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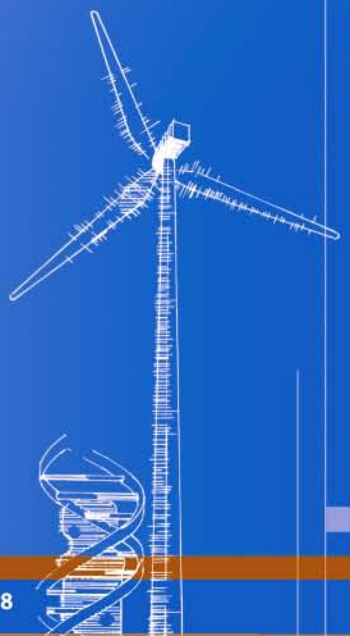
The Potential for Reducing Blade-Tip Acoustic Emissions For Small Wind Turbines

June 1, 2007—July 31, 2008

P. Migliore
Engineering Research and Project Management
Arvada, Colorado

Subcontract Report
NREL/SR-500-43472
February 2009



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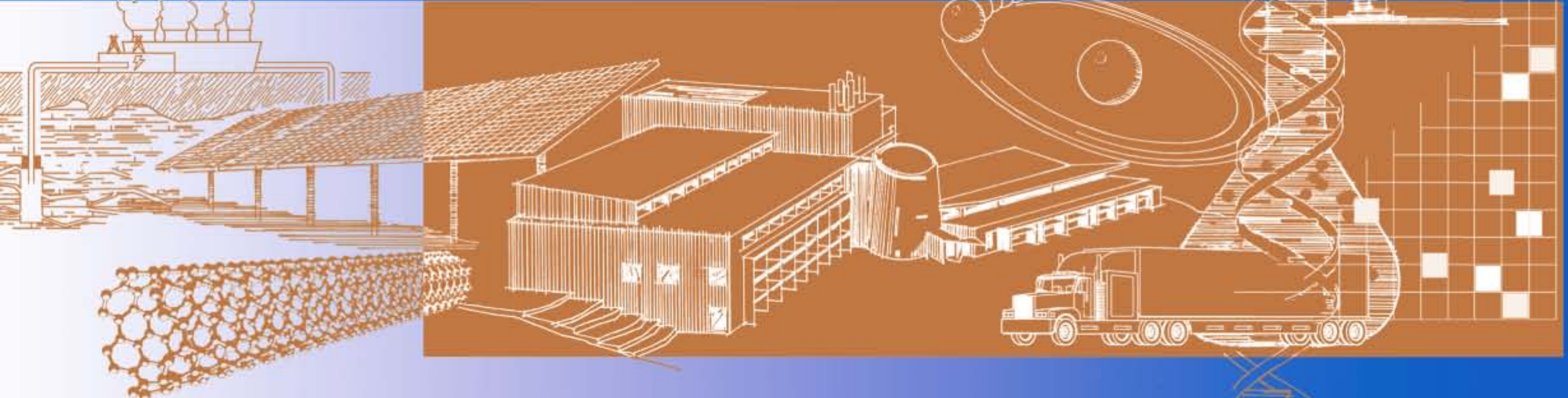

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Prepared under Subcontract No. LAM-7-77545-01

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Foreword

The U.S. Department of Energy (DOE), working through its National Renewable Energy Laboratory (NREL), is engaged in a comprehensive research effort to improve the understanding of wind turbine aeroacoustics. The motivation for this effort is the desire to exploit the large expanse of low wind speed sites that tend to be close to U.S. load centers. Quiet wind turbines are an inducement to widespread deployment, so the goal of NREL's aeroacoustic research is to develop tools that the U.S. wind industry can use in developing and deploying highly efficient, quiet wind turbines at low wind speed sites. NREL's National Wind Technology Center (NWTC) is implementing a multifaceted approach that includes wind tunnel tests, field tests, and theoretical analyses in direct support of low wind speed turbine development by its industry partners. NWTC researchers are working hand in hand with engineers in industry to ensure that research findings are available to support ongoing design decisions.

To that end, wind tunnel aerodynamic tests and aeroacoustic tests have been performed on six airfoils that are candidates for use on small wind turbines. Results are documented in two companion NREL reports:

> *Wind Tunnel Aeroacoustic Tests of Six Airfoils for Use on Small Wind Turbines*,
> Stefan Oerlemans, Principal Investigator, the Netherlands National Aerospace Laboratory

> *Wind Tunnel Aerodynamic Tests of Six Airfoils for Use on Small Wind Turbines*,
> Michael Selig, Principal Investigator, University of Illinois at Urbana-Champaign (UIUC)

A similar effort was undertaken for three airfoils that are candidates for use on large wind turbines. Results are reported in the following NREL report and in various conference papers.

> *Aeroacoustic Testing of Wind Turbine Airfoils*, William Devenport and Ricardo Burdisso, Principal Investigators, Virginia Polytechnic Institute and State University

These reports provide valuable airfoil databases for designers who wish to consider the airfoils tested[*]. But inevitably, designers will want to evaluate other airfoils that have not been tested. And not only are wind tunnel tests expensive, it is often difficult to schedule the facilities required within the over-all time frame of a project development plan. This dilemma begs the question "Is it really necessary to conduct wind tunnel tests, or can we rely on theoretical predictions?"

Predicting the aeroacoustic emission spectra of a particular airfoil shape is extremely difficult, but predicting the aerodynamic characteristics of a particular airfoil shape is routine practice. Nevertheless, there is always some uncertainty about the accuracy of the predictions in comparison to the results of wind tunnel tests or field performance, and there are questions about the efficacy of two principal airfoil analysis methods: the Eppler and XFOIL codes. To address these related issues, at least in part, a theoretical analysis was commissioned of the same airfoils tested in the wind tunnel. The results are documented in the following NREL report:

> *Theoretical Aerodynamic Analyses of Six Airfoils for Use on Small Wind Turbines Using Eppler and XFOIL Codes,* D.M. Somers and M.D. Maughmer, Principal Investigators, Airfoils, Inc.

Possessing both theoretically predicted aerodynamic characteristics and wind tunnel test data for the same six airfoils provides an extraordinary opportunity to compare the performance, measured by energy cap-

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[*] The extensive test data discussed in these reports can be provided in electronic format on compact disks (CDs) that may be obtained by calling the NWTC library at 303-384-6963.

ture, of wind turbine rotors designed with the different data. This will provide the insight needed to assist designers in deciding whether to pursue wind tunnel tests. Although some differences in the resulting blade planforms (chord and twist distributions) can be expected, a more important question relates to the difference in energy capture and its significance in driving the choices that need to be made during the preliminary design stage. These issues are addressed in a report that compares the differences in Eppler and XFOIL predictions to the UIUC wind tunnel tests and examines the planform and energy capture differences in resulting blade designs:

> *Comparison of Optimized Aerodynamic Performance of Small Wind Turbine Rotors Designed with Theoretically Predicted versus Experimentally Measured Airfoil Characteristics*, Michael Selig, Principal Investigator, University of Illinois at Urbana-Champaign (UIUC)

Another research effort undertaken in support of the U.S. wind turbine industry involves a series of aeroacoustic field tests conducted at the NWTC. Using well documented, consistently applied test procedures, noise spectra were measured for eight small wind turbine configurations. Test results provide valuable information to manufacturers as well as potential users of these turbines. To our knowledge, this is the first comprehensive database of noise data for small wind turbines. The results of this effort are documented in another NREL report:

> *Aeroacoustic Field Tests of Eight Small Wind Turbines*,
> J. van Dam and A. Huskey, Principal Investigators, NREL's National Wind Technology Center

Wind tunnel tests, field tests and theoretical analyses provided useful information for development and validation of a semi-empirical noise prediction code developed at NREL. This effort is described in the following reports:

> *Semi-Empirical Aeroacoustic Noise Prediction Code for Wind Turbines*,
> P. Moriarty and P. Migliore, Principal Investigators, NREL's National Wind Technology Center
>
> *Prediction of Turbulent Inflow and Trailing-Edge Noise for Wind Turbines*,
> P. Moriarty, G. Guidati and P. Migliore, Principal Investigators, NREL subcontracted research

The codes will be continuously improved, but may ultimately give way to more sophisticated, physics-based computational aeroacoustic codes also being developed by NREL and its subcontractors. For example, researchers at Florida State University (FSU) and the National Aeronautics and Space Administration (NASA) applied modern computational methods to analyze wind turbine blade tip noise. This work was reported in the journal article:

> *Large-Eddy Simulation of Wing Tip Vortex on Overset Grids*, Ali Uzun and Yousuff Hussaini of FSU and Craig Streett of the NASA Langley Research Center, Principal Investigators

In addition, a comprehensive research effort at the Pennsylvania State University was reported in a series of conference papers and other writings, including:

> *An Aeroacoustic Analysis of Wind Turbines*,
> Philip Morris, Lyle Long and Ken Brentner, Principal Investigators
>
> *A 3D Parabolic Equation Method for Wind Turbine Noise Propagation in Moving Inhomogeneous Atmosphere*, R. Cheng, Philip Morris and Ken Brentner, Principal Investigators

Rotational Effects on the Aerodynamics and Aeroacoustics of Wind Turbine Airfoils,
Steven Miller and Philip Morris, Principal Investigators

3-D Time-Accurate Inviscid and Viscous CFD Simulations of Wind Turbine Rotor Flow Fields,
Nilay Sezer-Uzol, Ankur Gupta and Lyle Long, Principal Investigators

Many of the documents described above are published as NREL reports. Some results are presented in various journal articles or conference papers. All of the NREL reports will be available on NREL's web site at http://www.nrel.gov/publications/. Collectively, these reports represent a significant compendium of information on the aerodynamics and aeroacoustics of contemporary wind turbines.

Clearly, this work represents a significant commitment of DOE resources as well as a significant commitment of personnel over an extended period. We are sure we express the sentiments of all the research participants in saying we sincerely hope the results of these efforts prove beneficial to the wind energy community.

Paul G. Migliore
NREL/NWTC Project Manager, Retired

Patrick Moriarty
NREL/NWTC Project Manager

Acknowledgements

The project reported herein began when the author was employed at NREL, with the Department of Energy providing the initial funding. The author developed the scope of work and designed the blade tip shapes to be tested. Southwest Windpower employees Ben Polito, Jean Lonjaret and David Calley donated their time to computerize these shapes and construct stereo lithographic models of them. The tooling and wind tunnel models were then fabricated by Novakinetics, LLC, which also conducted and documented structural tests of the models. Although DOE budget constraints caused the project to be canceled, Southwest Windpower and the author decided to jointly and privately fund the wind tunnel tests at Georgia Tech Research Institute (GTRI). Dr. Krishan Ahuja enthusiastically guided the planning and Mr. Adam Churney diligently conducted the tests. Ultimately, DOE was able to resume the project and provide funding for reporting the results and making them available to the U.S. small wind turbine industry. Dr. Patrick Moriarty of NREL is the project manager for this subcontract.

The author commends Southwest Windpower for its commitment to this research and is grateful to NREL and DOE for supporting its completion.

Executive Summary

Wind tunnel aeroacoustic tests of a typical small wind turbine blade were conducted in the open-jet test section of the Georgia Tech Research Institute (GTRI) Anechoic Flight Simulation Facility. The objectives of the tests were to determine the relative importance of tip shape, boundary layer tripping and trailing edge thickness on acoustic emissions. Six tip shapes, 3 boundary layer trip heights and 2 trailing edge thicknesses were investigated in a matrix of 72 velocity / angle of attack test points. No attempt was made to evaluate relative aerodynamic performance in comparison to aeroacoustic performance: nor was any attempt made to reconcile the potential impact of real-world atmospheric conditions compared to the idealized wind tunnel environment. Significant noise – including pure tones – was observed for certain test conditions. This was attributed to laminar boundary layer vortex shedding at low Reynolds numbers (Re). Aggressive boundary layer tripping eliminated the tones and reduced broadband noise. The various tip shapes performed similarly, but at a low velocity (Reynolds number = 170,000) a difference in overall sound pressure level of 3.8 dBA was observed between the best and worst tip shapes. At a greater velocity (Reynolds number = 315,000), more typical of wind turbine operating conditions, a difference of 1.3 dBA was observed. These differences are sufficient to justify the conclusion that tip shape can be important in further quieting an otherwise quiet wind turbine blade. Generally, only subtle differences were observed for the 2 trailing edge thicknesses of 1.1% and 0.8% chord that were tested. In 2 cases, however, increments of 1.2 dBA and 1.8 dBA were measured. Therefore, the author concludes that minimizing trailing edge thickness – subject to manufacturing limitations – is a worthwhile endeavor.

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1.0 Introduction

1.1 Overview

For the last several years the U.S. Department of Energy, working through its National Renewable Energy Laboratory (NREL), has engaged in a comprehensive research effort to improve the understanding of wind-turbine aeroacoustics. Motivation for this effort is the desire to exploit the large expanse of low-wind-speed sites that tend to be closer to load centers in the United States. Quiet wind turbines are an inducement to widespread deployment, and so the goal of NREL's aeroacoustic research is to develop tools for use by U.S. industry in developing and deploying highly efficient, quiet wind turbines at these low-wind-speed sites.

NREL's National Wind Technology Center (NWTC) has implemented a multifaceted approach that includes aerodynamic [1, 2] and aeroacoustic [3-5] wind-tunnel tests, field tests [6] and theoretical analyses [7-15] in direct support of low-wind-speed turbine development by its industry partners. The present report describes wind-tunnel aeroacoustic tests of six tip shapes that are candidates for use on small wind turbine blades. The test article was a prototype blade for Southwest Windpower's Skystream 3.7 turbine, which is a 1.8 kW, variable-speed, grid-connected machine. This blade incorporates NREL's S822 airfoil [16] for which there is extensive wind tunnel and field test information.

The tests were conducted in the open-jet test section of the Georgia Tech Research Institute (GTRI) Anechoic Flight Simulation Facility. The acoustic measurements were done for a range of tunnel speeds and angles of attack with and without boundary layer tripping to assess the effect of that factor on sound production. A brief investigation of trailing edge thickness also was conducted to evaluate the merit of special efforts to manufacture blades with sharp trailing edges. The objective of the tests was to determine the potential impact of these conditions rather than to identify particular optima.

1.2 Sources of Airfoil Noise

There are six different sources [17] that independently generate airfoil acoustic emissions: Inflow turbulence, turbulent boundary layer trailing edge interaction, separating flow, laminar boundary layer vortex shedding, trailing edge bluntness (von Karman) vortex shedding and tip vortex formation. These sources are superimposed to form the total noise spectrum of a wind turbine blade. The spectra often are summed to calculate an overall sound power[†] level.

Inflow turbulence noise caused by the interaction of the leading edge of an airfoil with a turbulent inflow often is called leading edge noise. Researchers currently think that sharp leading edge geometries are more susceptible to inflow turbulence noise.

The other sources of noise are collectively called airfoil self noise, because they are caused by the airfoil interacting with its own boundary layer and near wake. If the trailing edge thickness of the airfoil is very thin relative to the boundary layer thickness, as was the case for the models tested, there is very little trail-

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[†] Whereas sound *pressure* level is described in Reference 17 as a property of the observer location, the total strength of a source of sound is characterized by the sound *power* emitted by the source. In general, the sound power $\boldsymbol{P}$ transmitted through a surface $\boldsymbol{S}$ is the integral of the sound intensity $\boldsymbol{I}$ (energy transmitted per unit time and unit area) over the surface. If the surface $\boldsymbol{S}$ encloses the source of the sound, then $\boldsymbol{P}$ is the total sound power emitted by the source. The definition of sound power level is:

$L_w = 10 \cdot \log [\, \boldsymbol{P} \div \boldsymbol{P}_{\mathrm{ref}} \,]$ expressed in decibels, dB,

where $\boldsymbol{P}_{\mathrm{ref}} = 10^{-12}$ watts is the standard reference sound power. The human eardrum can detect incoming sound power as weak as one picowatt, and exposure to incoming sound power of more than one watt will result in some hearing loss.

ing edge bluntness noise. Two-dimensional airfoil models tested between endplates do not have a tip vortex or any associated noise, although interaction between the endplate boundary layer and model-endplate juncture could cause extraneous noise.

Turbulent boundary layer trailing edge noise generally is considered to be the most important source of airfoil self noise for modern wind turbine blades. In this phenomenon, the unsteady pressure waves in the turbulent boundary layer are amplified and radiated by the sharp trailing edge. As the angle of attack increases, the thickness of the turbulent boundary layer increases and large-scale unsteady structures can dominate noise production from the trailing edge. For fully separated flow, noise can radiate from the entire chord.

Laminar boundary layer vortex shedding noise is created by a feedback loop between vortices being shed at the trailing edge, and instability waves in the laminar boundary layer upstream. This source of noise can occur on either the suction or pressure side of the airfoil, and it can be particularly irritating because it often is manifested in pure tones that result from feedback amplification. It is not likely to be important for large turbines operating at a high Reynolds number, but there is ample evidence that it is significant for small wind turbines.

1.3 Designing Quiet Wind Turbine Blades

A strong desire for quiet wind turbines exists. This requires that mechanical and electrical noise sources associated with such elements as gearboxes, bearings, alternators, and power electronics must be eliminated. Engineers have been dealing with these issues for decades, however, and standard practices usually succeed in quieting these noise sources. Aeroacoustic emissions, however, which are not so well understood or controlled, often dominate wind turbine noise. Therefore, in recent years, considerable effort has been devoted to the elimination of wind turbine aeroacoustic noise, and tools are now available to design truly quiet wind turbines. The issue is whether designers and turbine manufacturers really are committed to this result. Designing for noise elimination requires a thorough process including analyses, wind tunnel tests, and field verification. Most design teams do not have the patience or resources necessary for rigorously completing the process.

A suitable airfoil family first must be chosen and – rather than focusing exclusively on aerodynamic efficiency – aeroacoustic performance must be heavily weighted. This does not necessarily require sacrificing aerodynamic performance: literature reveals the availability of quiet airfoils with desirable aerodynamic characteristics, such as high lift-to-drag ratio and benign stall behavior. Airfoil choice should be informed by wind tunnel tests which – in the overall context of wind turbine development – are not as costly as some fear. After the airfoil family is chosen there are ample analytical tools available to optimize the blade planform. However, there are judicious choices to be made in this endeavor as well. Outboard on the blade, where most of the sound originates, the design angle of attack should not be so aggressive as to exacerbate trailing edge noise from large-scale unsteady structures emanating (near stall) from the thickening boundary layer. Additionally, the spanwise diminution of lift should be gradual and smooth, to minimize noise associated with tip vortex shedding.

Assuming prudent airfoil choice and planform design, there still remain the issues of blade tip shape and trailing edge thickness. For small wind turbines operating at low Reynolds numbers (as they typically do) there also is the potential susceptibility to laminar boundary layer vortex shedding noise. Just how important are these phenomena and are they worth addressing during the design process? Those are the questions that the tests were designed to answer.

2.0 Description of Tests

2.1 The GTRI Wind Tunnel

The GTRI Anechoic Flight Simulation Facility illustrated in Figure 1 is an open-jet wind tunnel enclosed in an anechoic chamber lined with polyurethane foam wedges. The chamber, shown in Figure 2, is 4.3 m (14 ft) long, 4.3 m (14 ft) wide and 6.1 m (20 ft) high between wedge tips. It is mounted on massive springs and completely isolated from the rest of the acoustics laboratory. A spring-tensioned cable floor, which is suspended from the walls, provides easy access to the interior of the chamber for instrumentation and hardware changes and for calibration.

The enclosed test section is the potential-flow core of a 0.7 m (2.3 ft) diameter open jet nozzle capable of developing continuous free-jet velocities up to 95 m/s (312 ft/sec). Its intake is approximately 2.0 m (6.7 ft) by 2.8 m (9.3 ft) and the length of the working section between the free-jet nozzle exit and the collector is 2.74 m (9.0 ft). Airflow is generated by a diesel-driven fan. Air is drawn into the intake and through the honeycomb, screens and contraction fairing; across the anechoic room to the collector; and then through a diffuser, two right angle corners (with acoustically treated turning vanes), duct silencers and the transition section to the powered exhaust section. The air supply duct in the center of the open jet normally is used to study jet plumes. This duct was removed for the present tests and the wind turbine blade tip models were mounted at the nozzle exit.

The facility has been operated by GTRI in support of NASA (National Aeronautics and Space Administration) and aviation industry research projects on a nearly continuous basis for the last decade and previously was used by Lockheed. Recently there have been several major upgrades, including the replacement of acoustic wedges within the five years preceding these tests. Additional details of the facility are described by Ahuja et al [18].

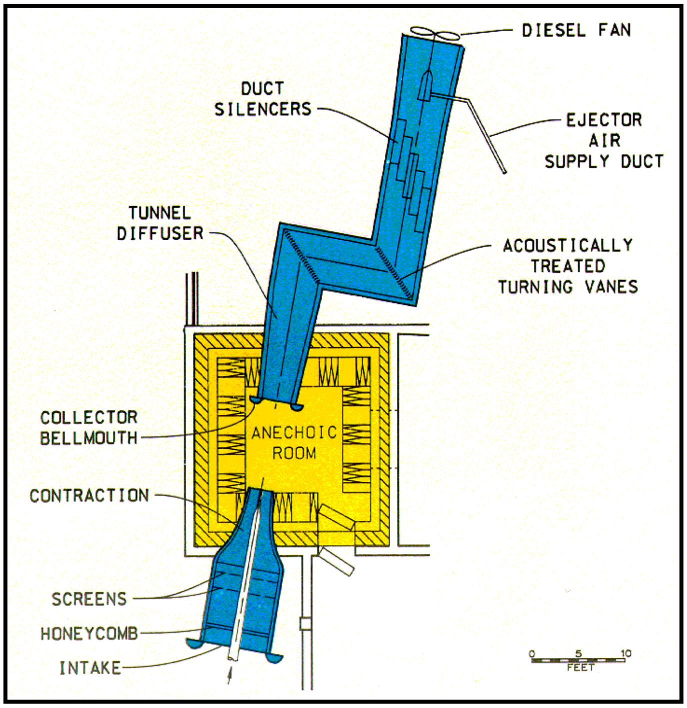


Figure 1. Cross-section of the GTRI Anechoic Flight Simulation Facility

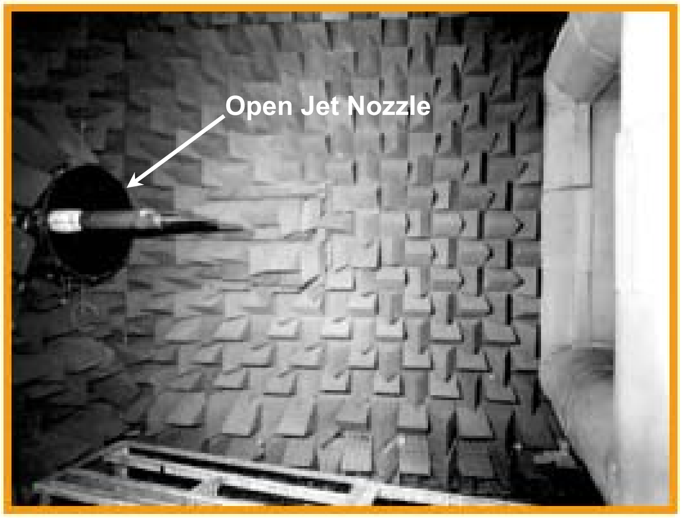


Figure 2. Anechoic chamber, exit nozzle and jet catcher; the small nozzle at the center of the open jet was removed and the test airfoil was mounted from a support hidden behind foam as shown in Figure 3.

2.2 Instrumentation

Acoustic measurements were made with 6.4 mm (¼-in) diameter B&K (Bruel & Kjaer) Type 4939 microphones. They can be placed anywhere in the anechoic chamber, but typically should be no closer than 0.4 m (1.2 ft) from wedge tips so as to avoid any wedge near-field effects. In the present tests, the microphones were located 3 m (10 ft) away from the wind turbine blade tip, below the pressure side of the airfoil, and were set at 90° and 30° angles as shown in Figure 3. B&K 2669 pre-amplifiers were used in combination with a Nexus conditioner amplifier connected to an Agilent E1421B mainframe computer (that subsequently operated a Signal Calc 620 frequency analyzer). All acoustic data were analyzed as narrow band frequency spectra with 25 Hz increments in the range of 0 kHz to 20 kHz

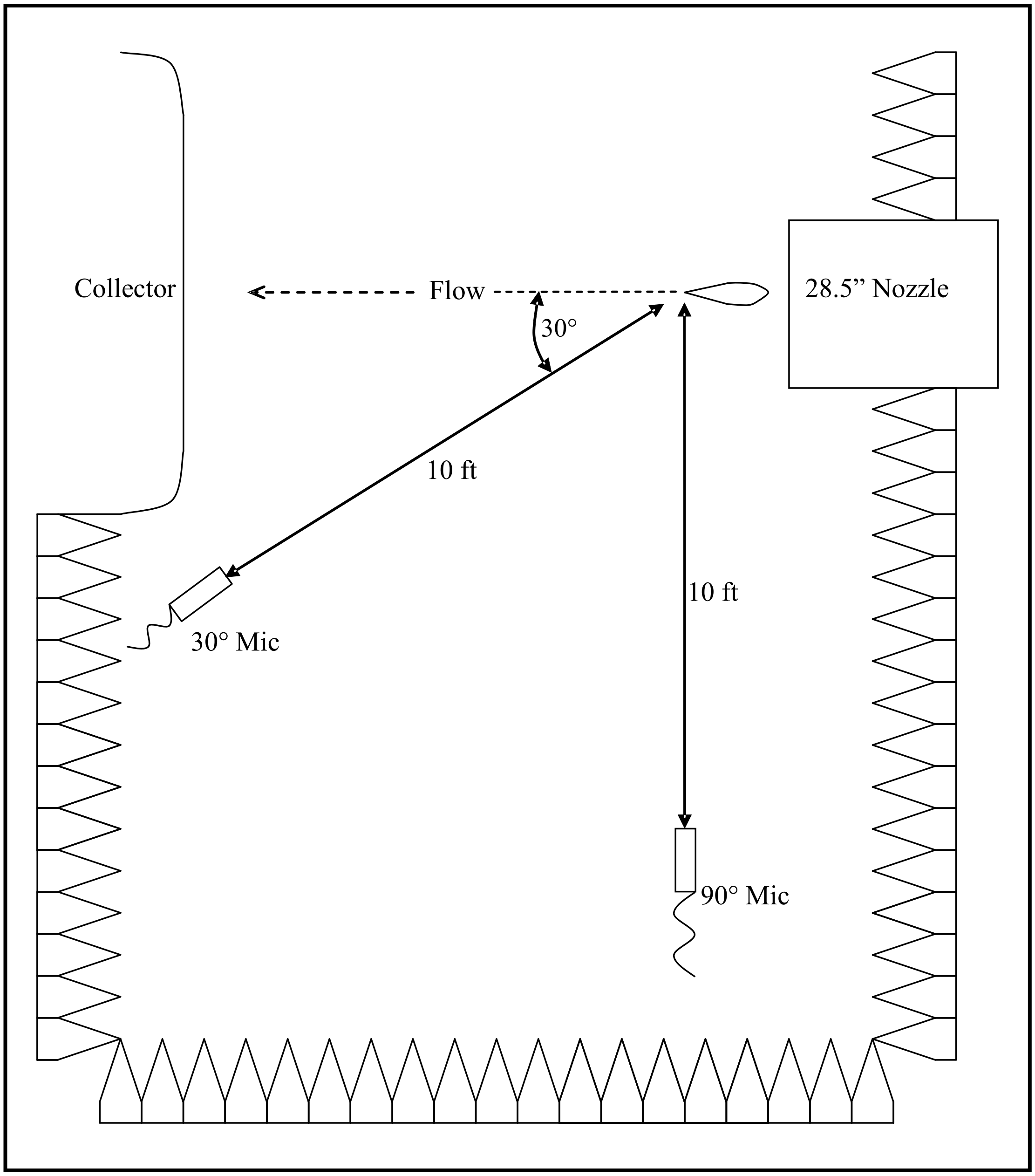


Figure 3. Microphone Locations

2.3 Measuring Angle of Attack

An electronic level accurate to 0.1 degree was used to measure angle of attack (α), as shown in Figure 4a. The zero angle was established at the inboard section of the blade where the removable tips were attached – approximately the 75% span location. A wooden clamping block was fabricated with its split line and upper surface machined parallel to the chord line of the model. The reference chord line A-B was established from the leading edge to the trailing edge of the exposed airfoil section. The electronic level then was placed on the top surface of the clamping block, which was used to mount the blade to the test facility. The angle of attack was set and measured for each test condition. This approach was sufficiently accurate because its objective was to make relative comparisons between blade tips.

Figure 4a. Angle of attack was measured with an electronic level.

2.4 Wind Tunnel Models

Tests were conducted on a realistic wind turbine blade provided by Southwest Windpower (SWWP) of Flagstaff, Arizona. The blade was taken from a prototype 1.8 kW fixed-pitch, variable-speed turbine called "Storm" which was developed under a DOE subcontract with technical assistance from the NWTC. The Storm, which had a 3.7 m (12.1 ft) rotor span, has been commercialized as the "Skystream" wind turbine. The outboard 330 mm (1.08 ft) of the blade – approximately 18 % of rotor span – was placed in the test section as shown in Figure 4b. Six removable blade tips were tested, each 232 mm (0.76 ft) long with a 92 mm (0.30 ft) root chord and comprising approximately 12.5 % of the rotor span. This was a deliberate choice, as it generally is accepted that the outboard 20% to 25% of the rotor is the primary source of aeroacoustic emissions.

The Storm and the Skystream employ NREL's S822 airfoil family, which was developed by Tangler and Somers [16] specifically for small wind turbines. The airfoil offered a good balance among several measures of merit, including aerodynamic performance, aeroacoustic performance and structural efficiency. The aeroacoustic performance of the S822 is well documented in reports by Oerlemans [3] and Migliore [4]. The aerodynamic performance is documented by Selig and McLanahan [1, 2]. This extensive documentation was another

Figure 4b. Blade section immersed in open jet flow.

reason for choosing the S822 for the present study. The six removable and interchangeable blade tips are shown in Figure 5. The shapes were developed by the author, Paul Migliore, who also provided final lofting for the outboard 25% of the Storm blade in an effort to create a low-noise planform. A mathematical description of each blade tip was provided to SWWP engineers, who created electronic files suitable for computer-controlled machining. Three dimensional master shapes then were fabricated on a stereo lithographic printer. The actual fiberglass parts were manufactured and fitted to the blade root stub by Novakinetics, LLC, of Flagstaff, Arizona. The parts were fastened to the root section with countersunk machine screws – three on the suction surface and three on the pressure surface. To mitigate potential aerodynamic and aeroacoustic effects, the screws and the chordwise joint were covered with tape before testing. Blenderm® surgical tape, having a thickness of 0.10 mm (0.004 inches) (manufactured by 3M Company) was used. For safety reasons the structural integrity of the blade tips was verified by conducting load tests to safety factors of 1.5 and 2.0 on the anticipated normal and axial forces, respectively.

PM-1, PM-2 and PM-3 are similar to shapes that have been studied [17] in Europe. PM-4 is a radical shape that hypothesizes the formation of vortices to energize the flow and prevent separation-induced noise in the region of the blade tip. PM-5 is a simple winglet that is hypothesized to displace the blade tip vortex away from the trailing edge, thereby reducing the intensity of the scattered acoustic waves. For all of the tips, the S822 shape was maintained regardless of the local chord length.

It is important to note that these particular shapes are not presumed to be the optimum of their types, nor is any one of them presumed to be superior among the infinity of possibilities. They simply represent a broad range of options demonstrating the potential sound reduction that could be obtained by optimizing blade tip shape for an otherwise quiet blade. This presumes, of course, an aeroacoustically efficient design with respect to blade planform, airfoil shape, and trailing edge geometry. Furthermore, no matter what sound reduction might result from application of a particular tip shape, the aerodynamic impact certainly must be considered.

Figure 5. Wind turbine blade segment used for the test model (top photo) and the removable blade tips (bottom photo) – from left to right –Storm baseline blade tip and removable tips PM-1 (leading edge sweep), PM-2 (trailing edge sweep), PM-3 (ogee shape), PM-4 (scalloped trailing edge) and PM-5 (winglet)

2.5 Test Matrix

Table 1 shows the tunnel speeds and angles of attack at which the models were tested. The tunnel speeds of 25 m/s (Re = 157,000), 50 m/s (Re = 315,000), and 75 m/s (Re = 472,000) were chosen to bracket the rotor speeds of an operating Storm turbine. The effective angle of attack of -1 degree is close to the angle of zero lift for the S822 airfoil and is typical of conditions where laminar boundary layer vortex shedding noise (pure tones) is typically exhibited [3, 4]. The maximum lift-to-drag ratio for the S822 airfoil occurs at the effective angle of 5 degrees, which would be the desired operating point for a variable speed turbine. The effective angle of 9 degrees is approximately where the S822 lift curve deviates from linear, thus representing insipient stall and, prospectively, separation noise. The angles of attack at which the models were set in the tunnel were different than the effective angles shown in Table 1. Corrections were made for the flow deflection associated with open jet wind tunnels. A heuristic approach, using the method of Brooks, Pope and Marcolini [19], resulted in the corrections shown in Table 2.

Table 1. Summary of Configurations and Test Conditions

		Effective Angle of Attack, a (degrees)								
Configuration		$a_{effective} = -1$			$a_{effective} = 5$			$a_{effective} = 9$		
Number	Description	Tunnel Speed (m/s)			Tunnel Speed (m/s)			Tunnel Speed (m/s)		
E1*	Empty Test Section	25	50	75	25	50	75	25	50	75
B1	Baseline Tip	25	50	75	25	50	75	25	50	75
1	Tip PM-1	25	50	75	25	50	75	25	50	75
2	Tip PM-2	25	50	75	25	50	75	25	50	75
3	Tip PM-3	25	50	75	25	50	75	25	50	75
4	Tip PM-4	25	50	75	25	50	75	25	50	75
5	Tip PM-5	25	50	75	25	50	75	25	50	75
B2	Basiline Tip Sharpened	25	50	75	25	50	75	25	50	75
E2*	Empty Test Section	25	50	75	25	50	75	25	50	75
*Angle of attack variation does not apply to tests with an empty test section.										

Table 2. Effective Angle of Attack Corrections for GTRI Open Jet Tunnel

		alpha setting	alpha effective	alpha correction
		-3.00	-2.47	-0.53
		-2.00	-1.64	-0.36
		-1.00	-0.82	-0.18
		0.00	0.00	0.00
		1.00	0.82	0.18
		2.00	1.64	0.36
		3.00	2.47	0.53
		4.00	3.29	0.71
		5.00	4.11	0.89
Settings for GTRI Tests		6.00	4.93	1.07
		7.00	5.75	1.25
		8.00	6.57	1.43
		9.00	7.40	1.60
		10.00	8.22	1.78
		11.00	9.04	1.96
		12.00	9.86	2.14
		13.00	10.68	2.32
		14.00	11.50	2.50
Model Chord (inches)	3.62	15.00	12.33	2.67
Tunnel open-jet dimension normal to chord line (inches)	28.00	16.00	13.15	2.85
Tunnel Speed (fps)	246.06	17.00	13.97	3.03
Sigma constant (Brooks, Pope and Marcolini)	0.003	18.00	14.79	3.21
Zeta constant (Brooks, Pope and Marcolini)	1.217	19.00	15.61	3.39
Reynolds Number x 10^{-6} (calculated)	0.472	20.00	16.44	3.56

3.0 Test Results

3.1 Background Noise – Empty Tunnel Tests

Before initiating tests of the wind turbine blade tips, it was necessary to determine the background noise level of the wind tunnel. Only by doing this is it possible to separate the effects of the models from extraneous noise sources in the wind tunnel and surroundings. The background noise is given by the spectra shown in Figures 6 through Figure 9, which are the original GTRI graphs (including original numbering, located in the lower right corner of each figure). To distinguish the individual plots, however, the graphs must be viewed in color.

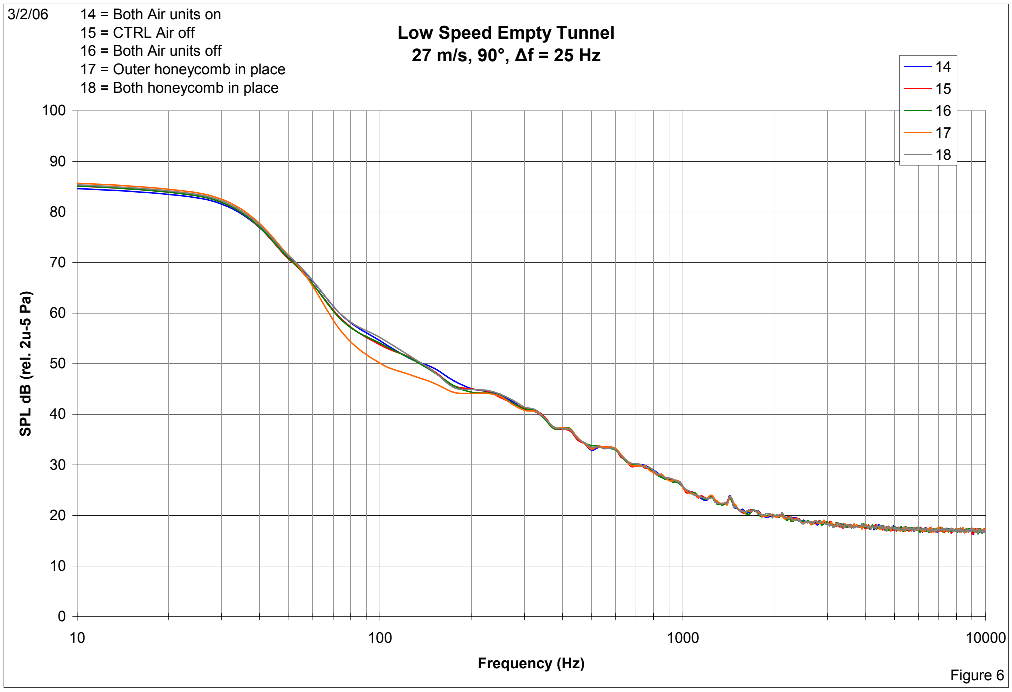


Figure 6

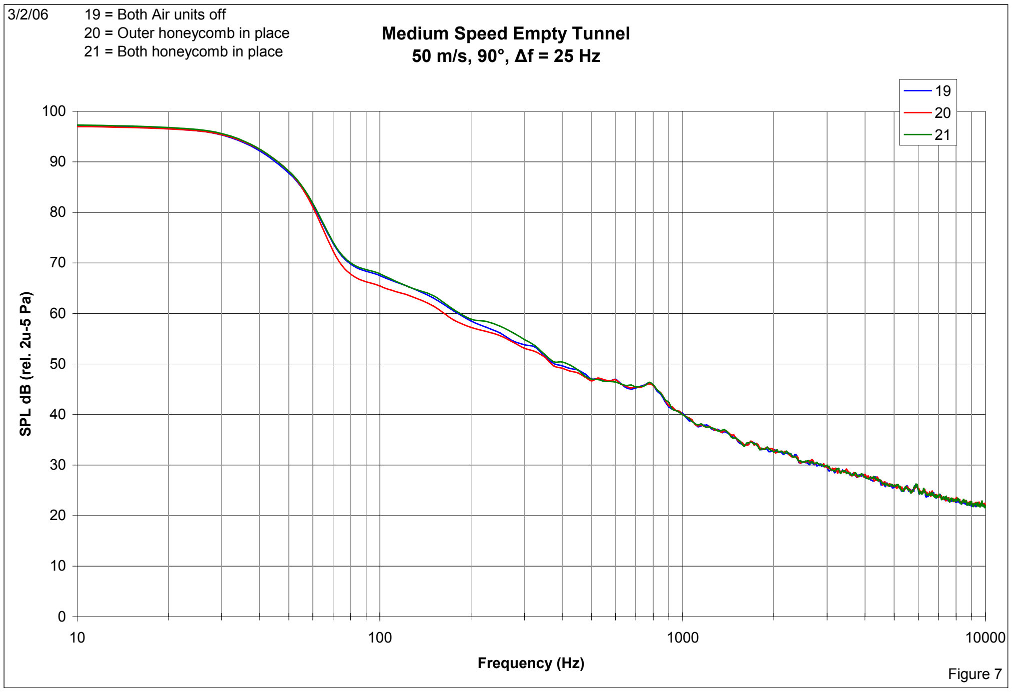
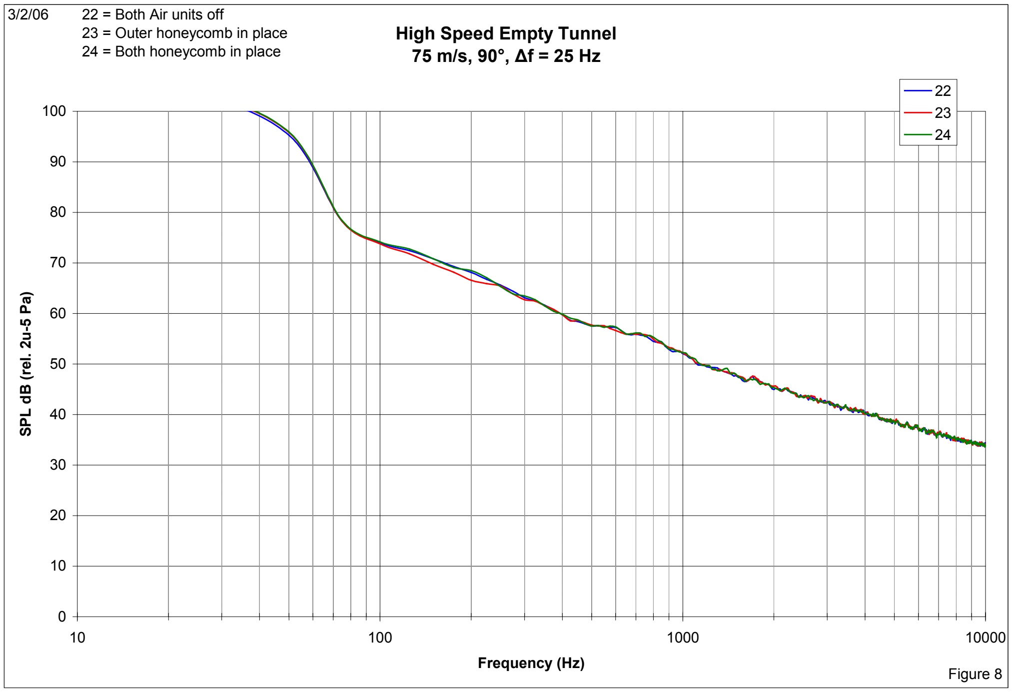


Figure 7

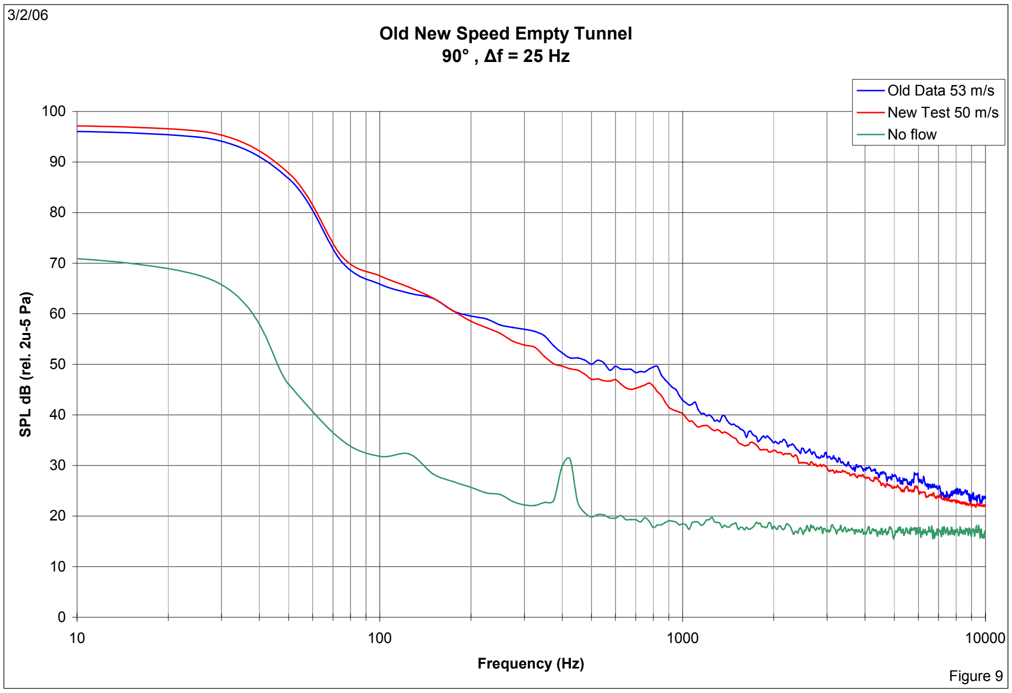


3/2/06

22 = Both Air units off
23 = Outer honeycomb in place
24 = Both honeycomb in place

High Speed Empty Tunnel
75 m/s, 90°, Δf = 25 Hz

Figure 8



3/2/06

Old New Speed Empty Tunnel
90° , Δf = 25 Hz

Figure 9

Note: To check the acoustic performance of the wind tunnel, background noise was compared to previous data from the spring of 2006, albeit at a slightly different tunnel speed. As Figure 9 illustrates, no anomalies were found.

3.2 Effect of Boundary Layer Tripping

Previous experience [3, 4] indicates that virtually all airfoils at low Reynolds number exhibit pure tones at some particular angles of attack. For other angles of attack, or at higher Reynolds numbers, the tones are likely to disappear. This phenomenon was attributed to laminar boundary layer vortex shedding. It therefore was expected that the wind turbine test blade would exhibit this same behavior unless turbulent flow was induced through effective boundary layer tripping. It is very difficult to predict the trip thickness required to accomplish this, so it was done empirically. We used a straight polyurethane protective tape (3M product number 8762) having a thickness of 0.2 mm (0.008 in) applied with its trailing edge at 5% of the chord on both the upper and lower blade surfaces. Several layers of tape were applied until the desired effect was observed through the acoustic measurements.

To avoid extraneous acoustic sources, the joint between the root section and the blade also was also taped during the tests. Blenderm® surgical tape (3M Company) having a thickness of 0.10 mm (0.004 inches) was used. The procedure for applying the tape was to begin at the 90% chord location on the pressure (concave) side of the airfoil; wrap toward and then around the trailing edge; wrap toward the leading edge; wrap toward the trailing edge; and terminate at the 95% chord location thereby overlapping the starting point. The tape was carefully adhered so as to leave no creases or bubbles and making sure to completely cover the joint and all of the screw heads.

Figure 10 through Figure 12 illustrate the impact of leading edge tape thickness and the effect of tripping the boundary layer to induce turbulent flow. At 27 m/s (Re = 170,000) and 11º angle of attack the flow is predominantly laminar, perhaps accompanied by some flow separation. Laminar boundary layer vortex shedding and / or flow separation produce strong tones in the frequency range of 1.5 kHz to 2.5 kHz. Three layers of tape (0.61 mm = 0.024 inches) are required to suppress these tones. At lower frequencies where tones are not present, heavy tripping reduces sound pressure level by 2 dB to 3 dB. At 50 m/s (Re = 315,000) the strong tones remain, but shift to a frequency range of 3.5 kHz 6.0 kHz. At 63 m/s (Re = 397,000) the tones are eliminated, and broadband noise is reduced over the entire frequency range by application of 3 layers of tape. This leading edge treatment was used for subsequent tests.

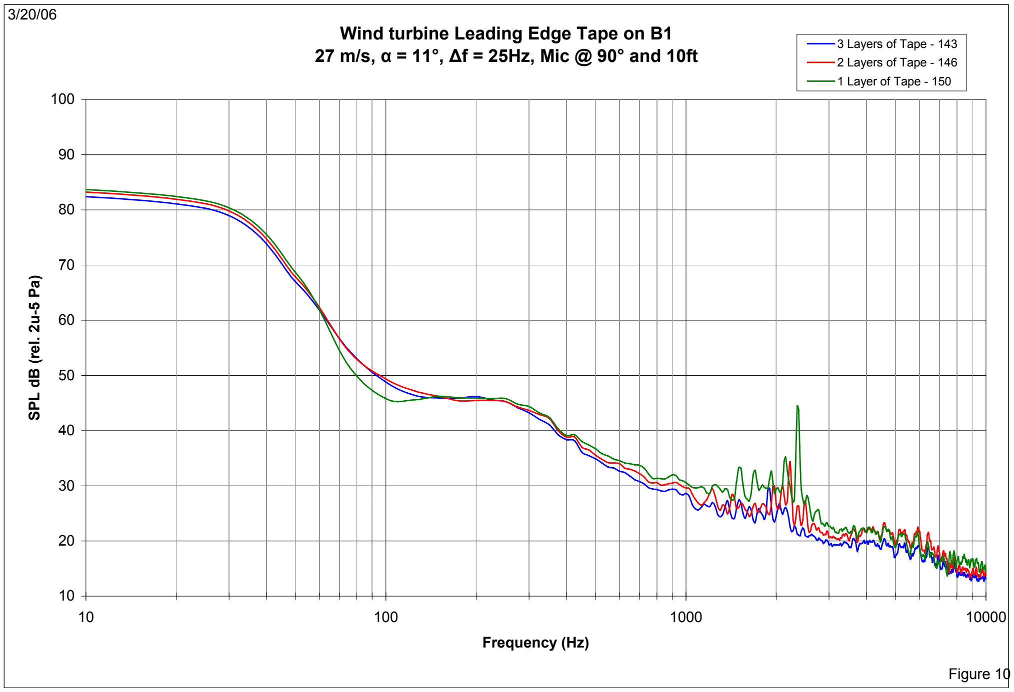


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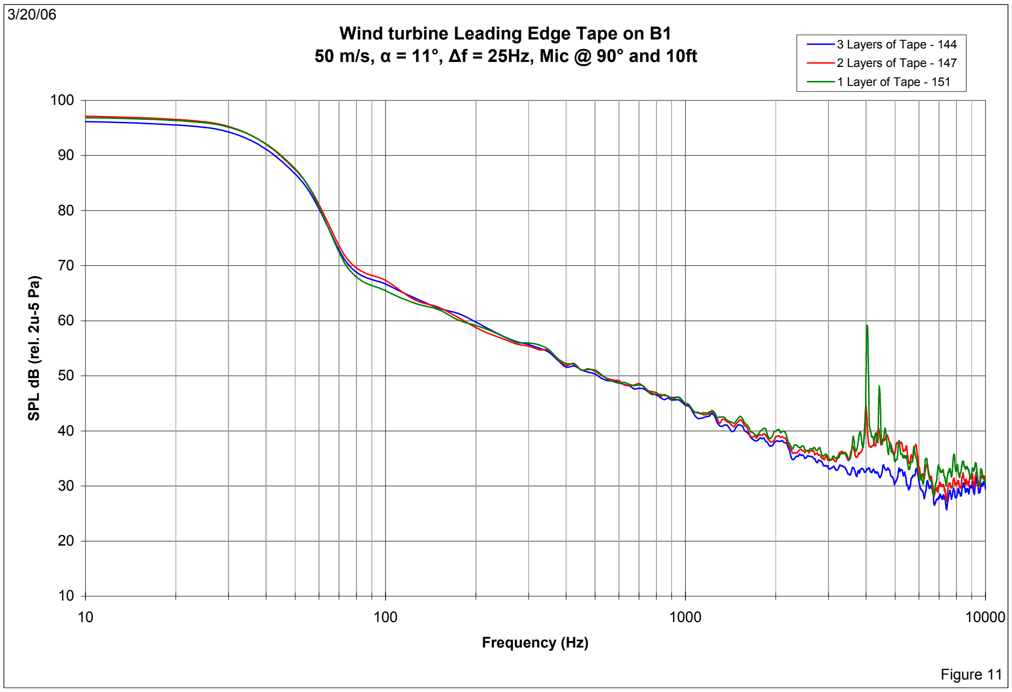
Figure 10



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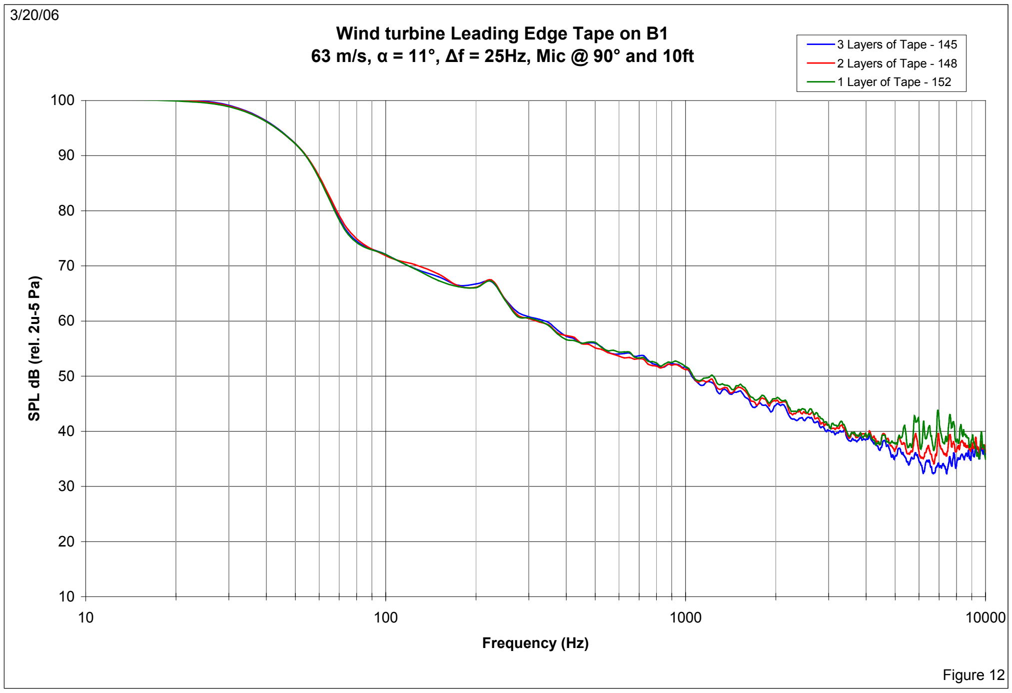
Wind turbine Leading Edge Tape on B1
50 m/s, α = 11°, Δf = 25Hz, Mic @ 90° and 10ft

Figure 11



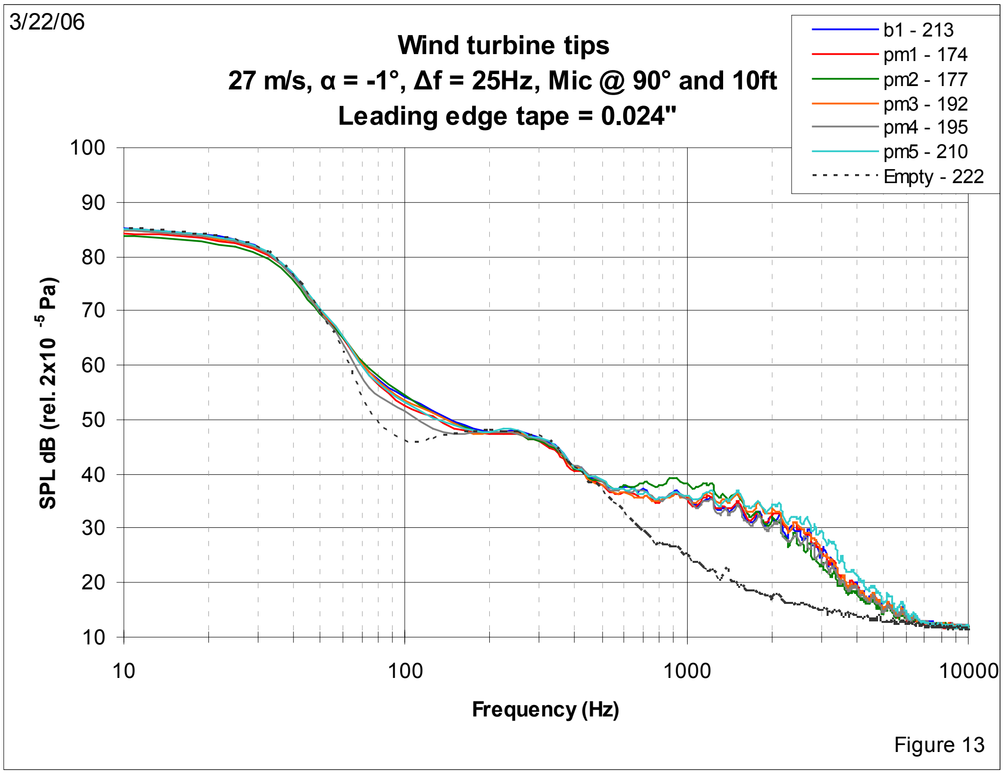
3/20/06

Wind turbine Leading Edge Tape on B1
63 m/s, α = 11°, Δf = 25Hz, Mic @ 90° and 10ft

Figure 12

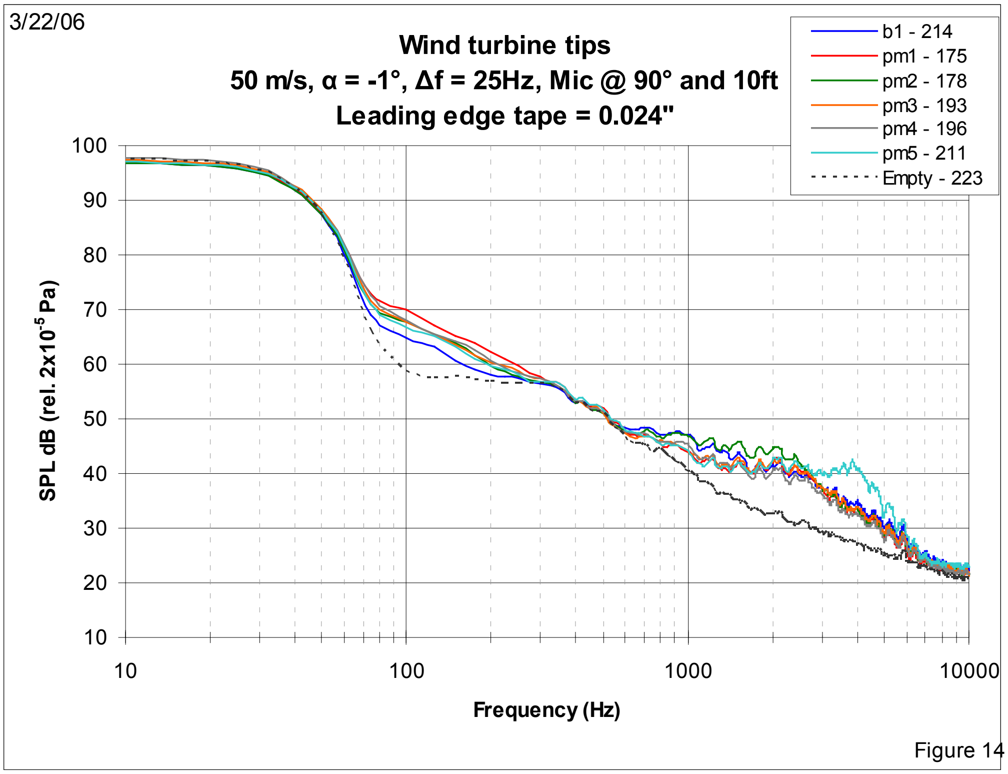
3.3 Effect of Blade Tip Shape

Acoustic spectra for the six blade tip shapes are given in the Figures 13-21. The important frequency range of 1 kHz to 5 kHz is more carefully examined in Section 4, Analysis of Test Results. Caution is advised in drawing conclusions without simultaneous consideration of turbine operating characteristics.


3/22/06

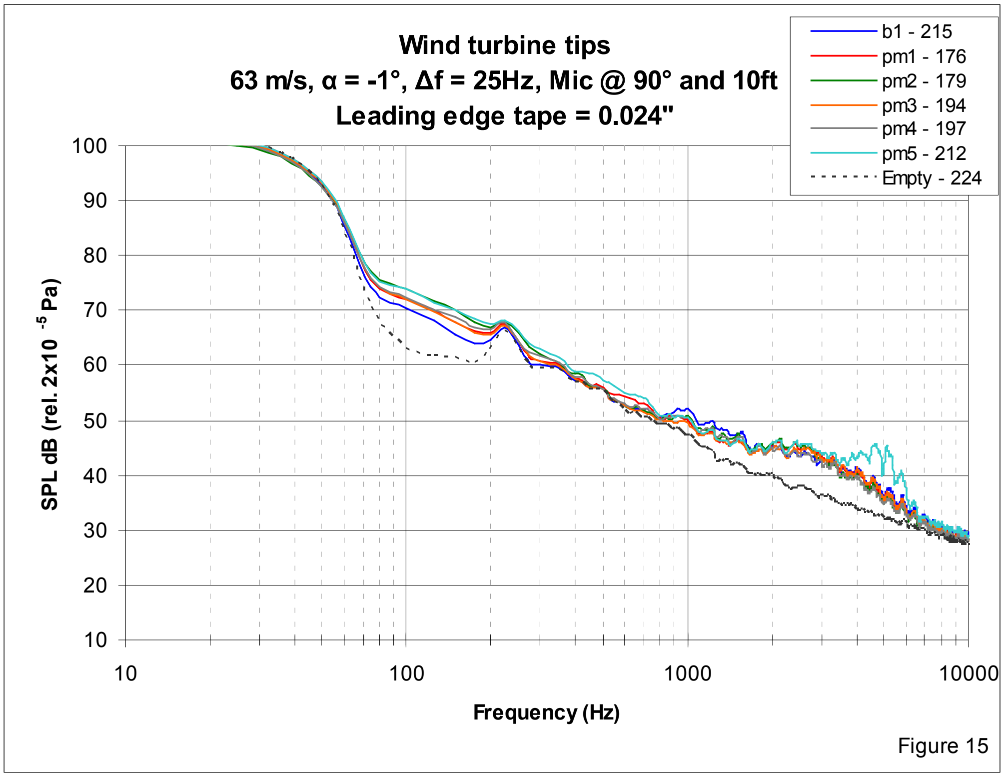
Wind turbine tips
27 m/s, α = -1°, Δf = 25Hz, Mic @ 90° and 10ft
Leading edge tape = 0.024"

Figure 13


3/22/06

Wind turbine tips
50 m/s, α = -1°, Δf = 25Hz, Mic @ 90° and 10ft
Leading edge tape = 0.024"

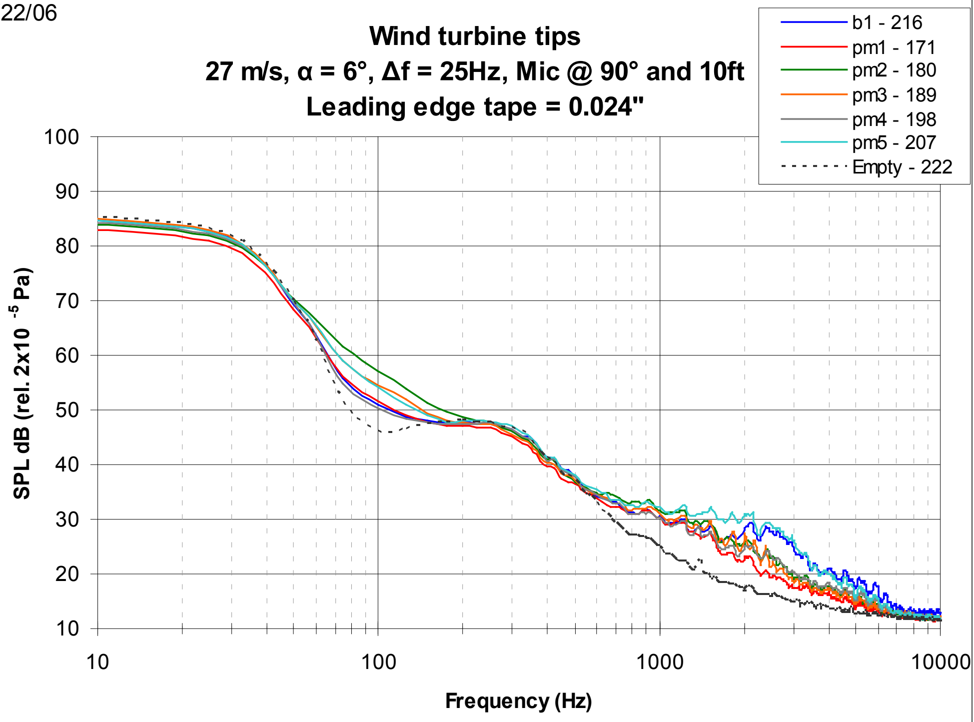
Figure 14



Wind turbine tips
63 m/s, α = -1°, Δf = 25Hz, Mic @ 90° and 10ft
Leading edge tape = 0.024"

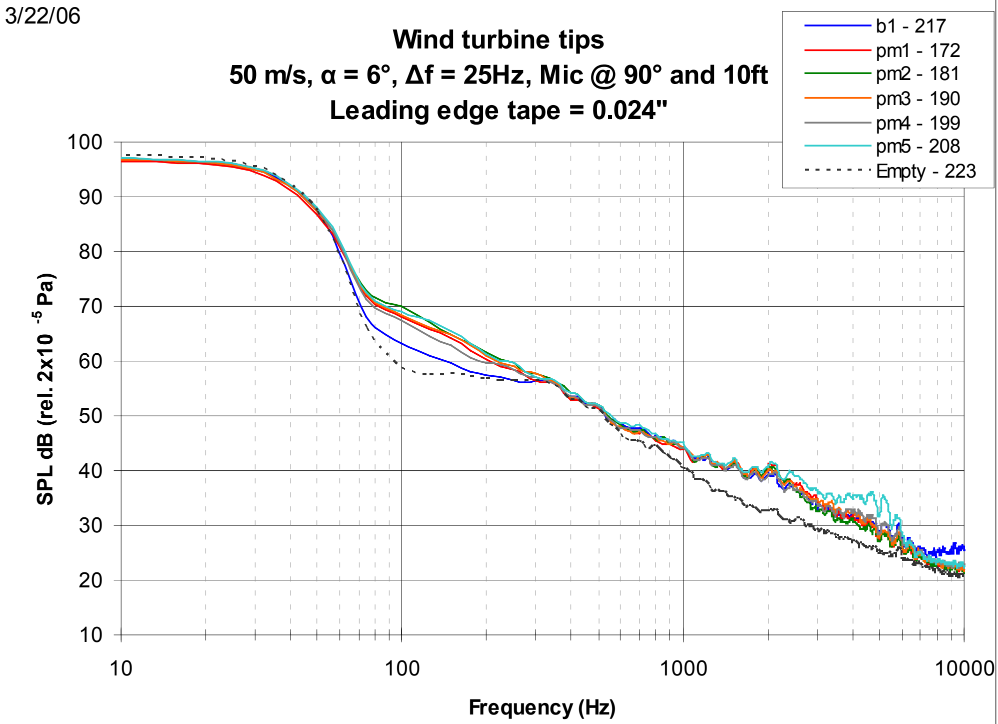
Figure 15

3/22/06



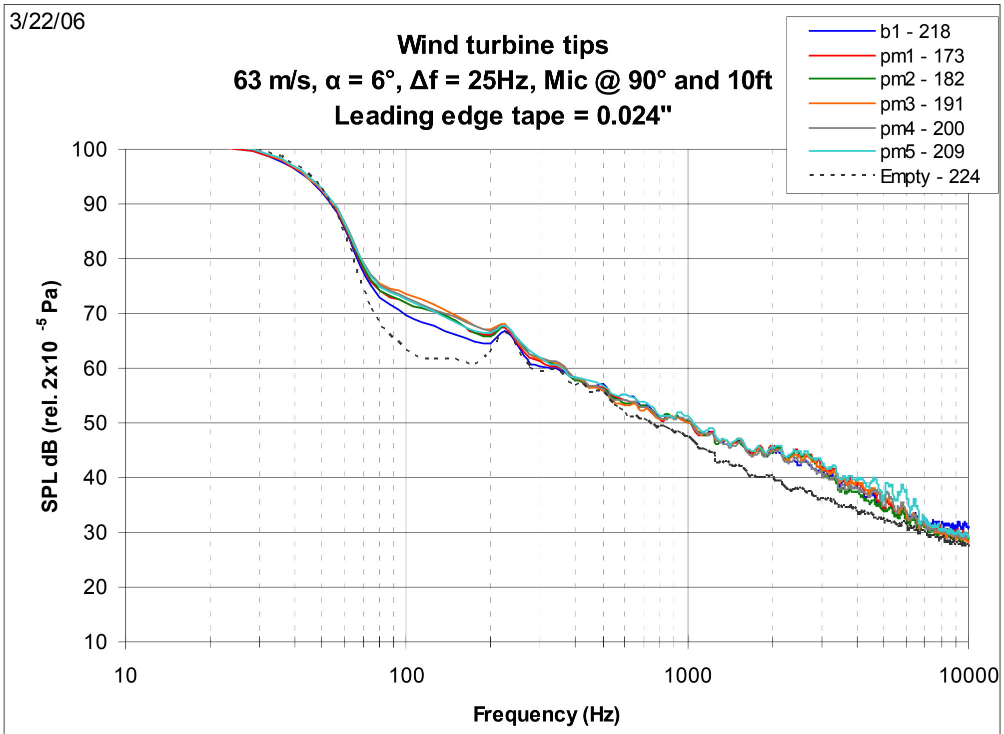
Wind turbine tips
27 m/s, α = 6°, Δf = 25Hz, Mic @ 90° and 10ft
Leading edge tape = 0.024"

Figure 16


3/22/06

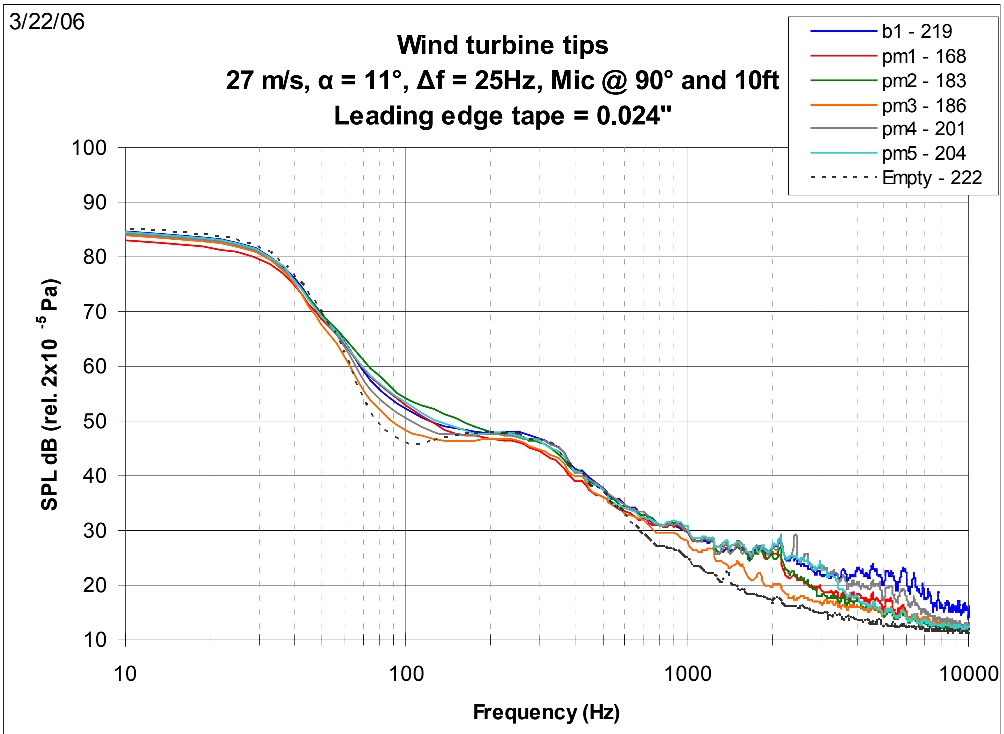
Wind turbine tips
50 m/s, α = 6°, Δf = 25Hz, Mic @ 90° and 10ft
Leading edge tape = 0.024"

Figure 17


3/22/06

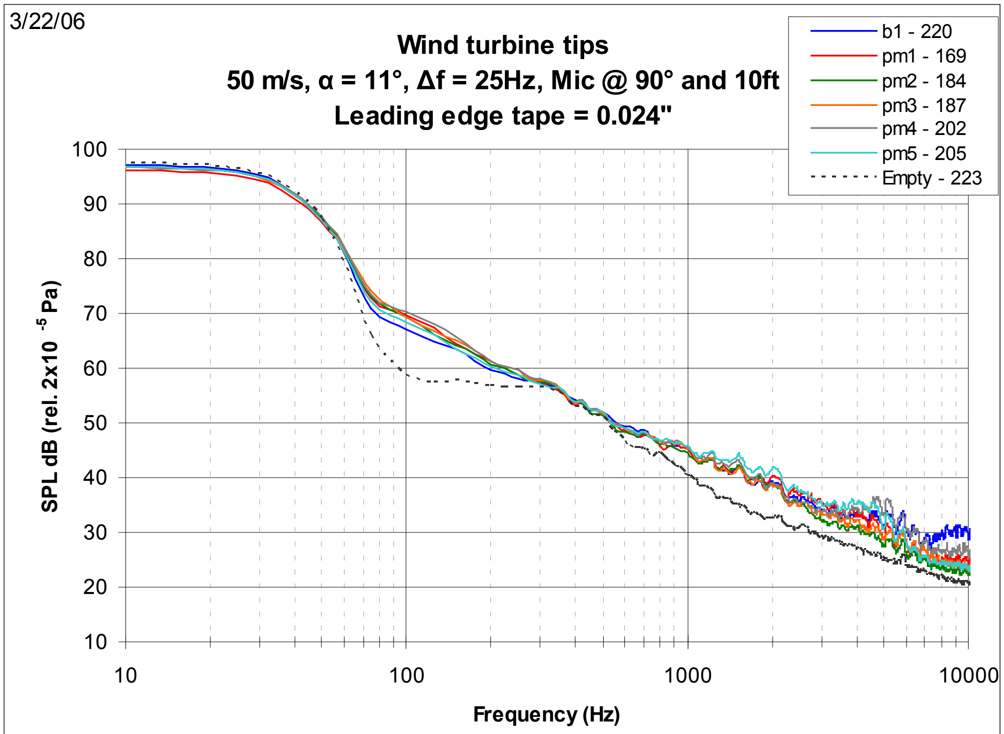
Wind turbine tips
63 m/s, α = 6°, Δf = 25Hz, Mic @ 90° and 10ft
Leading edge tape = 0.024"

Figure 18


3/22/06

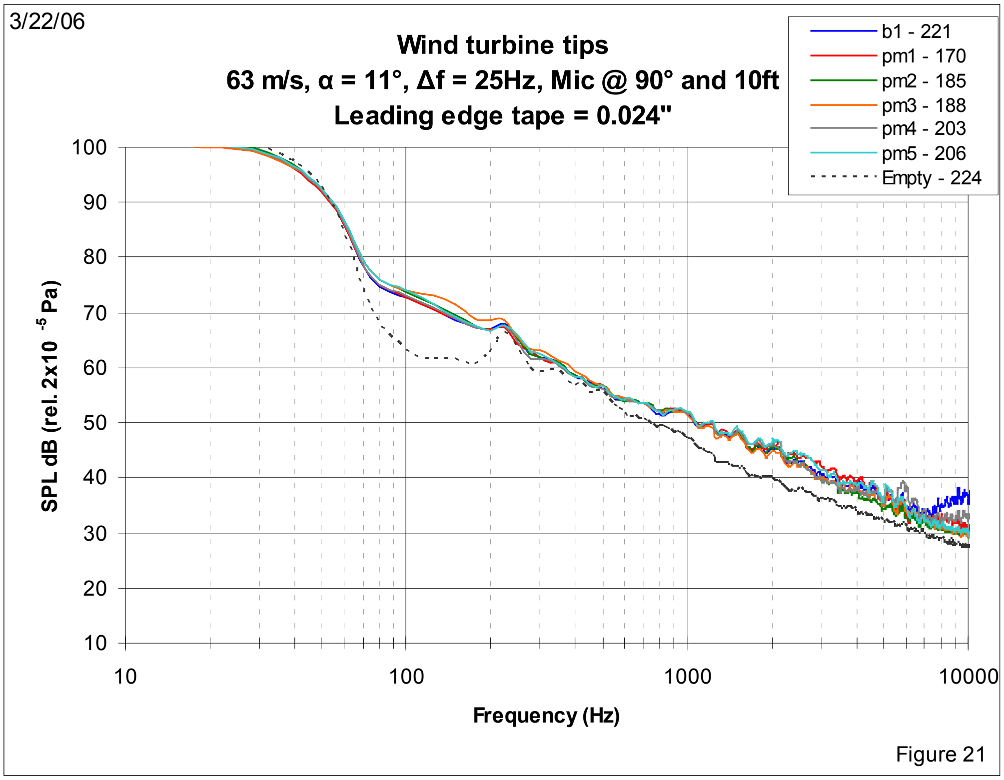
Wind turbine tips
27 m/s, α = 11°, Δf = 25Hz, Mic @ 90° and 10ft
Leading edge tape = 0.024"

Figure 19


3/22/06

Wind turbine tips
50 m/s, α = 11°, Δf = 25Hz, Mic @ 90° and 10ft
Leading edge tape = 0.024"

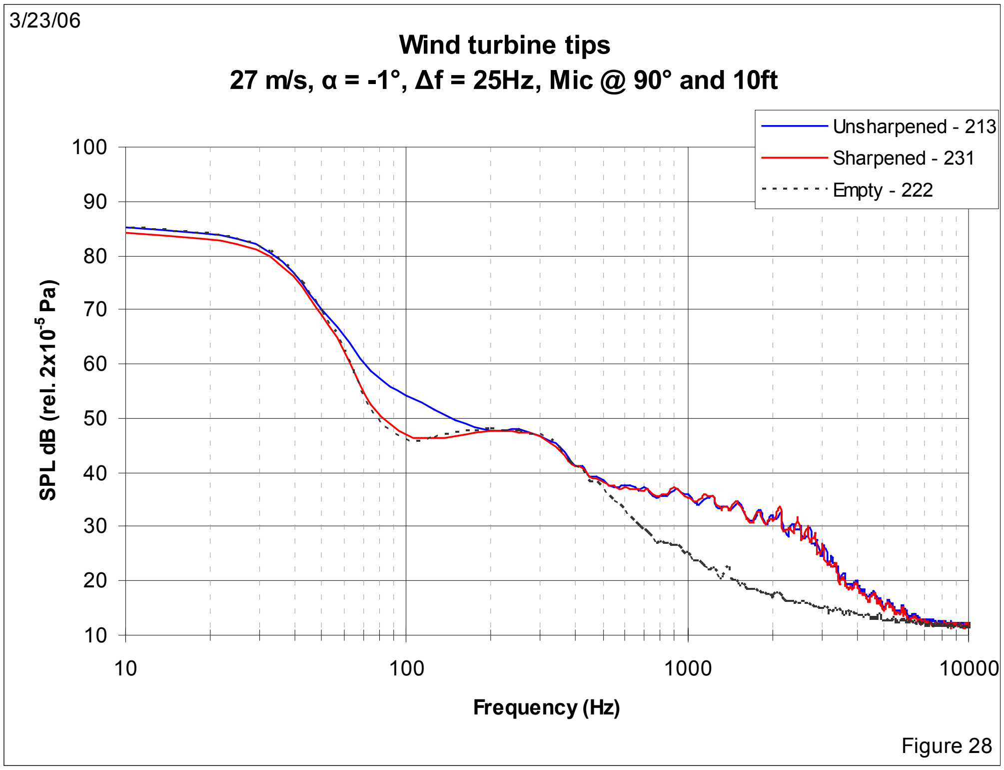
Figure 20



3.4 Effect of Trailing Edge Thickness

It is well known [20] that blunt trailing edges can be sources of noise related to vortex shedding. Acoustic modeling of this phenomenon typically relates sound pressure level to the geometry of the body, including trailing edge thickness and boundary layer characteristics, such as the displacement thickness. Regardless of the desire for thin trailing edges, constraints exist due to manufacturing limitations and damage considerations. Various "rules of thumb" often are used to establish targets for trailing edge thickness. Analytical and empirical studies both suggest that a trailing edge thickness of approximately 0.25% of chord length is not likely to result in additional noise. A thickness of approximately 0.50% of chord, which is difficult to achieve in fabrication, is thought to produce some additional – but acceptable – source of noise. Consequently, there was some interest in learning whether there is anything to be gained from a trailing edge thickness sharper than the baseline Storm blade.

Measured at a position that was 0.64 mm (0.025 in) forward of the trailing edge, the wind tunnel model and baseline blade tip B1 had a uniform trailing edge thickness of 1 mm (0.04 in) over the span of 0.33 m (13 in) immersed in the flow. This trailing edge thickness is approximately 1.1% of the model chord. Tests of this section were repeated after sharpening the trailing edge to a uniform thickness of 0.76 mm (0.03 in) or approximately 0.8% chord. Results are presented as sound pressure level spectra in Figure 22 through Figure 30. Details of the blade trailing edge sharpening are provided in Figure 31.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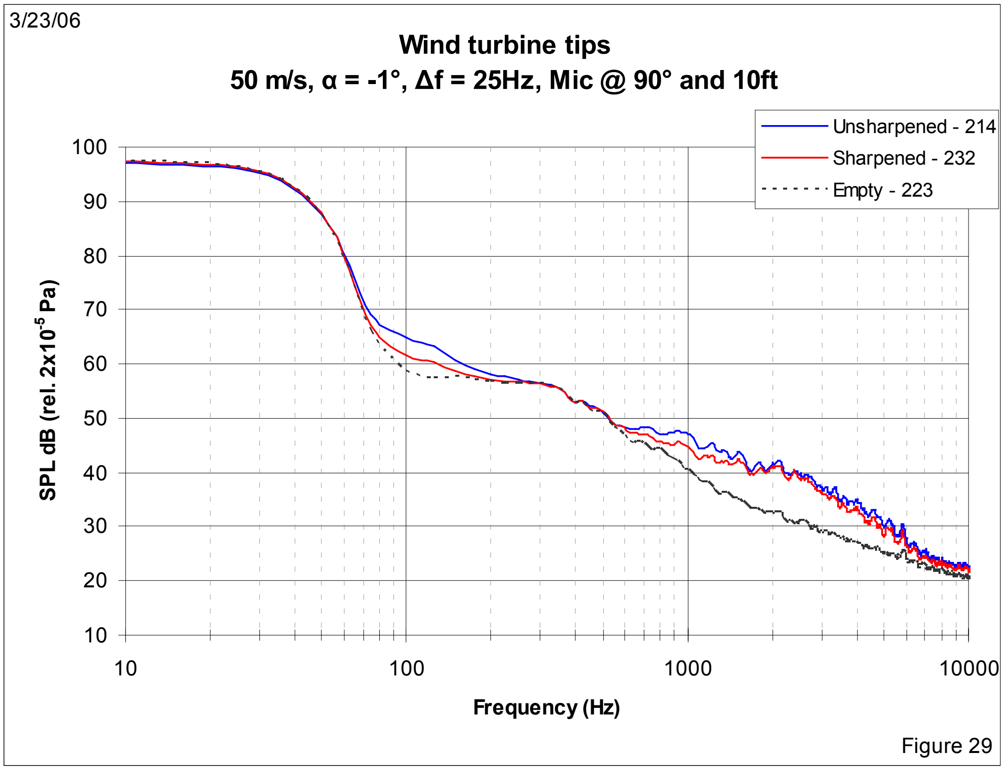
Wind turbine tips
27 m/s, α = -1°, Δf = 25Hz, Mic @ 90° and 10ft

Figure 28


3/23/06

Wind turbine tips
50 m/s, α = -1°, Δf = 25Hz, Mic @ 90° and 10ft

Figure 29

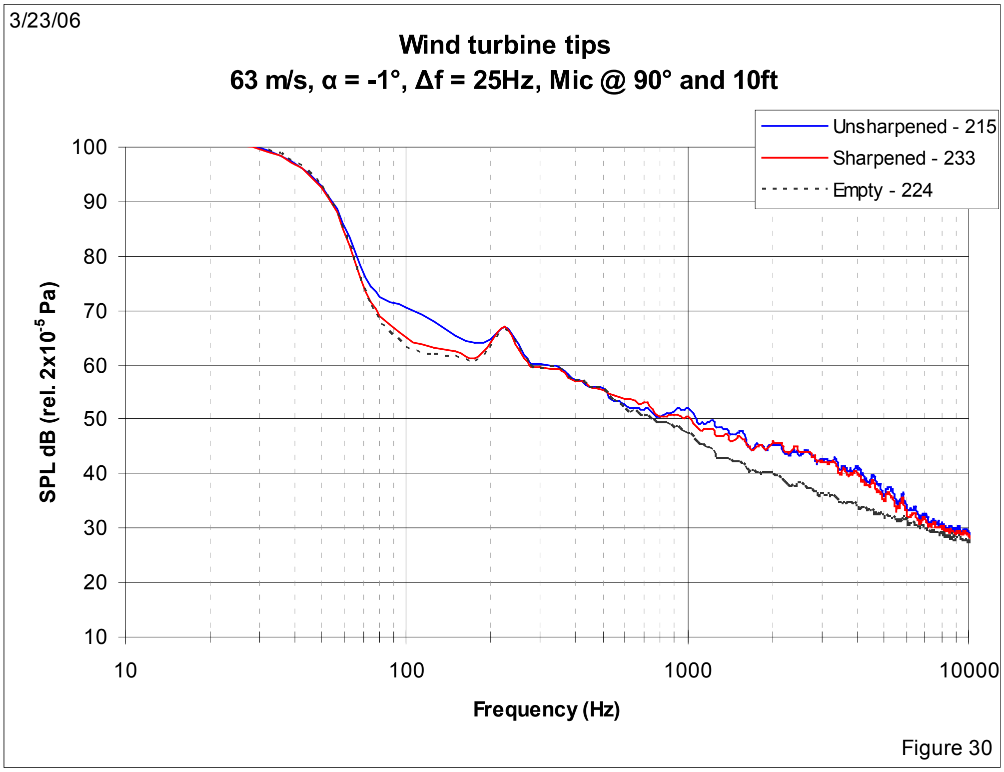


Figure 30

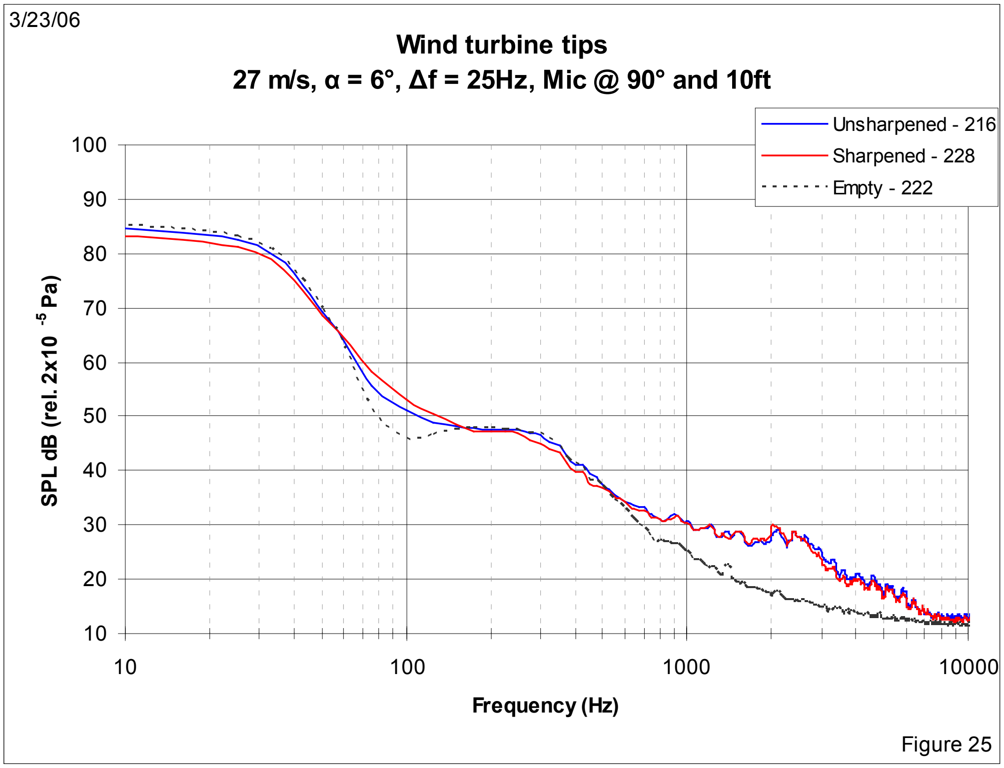
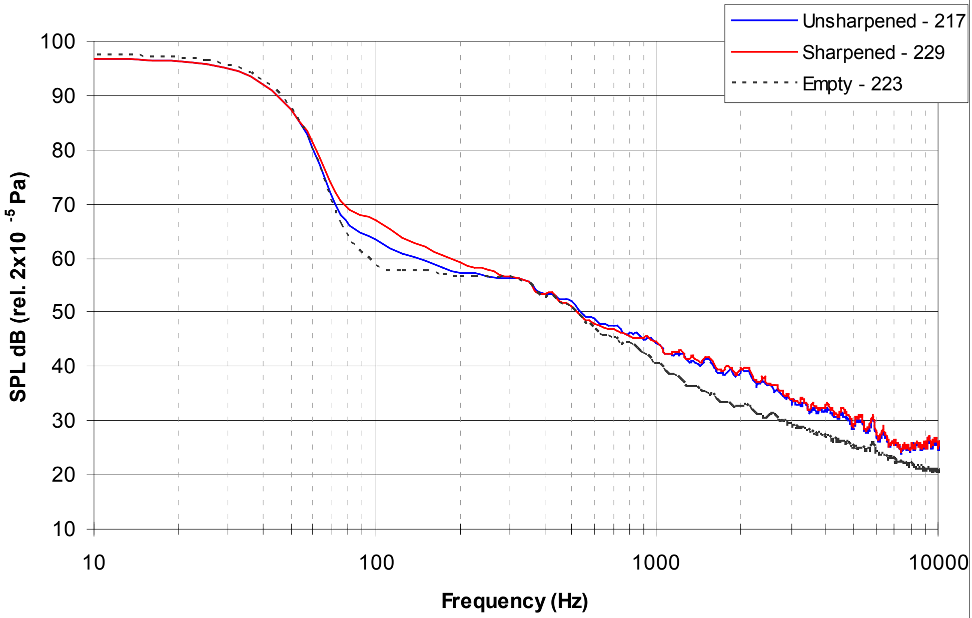


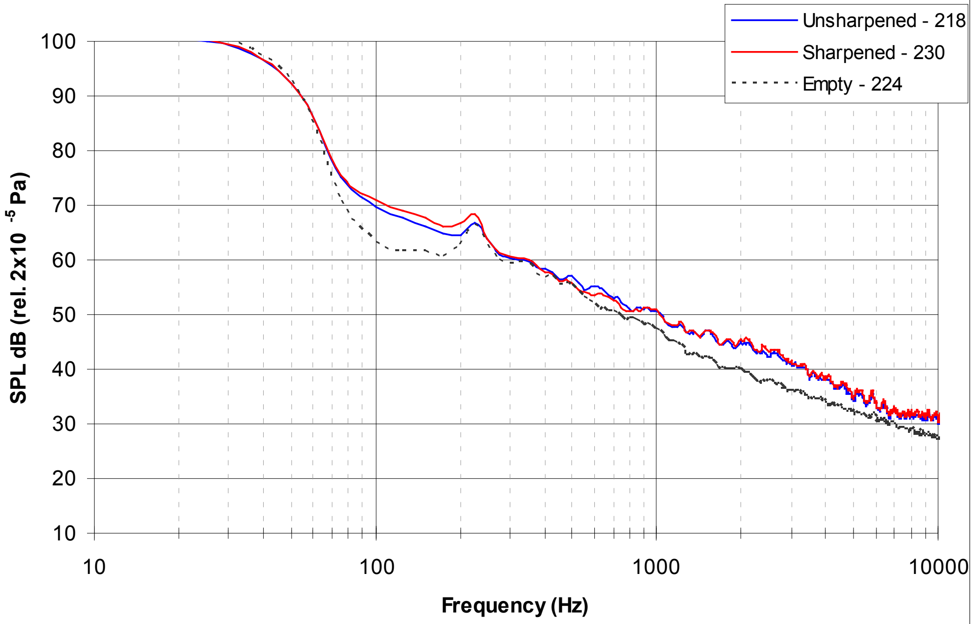
Figure 25



3/23/06

Wind turbine tips
50 m/s, α = 6°, Δf = 25Hz, Mic @ 90° and 10ft

Figure 26



3/23/06

Wind turbine tips
63 m/s, α = 6°, Δf = 25Hz, Mic @ 90° and 10ft

Figure 27

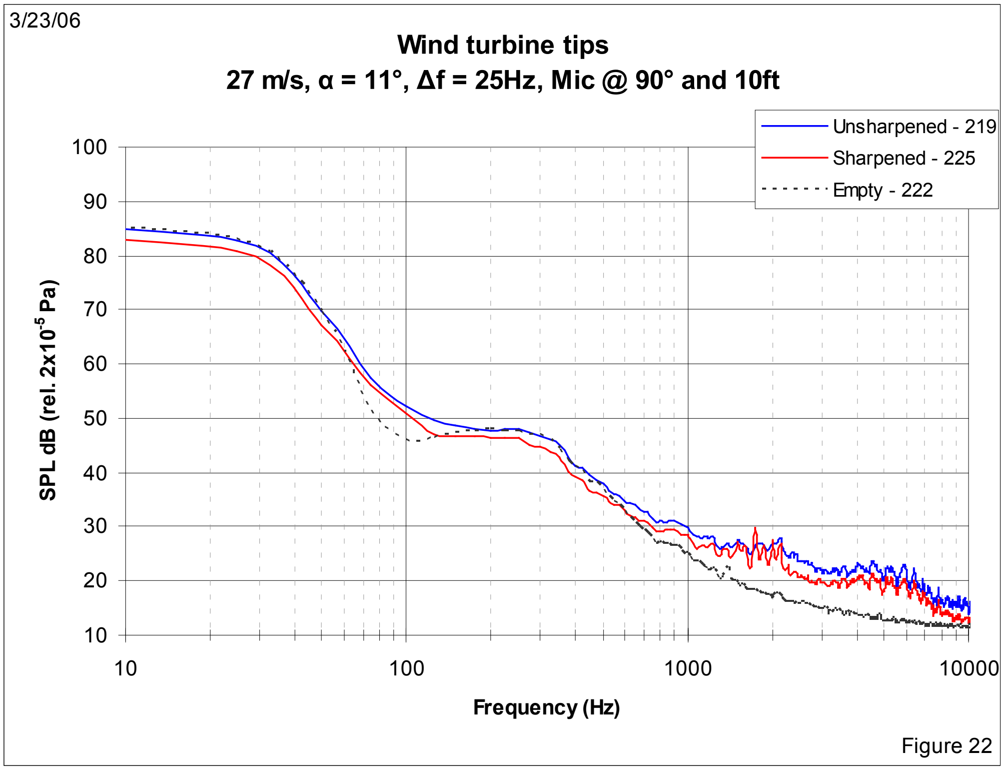


Figure 22

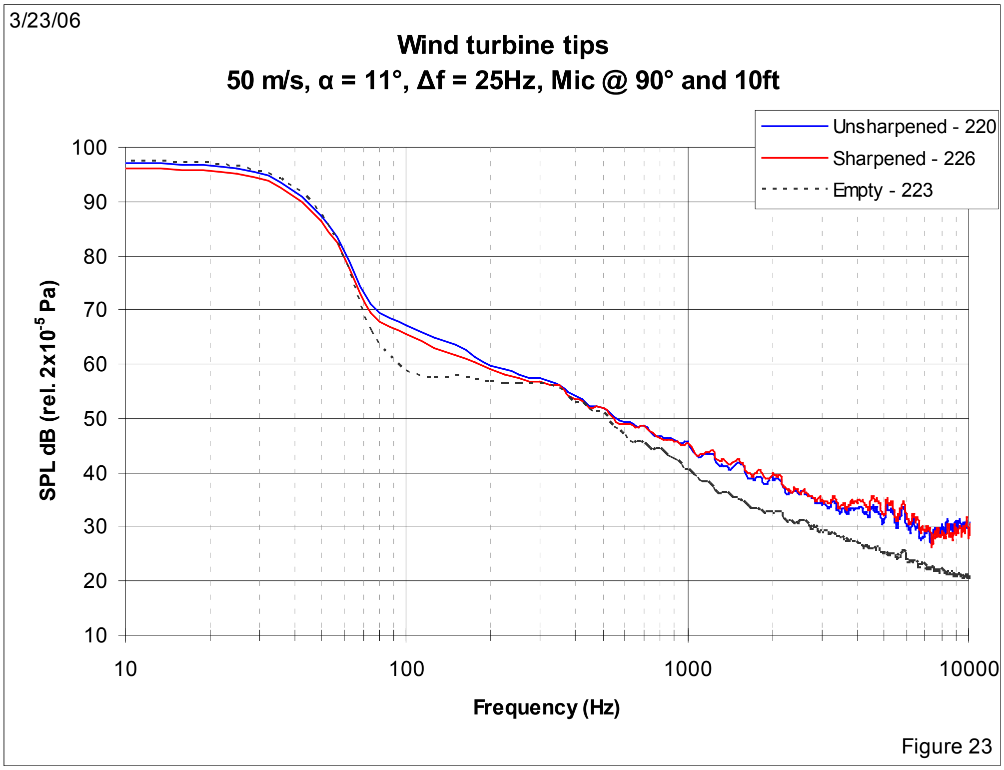


Figure 23

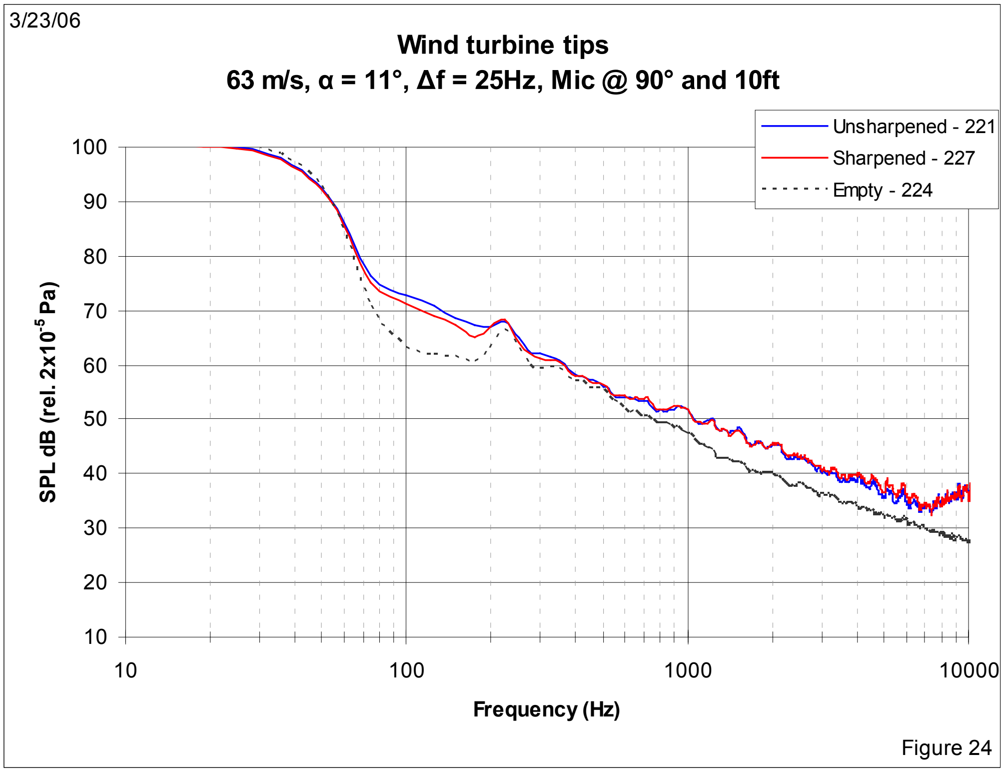
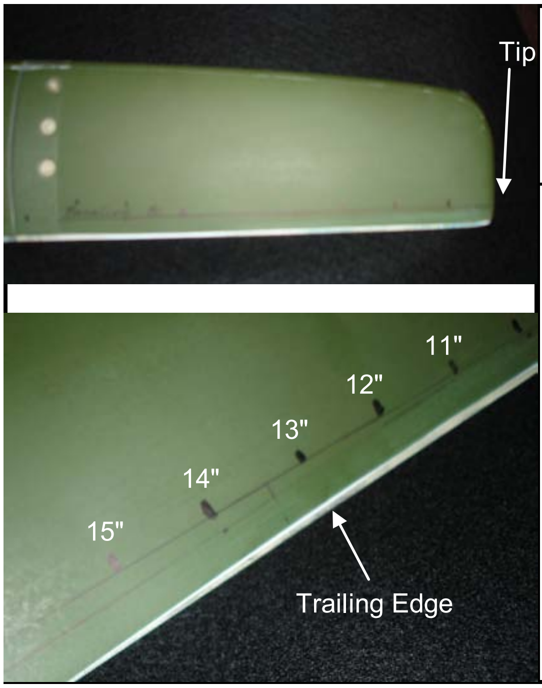


Figure 24



Distance From Tip (inches)	Orignal Thickness (inches)	Sharpened Thickness (inches)
1.00	0.040	0.030
2.00	0.040	0.030
3.00	0.040	0.030
4.00	0.040	0.030
5.00	0.040	0.030
6.00	0.040	0.030
7.00	0.040	0.030
8.00	0.040	0.030
9.00	0.040	0.030
10.00	0.040	0.030
11.00	0.040	0.030
12.00	0.040	0.030
13.00	0.040	0.030
14.00	0.040	0.030
15.00	0.040	0.035

Figure 31. The blade trailing edge was sharpened as shown in the table. Only the outboard 330 mm (13 inches) of the blade was immersed in the air flow.

4.0 Analysis of Test Results

The acoustic spectra of Figure 10 through Figure 30 provide some interesting information about the test configurations. Relative amplitudes in various frequency ranges are evident and pure tones are readily apparent. It also is useful, however, to characterize the perceived sound as a single quantity representing the total sound energy throughout the frequency range. This so-called overall sound pressure level (OASPL) is given by Equation 1, in which SPL_{FA} is the A-weighted sound pressure level at frequency F. For these analyses the summation was arbitrarily taken over the frequency range of 25 Hz to 10,000 Hz. SPL_{FA} is related to the un-weighted sound pressure level (SPL_{F}) by Equation 2 – a technique designed to reflect the response of the human ear, which does not respond equally to all frequencies. To describe sound in a manner representative of the human ear's response it is necessary to reduce the effects of the low and high frequencies with respect to the medium frequencies. The resultant sound level is said to be A-weighted, and the units are dBA. The A-weighted sound level is also called the noise level. [21]

$$\text{OASPL (dBA)} = 10 \log \sum 10^{(\text{SPL}_{\text{FA}}/10)}$$

Equation 1 (left) and Equation 2 (below)

$$\text{SPL}_{\text{FA}} = \text{SPL}_{\text{F}} + 2 + 20 \log \left\{[12200^2 \cdot \text{F}^4] \div [(\text{F}^2 + 20.6^2)\,(\text{F}^2 + 12200^2)\,(\text{F}^2 + 107.7^2)^{0.5}\,(\text{F}^2 + 737.9^2)^{0.5}]\right\}$$

The data that follow are presented first in tabular form and then in bar charts. Reiterating an important premise of this study, the absolute values of OASPL are of lesser interest than the differences between configurations, which are the measures of merit for deducing the effects of the test variables.

4.1 Effect of Boundary Layer Tripping

The graphs below are excerpts from Figure 10 through Figure 12 at 9 degrees effective angle of attack and tunnel speeds of 27 m/s, 50 m/s and 63 m/s (from left to right). One and 2 layers of trip tape clearly are not sufficient to suppress the aggressive noise mechanism, probably laminar boundary layer vortex shedding. As the tunnel speed (and Reynolds number) increases, the tones move to higher frequencies and it is likely that trailing edge noise becomes the dominant mechanism. Table 3 and Figure 32 indicate that at 27 m/s (Re = 170,000) with the boundary layer untripped, the blade has a sound pressure level 5.3 dBA greater than when it is heavily tripped. At 50 m/s (Re = 315,000) the effect still is pronounced and the increase is 4.2 dBA. Test data were not obtained at -1 degree and 5º degrees effective angles of attack, therefore all the details of this behavior cannot be deduced with confidence. However, it is not difficult to extrapolate from the wind tunnel data to the likely result when the wind turbine is in operation. Small wind turbines operating at low Reynolds numbers (as they do) are likely to exhibit considerable extraneous noise if aggressive boundary layer tripping is not affected. Indeed, this report's author has first-hand corroboration of this hypothesis from field tests of the Windward Engineering Endurance turbine and the Southwest Windpower Skystream turbine observed during developmental tests to optimize aerodynamic and aeroacoustic performance. In both cases, appropriate treatment of the blades resulted in substantial quieting of the wind turbines.

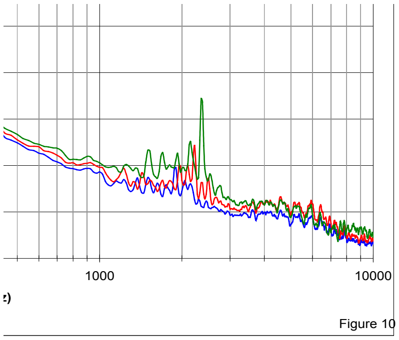


Figure 10

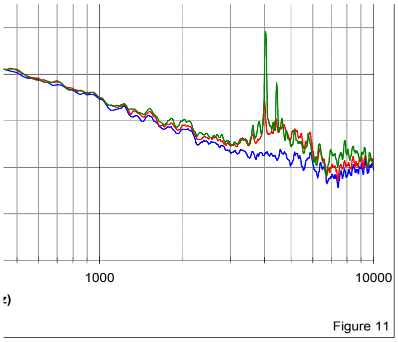


Figure 11

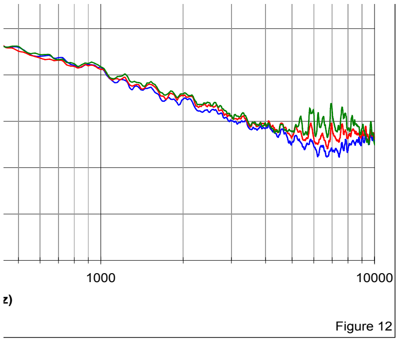


Figure 12

Table 3. Overall Sound Pressure Level (dBA) for Three Boundary Layer Trip Thicknesses

		Tunnel Speed		
	Alpha	**27**	**50**	**63**
One Layer (0.008")	**-1**			
	6			
	11	53.3	67.1	70.0

	V = 27 m/s		
	Alpha		
	-1	**6**	**11**
One Layer			53.3
Two Layers			49.8
Three Layers			48.0

		Tunnel Speed		
	Alpha	**27**	**50**	**63**
Two Layers (0.016")	**-1**			
	6			
	11	49.8	64.4	69.3

	V = 50 m/s		
	Alpha		
	-1	**6**	**11**
One Layer			67.1
Two Layers			64.4
Three Layers			62.9

		Tunnel Speed		
	Alpha	**27**	**50**	**63**
Three Layers (0.024")	**-1**			
	6			
	11	48.0	62.9	68.9

	V = 63 m/s		
	Alpha		
	-1	**6**	**11**
One Layer			70.0
Two Layers			69.3
Three Layers			68.9

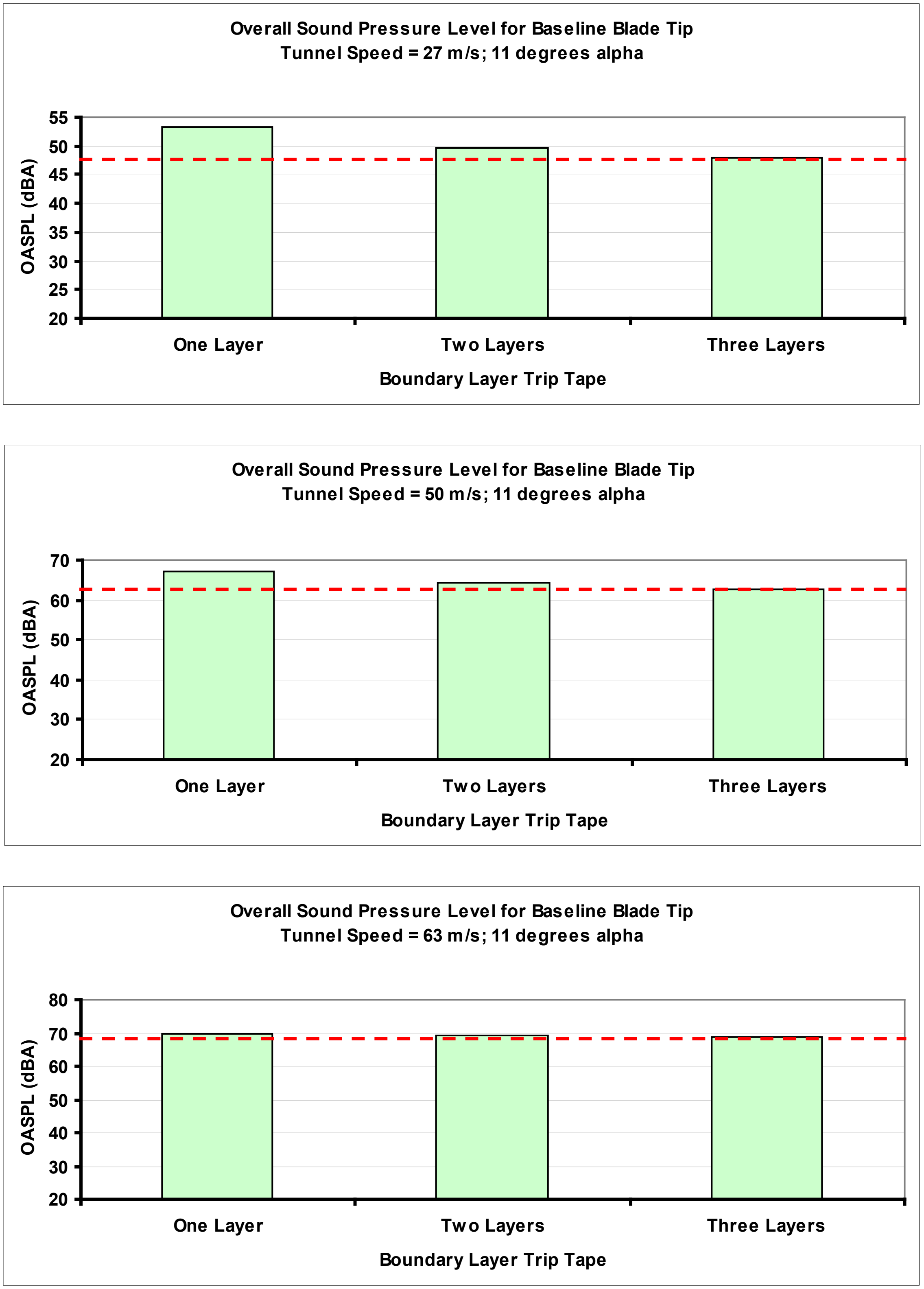


Figure 32. Overall sound pressure level (dBA) for three boundary layer trip thicknesses

4.2 Effect of Blade Tip Shape

Although it is important to understand the implications of boundary layer tripping (section 3.2, section 4.1) and trailing edge thickness (section 3.4, section 4.3), the greatest interest probably is regarding the effect of blade tip shape. Table 4 and Figure 33 summarize the test results.

Noticeable differences exist between blade and background (empty tunnel) noise. At 27 m/s the smallest and largest differences in OASPL are 1.9 dBA and 10.4 dBA, respectively. At 50 m/s, the smallest and largest differences in OASPL are 3.3 dBA and 6.2 dBA, respectively. At 63 m/s, the smallest and largest differences in OASPL are 3.1 dBA and 4.9 dBA, respectively. Thus, it seems reasonable to draw conclusions from the test data regarding the relative acoustic performance of the different tip shapes. It is interesting to note that at each tunnel speed the largest difference in OASPL occurred at an effective angle of attack of -1 degree. In this situation the blade is lightly loaded and acoustic sources other than trailing edge noise, such as laminar boundary layer vortex shedding and a blunt trailing edge, have an opportunity to dominate.

To draw useful conclusions regarding the efficacy of various blade tip shapes, it is necessary to consider the typical operating conditions for small wind turbines. Variable speed turbines attempt to operate at an angle of attack near the maximum lift-to-drag ratio. The angle of attack is determined by the tip speed ratio – the ratio of the blade tip speed to the wind speed. Logically, given a choice the designers would choose a blade tip shape that performed well (was quiet) at this operating point. For the test blade, that point is the effective angle of attack of 5 degrees (alpha = 6) and a tunnel speed of 50 m/s. Table 4 shows little difference among the 6 blade-tip shapes at that point, although PM-5 might as well be avoided. If the turbine is stall regulated, even if it is variable speed, then it might be worth looking at a representative operating point for that condition, which is the effective angle of attack of 9 degrees (alpha = 11) and a tunnel speed of 63 m/s. Again, there is nothing in the data to recommend a particular blade tip shape. If designers were to consider a turbine blade operating at low angles of attack and wind speeds, which might be the case for a fixed speed turbine near startup, then PM-2, PM-3 and PM-5 might as well be avoided.

It is possible to become mired in the small differences between several blade tip shapes that perform relatively well. The larger issue might be to avoid making a poor choice. At 50 m/s and an effective angle of attack of 5 degrees (alpha = 6) – a key operating point – there is a difference of 1.3 dBA between the best- and worst-performing blade tip shapes[‡]. It could be argued that this difference is too small to distinguish between PM-4 and PM-5, but it is also arguable that such a difference actually might exist between two competing shapes. At 27 m/s the difference is 3.8 dBA: this is a significant increment in the acoustic signature of a small wind turbine. The author interprets this result as implying that it is a worthwhile effort to conduct tests for the purpose of selecting a blade tip shape.

It is important to recognize that these observations regarding blade tip shape and its influence on acoustic emissions do not take aerodynamic performance into consideration. Both aerodynamic and aeroacoustic performance are of considerable importance in the design of wind turbines and it is extremely advantageous for designers to have reliable information on both topics before finalizing a rotor design.

[‡] The wind tunnel data are for only one blade. Most turbines employ three blades, and although a wind turbine rotor is not really a compact acoustic source, one could approximate the effect of three blades using Equation 3, in which $OASPL_3$ and $OASPL_1$ are the overall sound pressure level for three blades and one blade, respectively.

$$OASPL_3 = 10 \log \left[3 \cdot 10^{(OSPL_1/10)}\right] \qquad \text{Equation 3}$$

It can be shown from Equation 3 that regardless of the magnitude $OASPL_1$, tripling the number of sources increases the overall sound pressure level by 4.8 dBA.

Table 4. Overall Sound Pressure Level (dBA) for Six Blade Tip Shapes

		Tunnel Speed		
	Alpha	27	50	63
Empty Tunnel		44.9	59.3	65.3

		Tunnel Speed		
	Alpha	27	50	63
Baseline	-1	53.8	64.6	69.1
	6	50.4	62.8	68.7
	11	50.1	63.7	69.4

		Tunnel Speed		
	Alpha	27	50	63
PM-1	-1	53.8	63.6	69.0
	6	48.1	62.7	68.8
	11	48.5	63.3	69.6

		Tunnel Speed		
	Alpha	27	50	63
PM-2	-1	55.0	65.5	68.9
	6	49.9	62.7	68.5
	11	48.7	62.7	69.1

		Tunnel Speed		
	Alpha	27	50	63
PM-3	-1	54.5	63.8	68.5
	6	49.3	62.8	68.5
	11	46.8	63.0	68.9

		Tunnel Speed		
	Alpha	27	50	63
PM-4	-1	53.2	63.3	68.5
	6	48.9	62.6	68.4
	11	49.9	63.8	69.3

		Tunnel Speed		
	Alpha	27	50	63
PM-5	-1	55.3	65.1	70.2
	6	51.9	63.9	69.4
	11	49.5	64.3	69.7

	V = 27 m/s		
	Alpha		
	-1	6	11
Empty	44.9	44.9	44.9
Baseline	53.8	50.4	50.1
PM-1	53.8	48.1	48.5
PM-2	55.0	49.9	48.7
PM-3	54.5	49.3	46.8
PM-4	53.2	48.9	49.9
PM-5	55.3	51.9	49.5

	V = 50 m/s		
	Alpha		
	-1	6	11
Empty	59.3	59.3	59.3
Baseline	64.6	62.8	63.7
PM-1	63.6	62.7	63.3
PM-2	65.5	62.7	62.7
PM-3	63.8	62.8	63.0
PM-4	63.3	62.6	63.8
PM-5	65.1	63.9	64.3

	V = 63 m/s		
	Alpha		
	-1	6	11
Empty	65.3	65.3	65.3
Baseline	69.1	68.7	69.4
PM-1	69.0	68.8	69.6
PM-2	68.9	68.5	69.1
PM-3	68.5	68.5	68.9
PM-4	68.5	68.4	69.3
PM-5	70.2	69.4	69.7

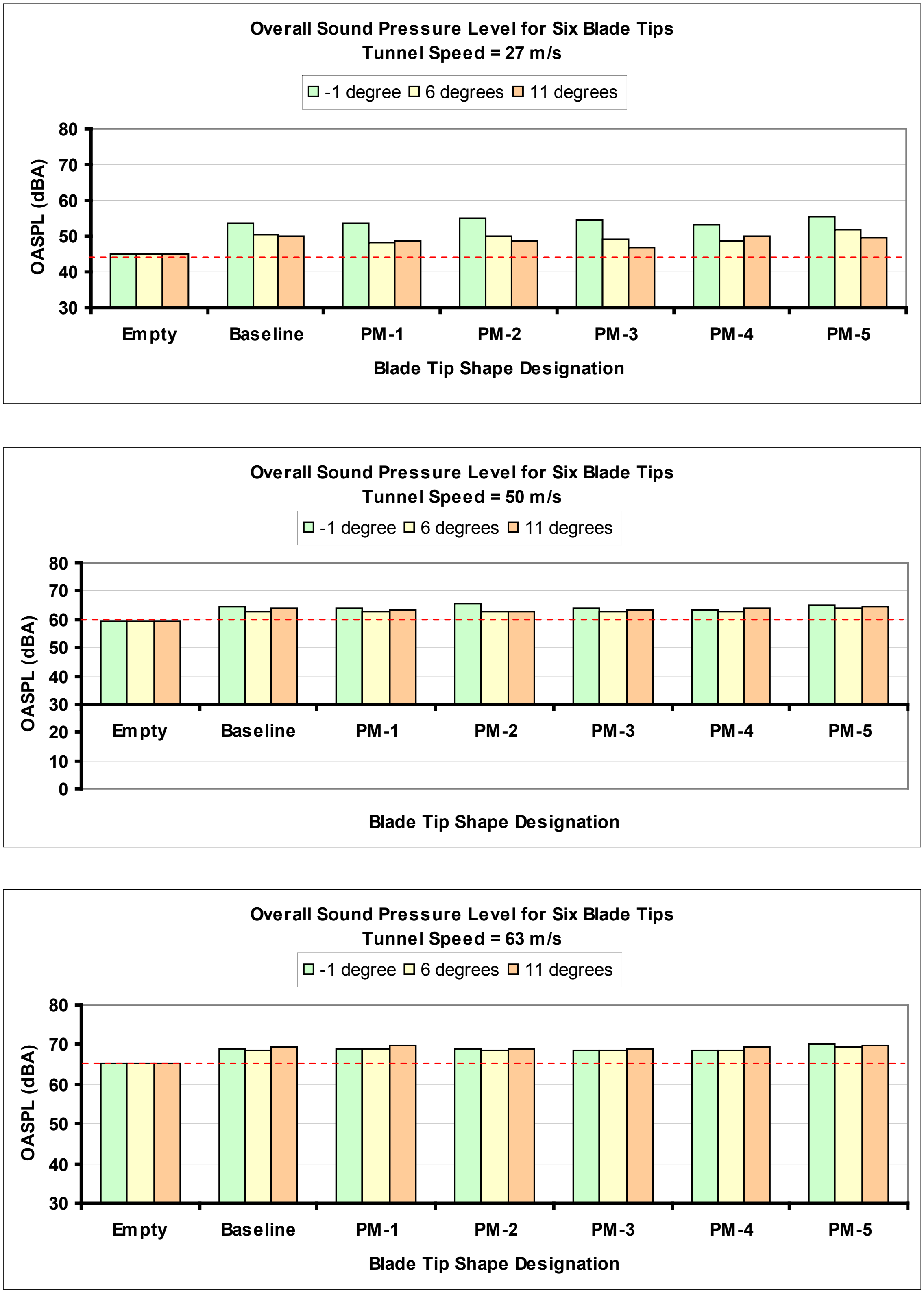
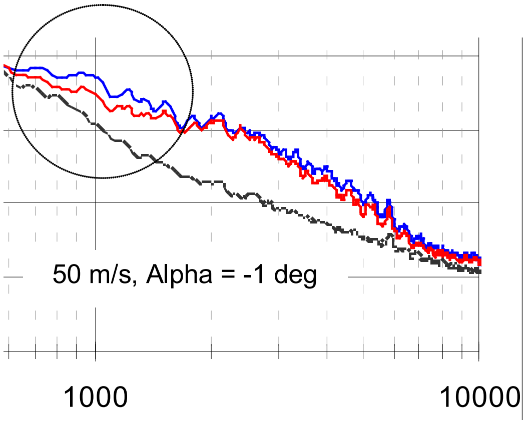


Figure 33. Overall sound pressure level (dBA) for six blade tip shapes

4.3 Effect of Trailing Edge Thickness

The spectra of Figures 22-30 show very little to distinguish between sharpened and unsharpened trailing edges. One exception seems to be the tunnel speed of 50 m/s and effective angle of attack of -1 degree shown in Figure 29, excerpted below (left). Table 5 indicates that the unsharpened blade has an OASPL 1.2 dBA greater than the sharpened blade. This is an unlikely operating condition for a wind turbine, perhaps corresponding to a sudden lull in wind speed. Considering the continually varying operating conditions, an increase in sound pressure level such as this is not likely to persist or be noticed against background noise. Another exception is at 27 m/s and an effective angle of attack of 9 degrees (alpha = 11 degrees) shown in Figure 22, excerpted below (right). Here the unsharpened blade has an OASPL 1.8 dBA greater than the sharpened blade. In this condition – hypothesizing substantially laminar flow on the forward portion of the airfoil, but with incipient separation – there could be some feedback interaction between the trailing edge and the vortices shed upstream. While these occasional, off-design conditions are not likely to cause noise issues, it seems prudent to sharpen blade trailing edges to the extent practical.



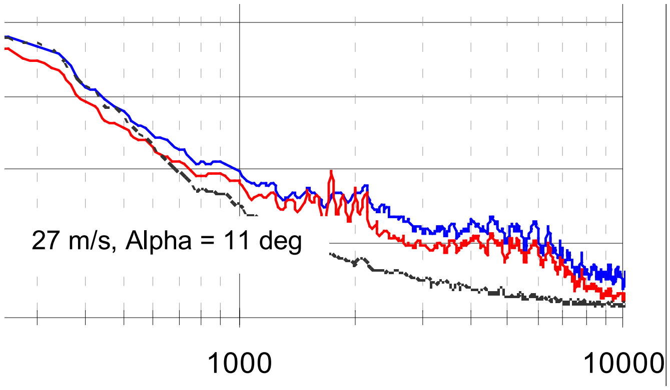


Table 5. Overall Sound Pressure Level (dBA) for Sharpened and Unsharpened Blades

		Tunnel Speed		
	Alpha	**27**	**50**	**63**
Empty Tunnel		44.9	59.3	65.3

	V = 27 m/s		
	Alpha		
	-1	**6**	**11**
Empty	44.9	44.9	44.9
Unsharpened	53.8	50.4	50.1
Sharpened	53.9	50.3	48.3

		Tunnel Speed		
	Alpha	**27**	**50**	**63**
Baseline Unsharpened	**-1**	53.8	64.6	69.1
	6	50.4	62.8	68.7
	11	50.1	63.7	69.4

	V = 50 m/s		
	Alpha		
	-1	**6**	**11**
Empty	59.3	59.3	59.3
Unsharpened	64.6	62.8	63.7
Sharpened	63.4	62.9	63.9

		Tunnel Speed		
	Alpha	**27**	**50**	**63**
Baseline Sharpened	**-1**	53.9	63.4	68.7
	6	50.3	62.9	68.7
	11	48.3	63.9	69.5

	V = 63 m/s		
	Alpha		
	-1	**6**	**11**
Empty	65.3	65.3	65.3
Unsharpened	69.1	68.7	69.4
Sharpened	68.7	68.7	69.5

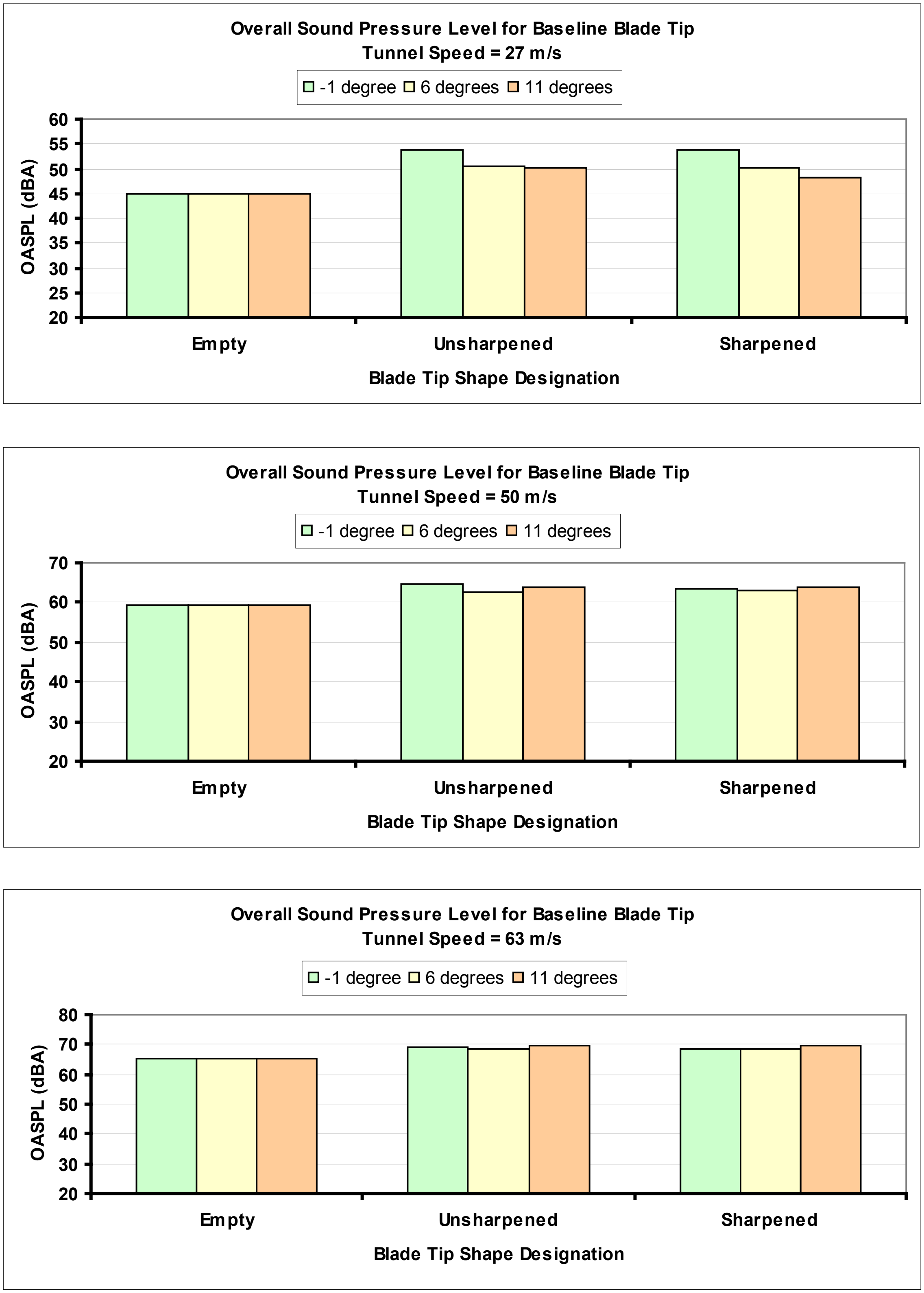


Figure 34. Overall sound pressure level (dBA) for sharpened and unsharpened blades

5.0 Summary and Conclusions

Wind tunnel aeroacoustic tests were conducted to investigate the effect of boundary layer tripping, tip shape and trailing edge thickness on the acoustic emissions of a small wind turbine blade. An actual blade from a prototype of Southwest Windpower's Skystream turbine was used, and the test matrix covered realistic operating conditions, including a Reynolds number range of 170,000 to 397,000. Preliminary measurements in the empty test section indicated that the background noise was sufficiently low to permit reasonable conclusions about relative differences between test configurations.

Measured results confirmed observations from previous wind tunnel and field tests regarding potential noise problems for small wind turbines operating at low Reynolds numbers. At certain tunnel speeds and blade angles of attack that are representative of actual operating conditions, significant pure tones and elevated broadband emissions were noticed. These are attributed to laminar boundary layer vortex shedding, which can be mitigated by aggressive boundary layer tripping. Extrapolating this result to real-world wind turbine designs, it can be concluded that blade leading edge trips are likely to be required to prevent annoying aeroacoustic noise. Field tests should be conducted to investigate this possibility.

Six blade tip shapes were tested, not to identify an optimum, but to establish the approximate difference that might exist between "good" and "bad" design choices. At low velocity (Reynolds number) and angle of attack, where subtle differences in geometry and flow conditions can be important, a 3.8 dBA difference in sound pressure level was measured between the best-and worst-performing tip shapes. At conditions representing more realistic operating conditions – near the airfoil's maximum lift-to-drag ratio – a 1.3 dBA difference was observed. Although conventional practice teaches not to ascribe excessive credence to differences of this magnitude, it is arguable, based on test results, that such differences very well could exist. Therefore, in the quest for very quiet wind turbine blades, the designer should carefully consider alternative tip shapes for an otherwise quiet blade.

The test blade with baseline tip shape was evaluated with two trailing edge thicknesses of 1.1% chord and 0.8% chord. The former is representative of deliberate attempts, constrained by manufacturing limitations, to achieve a thin trailing edge for the Storm and Skystream blades. At 1 of the 9 test conditions, the sharpened trailing edge resulted in a 1.2 dBA reduction in sound pressure level. At a second test condition, a difference of 1.8 dBA was observed. There were no noteworthy differences at the other test conditions. It is difficult to draw sweeping conclusions based on these limited test results; however, within the perspective of other data in the literature, it seems reasonable to conclude that minimizing trailing edge thickness is beneficial.

There are subtle but important differences between aeroacoustic testing in steady, low-turbulence rectilinear flow as opposed to the unsteady, turbulent, curvilinear flow of operating wind turbines. In the latter case, for example, the local velocity and angle of attack vary along the blade span and there can be important three-dimensional effects. Therefore, it is best to draw only general conclusions from the GTRI test results. Nevertheless, the data seem to support the conclusion that boundary layer tripping, tip shape and trailing edge thickness are worthy of consideration in attempting to design quiet blades for small wind turbines. Of similar import, but not considered here, is the tradeoff between aerodynamic noise and aerodynamic performance (energy capture).

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
02/02/2009

2. REPORT TYPE
Subcontract report

3. DATES COVERED *(From - To)*
6/1/2007 - 7/31/2008

4. TITLE AND SUBTITLE
The Potential for Reducing Blade-Tip Acoustic Emissions for Small Wind Turbines: June 1, 2007 – July 31, 2008

5a. CONTRACT NUMBER
DE-AC36-08-GO28308

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
P. Migliore

5d. PROJECT NUMBER
NREL/SR-500-43472

5e. TASK NUMBER
WER8.2101

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Paul Migliore, Engineering Research and Project Management
Arvada, Colorado

8. PERFORMING ORGANIZATION REPORT NUMBER
LAM7-77545-01

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER
NREL/SR-500-43472

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES
NREL Technical Monitor: Pat Moriarty

14. ABSTRACT *(Maximum 200 Words)*

This report describes the results of wind tunnel aeroacoustic tests conducted on a typical small wind turbine blade in the open-jet test section of the Georgia Tech Research Institute (GTRI) Anechoic Flight Simulation Facility.

15. SUBJECT TERMS
wind turbine blade aeroacoustic tests; Georgia Tech Research Institute; wind energy; wind turbine blade design

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	UL		

19b. TELEPHONE NUMBER (*Include area code*)

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18