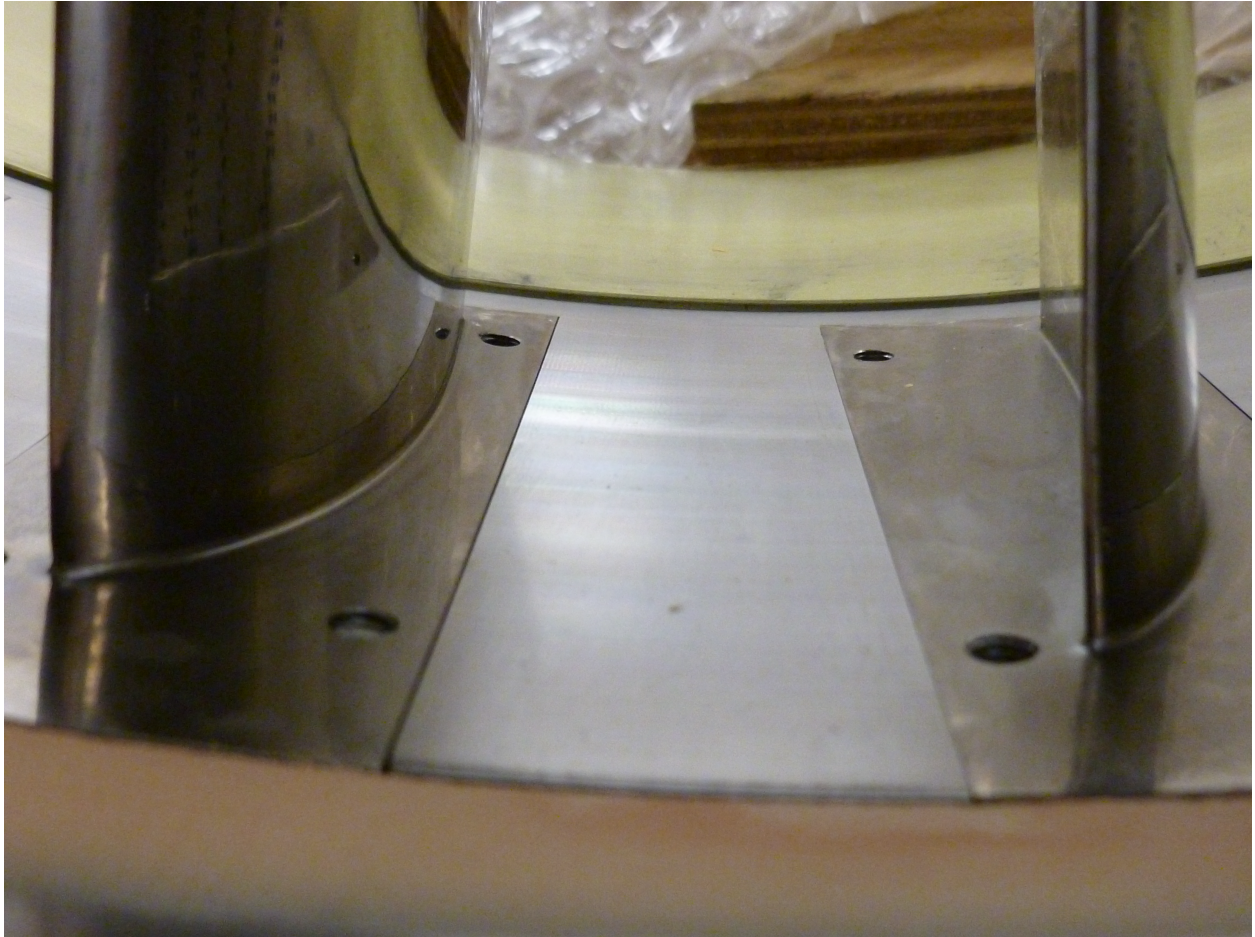


Figure 3.—View of Soft Vanes showing perforate toward front edge of vanes.



Figure 4.—Installed model in the NASA Glenn Research Center 9- by 15-Foot Low-Speed Wind Tunnel (9x15 LSWT) showing traversing and fixed microphone locations.

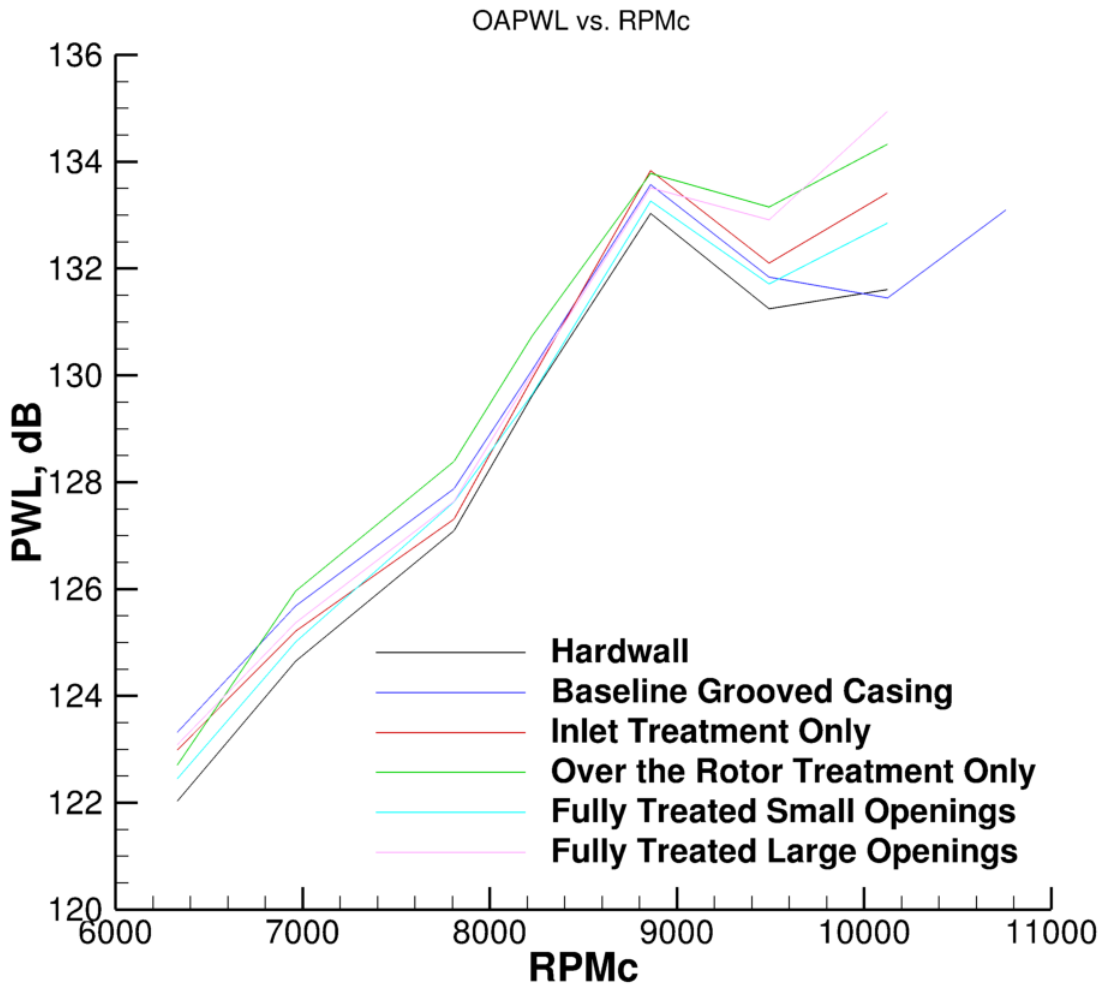


Figure 5.—Overall Power Levels versus Corrected RPM comparing the 6 different configurations of casing treatment on the SDT fan model.

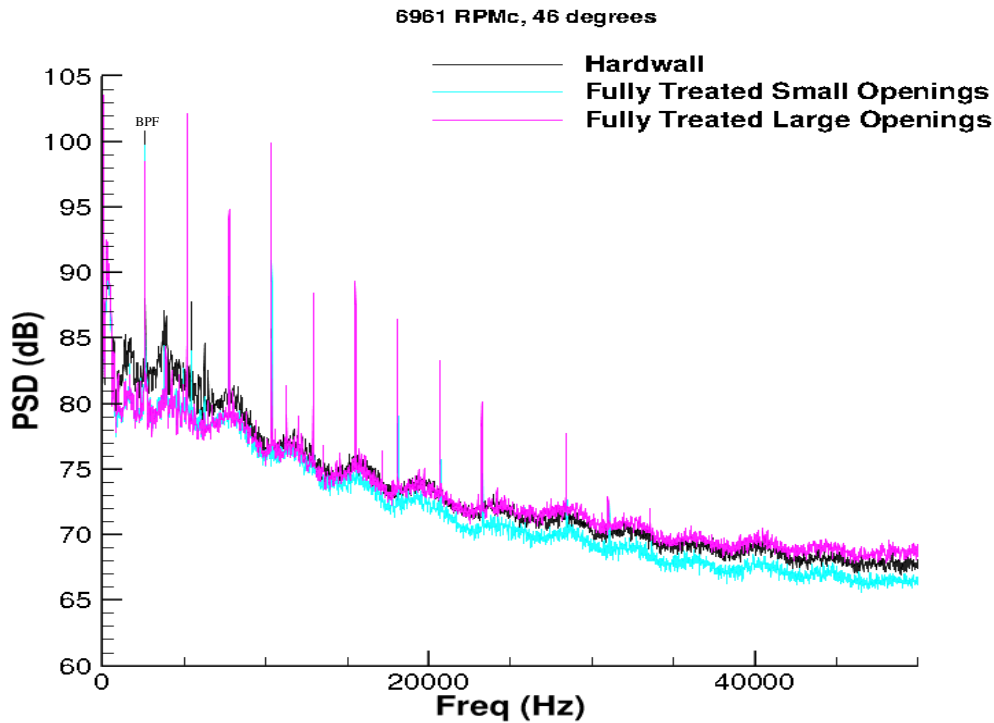
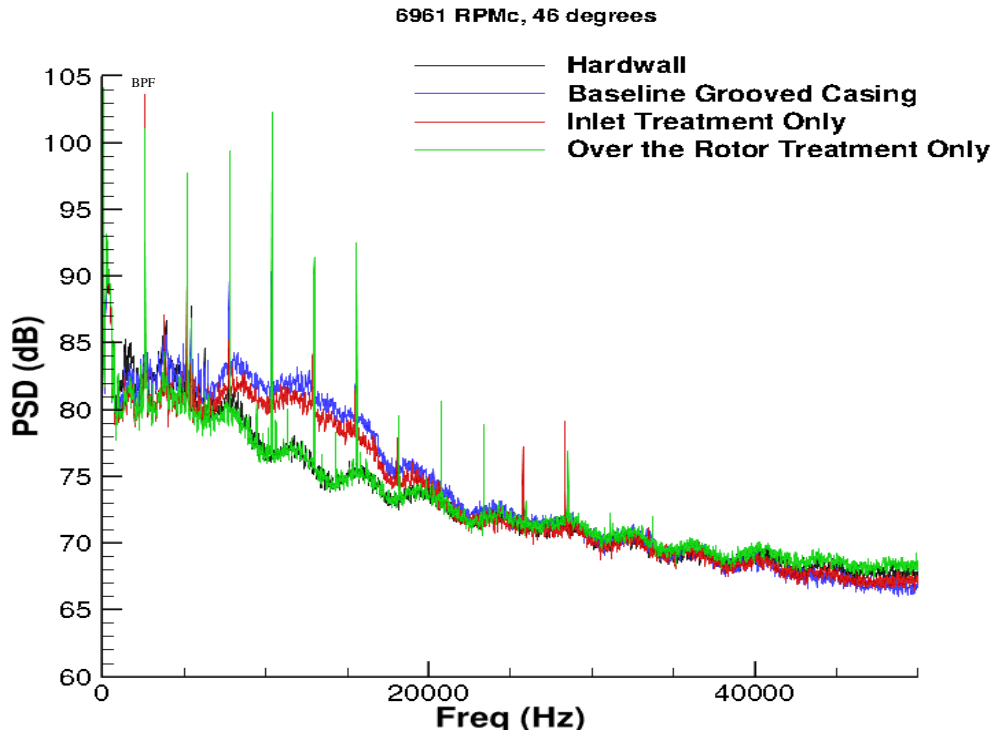


Figure 6.—The 1-ft lossless spectra for 6961 RPMc condition showing Hardwall, Baseline Grooved, Inlet Treatment, and Over the Rotor Treatment casing treatments (Top) and Hardwall, Fully Treated Small Openings, and Fully Treated Large Openings (Bottom) for 46 degrees emitted angle.

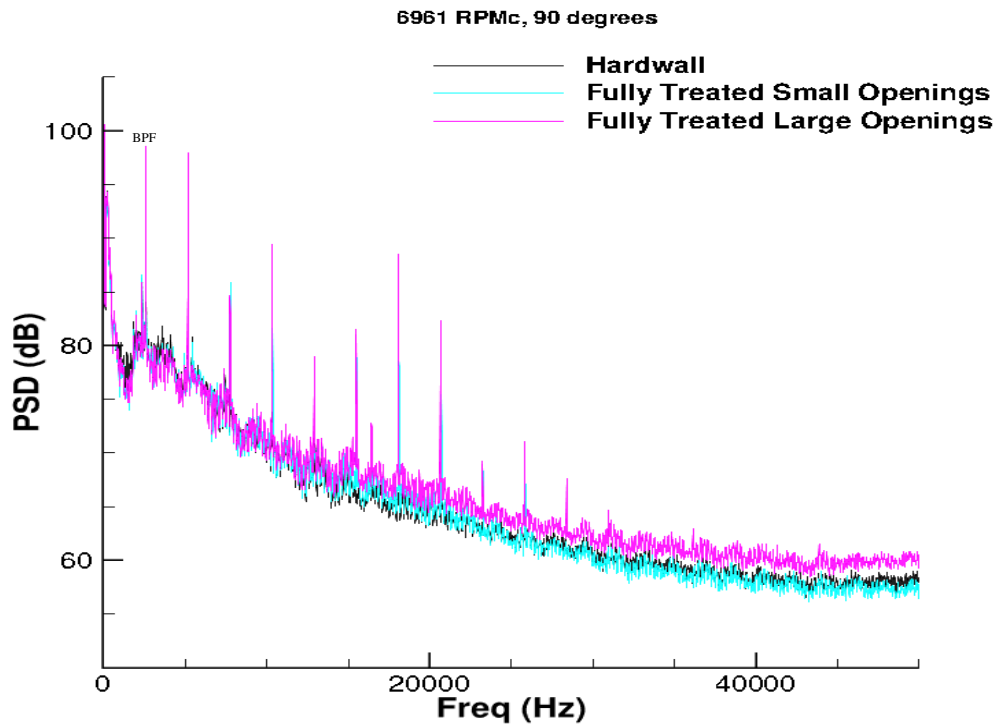
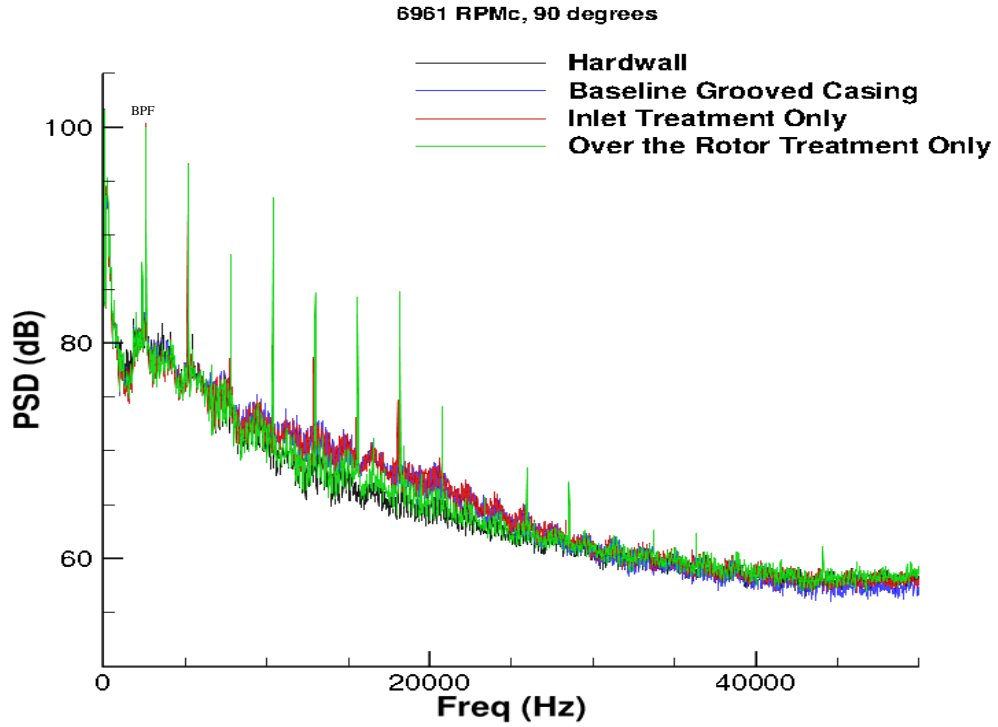


Figure 7.—The 1-ft lossless spectra for 6961 RPMc condition showing Hardwall, Baseline Grooved, Inlet Treatment, and Over the Rotor Treatment casing treatments (Top) and Hardwall, Fully Treated Small Openings, and Fully Treated Large Openings (Bottom) for 90 degrees emitted angle.

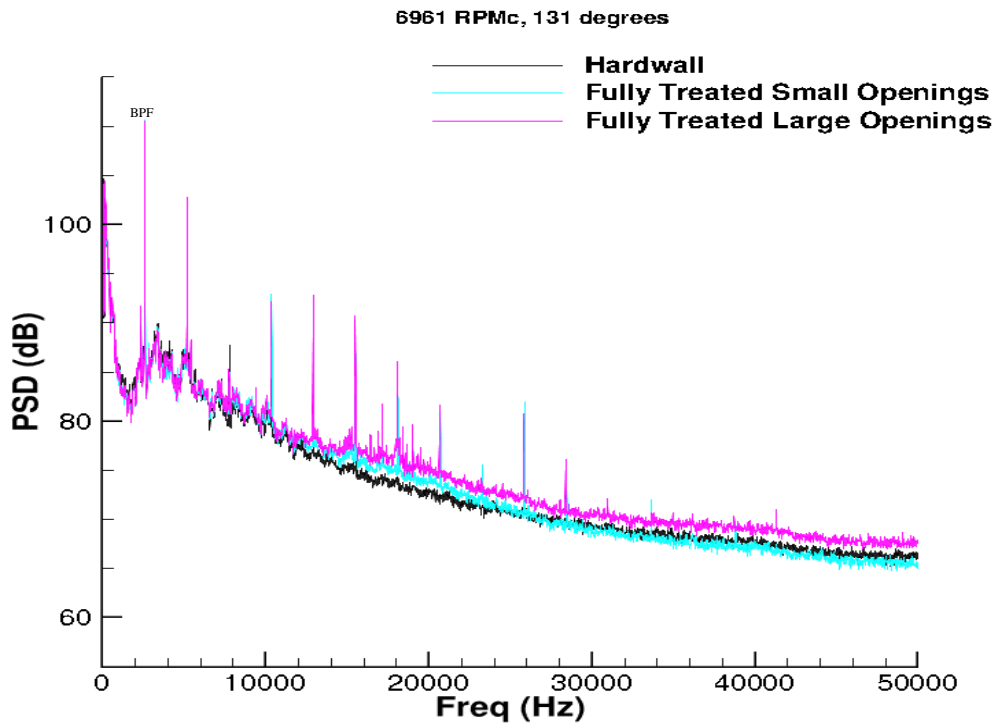
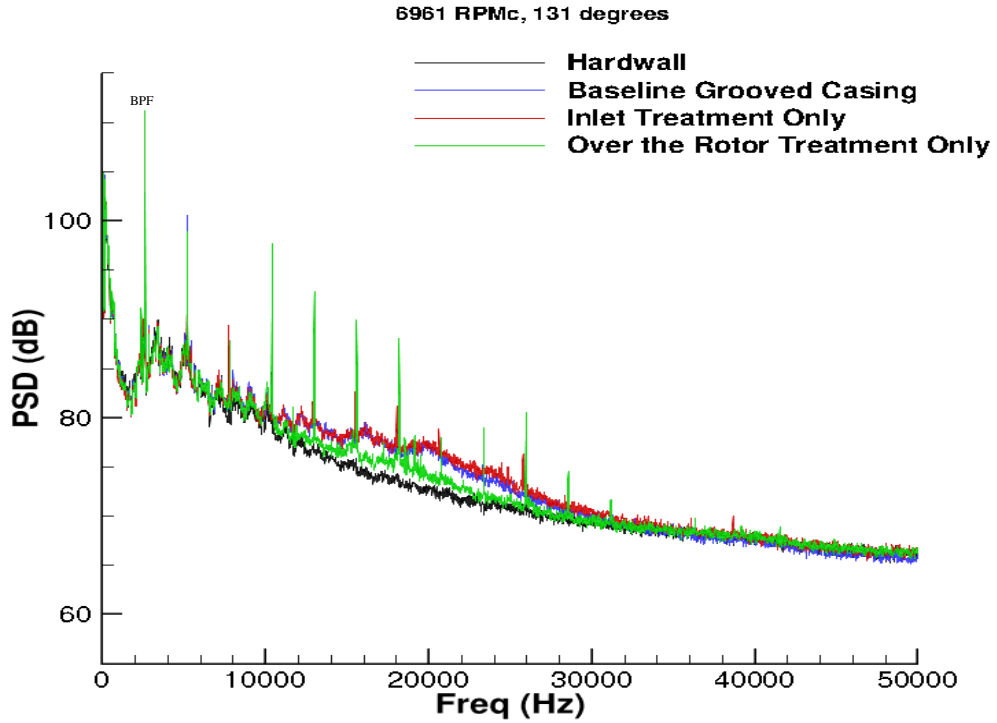


Figure 8.—The 1-ft lossless spectra for 6961 RPMc condition showing Hardwall, Baseline Grooved, Inlet Treatment, and Over the Rotor Treatment casing treatments (Top) and Hardwall, Fully Treated Small Openings, and Fully Treated Large Openings (Bottom) for 131 degrees emitted angle.

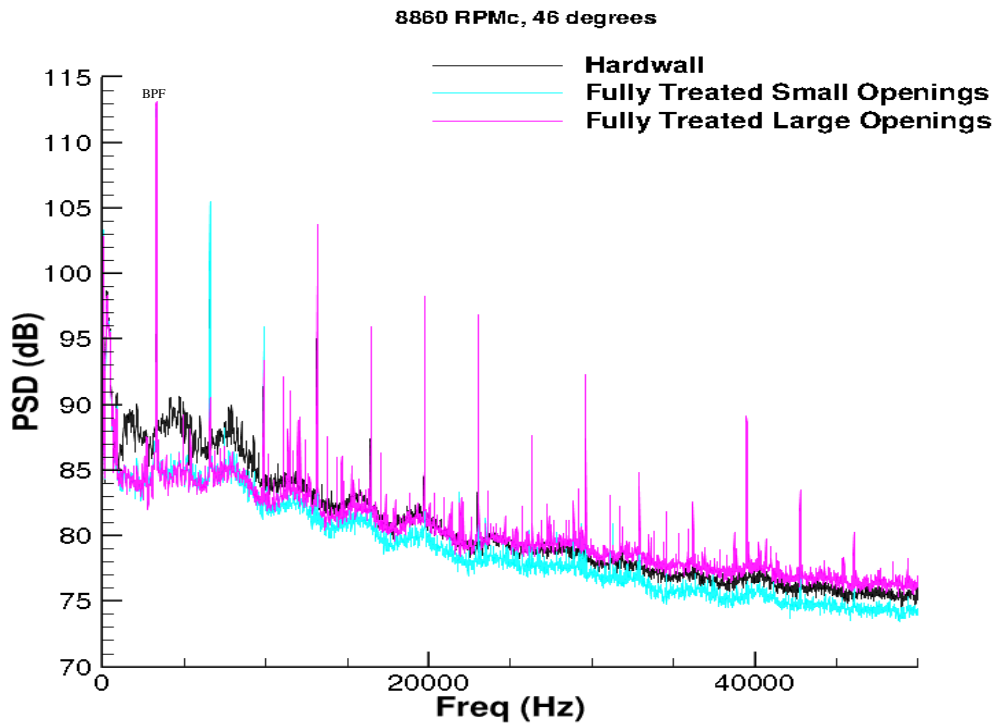
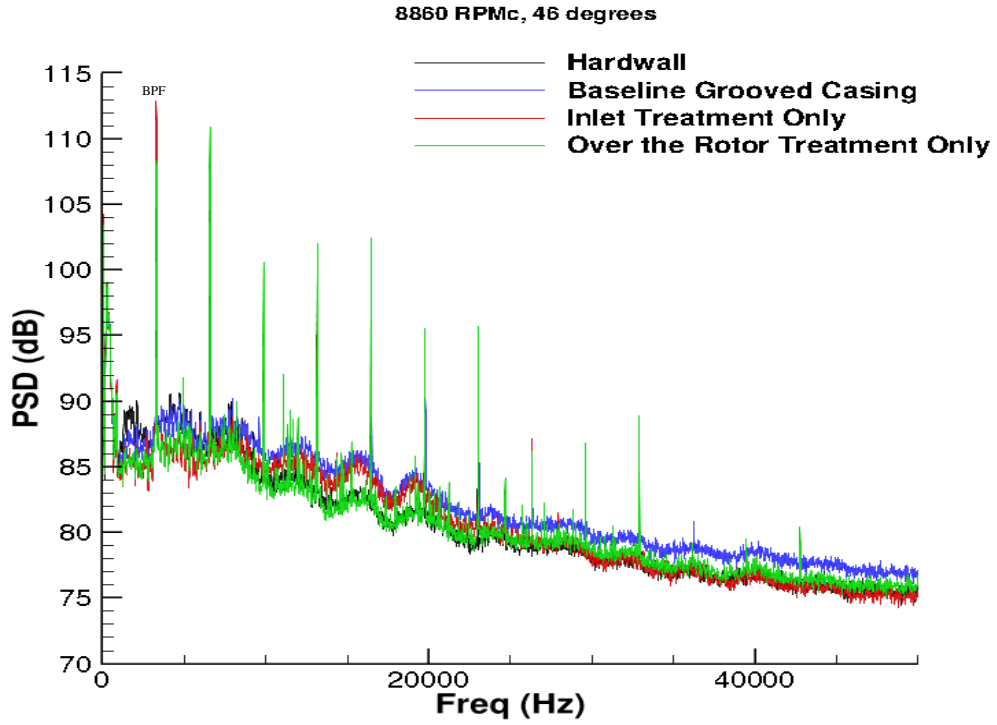


Figure 9.—The 1-ft lossless spectra for 8000 RPMc condition showing Hardwall, Baseline Grooved, Inlet Treatment, and Over the Rotor Treatment casing treatments (Top) and Hardwall, Fully Treated Small Openings, and Fully Treated Large Openings (Bottom) for 46 degrees emitted angle.

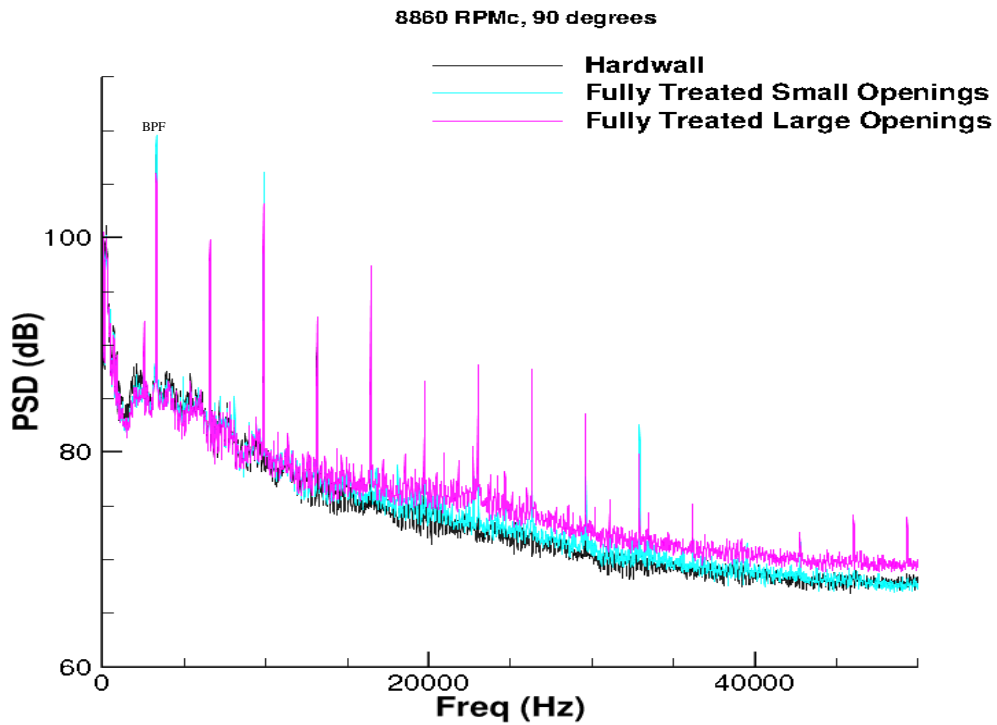
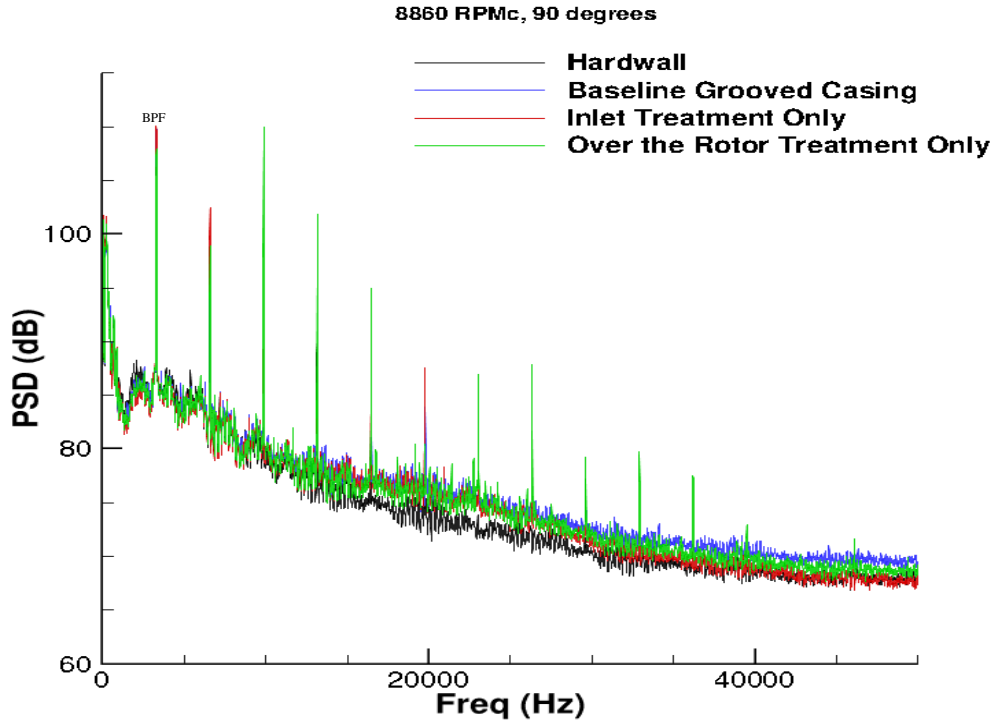


Figure 10.—The 1-ft lossless spectra for 8000 RPMc condition showing Hardwall, Baseline Grooved, Inlet Treatment, and Over the Rotor Treatment casing treatments (Top) and Hardwall, Fully Treated Small Openings, and Fully Treated Large Openings (Bottom) for 90 degrees emitted angle.

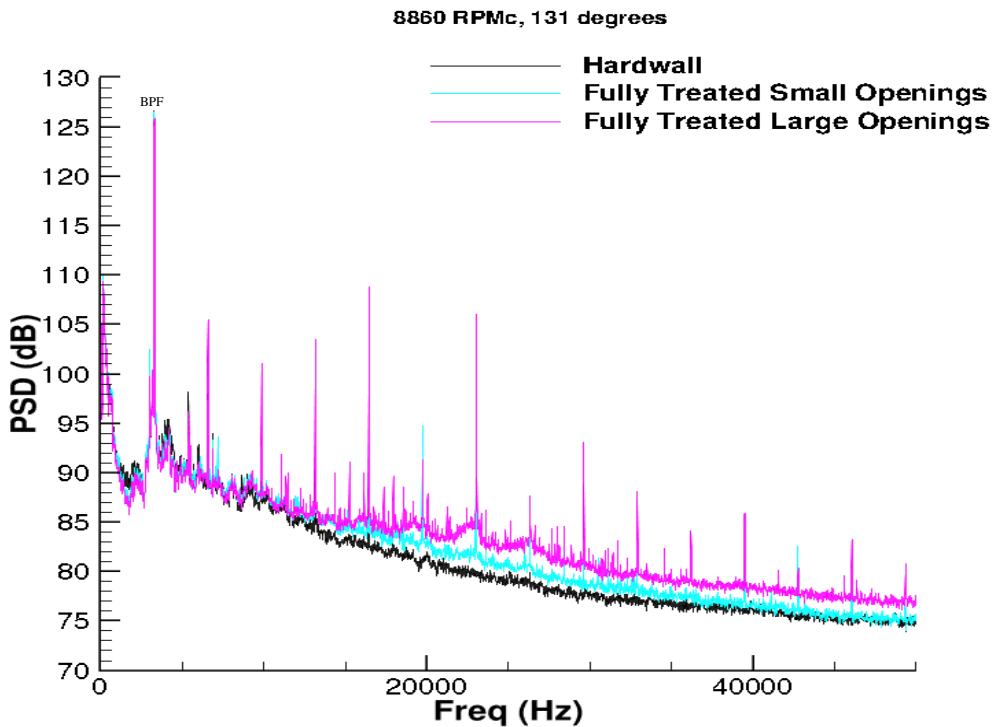
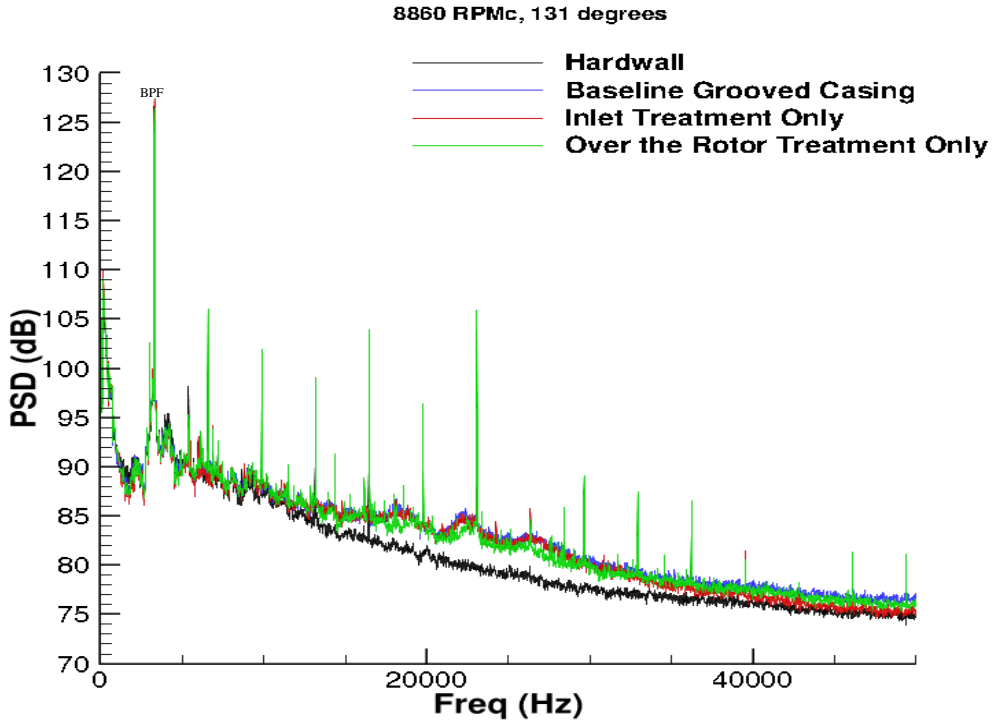


Figure 11.—The 1-ft lossless spectra for 8000 RPMc condition showing Hardwall, Baseline Grooved, Inlet Treatment, and Over the Rotor Treatment casing treatments (Top) and Hardwall, Fully Treated Small Openings, and Fully Treated Large Openings (Bottom) for 131 degrees emitted angle.

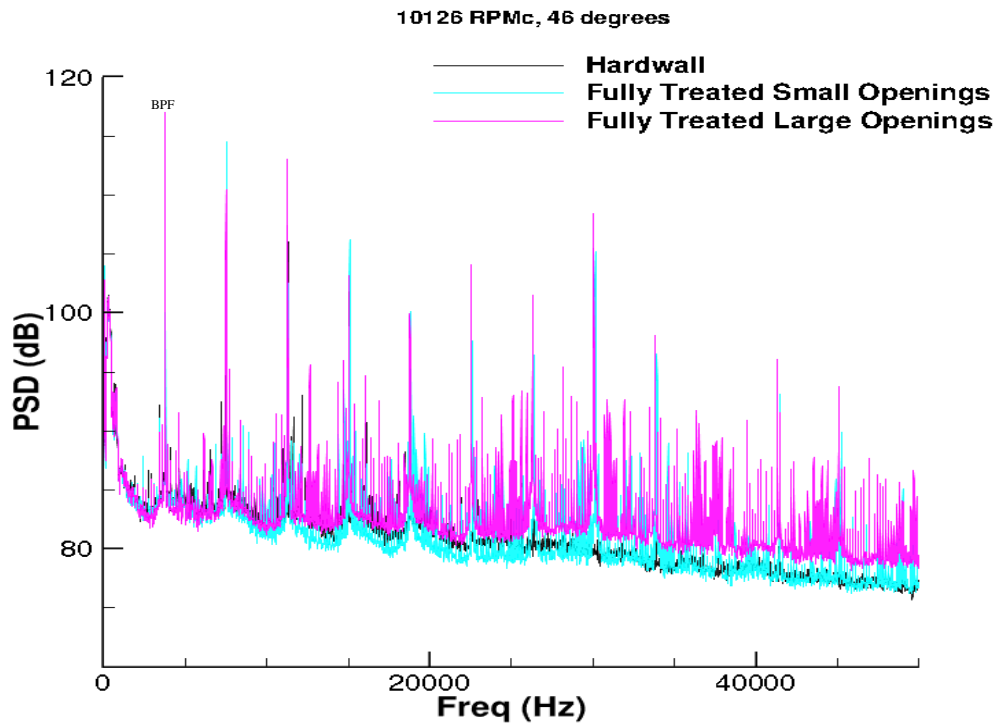
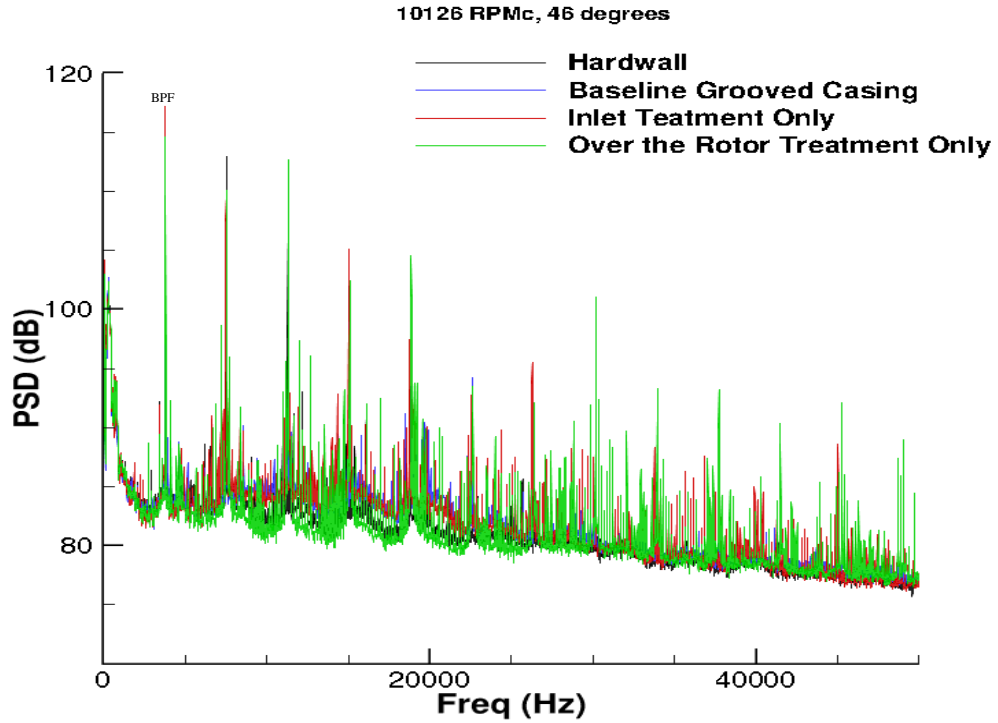


Figure 12.—The 1-ft lossless spectra for 10126 RPMc condition showing Hardwall, Baseline Grooved, Inlet Treatment, and Over the Rotor Treatment casing treatments (Top) and Hardwall, Fully Treated Small Openings, and Fully Treated Large Openings (Bottom) for 46 degrees emitted angle.

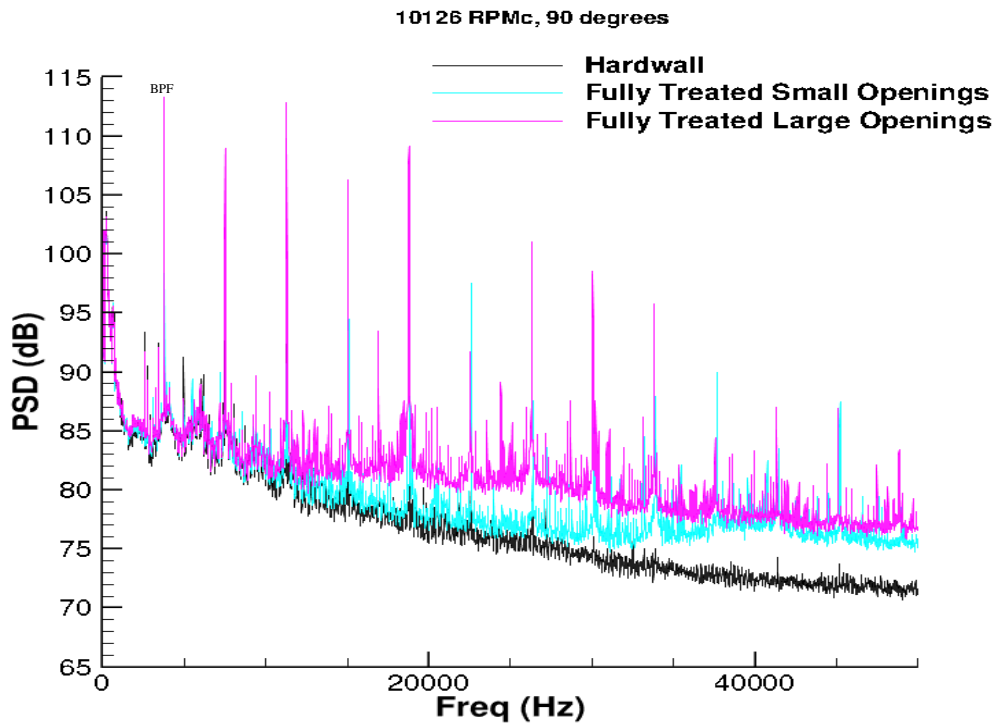
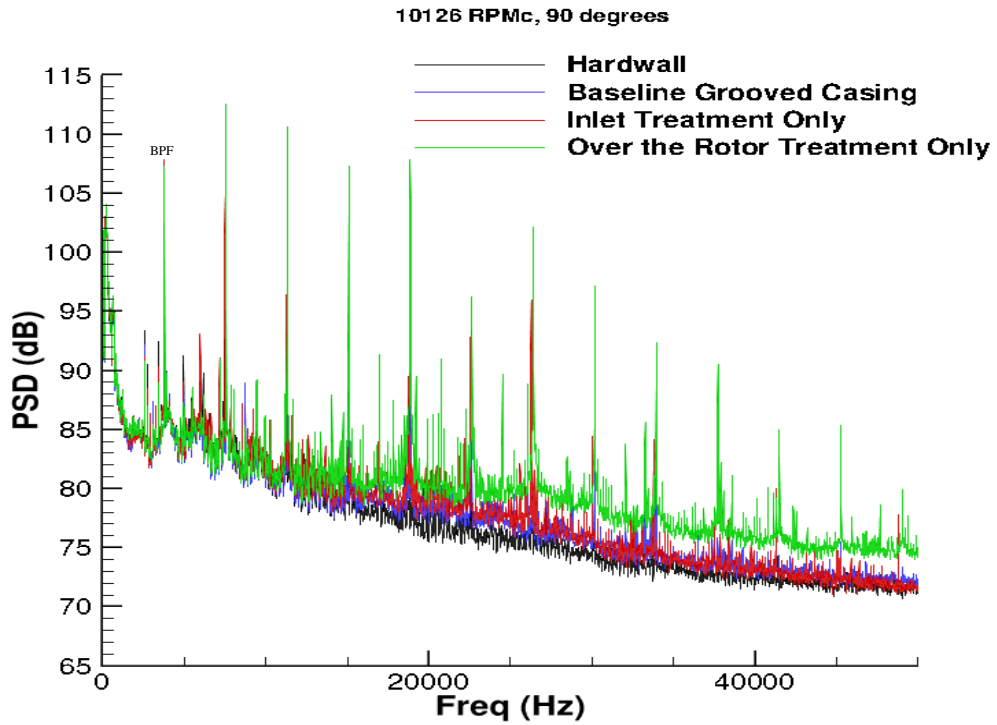


Figure 13.—The 1-ft lossless spectra for 10126 RPMc condition showing Hardwall, Baseline Grooved, Inlet Treatment, and Over the Rotor Treatment casing treatments (Top) and Hardwall, Fully Treated Small Openings, and Fully Treated Large Openings (Bottom) for 90 degrees emitted angle.

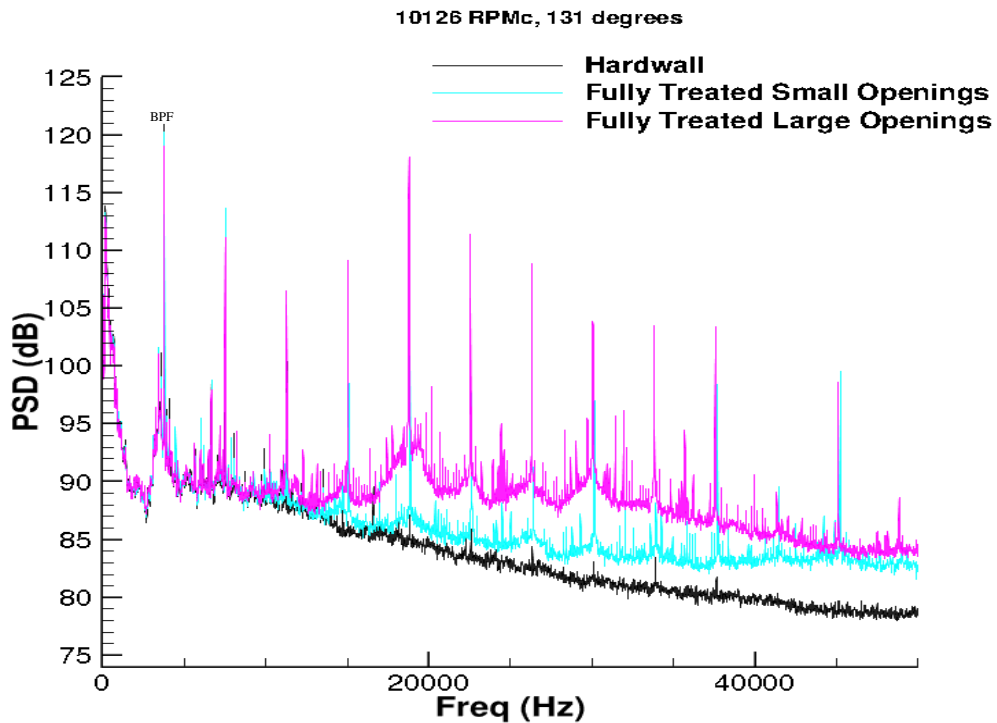
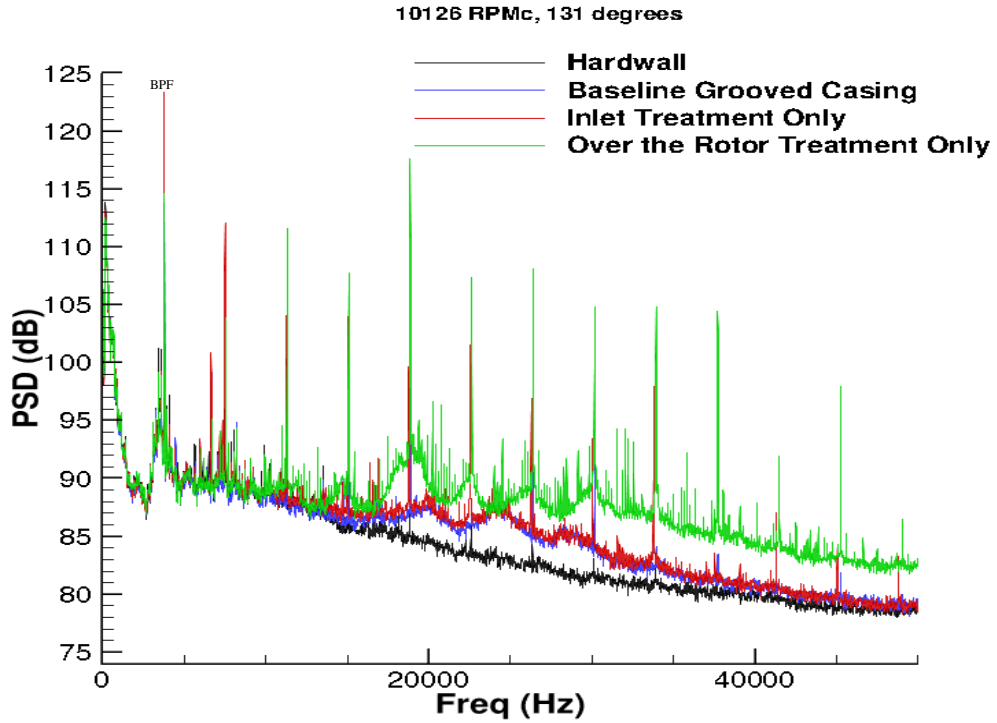


Figure 14.—The 1-ft lossless spectra for 10126 RPMc condition showing Hardwall, Baseline Grooved, Inlet Treatment, and Over the Rotor Treatment casing treatments (Top) and Hardwall, Fully Treated Small Openings, and Fully Treated Large Openings (Bottom) for 131 degrees emitted angle.

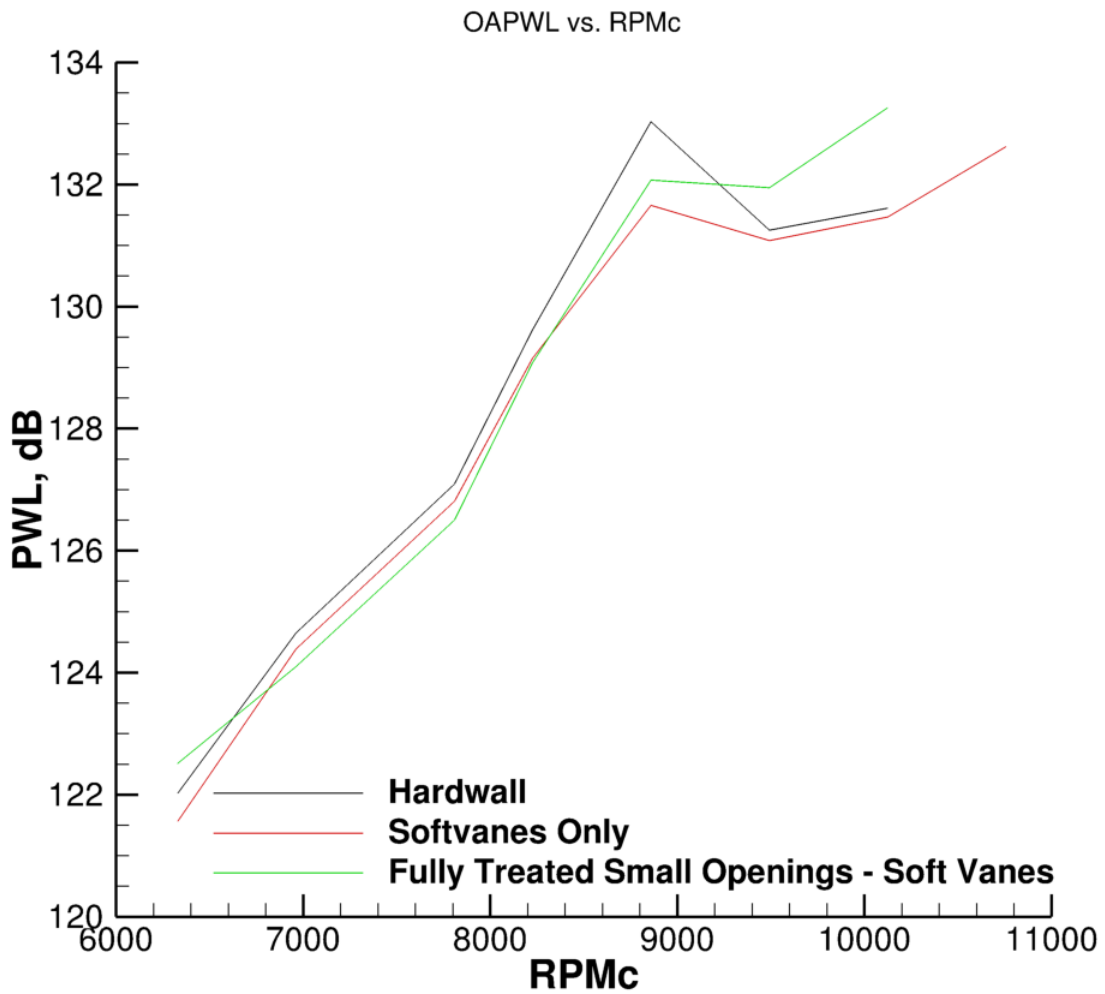


Figure 15.—Overall Power Levels versus Corrected RPM comparing Hardwall, Soft Vanes, and Soft Vanes with Fully Treated Small Opening Casing Treatment on the SDT fan model.

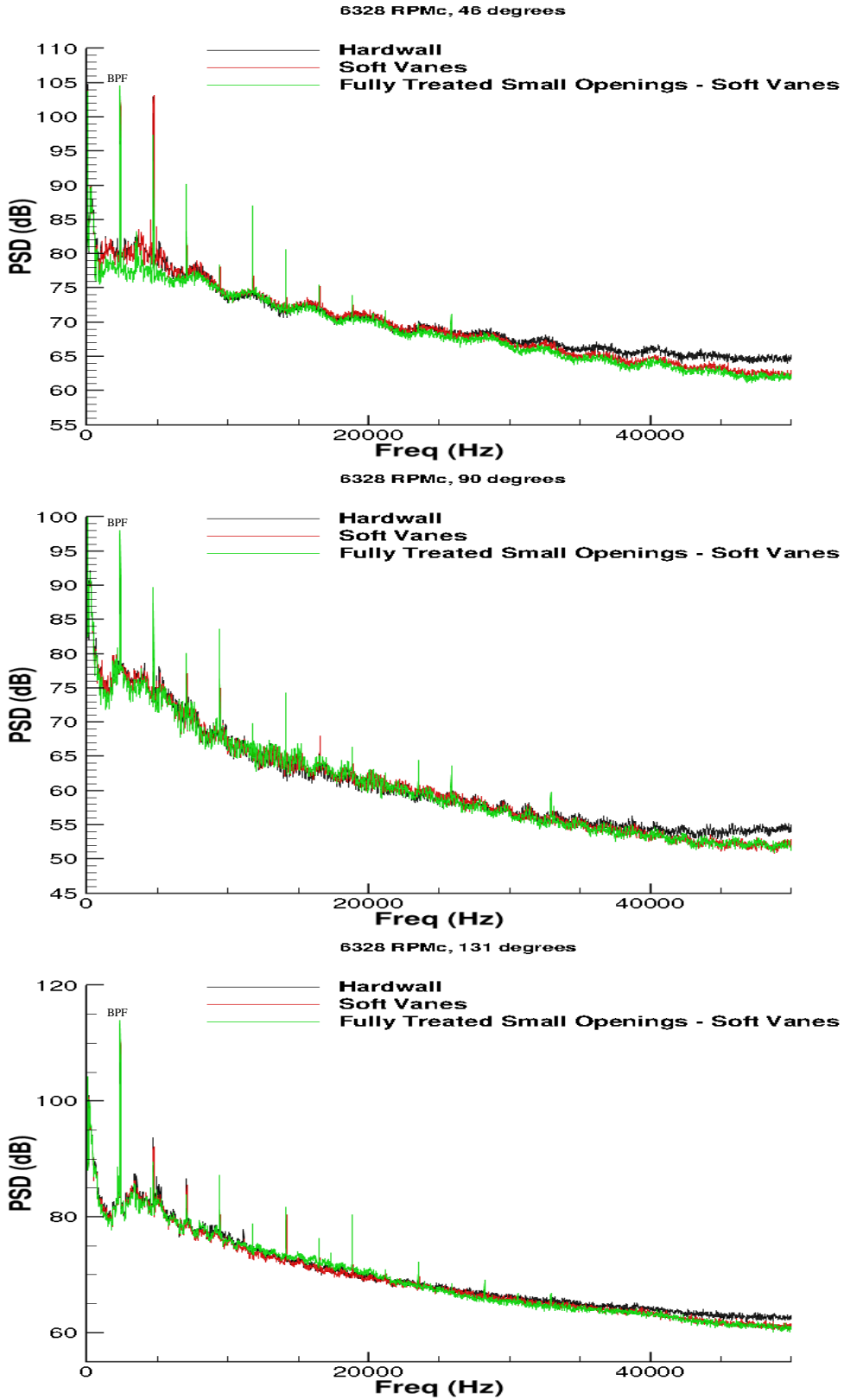


Figure 16.—The 1-ft lossless spectra for 6328 RPMc condition showing Hardwall, Soft Vanes, and Soft Vanes with Fully Treated Small Opening Casing Treatment at 46 (Top), 90 (Middle), and 131 (Bottom) degrees emitted angle.

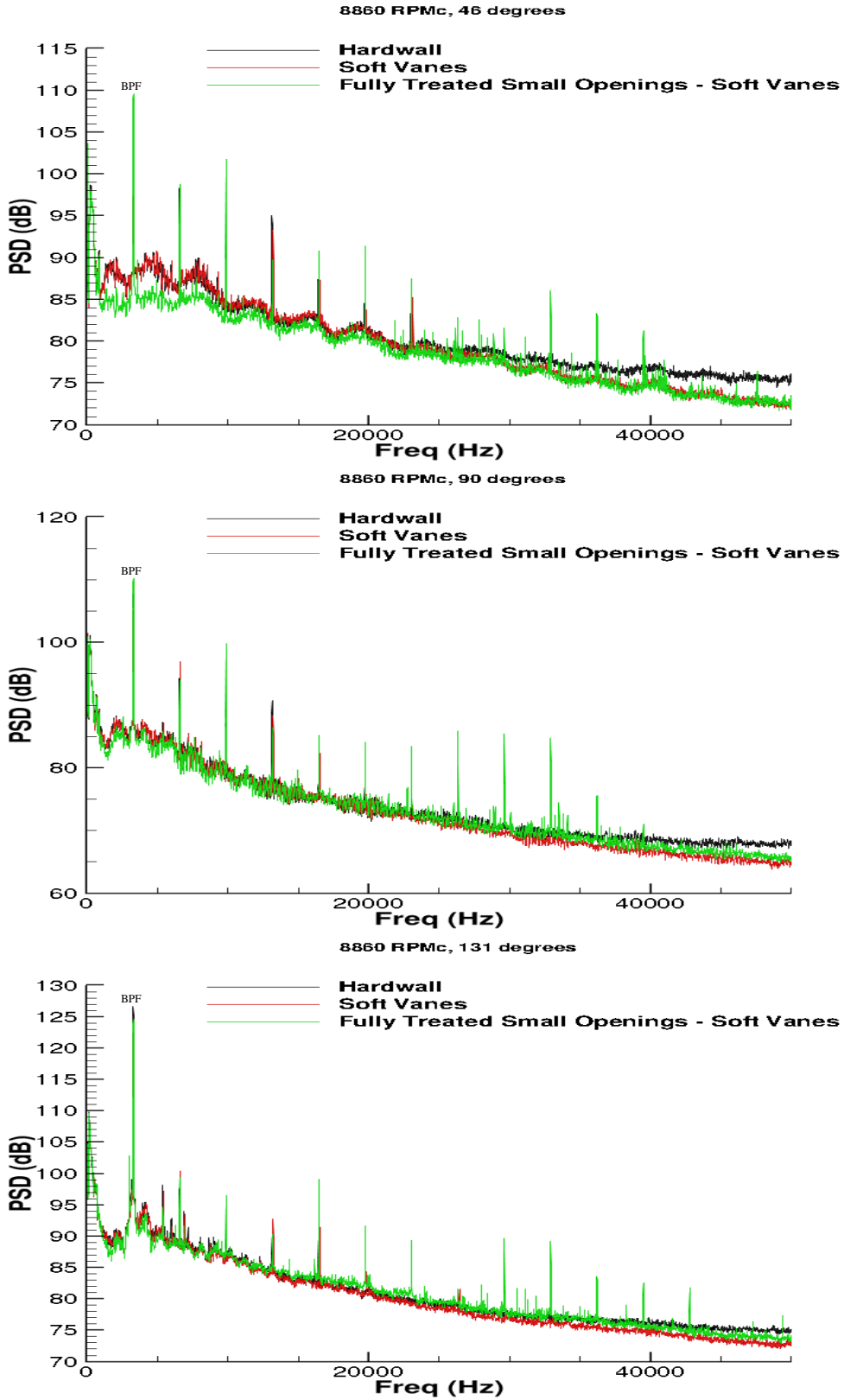


Figure 17.—The 1-ft lossless spectra for 8860 RPMc condition showing Hardwall, Soft Vanes, and Soft Vanes with Fully Treated Small Opening Casing Treatment at 46 (Top), 90 (Middle), and 131 (Bottom) degrees emitted angle.

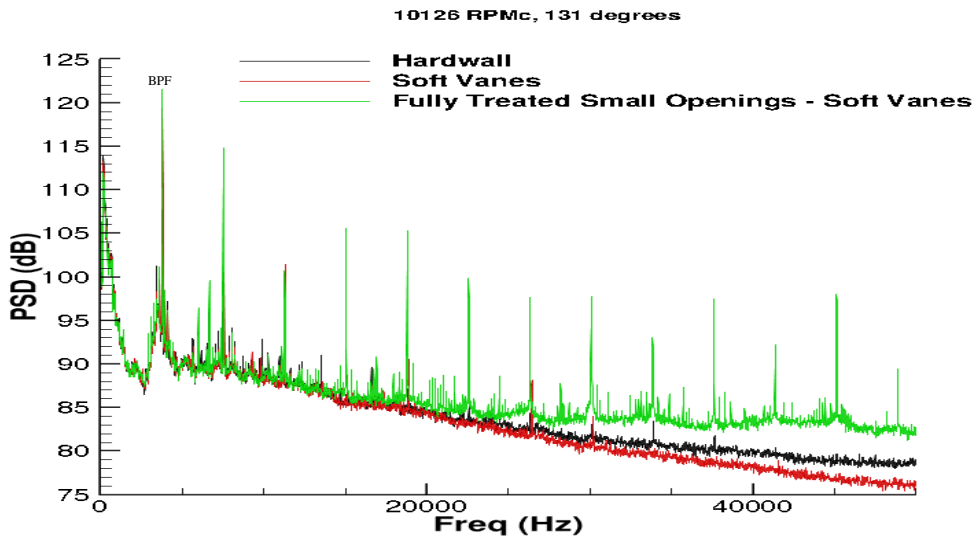
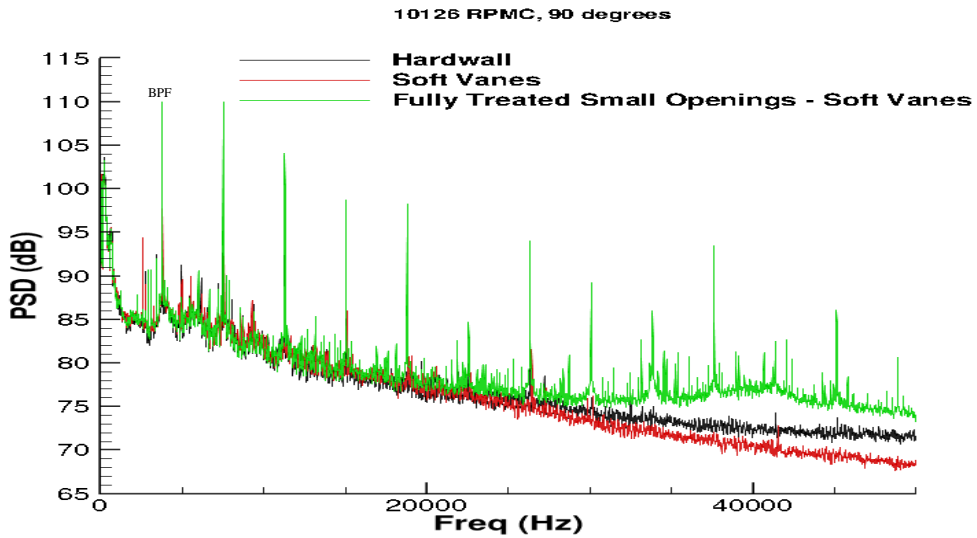
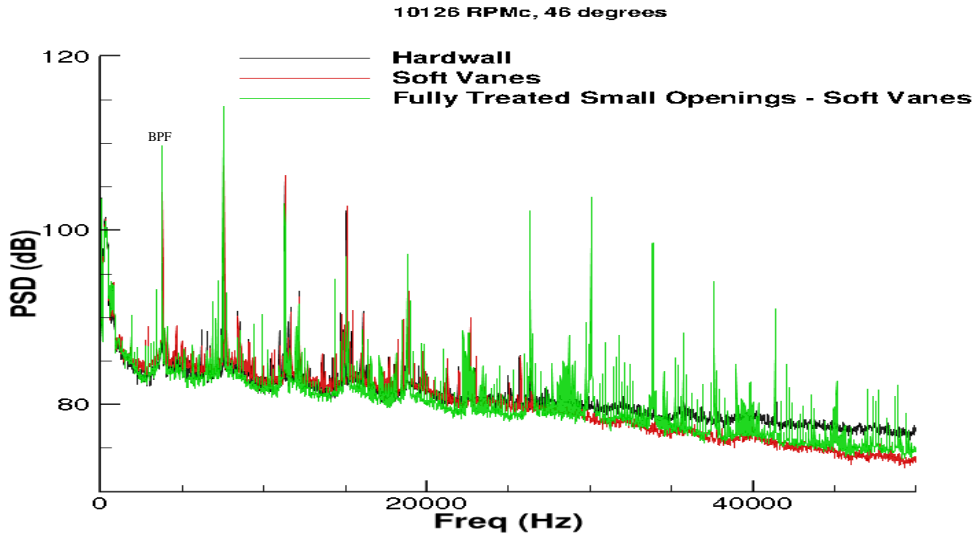


Figure 18.—The 1-ft lossless spectra for 10126 RPMc condition showing Hardwall, Soft Vanes, and Soft Vanes with Fully Treated Small Opening Casing Treatment at 46 (Top), 90 (Middle), and 131 (Bottom) degrees emitted angle.



