HELICOPTER ROTOR NOISE INVESTIGATION DURING ICE ACCRETION

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ABSTRACT

An investigation of helicopter rotor noise during ice accretion is conducted using experimental, theoretical, and numerical methods. This research is the acoustic part of a joint helicopter rotor icing physics, modeling, and detection project at The Pennsylvania State University Vertical Lift Research Center of Excellence (VLRCOE). The current research aims to provide acoustic insight and understanding of the rotor icing physics and investigate the feasibility of detecting rotor icing through noise measurements, especially at the early stage of ice accretion. All helicopter main rotor noise source mechanisms and their change during ice accretion are discussed. Changes of the thickness noise, steady loading noise, and especially the turbulent boundary layer – trailing edge (TBL-TE) noise due to ice accretion are identified and studied.

The change of the discrete frequency noise (thickness noise and steady loading noise) due to ice accretion is calculated by using PSU-WOPWOP, an advanced rotorcraft acoustic prediction code. The change is noticeable, but too small to be used in icing detection. The small thickness noise change is due to the small volume of the accreted ice compared to that of the entire blade, although a large iced airfoil shape is used. For the loading noise calculation, two simplified methods are used to generate the loading on the rotor blades, which is the input for the loading noise calculation: 1) compact loading from blade element momentum theory, icing effects are considered by increasing the drag coefficient; and 2) pressure loading from the 2-D CFD simulation, icing effects are considered by using the iced airfoil shape.

Comprehensive rotor broadband noise measurements are carried out on rotor blades with different roughness sizes and rotation speeds in two facilities: the Adverse Environment Rotor Test Stand (AERTS) facility at The Pennsylvania State University, and The University of Maryland Acoustic Chamber (UMAC). In both facilities the measured high-frequency broadband
noise increases significantly with increasing surface roughness heights, which indicates that it is feasible to quantify helicopter rotor ice-induced surface roughness through acoustic measurements. Comprehensive broadband noise measurements based on different accreted ice roughness at AERTS are then used to form the data base from which a correlation between the ice-induced surface roughness and the broadband noise level is developed. Two parameters, the arithmetic average roughness height, $R_a$, and the averaged roughness height, based on the integrated ice thickness at the blade tip, are introduced to describe the ice-induced surface roughness at the early stage of the ice accretion. The ice roughness measurements are correlated to the measured broadband noise level. Strong correlations (absolute mean deviations of 9.3% and 11.2% for correlation using $R_a$ and the averaged roughness height respectively) between the ice roughness and the broadband noise level are obtained, which can be used as a tool to determine the accreted ice roughness in the AERTS facility through acoustic measurement. It might be possible to use a similar approach to develop an early ice accretion detection tool for helicopters, as well as to quantify the ice-induced roughness at the early stage of rotor ice accretion.

Rotor broadband noise source identification is conducted and the broadband noise related to ice accretion is argued to be turbulent boundary layer – trailing edge (TBL-TE) noise. Theory suggests TBL-TE noise scales with Mach number to the fifth power, which is also observed in the experimental data. The trailing edge noise theories developed by Ffowcs Williams and Hall, and Howe both identify two important parameters: boundary layer thickness and turbulence intensity. Numerical studies of 2-D airfoils with different ice-induced surface roughness heights are conducted to investigate the extent that surface roughness impacts the boundary layer thickness and turbulence intensity (and ultimately the TBL-TE noise). The results show that boundary layer thickness and turbulence intensity at the trailing edge increase with the increased roughness height. Using Howe’s trailing edge noise model, the increased sound pressure level (SPL) of the
trailing edge noise due to the increased displacement thickness and normalized integrated turbulence intensity are 6.2 dB and 1.6 dB for large and small accreted ice roughness heights, respectively. The estimated increased SPL values agree well with the experimental results, which are 5.8 dB and 2.6 dB for large and small roughness height, respectively.

Finally a detailed broadband noise spectral scaling for all measured broadband noise in both AERTS and UMAC facilities is conducted. The magnitude and the frequency spectrum of the measured broadband noise are scaled on characteristic velocity and length. The peak of the laminar boundary layer – vortex shedding (LBL-VS) noise coalesces well on the Strouhal scaling in those cases. For the measured broadband noise from a rotor with relatively large roughness heights, no contribution of the LBL-VS noise is observed. The velocity scaling shows that the TBL-TE noise, which is the dominant source mechanism, scales with Mach number to the fifth power based on the absolute frequency. The length scaling shows that the TBL-TE noise scales well on the absolute roughness height based on Howe’s TE noise theory.
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Chapter 1

Introduction

1.1 Helicopter icing problem

Icing is one of the common problems that jeopardize the flight safety of aircraft, especially for helicopters. Rotor systems are more likely to be affected by icing due to their comprehensive mission requirements, such as helicopters working at high mountainous areas that are dominated by low temperatures and high liquid water content. A Royal Canadian Mounted Police (RCMP) helicopter taking off from a severe “icing environment” is shown in Fig. 1-1 [1]. Unfortunately this is its final take-off before it completely lost the power and crashed due to the icing. Such environments with low temperatures and high liquid water content as shown in Fig. 1-1 is not uncommon to police and rescue helicopters.

Figure 1-1. RCMP helicopter final take-off in a severe “icing environment” [1].
In addition to that fact, only 5% of U.S. rotorcraft are equipped with an ice protection system (IPS), most of which are military helicopters, due to economical drawbacks related to power consumption and manufacturing complexity [2]. For helicopters without IPS, the general rule is to avoid flying in such icing conditions to eliminate the possibility of icing related accidents. As a result, early ice detection has become critically important for helicopter safety and efficiency. It is essential for any helicopter to have the ability to sense the ice forming so that the pilot can fly the aircraft out of the “icing environment”, or the de-icing system, if equipped, can be actuated in a timely manner.

1.1.1 Helicopter icing classification

Helicopter icing usually consists of three categories, in the following order of importance [1]:

- Rotor system icing
- Engine icing
- Airframe icing

Rotor system icing includes rotor blade icing and rotor control system icing (hub, pitch link, etc.). Engine icing refers to the ice produced on an engine throat near the first compressor stage. This sort of icing is not a serious problem since there is sufficient heat available from hot air bleeds and hot oil to heat the throat area, except when the ice is ingested by high performance turbines, in which case the engine flame can be put out by a sudden mass of slush, even as small as 350cc water equivalent [2,3]. Airframe icing mainly concerns the profile drag increase due to fuselage ice accretion, windscreen icing, and the failure of sensors and detectors mounted outside the fuselage. In this study, the focus is only placed on rotor blade icing. Rotor control system icing, engine icing, and airframe icing are not addressed because they are not high priorities in helicopter icing research.
1.1.2 Performance degradation

When ice starts to accrete on the rotating blades of a helicopter (mostly on the leading edge [2]), penalties such as increased drag and decreased lift occur [4-6]. This degradation is mainly caused by the increased surface roughness on rotor blades which leads to a premature flow separation and a stall at low angle of attack (AOA). Obviously, in such circumstances, more power from the engine is demanded to maintain the rotor RPM, which is shown by an increase in torque (about 20%) [2]. In addition, the unevenly shaped and distributed ice can cause extra vibrations due to mass imbalance [7, 8]. The deterioration of the performance of rotor blades during ice accretion may also endanger the emergency landing capabilities of a helicopter [2]. A 20% torque increase would require higher descent speeds in autorotation.

Ice shedding is another problem during ice accretion on rotor blades. The shear stresses created by centrifugal forces at the interface between the ice and the leading edge of the airfoil increases linearly with ice thickness [9]. When ice accretes to the extent that the increasing shear stresses exceed the adhesive shear strength, ice shedding will happen, which can cause a rotating imbalance, resulting in severe vibration and control difficulties. Detached ice can even cause serious damage if it is ingested in the engine or tail rotor.

1.1.3 The importance of surface roughness

As droplets impact a blade surface, surface roughness is created as the droplets form water beads or rivulets on the surface. At the onset of ice accretion on an airfoil, the surface roughness could vary significantly as a function of liquid water content (LWC), water droplet median volume diameter (MVD), impact velocity \( V \), and temperature \( T \) [3, 10, 11]. Typical surface roughness introduced by ice on an airfoil at different icing time is shown in Fig. 1-2. It is
well known that the presence of the surface roughness would strongly affect the flow behavior – boundary layer growth and the boundary layer transition [12-15]. Consequently penalties such as drag increase, premature flow separation, and early stall at low angle of attack would occur. Another important effect of surface roughness is it significantly changes the associated surface energy exchange – surface heat transfer [16-18], which would affect the final airfoil ice shape.

Figure 1-2. Ice-induced surface roughness at 15, 30, and 50 second [10]. Icing condition: \( T = -15.2 ^\circ C, V = 77\ m/s, MVD = 200\mu m, LWC = 0.75\ g/m^3\).

A comprehensive understanding of the ice-induced roughness growth and distribution and its effects on airfoil flow characteristics, heat transfer, and ice accretion shape is critical for the study of the helicopter icing physics. However, surface roughness effects on both airfoil aerodynamic performance degradation and heat transfer coefficients are not well understood and require further investigation.
1.2 Helicopter rotor noise during ice accretion

At the onset of helicopter icing, the change of the flow behavior and the change of the blade airfoil shape is likely to affect the helicopter main rotor noise. However, there are almost no studies of helicopter noise during ice accretion found in published literature. Different helicopter main rotor noise source mechanisms and their potential change during ice accretion are introduced in this section. The investigation of helicopter noise during ice accretion is thought to be able to aid the understanding of the helicopter icing physics and to provide a potential new ice detection method through noise measurements.

Helicopter main rotor noise contains both discrete frequency and broadband noise components. The discrete frequency noise is composed of the deterministic components of thickness, loading, and high-speed impulsive (HSI) noise. Broadband noise consists of the non-deterministic loading noise sources classified as turbulence ingestion noise, blade wake interaction (BWI) noise and blade self-noise [19, 20].

1.2.1 Discrete frequency noise

Thickness noise is generated from the fluid displacement caused by rotating blades. It is governed by the rotor speed and the airfoil thickness distribution [21]. Consequently, in the thickness noise prediction, the main contribution is from the blade tip region due to the high tip velocity. The radiated direction of thickness noise is primarily along the rotor disk plane in front of the rotor as shown in Fig. 1-3, which illustrates the directivity of different helicopter main rotor noise sources. During ice accretion, blade thickness, especially at the leading edge may change dramatically due to the accreted ice, so thickness noise change due to ice accretion is expected.
The lower frequency harmonic noise from non-impulsive loading sources is normally defined as helicopter “loading noise” [19]. The impulsive loading noise due to blade-vortex interaction (BVI) and the non-deterministic loading associated with the broadband noise are treated separately. Loading noise is caused by the accelerating force on the fluid generated by moving blade surface [19], which usually propagates below the rotor disk (Fig. 1-3). Loading noise usually is the dominant source of rotor noise and has been a major concern for helicopter civil operation due to its magnitude and directivity. As previously introduced, drag increase and lift decrease would occur when ice starts to accrete on blades, which leads to a change of force on the fluid. Loading noise, consequently, should be changed by the ice accretion.

Blade Vortex-Interaction (BVI) noise is a specific type of loading noise that is due to a shed tip vortex interacting with the following blades [22, 23]. Such interaction induces a very rapid fluctuation in aerodynamic force on the airfoil resulting in the generation of BVI noise. BVI noise has been identified as the most annoying noise source for residential communities [22]. However, noticeable change of BVI noise during ice accretion is not expected due to the limited effect of icing on blade tip vortex shedding, so it is not included in this study.

High-speed impulsive (HSI) noise is generated during high-speed forward flight due to the compressibility effect in the transonic flow range [24]. It is an intense and annoying noise source and usually propagates along the rotor disk plane in a direction similar to thickness noise (Fig. 1-3). HSI noise is a significant noise source when it occurs, but HSI noise only occurs on the advancing side of the rotor in high-speed flight conditions which may not exist or change much during ice accretion. Furthermore, when ice has accreted on the blades the power required increases and the helicopter may not have the power to travel at high speeds. Therefore, HSI noise is not considered in this study either.
1.2.2 Broadband Noise

In the helicopter main rotor noise spectrum, the mid to high frequency range is dominated by broadband noise, which is generated by a wide range of mechanisms. Generally broadband noise can be divided into following sources:

1. Turbulence ingestion noise
2. Blade wake interaction (BWI) noise
3. Blade self-noise

Turbulence ingestion noise is due to the rotor disk ingestion of atmospheric and recirculated wake turbulence [25, 26] and is important for hover and low speed flight [27]. Turbulence ingestion noise can exceed the noise from other sources when helicopter is operating in gusty or unstable atmospheric conditions due to the ingestion of atmospheric turbulence [27]. BWI noise is a broadband noise due to the interaction of the rotor blades with the turbulent portion of the wakes of previous blades [28]. It occurs in level flight to mild climb conditions,
and is mid-frequency broadband noise [27]. These two broadband noise sources are not considered in this study because they are not thought to be relevant to the icing problem. A broadband noise source mechanism identification in Chapter 4 will present more details why the turbulence ingestion noise and the BWI noise are not affected by icing.

The blade self-noise is produced by the interaction between a blade and the turbulence generated in its own boundary layer and near wake. It is the only source of broadband noise due to the blade that encounters uniform and steady inflow. It is greatest during mild to steep climb conditions, and is a source of high-frequency broadband noise. According to the comprehensive research work on blade self-noise done by Brooks et al. [27, 29-32], five self-noise mechanisms due to specific boundary layer phenomena are identified, as shown in Fig. 1-4: 1) turbulent boundary layer-trailing edge (TBL-TE) noise, 2) separation-stall noise, 3) laminar boundary layer-vortex shedding (LBL-VS) noise, 4) trailing edge bluntness-vortex shedding noise, and 5) blade tip formation noise.
Figure 1-4. Illustration of flow conditions producing blade self-noise [29].

The TBL-TE noise is produced at high Reynolds numbers, when the turbulence in the turbulent boundary layer passes over the trailing edge. It is well known that the existence of surface roughness (on a wall or an airfoil) will affect the boundary layer growth and the turbulence generated, which would then affect the TBL-TE noise for an airfoil case. Many research efforts have been conducted to measure and predict rough wall boundary layer flows and pressure fluctuations [33-35], as well as the rough wall noise [36-40]. Devenport and coworkers [38-40] demonstrated that surface pressure fluctuations due to surface roughness relate directly to far-field noise generation. They also developed a correlation between the far-field noise generated by a boundary layer over a rough surface and the surface pressure wavenumber spectrum and the roughness geometry. Consequently the relationship between surface roughness, and the resulting turbulence, is expected to strongly affect the TBL-TE noise. The investigation of trailing edge
noise due to ice-induced surface roughness is a main research topic of this study. Because at the early stage of the ice accretion, the “ice” essentially changes the surface roughness rather than forming an ice shape with a significant amount of ice, it is critical to understand how the TBL-TE noise changes with different ice-induced surface roughness for developing an early icing detection tool through acoustic measurements. A detailed trailing edge noise theory and research review is presented in the next sub-section.

The separation-stall noise is caused by the shed turbulent vorticity when separation happens near the trailing edge (small AOA), or radiated by the large-scale separation at high AOA [29]. The importance of airfoil stall noise was demonstrated by Fink and Bailey [41] in airframe noise where more than a 10 dB noise increase would be perceived during stall. It is obvious that separation-stall noise would be affected by the ice accretion since phenomena such as premature flow separation and stall in low AOA would always happen during ice accretion. However the separation-stall noise is not thought to exist at the early stage of the ice accretion which is the main focus of the current study. So it will not be discussed further.

The LBL-VS noise is generated at low Reynolds numbers, when a laminar boundary layer extends to the trailing edge. Instabilities from the laminar boundary layer cause separation bubbles which may then form a vortex that interacts with the trailing edge [43]. The LBL-VS noise is tonal in nature and the exact frequency of the tone is a function of the chord length and flow velocity over the airfoil [29]. For a clean rotor, from which the broadband noise result will be used to compare with that from the iced rotor, the LBL-VS noise would exist in most operating conditions. In addition, at the very beginning of the ice accretion, the ice-induced surface roughness may not fully trip the airfoil boundary layer from a laminar boundary to a turbulent boundary layer. The LBL-VS noise is expected to exist during the early stage of ice accretion. Consequently, the LBL-VS will be investigated in the current study.
The trailing edge bluntness-vortex shedding noise is another type of TE noise, which is due to the vortex shedding from blunt trailing edges. Obviously the trailing edge bluntness-vortex shedding noise is highly related the airfoil TE thickness. However, the accreted ice normally grows along the leading edge, which would not affect the TE thickness. So the trailing edge bluntness-vortex shedding noise is not thought to be affected by ice accretion and won’t be considered in this study.

The tip vortex formation noise is generated from the turbulence in the locally separated flow region at the tip of a lifting blade, where the tip vortex is formed as shown in Fig. 1-4. Brooks et al. [29] considered this mechanism for noise production to be TE noise due to the passage of the turbulence over the TE of the tip region. However, the blade tip region is not thought to be changed much by the accreted ice, especially at the early stage of the ice accretion. The tip vortex formation noise will not be addressed in this study either, as it is not thought to be directly relevant to the effects of ice accretion.

1.3 Trailing edge noise

As discussed in the previous section, the TBL-TE noise is thought to be affected by the ice accretion due to the influence of ice-induced surface roughness on the rotor blade boundary layer. An introduction to trailing edge noise and a literature review are presented in this section.

Trailing edge (TE) noise is considered to be a major noise source mechanism in many engineering applications such as aircraft [44], submarines [45] and wind turbines [46]. There are two types of TE noise [43]: 1) Blunt TE noise due to the bluntness of the airfoil TE; 2) TBL-TE noise due to turbulence within the boundary layer interacting with the TE. Both are illustrated in Fig. 1-5. The turbulent eddies developed along the airfoil are intensified by the sharp TE
(acoustic impedance discontinuity) which converts (through scattering by the sharp trailing edge) the turbulent energy into acoustic energy in a more efficient manner than turbulent eddies directly. When the dimensions of the airfoil (chord $C$) are large compared with the radiated acoustic wavelength ($\lambda$), the TE will diffract turbulence induced quadrupole noise. In this case, the intensified radiated noise scales with the fifth power of the Mach number $M^5$; when the airfoil dimensions are small compared with the radiated acoustic wavelength ($C \ll \lambda$), the radiated sound is of dipole character with strength proportional to the fluctuating total force amplitude. This type of noise amplitude scales with $M^6$. [47, 48].

Figure 1-5. Two types of TE noise: Blunt TE noise and TBL-TE noise [43].

From the theoretical side, the prediction of TE noise has always been a challenge due to the complexity of the noise source mechanisms, which are associated with turbulent fluid flow and its interaction with a TE. As summarized by Doolan [48], a schematic “road map” that shows different methods for the prediction of TE noise is shown in Fig. 1-6. TE noise prediction has been classified into three categories: empirical, direct and hybrid methods.
Three or four decades ago, engineers were limited by computational capability, and relied upon empirical models developed from experimental measurements. Depending upon the information used in the empirical model to predict the TE noise, there are two empirical methods: the boundary layer method and the surface pressure formulation [48]. The most well-known empirical model based on boundary layer properties was developed by Brooks, Pope and Marcolini [29], known as the BPM model. Good comparisons between the predicted TE noise and the experimental results have been achieved for a model rotor [27]. The BPM model has also been widely used in wind turbine noise predictions. The NAFNoise [52] code developed by the National Renewable Energy Laboratory (NREL) incorporated a boundary layer properties prediction tool XFOIL [53] into the solution algorithm of the BPM model to obtain more accurate boundary layer properties that are used as inputs into the noise prediction empirical formulae. Another more straightforward TE noise empirical model was developed by Schlinker and Amiet [54] before the BPM model was available. For the boundary layer method, boundary layer properties such as the boundary layer thickness and Reynolds number are the only inputs needed.
for these boundary layer empirical models which makes these boundary layer models convenient to use.

Another empirical method for TE noise predicting is based on the measurement of the surface pressure fluctuations. The peak radiated sound spectrum can be estimated by [55],

$$
\Phi_{p,rad}(r, \omega)_{\text{PEAK}} \approx \frac{1}{2\pi} M_c \frac{s \Lambda^2_3}{r^2} \phi_{pp}(x, k_3, \omega)
$$

(1.3)

where $M_c$ is the average convective Mach number of turbulence past the TE, $\Lambda_3$ is the spanwise turbulent length scale, $\omega$ is the radial frequency, $\phi_{pp}$ is the transverse surface pressure fluctuation spectrum, with a spatial Fourier decomposition across the span (into wavenumbers, $k_3$) and across time (into frequencies, $\omega = 2\pi f$). Good noise predictions were achieved by Brooks and Hodgson [31] using data obtained from simultaneous noise and surface pressure measurements. A better agreement between theory and experiment was obtained by Casper and Farassat [55] using the Formulation 1-B surface pressure formulation technique. However as these methods are empirical, they are limited to the range of experimental parameters that was used to developed them. For example, the only airfoil geometry is NACA0012, Reynolds number ranges from $4 \times 10^4$ to $3 \times 10^6$, and the blade has no spanwise variation, etc.

The direct method of TE noise prediction refers to the direct numerical simulation (DNS) or the compressible large eddy simulation (LES), which calculates the properties of the noise source and propagates acoustic disturbances to the far-field in a single simulation. Although computational power has been dramatically increasing, the computation time of the direct method is still too large to be used practically. There are limited applications of the direct method to TE noise in the literature. Sandberg et al. [56, 57] are the very first researchers that performed the DNS of noise generated at an infinitely thin TE. Due to the extreme computational cost required to simulate the turbulence in the boundary layer, as well as resolve the noise propagation, the
direct approach will not be used routinely in the foreseeable future, especially for high Reynolds number TE noise studies.

Currently, the most popular way to compute the TE noise is the hybrid method, which splits the noise prediction into a turbulence part to calculate the Reynolds stresses, and a noise propagation part that uses results from the turbulence part as noise source terms. A good example of the hybrid CAA approach to TE noise prediction is the work of Wang and Moin [58]. An incompressible LES simulation is used to solve for the airfoil turbulent flow. The incompressible flow assumes infinite sound speed in the fluid so there is no coupling between the acoustic pressure and the hydrodynamic pressure. The noise radiation is then calculated based on the Ffowcs Williams Hall’s analogy. An example of the predicted TE noise spectrum is shown in Fig. 1-7. Different methodologies can be used for simulating the unsteady flow such as RANS (with synthetized turbulence) [59], compressible DNS/LES [60], and incompressible DNS/LES used by Wang [58]. At the same time a variety of acoustic solution methodologies are available, such as the acoustic analogy, linearized Euler equations (LEE) [85], etc. Different combinations provide various hybrid noise prediction methods. They are discussed more completely by Doolan [48] and Colonius [59].
Figure 1-7. Normalized spectrum of the radiated noise predicted using LES-acoustic analogy hybrid by Wang and Moin [58]. Solid curve: Noise prediction; Shaded area: Experimental data of Blake [47].

Despite the prevalence of TE noise in engineering applications, little conclusive information about the 2D airfoil or 3D blade TE noise due to icing/roughness is found in published literature. The most relevant study was performed by Brooks et al. [29]. In their study, a boundary layer tripping technique was applied to ensure a fully developed turbulent boundary layer at the TE during the investigation of TBL-TE noise. Such a tripping technique (applying a strip on the airfoil from the leading edge to 20% chord with a random distribution of grit) is very similar to the ice-accreted roughness (actual or simulated) considered in the present work. The typical measured noise spectrum from both tripped and untripped airfoils are shown in Fig. 1-8. The spectral difference, both the magnitude and the shape, indicates that the tripping, which is essentially a result of the surface roughness, has a strong effect on the broadband noise. However, the effect of the grit size on noise was not discussed by Brooks et al., as only one grit size was used for the tripping of most of the airfoils. Different surface roughness height during various icing time is expected to results in different TBL-TE noise.
1.4 Research objectives

Compared to its fixed-wing counterparts, helicopter rotor ice accretion is not well understood due to complexities in the 3-D environment with inherent unsteady and rotational flow. Two phase flows (water and air) interacting with a rotating blade have yet to be examined from a physical standpoint and this is needed to develop accurate models. To address these issues, a helicopter icing physics, modeling and detection project was proposed at The Pennsylvania State University Vertical Lift Research Center of Excellence (VLRCOE). The main objective is to gain a fundamental understanding of ice accretion on helicopter rotor blades. Three research...
groups – experimental, computational fluid dynamics (CFD), and acoustics have been working together.

The present work is the acoustic part of this joint helicopter icing physics, modeling, and detection project. The objectives of the present work are as follows:

1) To study how different rotor noise source mechanisms, for example, thickness noise, steady loading noise, and broadband noise, change due to ice accretion experimentally and computationally and to understand the relationship between ice-induced surface roughness, accreted ice shape, and the resulting rotor noise.

2) To determine if different rotor noise source mechanisms can be used to detect the formation and location of accreted ice, especially at the early stage of ice accretion when the “ice” essentially changes the surface roughness of the lifting surface. The reason to focus the investigation of rotor noise at an early stage of the ice accretion is because when a significant amount of ice accretes on the blade, acoustic detection of the ice is probably unnecessary, a significant performance degradation would be apparent. Such a condition is shown in Fig. 1-9, which is an example of a helicopter rotor icing feature generated at The Pennsylvania State University Adverse Environment Rotor Test Stand (AERTS) facility after a long exposure time (4.1 min) within the icing cloud [62].

3) To correlate the rotor noise to the ice-induced surface roughness height and to develop a tool to predict the roughness height from giving rotor noise based on such a correlation.

4) To identify the rotor broadband noise source related to the ice-induced surface roughness and to physically understand the cause of broadband noise change due to ice accretion.
1.5 Thesis outline

The dissertation is organized into the following chapters:

**Chapter 2: Rotor Discrete Frequency Noise during Ice Accretion**

The thickness noise and the steady loading noise are calculated for a hovering rotor during ice accretion. The blade loading due to ice accretion is accounted by using two simplified methods: 1) Increased airfoil drag coefficient; 2) 2-D CFD simulation. Comparisons are made with the noise of clean rotors to study how the thickness and the steady loading noise are changed by the accreted ice.

**Chapter 3: Rotor Broadband Noise during Ice Accretion – Experimental Setup**

Broadband noise during ice accretion is then investigated. Chapter 3 presents the experimental setup of the broadband noise experimental study in two facilities: 1) Adverse Environment Rotor Test Stand (AERTS) at The Pennsylvania State University; and 2) University of Maryland Acoustic Chamber (UMAC).
Chapter 4: Rotor broadband noise theoretical investigation

In this chapter, the comprehensive measured broadband noise results are presented. In both facilities the measured high-frequency broadband noise increases significantly with increasing surface roughness heights. Rotor broadband noise source identification is conducted and the broadband noise related to ice accretion is thought to be the TBL-TE noise. Theory suggests TBL-TE noise scales with Mach number to the fifth power, which is also observed in the experimental data – confirming that the dominant broadband noise mechanism during ice accretion is likely TE noise.

Two parameters, the arithmetic average roughness height, $R_a$, and the averaged roughness height, based on the integrated ice thickness at the blade tip, are introduced to describe the ice-induced surface roughness at the early stage of the ice accretion. The ice roughness measurements are correlated to the measured broadband noise level. Strong correlations between the ice roughness and the broadband noise level are obtained, which can be used as an early ice accretion detection tool for helicopters, as well as to quantify the ice-induced roughness at the early stage of rotor ice accretion.

Chapter 5: Trailing Edge Noise Numerical Investigation

The TE noise theories developed by Ffowcs Williams and Hall, and Howe, both identify two important parameters: boundary layer thickness and turbulence intensity. Numerical studies of 2-D airfoils with different ice-induced surface roughness heights are conducted to investigate the extent that surface roughness impacts the boundary layer thickness and turbulence intensity (and ultimately the TBL-TE noise). The results show that boundary layer thickness and turbulence intensity at the TE increase with the increasing roughness height. Using Howe’s TE noise model, the increased sound pressure level (SPL) of the TE noise due to the increased displacement thickness and normalized integrated turbulence intensity are 6.2 dB and 1.6 dB for large and small accreted ice roughness heights, respectively. The estimated increased SPL values
agree well with the experimental results, which are 5.8 dB and 2.6 dB for large and small roughness height, respectively.

Finally, detailed broadband noise spectral scaling for all measured broadband noise in both AERTS and UMAC facilities is reported.

Chapter 6: Conclusions

Concluding remarks of the study are given and significant original contributions are highlighted.
Chapter 2

Rotor Discrete Frequency Noise during Ice Accretion

As introduced in Chapter 1, the discrete frequency noise (thickness and steady loading noise) is expected to be changed by the accreted ice. In this chapter, the thickness noise and the steady loading noise calculations are performed for rotors during ice accretion. Comparisons are made with the noise of clean rotors to study how the discrete frequency noise is changed by the accreted ice.

2.1 Thickness noise

Thickness noise is generated from the fluid displacement caused by rotating blades. It is governed by the rotor speed and the airfoil thickness distribution [21]. Consequently, in the thickness noise prediction, the main contribution is from the blade tip region due to the high tip velocity. During ice accretion, blade thickness at the leading edge, especially near the blade tip where the flow velocity is high, may change dramatically, so a thickness noise change due to ice accretion is expected.

The iced airfoil used in the calculation of thickness noise is measured under the following icing conditions [62]: temperature -8.2°C; median volume diameter of the water droplets (MVD) 27 micron; liquid water content of the icing cloud (LWC) 0.96 g/m³; ice exposure time 4.2 min, RPM 417, blade tip velocity 56.9 m/s. The clean airfoil has the shape of NACA0012. Both clean and iced airfoils are shown in Fig. 2-1. The airfoil shapes are used on a hovering rotor with four 8m blades for the noise prediction. For simplicity, no blade twist is used and the rotational speed is 30 rad/s. The rotor noise is calculated by using PSU-WOPWOP [63], an advanced rotorcraft
acoustic prediction code. The observer is in the rotor plane, 10 radii away from the rotor hub. This location (in the rotor plane) is where thickness noise is expected to be maximum.

![Airfoil Diagram]

(a) clean airfoil

(b) iced airfoil

Figure 2-1. Airfoil used in thickness noise calculation.

A comparison of thickness noise acoustic pressure time histories, as shown in Fig. 2-2, shows that the thickness noise does not change significantly during ice accretion (Fig. 2-1). The small extent of thickness noise change is because the volume of the actual ice accretion is very small compared to that of the blade, even though for this case the amount of the accreted ice is considered to be large. The airfoil thickness is not changed enough by the ice accretion to noticeably affect the rotor thickness noise.
2.2 Steady loading noise

When ice starts to accrete on blades, drag increases and lift is likely to decrease. Consequently loading noise, caused by the accelerating force on the fluid generated by the moving blade surface [19], would be changed by the ice accretion. Due to the lack of rotor loading input data during ice accretion, the exact steady loading noise due to ice accretion cannot be calculated. In this study, two types of simple loading are used to qualitatively estimate the steady loading noise change during ice accretion: 1) loading from blade element momentum theory; 2) pressure loading from a 2-D CFD simulation.

2.2.1 Compact loading

The first method used to generate a rotor loading is the blade element momentum theory, which combines both blade element theory and momentum theory. The same rotor configuration
is used in the thickness noise calculation: a hovering rotor with four 8m NACA0012 blades; the blade rotational speed is 30 rad/s. Loading along the quarter chord line is output from blade element momentum theory method, and is then used by PSU-WOPWOP (as a chordwise compact patch in PSU-WOPWOP terminology) to calculate the rotor steady loading noise. The compact loading patch is a 1-D surface (with units of force per distance), which integrates the loading vector along the blade.

According to Han and Palacios’s airfoil performance degradation investigation during ice accretion [64], the drag coefficient could be increased by a factor of five due to the accreted ice. The change of the lift coefficient is not considered here because lift does not decrease too much at low AOA such as the case in hover. Consequently the effect of the ice accretion is considered by introducing a higher section drag force into the loading noise calculation. A simple schematic of the ice formation on a blade is shown in Fig. 2-3. The ice mainly accretes on the outboard portion of the blade. The extent that the accreted ice extends along the span, from the tip toward the root, depends on different ice condition parameters, such as the blade rotational speed, icing time, and the MVD, etc. Two different distributions of ice accretion on the blade are used in the current loading noise calculation. One is where ice only accretes on the outer 30% of the blade, in the second case ice accretes on the outer 50% of the blade. Accordingly, the drag coefficient distribution on the blade is shown in Fig. 2-4.

Figure 2-3. Schematic of the ice accretion model.
Figure 2-4. Drag coefficient distribution on clean and iced blades.

Loading noise of the two different ice distributions in spanwise direction, as well as their comparison with the clean blade is shown in Fig. 2-5. The same in-plane observer is used as that in the thickness calculation because drag change is expected to be dominant, and the noise from the drag component of loading noise peaks in the rotor plane. It can be seen that the loading noise is changed noticeably by ice accretion. Another point that should be noticed is that the outer 30% of the rotor generates most of the loading noise. This is expected because the loading noise is proportional to the square of the flow speed.
Figure 2-5. Comparison of steady loading noise (due to Cd increase) between clean airfoil and iced airfoil.

The change of the total acoustic pressure which is the sum of the thickness and steady loading acoustic pressure is noticeable too as shown in Fig 2-6, which is largely due to the change of loading noise. However the relative change is not as noticeable as for the pure loading noise because at this in-plane observer location in hovering case, thickness noise dominates.

Figure 2-6. Comparison of total noise between clean airfoil and iced airfoil.
2.2.2 Pressure loading

A 2-D CFD simulation is conducted on both clean and iced airfoils as shown in Fig. 2-2. This CFD simulation work was performed by Brown [89]. The CFD solver used is NPHASE-PSU developed by Kunz [65]. The angle of attack used is 6 degrees. The simulated Reynolds number is $8.6 \times 10^6$ based on a 1 m chord length. The loading at different blade spanwise locations is calculated by using the simulated 2-D surface pressure and skin friction coefficient and the local flow velocity. The loading of the entire blade is then used for the rotor loading noise prediction by PSU-WOPWOP. The total noise of both clean and iced blades at the same observer as used previously, located in the rotor plane, is shown in Fig. 2-7. The same results are observed as for the compact loading noise: the total noise is changed noticeably by the accreted ice, however, it is unlikely to be sufficient for detection of the early stages of ice accretion.

![Total acoustic pressure graph](image)

Figure 2-7. Comparison of total noise (from CFD pressure distribution) between clean airfoil and iced airfoil.

Notice that even though the iced airfoil used in the thickness and loading noise calculations above has a relatively large ice thickness, (formed during a long ice exposure duration–4.2 min) the total acoustic pressure has a change of approximately 5%. A conclusion
can be drawn that an imperceptible change in rotor thickness and loading noise would be expected from the early stage of ice accretion. It can further be concluded that it is essentially impossible to detect or quantify the surface roughness by using the change of discrete frequency noise (thickness and loading noise).
Chapter 3

Rotor Broadband Noise during Ice Accretion – Experimental Setup

In the last chapter, an investigation of the rotor discrete frequency noise during ice accretion was described. The conclusion is that the accreted ice at the blade leading edge (both ice-induced surface roughness and the glaze ice case) affects the discrete frequency noise noticeably, but not sufficiently large for ice accretion detection. In this chapter and the following ones, the focus is placed on the study of rotor broadband noise at the early stage of the ice accretion. As introduced in Chapter 1, the rotor broadband noise, especially the TBL-TE noise is expected to change during ice accretion at the early stage when the accreted ice is essentially the ice-induced surface roughness. Because the surface roughness has a profound influence on the boundary layer behavior (boundary-layer transition and boundary-layer growth) this would then affect the rotor broadband noise generation.

It is challenging to obtain comprehensive blade unsteady loading information during ice accretion with either CFD computations or experimental measurements. Without unsteady loading and flow field data makes direct rotor broadband noise calculation infeasible. Consequently, rotor broadband noise studies were conducted to establish the relationship between the broadband noise and surface roughness. Comprehensive broadband noise experimental data, with different blade sizes and planforms, different roughness configurations (real ice-induced surface roughness and different synthetic roughness), different rotor rotational speeds, and a wide tip Mach number range, were obtained by conducting measurements in two facilities: the AERTS facility at The Pennsylvania State University, and the University of Maryland Acoustic Chamber (UMAC) at The University of Maryland. Experimental setups of both facilities are reported in this chapter. The experimental results are then analyzed by using broadband noise theories and numerical methods in Chapters 4 and 5 respectively.
3.1 Experimental setup – AERTS

Proof-of-concept measurements were performed in the AERTS facility at Penn State to explore the effect of different surface roughness severity or heights on rotor broadband noise. Figure 3-1 shows the facility with two NACA 0012 test blades (“paddle” blades). The test stand is located inside a cold chamber that is capable of maintaining constant temperatures ranging from 0 to -25°C during icing tests. The rotor hub was taken from a QH-50 DASH (Drone Anti-Submarine Helicopter) unmanned helicopter. The test section dimension is 6 m by 6 m by 3.5 m, which can accommodate test blades with dimensions up to 0.813 m chord and 3 m diameter. Figure 3-2 shows the water nozzle array system of the facility. A total of 15 standard icing nozzles (shown in blue dots) were installed in the AERTS facility, arranged in 2 concentric circles, with 5 nozzles in the inner circle and 10 nozzles in the outer circle. The nozzles are operated by a nozzle control system, which enables the usage of any combination of nozzles to produce the required icing cloud in terms of liquid water content (LWC) and cloud uniformity. A detailed description of the AERTS facility and the validation of its ice reproduction capabilities can be found in [3, 62]. For the present study, a concern is the acoustic environment in the AERTS facility. The octagonal side walls (hard wall), the flat ceiling, as well as the complicated rotor stand shape under the rotor plane, prevent the facility from being an ideal acoustic test chamber. The unfavorable acoustic situation in the AERTS facility is considered to be acceptable for the current proof-of-concept testing because the goal was not a detailed characterization of the source noise, but rather a measure of how much the noise changes after ice accretion. Also, one of the original goals of measuring the noise after ice accretion was to provide a simple, non-intrusive technique for quickly determining the surface roughness of accreted ice without mechanical measurements.
Figure 3-1. AERTS facility with test blades mounted.

Figure 3-2. AERTS nozzle spray system (spraying) on the facility ceiling.

One of the test blade geometries used in this study is shown in Fig. 3-3. The blade radius is 1.372 m (54 in.). The outboard part is the ice-shape monitoring area, labeled as the “paddle” blade. The chord of the “paddle” blade section is 53.34 cm (21 in.), which was designed to have
the same profile (NACA 0012) and chord length as an airfoil used in several icing experiments at the NASA Icing Research Tunnel (IRT) [66, 67]. The ice-shape monitoring section (paddle) is connected to an inboard carrier blade (NACA 0015 airfoil) with a smaller chord length 17.3 cm (6.8 in.) through a non-lifting adapter as shown in Fig. 3-3.

Another blade planform, a modified QH-50 blade, was also used (Fig. 3-4). The blade length was truncated to 1.27 m (50 in.) to fit into the AERTS test section. The QH-50 blade is a tapered blade: the tapered region extends from a radius of 0.69 m (27 in.) to the blade tip. The chord length is 25.4 cm (10 in.) and 29.21 cm (11.5 in.) at blade tip and the end of the tapered region respectively as shown in Fig. 3-4. Broadband noise measurement results from this blade were expected to show a clearer trend than that from the “paddle” blade because there are no sudden geometry changes (as in the case of the “paddle” blade).

Figure 3-3. AERTS “paddle” blade geometry.
A 1/4” microphone (PCB 130E21) was used for all rotor broadband noise measurements in AERTS and was located above the rotor plane, as shown in Fig. 3-5(a). This microphone location was in a region where broadband noise is expected to be significant and avoided taking measurements near the complicated cover shape of the rotor stand. It was also placed relatively far (0.4 m) from the side wall to avoid a potential strong acoustic reflection. The vertical distance from the microphone to the rotor plane is 0.46 m. The distance from the microphone to the rotor shaft axis is 1.26 m. A schematic of the microphone location is shown in Fig. 3-5(b). The microphone location for all the broadband measurements at AERTS was fixed at this position.
Figure 3-5. AERTS microphone location
The data acquisition system used was a PCB signal conditioner 481A and LabVIEW software. The acoustic pressure time history was sampled at 48 KHz, which would give a maximum of 24 KHz frequency-domain data based on the Nyquist criteria.

3.1.1 Broadband noise measurements based on blades with sandpaper

First, rotor broadband noise measurements from blades with sandpaper simulating the accreted ice were conducted. Sandpaper with different grit sizes was applied to the leading edge of the “paddle” blade and the modified QH-50 blade to represent the ice-induced surface roughness at the early stage of the ice accretion. The advantage of sandpaper over accreted ice is that the roughness element size of the sandpaper is provided by the vendor. Consequently, no roughness height characterization is needed. The sandpaper was applied at the leading edge of blade on both upper and lower surface. For the “paddle” blade, the chordwise extent of the sandpaper is 10% of the chord, which is representative of the extent of ice-induced surface roughness. As can be seen in Fig. 3-5(a), the leading edge of the “paddle” blade is covered by the sandpaper with a grit size P16. For the QH-50 blade, the chordwise length of the sandpaper is the same as used in “paddle” blade (2 in.). But the spanwise extent of the sandpaper is twice (24 in.) that of the “paddle” blade as shown in Fig. 3-6. The inboard part of the blade was not covered by the sandpaper because the noise change due to the roughness from that part is considered to be negligible compared to the noise generated from the tip part of the blade due to the lower flow speed.
Different grit size sandpapers were used to represent different surface roughness heights corresponding to different time intervals of the ice accretion. The sandpaper grit sizes are shown in Table 3-1. The smaller the sandpaper grit size is, the larger the roughness size it has. The RPMs used for the broadband noise measurements were 200, 300 and 400 RPM corresponding to tip speeds of 29.7 m/s, 44.6 m/s, and 59.4 m/s separately for the “paddle” blade, and 32.9 m/s, 49.3 m/s, and 65.8 m/s separately for the QH-50 blade.

Table 3-1. Sandpaper grit size table

<table>
<thead>
<tr>
<th>Sandpaper grit size</th>
<th>Averaged grit diameter (micron)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td></td>
</tr>
<tr>
<td>P16</td>
<td>1320</td>
</tr>
<tr>
<td>P24</td>
<td>715</td>
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<tr>
<td>P36</td>
<td>535</td>
</tr>
<tr>
<td>P60</td>
<td>269</td>
</tr>
<tr>
<td>Fine</td>
<td></td>
</tr>
<tr>
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<td>201</td>
</tr>
<tr>
<td>P100</td>
<td>141</td>
</tr>
</tbody>
</table>
3.1.2 Broadband noise measurements based on blades with accreted ice

As described above, the “paddle” blade was specially designed for the ice-shape monitoring by having the specific airfoil and chord length. Consequently, ice accretion experiments, as well as the broadband noise measurements were only conducted on “paddle” blades. In order to protect the microphone from the icing cloud, the microphone was removed from the chamber during the ice accretion test, and then remounted at the same location as it was during the sandpaper test (above the rotor) after the ice has been accreted on the “paddle” blades.

To only focus on the broadband noise generated by the ice-shape monitoring section with ice-induced surface roughness, the ice generated on the inboard carrier blade and the transition adapter was removed. Finally, the broadband noise was measured in the cold environment to make sure the accreted ice did not melt.

The ice-accretion conditions used to generate different ice surface roughness are listed in table 3-2. The rotor RPM was set to 450 for all ice accretion tests (blade tip speeds of 66.7m/s), so a 450 RPM was used for the broadband noise measurement and analysis. Broadband noise at lower RPMs (300 and 400 RPM) was also tested. The first 13 cases were used to form the data base from which a correlation between the ice-induced surface roughness and the broadband noise level was developed. Four additional cases were added after the correlation was developed to validate the proposed relationship. Detailed correlation development between the ice-induced surface roughness and the broadband noise level will be described in Chapter 4. Notice that the maximum icing time for all cases is 2 minutes. This is because the focus of the current study is placed on the broadband noise investigation at the early stage of the ice accretion (early icing detection). Too long an ice accretion time would generate glaze ice (with big horns) or rime ice, neither of which has the desired roughness behavior. An important reason to limit the ice accretion time to 2 minutes is that Shin [67] showed the ice roughness element size grew with
time up to 2 minutes, and then became constant for a while before changing into the glaze or rime ice.

Table 3-2. Icing conditions with different ice-induced surface roughness

<table>
<thead>
<tr>
<th>Test Case Number</th>
<th>RPM</th>
<th>$V_{tip}$ (m/s)</th>
<th>$T_{static}$ (°C)</th>
<th>MVD (µm)</th>
<th>Icing Time (s)</th>
<th>LWC (g/m³)</th>
<th>Integrated MSP Value ($\text{Pa}^2$)</th>
<th>Arithmetic Average Roughness Height $R_a$ (mm)</th>
<th>Averaged Roughness Height Based on Ice Area $aa$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>450</td>
<td>66.7</td>
<td>-5.54</td>
<td>30</td>
<td>94</td>
<td>1.7</td>
<td>0.14933</td>
<td>1.3262</td>
<td>4.0113</td>
</tr>
<tr>
<td>2</td>
<td>450</td>
<td>66.7</td>
<td>-5.86</td>
<td>30</td>
<td>94</td>
<td>1</td>
<td>0.10543</td>
<td>0.8972</td>
<td>2.7256</td>
</tr>
<tr>
<td>3</td>
<td>450</td>
<td>66.7</td>
<td>-5.78</td>
<td>30</td>
<td>75</td>
<td>1</td>
<td>0.08414</td>
<td>0.7529</td>
<td>2.1197</td>
</tr>
<tr>
<td>4</td>
<td>450</td>
<td>66.7</td>
<td>-9.90</td>
<td>30</td>
<td>94</td>
<td>0.6</td>
<td>0.11100</td>
<td>1.0370</td>
<td>2.7816</td>
</tr>
<tr>
<td>5</td>
<td>450</td>
<td>66.7</td>
<td>-5.58</td>
<td>20</td>
<td>94</td>
<td>0.25</td>
<td>0.06249</td>
<td>0.4360</td>
<td>0.7394</td>
</tr>
<tr>
<td>6</td>
<td>450</td>
<td>66.7</td>
<td>-5.90</td>
<td>20</td>
<td>120</td>
<td>1</td>
<td>0.12476</td>
<td>1.2307</td>
<td>2.8757</td>
</tr>
<tr>
<td>7</td>
<td>450</td>
<td>66.7</td>
<td>-5.76</td>
<td>20</td>
<td>94</td>
<td>1</td>
<td>0.06861</td>
<td>0.7878</td>
<td>1.96454</td>
</tr>
<tr>
<td>8</td>
<td>450</td>
<td>66.7</td>
<td>-5.58</td>
<td>20</td>
<td>94</td>
<td>1.3</td>
<td>0.09889</td>
<td>0.9645</td>
<td>2.1726</td>
</tr>
<tr>
<td>9</td>
<td>450</td>
<td>66.7</td>
<td>-5.50</td>
<td>20</td>
<td>120</td>
<td>1.3</td>
<td>0.13670</td>
<td>1.2660</td>
<td>3.4491</td>
</tr>
<tr>
<td>10</td>
<td>450</td>
<td>66.7</td>
<td>-5.55</td>
<td>30</td>
<td>75</td>
<td>1.3</td>
<td>0.10620</td>
<td>1.0251</td>
<td>2.6315</td>
</tr>
<tr>
<td>11</td>
<td>450</td>
<td>66.7</td>
<td>-5.90</td>
<td>30</td>
<td>94</td>
<td>1.3</td>
<td>0.12554</td>
<td>0.9972</td>
<td>2.9373</td>
</tr>
<tr>
<td>12</td>
<td>450</td>
<td>66.7</td>
<td>-5.56</td>
<td>30</td>
<td>120</td>
<td>1.3</td>
<td>0.14629</td>
<td>1.1850</td>
<td>4.1482</td>
</tr>
<tr>
<td>13</td>
<td>450</td>
<td>66.7</td>
<td>-10.30</td>
<td>30</td>
<td>94</td>
<td>0.75</td>
<td>0.14274</td>
<td>1.2617</td>
<td>3.5734</td>
</tr>
<tr>
<td>14(validation)</td>
<td>450</td>
<td>66.7</td>
<td>-5.68</td>
<td>20</td>
<td>75</td>
<td>1.3</td>
<td>0.09184</td>
<td>0.7428</td>
<td>1.8359</td>
</tr>
<tr>
<td>15(validation)</td>
<td>450</td>
<td>66.7</td>
<td>-5.90</td>
<td>20</td>
<td>50</td>
<td>1.3</td>
<td>0.07009</td>
<td>0.5044</td>
<td>1.1050</td>
</tr>
<tr>
<td>16(validation)</td>
<td>450</td>
<td>66.7</td>
<td>-5.70</td>
<td>30</td>
<td>50</td>
<td>1.3</td>
<td>0.77813</td>
<td>0.5942</td>
<td>1.5424</td>
</tr>
<tr>
<td>17(validation)</td>
<td>450</td>
<td>66.7</td>
<td>-5.78</td>
<td>30</td>
<td>94</td>
<td>1.3</td>
<td>0.11868</td>
<td>1.2092</td>
<td>3.04662</td>
</tr>
</tbody>
</table>

The typical ice-induced surface roughness shapes, as seen looking toward the end of the blade toward the blade tip, are shown in Fig. 3-7. In the figure, case 12 (left) is one of the roughest shapes among all cases and case 15 (right) is one of the smoothest.
Another set of broadband noise measurements due to surface roughness was conducted in the University of Maryland Acoustic Chamber (UMAC). Advantages of having tests in the UMAC include: 1) it is an anechoic chamber, which makes it a more ideal acoustic chamber than AERTS; 2) the rotor test stand is able to maintain a high rotational speed. The corresponding blade tip Mach number can reach as high as 0.7, which is a representative value of a full-scale helicopter (AERTS can reach a Mach number up to 0.3) and 3) the blade chord size and the surface roughness height applied on such a blade is different compared to what have been used in the AERTS test. Testing with different chord size, roughness height, and different rotor RPM make it possible to investigate the correlation between broadband noise frequency content and these parameters. The disadvantage of testing in UMAC is that the rotor broadband noise from the blade with real ice-induced surface roughness cannot be tested - only representative surface roughness can be used.

The UMAC is an octagonal 6.1 m (20 ft) by 6.1 m (20 ft) wide, 9.1 m (30 ft) tall acoustically treated facility. Four different blade surface roughness sizes as well as the clean
blade were used to investigate different roughness height effects on rotor broadband noise. For each blade set, broadband noise was measured at every tenth of a tip Mach number from 0.1 to 0.7 by a single microphone.

3.2.1 UMAC rotor system

Figure 3-8 shows the rotor system of the UMAC, which is a single bladed, counterweighted, rigid rotor with a 2° downward collective pitch. This produces a very small amount of downward thrust in order to push the rotor wake above the rotor plane and provide as clean an acoustic environment as possible. More details about the facility can be found in [68, 69].

![Figure 3-8. UMAC rotor system.](image)

Figure 3-9 shows the rotor blade used in this test, which is a rectangular NACA0012 blade with no twist. The chord and radius length are 0.0762m (3 in.), and 0.9398m (37 in.) respectively.
3.2.2 Surface roughness application

Four different surface roughness sizes were applied in this test to represent different surface roughness heights corresponding to different time intervals of a real ice accretion case. Due to the relatively small size of the blade, sandpaper could not be applied on the clean blade to
represent the ice-induced surface roughness as in the AERTS test. The thickness of the sandpaper layer itself (rather than the grit on the sandpaper) is large compared to the blade thickness. This is expected to cause extra effects on the blade boundary layer characteristics, as well as the TE turbulence, which would finally influence the rotor broadband noise. Consequently, two alternative roughness application techniques (roughness elements only) are used: 1) commercial glass beads/sugar crystals with a range of sizes and 2) commercial texture paint. In order to protect the blade surface, Kapton tape was first applied on the blade leading edge before the glass beads/ sugar crystals or the texture paint were applied on the Kapton tape. Figure 3-10 shows the clean blade with the kapton tape applied on its leading edge. Kapton tape provides several unique advantages for this test that other tapes do not. First, it is very thin (0.03 mm) so it doesn’t affect the blade boundary layer characteristics to influence the rotor broadband noise. As the measured sound pressure level (SPL) results shown in Fig. 3-11, broadband noise of the clean blade with and without the Kapton tape match well with each other. Secondly, it is easy to apply and remove without extra adhesive left on the blade. Since there was only one blade, it is very important that the tape should not cause any extra roughness (due to latent adhesive) during repeated use.
Glass beads with diameter size 0.5mm and sugar crystals with averaged size 1.02 mm were used as the first roughness application method. A thin layer of polyurethane was painted on the kapton tape to hold the glass beads in place. The glass beads/sugar crystals were then applied
uniformly on top of the polyurethane before it dried. The polyurethane was then allowed to dry. Another thin layer of white paint was applied on top of the glass beads and the polyurethane to further increase the ability of the glass beads to remain in position while resisting the centrifugal force during rotation. Figs. 3-12 and 3-13 show glass beads and sugar crystals respectively.

Figure 3-12. UMAC blade with 0.5 mm glass beads.

Figure 3-13. UMAC blade with 1.02 mm sugar crystals.
The second method used to apply surface roughness was the use of commercial texture paint. The brand and model used in this test was KRYLON texture paint SILVER and OBSIDIAN. Figs. 3-14 and 3-15 show the blade paint with these two texture paints (different roughness elements sizes) respectively. For both glass beads/sugar crystals and texture paints, they were applied on the leading edge of the clean blade (both upper and lower surface). The chordwise extent of the roughness application is 15% of the chord.

Figure 3-14. UMAC blade with texture paint (SILVER, height ≈ 0.1 mm).
A roughness height characterization was carried out because the roughness size of the sugar crystals and the texture paint was not known. In this process, a digital dial indicator was used to measure the surface roughness height of the sugar crystal and the two texture paints. The digital dial indicator has a resolution of 10 μm, which is one order of magnitude smaller than the height of the texture paint. A photo of the digital dial indicator used for measurements on the texture paint (SILVER) roughness is shown in Fig. 3-16. The surface roughness was applied onto a rectangle (6 cm by 5 cm) on a plexiglass board. Other texture paints were also considered and measured, as shown in Fig. 3-16; but only SILVER (on first row, second left) and OBSIDIAN (on second row, second left) were chosen for acoustic testing. The measurements were taken based on the texture paint on the plexiglass board. A total of 20 locations on the sample region were measured for each texture paint characterization. The 20 locations measured, which are on a 5 by 4 grid with 1 cm intervals, are shown in Fig. 3-17. The measured peak-to-valley roughness heights, as well as the calculated arithmetic averages, medians, and standard deviations of the roughness heights for sugar crystal and texture paint (SILVER and OBSIDIAN) are shown in
Table 3-3, 3-4, and 3-5 respectively. The arithmetic averages of measured peak-to-valley roughness heights for the sugar crystal and the texture paints (OBSIDIAN and SILVER) are 1.02 mm, 0.20 mm, and 0.12 mm, respectively.

Figure 3-16. Texture paint roughness height characterization.

Figure 3-17. Schematic of texture paint roughness height measurement locations.
### Table 3-3. Measured roughness heights of the sugar crystal

<table>
<thead>
<tr>
<th>Peak-to-valley roughness height (mm)</th>
<th>Median (mm)</th>
<th>Standard deviation (mm)</th>
<th>Arithmetic average (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.85</td>
<td>1.15</td>
<td>1.12</td>
<td>0.55</td>
</tr>
<tr>
<td>1.21</td>
<td>1.23</td>
<td>0.65</td>
<td>1.29</td>
</tr>
<tr>
<td>0.78</td>
<td>0.99</td>
<td>1.12</td>
<td>0.93</td>
</tr>
<tr>
<td>0.77</td>
<td>1.20</td>
<td>1.31</td>
<td>0.63</td>
</tr>
<tr>
<td>1.21</td>
<td>0.88</td>
<td>1.27</td>
<td>1.32</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 3-4. Measured roughness heights of the texture paint-SILVER

<table>
<thead>
<tr>
<th>Peak-to-valley roughness height (mm)</th>
<th>Median (mm)</th>
<th>Standard deviation (mm)</th>
<th>Arithmetic average (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.14</td>
<td>0.08</td>
<td>0.11</td>
<td>0.09</td>
</tr>
<tr>
<td>0.16</td>
<td>0.16</td>
<td>0.07</td>
<td>0.13</td>
</tr>
<tr>
<td>0.04</td>
<td>0.14</td>
<td>0.12</td>
<td>0.13</td>
</tr>
<tr>
<td>0.17</td>
<td>0.18</td>
<td>0.16</td>
<td>0.1</td>
</tr>
<tr>
<td>0.08</td>
<td>0.07</td>
<td>0.12</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 3-5. Measured roughness heights of the texture paint-OBSIDIAN

<table>
<thead>
<tr>
<th>Peak-to-valley roughness height (mm)</th>
<th>Median (mm)</th>
<th>Standard deviation (mm)</th>
<th>Arithmetic average (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.19</td>
<td>0.16</td>
<td>0.23</td>
<td>0.27</td>
</tr>
<tr>
<td>0.13</td>
<td>0.17</td>
<td>0.25</td>
<td>0.26</td>
</tr>
<tr>
<td>0.15</td>
<td>0.12</td>
<td>0.23</td>
<td>0.09</td>
</tr>
<tr>
<td>0.28</td>
<td>0.25</td>
<td>0.18</td>
<td>0.22</td>
</tr>
<tr>
<td>0.29</td>
<td>0.21</td>
<td>0.16</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.2.3 Microphone measurement system

One 1/4” microphone (PCB 378C01) was used in this test. It has a high frequency capability up to 100KHz. High-frequency performance of the microphone was expected to be critical in these tests. The manner in which the broadband noise frequency content changes with turbulence scale, blade size, and rotor rotational speed was not known before the test. However, the relationship between the broadband noise frequency range and the rotational speed (tip Mach number) in the AERTS test showed that rotor broadband noise due to different blade surface roughnesses tends to separate at even higher frequencies when the rotational speed increases. Consequently, for high rotational speed tests in UMAC, a microphone with a frequency range up to 100KHz (compared to the 25KHz microphone used in AERTS test) was used and the measurement results showed that this frequency range was high enough for the current test.

The microphone was located out of the rotor plane with a distance 0.98R2 (R2 = 0.9398m) away from the hub center and a 20 degree elevation angle as can be seen in Fig. 3-8. The microphone location was set to be the same relative location as the AERTS test for comparison.

3.2.4 Data acquisition system

Data was acquired using the same PCB signal conditioner as used in the AERTS test, and the LabVIEW software. Acoustic pressure time history was sampled at 200 KHz, which would give a maximum 100 KHz frequency-domain data based on the Nyquist criterion. Such a high sampling rate (200 KHz) caused a problem that LabVIEW is not able to record and save the time-domain signal in a real-time manner. LabVIEW could not buffer the data as fast as it sampled the data. This led to a result that the final saved 4-second acoustic pressure time history is not
continuous: a random jump exists at every 5000 points. However, such discontinuous data would not affect high frequencies (for example, frequencies larger than 200Hz which covers the frequency range interested in the current research) noise analysis if the FFT treatment uses a segment length less than 5000 points without data overlapping. Detailed analysis about the effect of discontinuous data on frequency analysis is shown in the Appendix A.

3.2.5 UMAC test matrix

Test matrix of the UMAC test is shown in Table 3-5. Four different blade surface roughness sizes as well as the clean blade are tested every tenth of a tip Mach number from 0.1 to 0.7. For the clean blade at tip Mach number between 0.6 and 0.7 where the transition between laminar flow to turbulent flow is expected to happen, the broadband noise is recorded at every 0.01 tip Mach number. These data are used to analyze the laminar boundary layer vortex shedding (LBL-VS) noise during the flow transition.

Table 3-6. UMAC test matrix

<table>
<thead>
<tr>
<th></th>
<th>Tip Mach number</th>
</tr>
</thead>
<tbody>
<tr>
<td>clean blade</td>
<td>0.1, 0.2, 0.3,…, 0.7, 0.61, 0.62, …, 0.69</td>
</tr>
<tr>
<td>glass beads 1.02 mm</td>
<td>0.1, 0.2, 0.3,…, 0.7</td>
</tr>
<tr>
<td>glass bead 0.5 mm</td>
<td>0.1, 0.2, 0.3,…, 0.7</td>
</tr>
<tr>
<td>texture paint OSBIDIAN (0.2 mm)</td>
<td>0.1, 0.2, 0.3,…, 0.7</td>
</tr>
<tr>
<td>texture paint SILVER (0.1 mm)</td>
<td>0.1, 0.2, 0.3,…, 0.7</td>
</tr>
</tbody>
</table>
Chapter 4

Rotor Broadband Noise Experimental Investigation

This chapter presents the measurements of the rotor broadband noise due to different surface roughness – sandpapers and the ice-induced surface roughness used in AERTS; texture paints, glass beads and sugar crystals used in UMAC – in the first section. Then in the second section, rotor broadband noise source identification is conducted based on theories of the different rotor broadband noise source mechanisms. The broadband noise related to ice accretion is thought to be the TBL-TE noise. In the next section, the TE noise theory is discussed. Two important parameters highly related to ice accretion: boundary layer thickness and turbulence intensity are identified. In the final section, a correlation between the ice-induced surface roughness and the broadband noise level is developed, which can be used as a tool to determine the accreted ice roughness in the AERTS facility through acoustic measurement. It might be possible to use a similar approach to develop an early ice accretion detection tool for helicopters, as well as to quantify the ice-induced roughness at the early stage of rotor ice accretion.

4.1 Typical broadband noise measurement results

4.1.1 AERTS test results

A sample rate of 48,000 samples per second was used in the acoustics data acquisition of the AERTS test. Acoustic pressure data was recorded for 4 seconds for each broadband noise measurement. The measured time-domain broadband results data were analyzed and presented as the pressure spectra on a linear frequency scale. An averaging process was applied to each sound pressure level (SPL) spectrum to show a smoother and clearer SPL trend. The segment length of each data time series used for averaging was 300 data points (0.00625 second), with 50% overlap.
(150 data points) with respect to the adjacent segment. A Hanning window was applied to each time segment. The averaged SPLs for “paddle” blades with sandpapers of different surface roughness heights and the clean blades for the 400 RPM rotational speed are shown in Fig. 4-1. The background noise (BG) is also shown. This is the noise from the rotating rotor stand without any blades. A clear trend can be seen in the frequencies higher than 12 kHz. The rougher surface (smaller grit size) gives a higher SPL value. SPL values from the other two rotational speeds – RPM 200 and 300 – show same trend, the results are shown in Appendix B.

![Figure 4-1](image-url)  
Figure 4-1. “Paddle” blades test results: SPL from different sandpaper roughness, clean blades, and background noise.

For the modified QH-50 blades, a wider range of grit sizes were used in the test. The noise spectra are shown in Fig. 4-2. Essentially the same acoustic trend is achieved, but the separation of the SPL curves for different roughness heights is greater than the “paddle” blades test in the high frequencies. The SPL from each roughness is separated by at least 2 dB in the high-frequency region. This demonstrates the feasibility of the detection of variations in surface roughness through broadband noise measurement.
Figure 4-2. Truncated QH-50 blades test results: SPL from different sandpaper roughness, clean blades, and background noise.

Fig. 4-3 shows the “paddle” blades SPL spectra comparison between clean blades and the two example roughness shapes shown in Fig. 3-7, where the surface roughness was due to actual ice accretion. In the cases shown in Fig. 4-3, the rotational speed was slightly higher, 450 RPM, but have all the same features as the sandpaper generated roughness (Fig. 4-1). From Fig. 4-3, it is clear that these two different surface roughness cases can be distinguished by looking at the SPL in the high frequencies. For example, case 12 (large surface roughness) is approximately 2 to 3 dB noisier than case 15 (small surface roughness) at frequencies larger than 15 kHz, even if the ice roughness elements are not as uniformly distributed as those of the sandpaper. To clearly show the trend, SPL from other ice-induced surface roughness (other cases in Table 2) are not shown, but can be found in Appendix B. However, measured broadband noise levels from different ice roughness (icing conditions) can be correlated very well with the ice-induced surface roughness heights. The detailed development of such a correlation procedure will be presented in the last section of this chapter.
Figure 4-3. “Paddle” blades test results: SPL from two different ice-induced surface roughness and their comparison with that from the clean blades.

4.1.2 UMAC test results

The rotor blades in the UMAC test had considerably smaller chord and the rotation rates were significantly higher. Therefore, the sample rate used during data acquisition for the UMAC test was 200,000 samples per second. 4 seconds of acoustic pressure data were recorded for each broadband noise measurement. Again an averaging process is applied to each SPL spectrum in which the segment length of each time series used is 5000 data points (0.025 second), but with no overlap. A comprehensive tip Mach number range from 0.1 to 0.7 was covered for the rotor broadband noise measurements. A typical SPL comparison between roughened blades and the clean blade at tip Mach number equal to 0.4 is shown in Fig. 4-4 (Results of other tip Mach numbers are documented in Appendix B). A similar trend is obtained that the rougher blade gives a higher SPL at high frequencies (larger than 30 kHz). Notice that for this UMAC test (Mach number 0.4) the lowest frequency where SPL from different surface roughness can be distinguished from each other occurs at an even higher frequency than the AERTS test (Mach
number 0.17): i.e., 30 kHz as opposed to 12 kHz. Such an increase in frequency was expected for the UMAC test. The broadband noise frequency content is expected to correlate with rotor rotational speed, as well as the blade size, roughness height and turbulence scale. However, a more comprehensive acoustic experiment with different blade scales and roughness sizes, as well as detailed 2-D wind tunnel flow tests would be needed to investigate such a correlation relationship in detail.

In Fig. 4-4, another interesting feature lies in the SPL from the clean blade, which shows a SPL magnitude “peak” around 30 kHz where the SPL level for the clean blade is higher than that from the roughened blades. This peak is thought to be due to the laminar boundary layer vortex shedding (LBL-VS) noise. Similar test results are also reported by Brooks et al. [70], and Peterson et al. [25].

![Tip Mach number 0.4](image)

Figure 4-4. UMAC test results: SPL from 4 different surface roughness and their comparison with that from the clean blade.
4.2 Broadband noise source mechanism identification

As introduced in Chapter 1, helicopter rotor broadband noise sources can be divided into: 1) turbulence ingestion noise; 2) BWI noise; and 3) blade self-noise. Blade self-noise includes five individual source mechanisms: TBL-TE noise; separation-stall noise; LBL-VS noise; trailing edge bluntness-vortex shedding noise; and tip vortex formation noise, as described by Brooks et al. [29]. It is critical to identify the noise source mechanism that causes the rotor broadband noise increase due to ice-induced surface roughness from the mechanisms listed above before any physical understanding or explanation can be made.

Helicopter rotor turbulence ingestion noise is caused by the interaction between the distorted atmospheric turbulence and rotor blades. It is obvious that the ice-induced surface roughness on rotor blades would not affect the atmospheric turbulence. So turbulence ingestion noise is not considered in the present work. BWI noise is a broadband noise source due to the interaction of the rotor blades with the turbulent portion of the wakes of previous blades, particularly about tip vortices [27]. It is found primarily in level flight to mild climb conditions and depends, to first order, on the rotor tip-path-plane angle [27]. However, the present experiments in both the AERTS and UMAC facilities are hover tests of lightly loaded rotors with a zero degree tip-path-plane angle. So BWI noise is not expected to be affected noticeably by ice accretion in these facilities. Another reason that the BWI noise is not considered to be the primary source mechanism during ice accretion is that BWI noise contributes at relatively low frequency, which is in contrast to the high frequency range where the changes in broadband noise due to ice accretion are observed. As shown in Fig. 4-5, from Brooks and Burley [27], the measured noise spectra of a model BO-105 helicopter with different tip-path-plane angles (used in their BWI noise investigation), the frequency range over which BWI noise appears is from about 1.5 kHz to 6.5 kHz as indicated. An additional frequency scale is also presented in Fig. 4-5, which
corresponds to what an observer would hear for an equivalent full-scale rotor scaling on the blade passage frequency (BPF). By performing the same frequency scaling, the frequency ranges (if the BWI noise exists) in AERTS (RPM 450 as shown in Fig. 4-3) and UMAC (RPM 1370 as shown in Fig. 4-4) should be 0.3 kHz - 1.4 kHz, and 0.5 kHz - 2.0 kHz, respectively. These are much lower than the SPL frequency ranges with increased levels caused by the ice-induced surface roughness.

Figure 4-5. Noise spectra of a model BO-105 helicopter rotor measured in DNW by Brooks and Burley [27].

Of the different blade self-noise source mechanisms, as discussed in Chapter 1 only the TBL-TE noise is considered to be the likely cause of the increased rotor broadband noise due to the ice-induced surface roughness. TBL-TE noise is generated when the blade boundary layer turbulence passes over the sharp TE. The ice-induced surface roughness at the leading edge and the resulting turbulence changes are expected to primarily affect the TBL-TE noise.
4.3 Trailing edge noise theory

One of the first analytical solutions based on Lighthill’s acoustic analogy [49, 50] for turbulence diffraction about a semi-infinite plane (trailing edge) is given by Ffowcs Williams and Hall [51]. They point out that trailing edge acoustic intensity increases in proportion to the fifth power of the flow velocity. Howe [45] then extended Ffowcs Williams and Hall’s scaling law of a single eddy to all eddies along a plate with a spanwise extent $L$. Howe’s trailing edge noise scaling formula is shown below,

$$\langle p^2 \rangle \sim \rho^2 v'^2 \frac{U^3}{c} \left( \frac{L}{R^2} \right) D,$$

where $\langle p^2 \rangle$ is the mean-square sound pressure at the observer location at a distance $R$, $\rho$ is the density of the medium $v'$ is the mean-square turbulence velocity which is equal to $UI$, with $U$ the turbulence convection velocity and $I$ the turbulence intensity, $c$ is the speed of sound, $l$ a characteristic turbulence correlation scale, and $L$ the spanwise extent of the plate. $D$ is the directivity parameter which equals 1 for observers normal to the surface from the trailing edge [29]. For analyzing the increase of trailing edge noise due to ice-induced surface roughness, two important parameters are emphasized here: boundary layer (displacement) thickness ($\sim l$) and turbulence intensity (turbulence velocity). These are expected to be strongly affected by different surface roughnesses and likely result in a related trailing edge noise change.

4.4 Correlation between surface roughness height and broadband noise level

As introduced in Chapter 1, the surface roughness due to ice accretion plays an important role in helicopter rotor icing physics. The surface roughness has profound influence on the boundary layer behavior and it substantially impacts the surface heat transfer and the resulting ice accretion shapes. However, there is insufficient data to characterize the size and shape of the
Surface roughness as a function of icing conditions and time [71], and there is almost no data for helicopter rotors. Quantification of surface roughness through acoustic modeling and measurements would help the development of icing condition characterization and icing shape modeling for rotorcraft. In this subsection, a correlation between the ice-induced surface roughness and the broadband noise level is developed. As indicated in the previous section, the present work is the acoustic part of a helicopter icing physics investigation project. The main application of this technique to quantify surface roughness is to provide the icing experimental group the predicted roughness height after measurement of the broadband noise. The surface roughness of accreted ice for a given icing condition is needed to provide accurate heat transfer coefficients, which ultimately will permit more accurate ice accretion shape predictions. The correlation may also provide the basis for an early stage helicopter ice accretion detection tool.

4.4.1 Ice-induced surface roughness digitization

To correlate the ice surface roughness to the broadband noise, one needs to quantify the ice-induced surface roughness. A specific concern to describe the roughness in the present work is that all the roughnesses used are from the relatively early stage of the ice accretion. As described by Shin [72], roughness shapes from different icing conditions follow the same initial trend at the beginning of the exposure to the icing cloud as shown in Fig. 4-6. Three regions are identified in the initial ice accretion phase: region A is the smooth zone which is just a smooth layer of ice, region B is the roughness zone in which the roughness develops on an ice substrate that has a fairly uniform thickness, and region C is where some small ice bumps develop at various spots but without the ice substrate.
This initial roughness trend is confirmed by the present work as shown in Fig. 4-7. The smooth zone and rough zone can be seen in Fig. 4-7 (a), and the ice roughness feature is clearly shown in Fig. 4-7 (b). Fig. 4-7 also shows an example of the blade tip roughness digitization process. A small grid attached to end of the blade tip is used as a length reference during digitization. The grid size is 1.88 mm×1.88 mm and is placed parallel to the airfoil chord line. The GetData Graph Digitizer [90] is used in the roughness digitization process. For each case, the coordinate for digitization is the same, which is defined based on the grid. The origin is located at the left and bottom corner, the x-axis is along the bottom of the grid and the y-axis along the left border as shown in Fig. 4-7 (a).
Figure 4-7. Photo of the surface roughness digitization at the blade tip (case 12).

Then both the clean airfoil and the roughness boundary are digitized, as shown in Fig. 4-8 (a). The digitized roughness boundary (red line) is unwrapped along the clean airfoil arc in order to measure the roughness height and the ice area as shown in Fig. 4-8 (b). The X-axis represents the unwrapped clean airfoil profile. The grey color region between the clean airfoil profile (X-
axis) and the roughness profile (red line) is used to calculate the accreted ice area, in which the zero arc length value means the stagnation point. Digitized points on negative x-axis represent the roughness on the upper surface of the airfoil and those on the positive x-axis represent the roughness on the lower surface.

Figure 4-8. Digitized roughness profile.
Fig. 4-9 shows digitized roughness profiles from different icing conditions. For the sake of clarity, not all roughnesses are shown in this figure. For each roughness profile, the three zones are distinguishable. However, the length of the smooth zone and roughness zone are different from case to case, as is the roughness height.

![Figure 4-9. Different digitized roughness profile.](image)

A common parameter used to describe the ice-induced surface roughness is the roughness element diameter [67, 72-73], which is an average of hundreds of elements measured in the region right after the smooth zone, based on the assumption that a single roughness element is a hemisphere. However, the diameter of the roughness element may not be a suitable metric in the present work. The present work only focuses on the ice-induced roughness at the early stage of the ice accretion, during which the roughness elements may have some different characteristics compared to the well-developed elements. For example, the roughness elements were not observed to be nearly hemispherical in the present work (Fig. 4-7); hence, the diameter of the elements is not particularly representative of the roughness height. Furthermore, the diameter of the roughness element does not appear to be directly connected to the broadband noise.
Consequently, rather than using the roughness element diameter, two different parameters were considered in the present work to describe different ice-induced roughness heights at the early stage of the ice accretion, and as a correlation parameter for broadband noise level. These were, 1) the arithmetic average of the roughness height $R_a$, and 2) an averaged roughness height $\bar{a}$ based on the accreted ice area (area under the roughness curve as shown in Fig. 4-8 (b)).

The arithmetic average of the roughness height $R_a$ is commonly used in research areas such as tribology and lubrication. The formula for $R_a$ is shown below when the roughness profile contains $n$ ordered, equally spaced points along the trace:

$$R_a = \frac{1}{n} \sum_{i=1}^{n} |y_i|,$$

(4.2)

where $y_i$ is the vertical distance from the mean line of the $i^{th}$ data point.

The mean line calculated in the present work is a moving average that averages a total number of 21 data points for the current point. The sample includes the current point, 10 data points before the current point and 10 data points after. An example of the calculated mean line and the original digitized roughness profile is shown in Fig. 4-10. $R_a$ values for different icing conditions are shown in Table. 3-2. The advantage of using $R_a$ is that only roughness effects are considered, the thickness of the ice layer in the smooth zone and the ice substrate under roughness in the rough zone won’t contribute to $R_a$. This feature is expected to permit a better correlation relationship with the broadband noise, because the smooth zone near the stagnation point is considered to have little contribution to the broadband noise change, and this region is removed by using $R_a$. 
The other parameter used is an averaged roughness height $a$, which is the area under the digitized measurement of the accreted ice (Fig. 4-8 (b)) divided by a constant perimeter $2\pi R$ ($R$ is the airfoil leading edge radius and is 8.64 mm for the “paddle” blade). The constant circle perimeter used here is to follow the notation of Anderson et al. [73], in which twice the airfoil leading edge radius length is used to non-dimensionalize the ice-induced roughness height. This roughness height can be treated as an “averaged ice roughness height” around a circle whose radius is that of the airfoil leading edge.

The roughness description parameters defined in the present work are used to correlate with the broadband noise, which is expected to be related to the boundary layer transition location as well as the boundary layer thickness at the TE. However, there has not been any investigation to find where boundary layer transition takes place along the ice roughness [67], and it is still not clear whether the boundary layer transition is affected by the overall roughness or just the roughness in the rough zone. Even the ice layer thickness in the smooth zone could have a contribution to the change of the boundary layer characteristics. But the contribution (if any) is
not currently known. To address these questions it is necessary to make detailed boundary layer measurements at different positions along the iced airfoil, but such measurements are beyond the scope of the present work. Due to the lack of knowledge of the detailed physics of the boundary layer and its dependence on the ice-induced roughness, the average roughness height used in the present work, which can be treated as an overall average height of the smooth ice layer height in the smooth zone, and the roughness height in roughness and ice feature zones, is considered to be an acceptable parameter to correlate with the broadband noise level.

The accreted ice area was treated as the area between the clean airfoil and the roughness profile. For each case, it was calculated by integrating the area between the roughness profile and the x-axis (clean airfoil arc) in the unwrapped digitized roughness profile, shown as the gray region in Fig. 4-8 (b). Values of the averaged roughness height based on such accreted ice area from different icing conditions are also shown in Table. 3-2.

Subjective error in defining the clean airfoil and the roughness profile was estimated by comparing the results from two different digitizations of the same images. For those cases for which duplicate analyses were performed (cases 1 - 6), the maximum uncertainty indicated was less than 3% for the arithmetic average roughness height $R_a$ and 5% for the accreted ice area. The uncertainty error percentage for each case is calculated by using the absolute difference of the roughness height or accreted ice area value between two digitizations divided by that the value of the first digitization.

One obvious concern for both description parameters used in the present work is that only the roughness at the blade tip is considered, rather than for the entire blade. This is thought to be reasonable because the airspeed was found to have little effect on the ice-induced roughness height [72], which means the roughness on the rotor blades at different spanwise locations should not change much. This conclusion is confirmed in the present work by the observation that no significant ice roughness change is observed along the “paddle” blade span for any of the cases.
Consequently, the present work assumes that the roughness change in the spanwise direction on the “paddle” blade test section (12 in. long, flow speed range: 52.3 – 66.7 m/s) is negligible. It was observed that the ice roughness changed from the blade tip to the root; however, only the ice accretion on the “paddle” was considered in this work, and ice roughness on other sections of the rotor blade were removed before all broadband noise measurements. Furthermore, only the tip region is expected to contribute to significantly to the broadband noise because the unsteady loading is expected to be highest at the tip due to the higher flow velocity over the blade surface.

4.4.2 Effect of the angle of attack

Angle of attack (AOA) effects on the broadband noise were investigated before developing the roughness quantification correlation. The purpose is to estimate and compare the effects on the broadband noise from different AOAs and that from roughness elements. Four different AOAs (collective pitch): -2 degree, 0 degree, 2 degree and 4 degree were used in the broadband noise measurements for both clean blades and iced blades. A single ice shape was used at the various angles of attack – not ice generated at the various angles of attack. The overall broadband noise spectrum is shown in Fig. 4-11.
Figure 4-11. SPL from different AOAs for both iced blades and clean blades.

In general, different AOAs do not change the broadband noise significantly in the high frequency range (frequencies greater than 10K Hz), which is the range used to distinguish different surface roughness as in the present work. Examination of the noise levels in the high frequencies of clean blades and iced blades separately, the noise change due to different AOAs is less than approximately 1 dB, while the change due to the ice roughness is on the order of 4-5 dB. Consequently the conclusion is drawn that the effect of the AOA, over a reasonable range of AOAs, is less significant than the effect of different roughnesses.

4.4.3 Roughness and noise correlations

The broadband noise level used in both correlations is an integrated mean square pressure (MSP) value (Pa$^2$) in the frequency range from 10 kHz to 24 kHz, shown as the gray region shown in Fig. 4-12. The selection of the integrated frequency range is based on the earlier observations of the frequency range where the broadband noise of different roughnesses was distinct.
Fig. 4-13 shows the correlation between the arithmetic average roughness height and the integrated broadband noise level. The point with zero arithmetic average roughness height (point on x-axis) represents the clean blade case. The 17% error from the broadband noise measurement indicated as the horizontal error bar is shown in Fig. 4-13, while the 3% roughness digitization error is represented by the vertical error bar. The trend line is calculated based on the linear least squares method and is referred to as the correlation relationship for the prediction of the ice-induced surface roughness through measured broadband noise level. It’s equation is given by: $y = 10.36x - 0.1775$. The overall correlation relationship is a simple, but strong positive correlation. The absolute mean deviation in percentage for this correlation data is 9.3%, which is calculated by the following formula:

$$\sum_{i=1}^{n} \left| \frac{h_{exp}^i - h_{pre}^i}{h_{pre}^i} \right| \times 100\%$$  \hspace{1cm} (4.3)

Where $h_{exp}^i$ is the $i^{th}$ arithmetic average roughness height from the experiment measurement, $h_{pre}^i$ is the roughness height predicted from the trend line. Another correlation parameter: the
Pearson correlation coefficient [88] is also used to assess the linear dependence between the broadband noise and the ice-induced surface roughness height. The Pearson correlation coefficient gives a value between +1 and −1 inclusive, where 1 is total positive linear correlation, 0 is no linear correlation, and −1 is total negative linear correlation. For the relationship showed in Fig. 4-13, the Pearson correlation coefficient calculated based on it is 0.9208, which means the correlation is very strong.

The four red square points shown in Fig. 4-13 are the validation cases used to validate the developed correlation between the arithmetic average roughness height and the broadband noise level. A good validation trend is achieved, with a 7.9% absolute mean deviation.

![Figure 4-13. Correlation between the arithmetic average roughness height and the integrated broadband noise level.](image)

Different averaged roughness heights, which are the accreted ice areas divided by a constant circle perimeter $2\pi R$ (53.16 mm), are also correlated to the integrated broadband noise level. The correlation result is shown in Fig. 4-14. The roughness digitization error is 5% for this averaged roughness height (accreted ice area), which is represented by the vertical. The trend line equation is: $y = 34.241x - 1.1143$. Similarly strong correlation results are obtained (as compared to Fig.
4-13), with an absolute mean deviation of 11.2%. The Pearson correlation coefficient is 0.9592. The validation points fall almost exactly on the trend line, which shows a better validation with a 7.6% absolute mean deviation.

Figure 4-14. Correlation between the averaged roughness height based on accreted ice area and the integrated broadband noise level.
Chapter 5

Trailing Edge Noise Numerical Investigation

As emphasized in Chapter 4, the boundary layer thickness and turbulence intensity due to surface roughness are thought to be two key parameters that cause the trailing noise edge noise increase due to the surface roughness. Due to a lack of experimental measurements of the boundary layer thickness and turbulence intensity due to surface roughness, 2-D numerical simulations were performed to investigate the effects of these on TE noise due to surface roughness. In this chapter, the changes of boundary layer thickness and turbulence intensity due to different surface roughness were predicted; the increased TE noise due to changes of boundary layer thickness and turbulence intensity was estimated by using Howe’s TE noise scaling formula. The goal is to qualitatively explain the present experimental findings that the higher roughness height tends to give a higher noise level. In the final section, TBL-TE and LBL-VS noise spectral scaling is performed.

5.1 Numerical case setup

The commercial CFD software STAR-CCM+ [74] was used to perform the numerical simulation study of the present work. Steady, two-dimensional Reynolds-averaged Navier-Stokes (RANS) computations, with the SST k-omega turbulence model [75] were performed. The numerical simulations in this chapter were run by David Hanson, who works in the CFD group under this icing physics research project. All the rest work (data post-processing, results analysis, etc.) were done by the author.
Three different airfoil shapes at 0 degree angle of attack were investigated: 1) a NACA 0012 clean airfoil with a chord length equal to 0.5334m, which is the same as the “paddle” blade used in AERTS; 2) a NACA 0012 airfoil with small ice-induced surface roughness (case 15 in Fig. 3-7 (b) and Table 3-2); and 3) a NACA 0012 airfoil with large ice-induced surface roughness (case 12 in Fig. 3-7 (a) and Table 3-2). The two roughened airfoil shapes are digitized from the iced airfoils generated in the AERTS test. The digitized iced leading edges are shown in Fig. 5-1 and 5-2. Details of the ice shape digitization procedure is reported in Chapter 4.

Figure 5-1. Airfoil shape with small ice-induced surface roughness (case 15).
For each airfoil shape, simulations were performed at a same freestream velocity Mach number range: 0.1 ~ 0.7. The Reynolds number based on the airfoil chord length and the freestream velocity ranged from: $1.12 \times 10^6$ to $8.10 \times 10^6$. Zero gradient boundary conditions were applied at the inlet and outlet, which means that pressure, and temperature were held constant. Walls were no-slip walls at a constant temperature of 313.15 K. The incoming turbulence intensity was set to be 0.01 and turbulent viscosity ratio was 10. The eddy viscosity ratio is the ratio between the turbulent viscosity and the molecular dynamic (laminar) viscosity. A structured C-grid was chosen as the mesh topology for all three airfoils, with the grid wrapping around the airfoil from the downstream far field, around the lower surface to the upper, then back to the downstream again. To minimize disturbances caused by boundary conditions, the size of the computational domain was chosen sufficiently large. The front of the simulation domain is a half circle with a radius of 10 m, then the domain continues 30 m downstream. The boundary layer around the airfoil is resolved with corresponding $y+$ values of the order $O(1)$. The resulting grid consists of approximately ~260,000 control volumes for iced cases, and 70,000 control volumes for clean cases. The grid structures are shown in Figs. 5-3 and 5-4.
Figure 5-3. Structured C-grid of the iced airfoil with small roughness height (case 15).
Figure 5-4. Structured C-grid of the iced airfoil with large roughness height (case 12).
5.2 Numerical method validation

Before running iced airfoil simulations, a clean NACA 0012 airfoil has been simulated to demonstrate the accuracy and efficiency of the current simulation method.

The validation case used is one of the turbulence archive test cases from the NASA turbulence resource [76]: 2-D NACA0012 Airfoil Validation Case. Simulation results from different CFD solvers with the same turbulence model: SST k-omega, as well as the test data done by Gregory were used to validate the numerical simulation method of the present work. The validation case setup is listed below.

The definition of the NACA 0012 airfoil is slightly altered from the original definition so that the airfoil closes at chord = 1 with a sharp TE. The NACA0012 airfoil formula used is:

\[
y = \pm 0.594689181 \times \left[ 0.298222773 \times \sqrt{x} - 0.127125232 \times x - 0.357907906 \times x^2 + 0.291984971 \times x^3 - 0.105174606 \times x^4 \right]
\]  

(5.1)

The Reynolds number based on airfoil chord used in this validation case was 3.2 million. A C-grid mesh topology was also used for the current validation case, which is the same topology used in the present research. The grid size is 897 × 257, which was considered to be appropriate for the level of validation explored here. Only the case of zero angle of attack was simulated and validated because other angles of attack will not be investigated in the present work.

Simulation results of pressure coefficient \(c_p\) and skin friction coefficient \(c_f\) distribution on the airfoil, as well as their comparison with results of three other different CFD solvers CFL3D, FUN3D and NTS, and Gregory’s test data [77-81] for \(c_p\) are shown in Figs. 5-5 and 5-6. Simulation results from the present numerical method agree well with all three other CFD solvers, as well as with the test data for \(c_p\). A small discrepancy between current simulation method and other CFD solvers can be observed in the skin friction coefficient \(c_f\) as shown in Fig. 5-6. The
sudden drop of $c_f$ near the leading edge is thought to be caused by the transition. The small discrepancy is due to different transition models used in the current numerical method compared to the other three CFD solvers. However, this was not considered to affect the velocity, nor the turbulence intensity profile noticeably at the airfoil TE, which is the main interest of the current simulation.

Figure 5-5. Pressure coefficient validation

Figure 5-6. Skin friction coefficient validation.
Fig. 5-7 presents a comparison of mean velocity profiles normalized by friction velocity plotted in terms of wall units to the law of the wall at the airfoil TE. As one can observe, good agreement with the law of the wall is achieved for the viscous sublayer region, $u^+ = y^+$. However, a small shift in the mean velocity profiles is observed for the log-law region ($u^+ = \log(y^+)/0.41 + 5.0$) when $y^+$ is larger than 40. Notice that the mesh used on the present simulation is not considered to have a high resolution in the log-law region. Therefore the predicted friction velocity may deviate, which would cause the discrepancy. The Von Kármán constant (0.41) and the $C^+$ constant (5.0) used here are values recommended for the smooth wall experiments [82] instead of the values recommended for airfoils. This also could be the cause of this mismatch along the log-law region.

![Law of the wall](image)

**Figure 5-7.** Law of the wall validation.

The generally good comparison shown in the pressure coefficient $c_p$, skin friction coefficient $c_f$, and the law of the wall indicate that the numerical simulation method used in the present study is able to provide accurate results, such as the velocity profile and the turbulent
kinetic energy at the airfoil TE, which will be used to calculate the boundary layer thickness and the turbulence intensity.

5.3 Numerical simulation Results

TE velocity profiles perpendicular to the chord line for the three different airfoil shapes are shown in Fig. 5-8 for a freestream Mach number of 0.2. This Mach number is the same as the tip Mach number of the broadband noise test based on the ice-induced surface roughness performed in AERTS. Both iced airfoils have a larger boundary layer thickness than the clean airfoil. Case 12, which has the largest roughness height, also has a larger boundary layer thickness than case 15. The boundary layer displacement thicknesses found from Fig. 5-8 are $3.02 \times 10^{-3}$ m, $3.44 \times 10^{-3}$ m, and $4.85 \times 10^{-3}$ m for clean airfoil, small roughness airfoil (case 15), and large roughness airfoil (case 12), respectively. This is the same trend seen in the increased SPL level as shown in Fig. 4-3.

![Figure 5-8. Velocity profile at TE.](image)
Fig. 5-9 shows the turbulence intensity of different airfoil shapes at the TE for the Mach number 0.2 case. A normalized integrated turbulence intensity [83] is used to measure the level of turbulent kinetic energy at the TE. This parameter is then used in Howe’s TE noise scaling law to estimate the effect of the turbulence intensity on the TE noise in the next subsection. The equation used to calculate the normalized integrated turbulence intensity is given by Equation 5.2, where $\hat{I}$ is the normalized integrated turbulence intensity, $c$ is the chord length of the airfoil, and $\delta$ is the boundary layer thickness. Integrations based on Fig. 5-9 give $\hat{I}$ values for the clean airfoil, small roughness airfoil (case 15), and high roughness airfoil (case 12) are $1.87 \times 10^{-3}$, $2.10 \times 10^{-3}$, and $2.99 \times 10^{-3}$, respectively. This indicates that a higher roughness height would induce increased turbulent kinetic energy (turbulence intensity) at the TE, which would also correspond to the increased TE noise.

$$\hat{I} = \frac{1}{c} e^{1.5\delta} \int_0^1 I(y) dy$$

(5.2)

![Figure 5-9. Turbulence intensity profile at TE.](image)
5.4 Increased trailing edge noise estimation

Howe’s TE noise scaling law (Equation 5.3) is used here to estimate the increased SPL due to the increased boundary layer thickness and the increased turbulence intensity. \( \bar{\delta} \) is the normalized integrated turbulence intensity described in the previous subsection. \( \delta_1 \), the displacement thickness (rather than the boundary layer thickness or momentum thickness) is chosen as the characteristic length scale used in the noise calculation, which is suggested by the BPM model [29].

\[
\Delta SPL = \left\{ 10 \log \left( \frac{\bar{\delta}^2 M^5 \delta_1 \bar{L}}{\bar{D}} \right) \right\} - \left\{ 10 \log \left( \frac{I^2_{clean} M^5 \delta_1^{clean} \bar{L}}{\bar{D}} \right) \right\} \tag{5.3}
\]

The estimated increased SPL results are shown in Table 5-1. The measured increased SPL levels (as shown in Fig. 4-3) at 18 kHz are also shown in Table 5-1 for comparison purposes. For case 12 with high ice-induced surface roughness height, the total estimated SPL increase (effects due to both displacement thickness \( \delta_1 \) and normalized integrated turbulence intensity \( \bar{\delta} \)) is 6.15 dB, while the measured noise increase is 5.8 dB; For case 15 with small roughness, the total estimated SPL increase is 1.55 dB, while the measured noise increase is 2.6 dB. Given the approximate nature of the Howe’s theory and the use of RANS computations, quite good agreement is achieved between the estimated trailing noise increase based on the TE noise theory and the measured noise increase. This result demonstrates that both the boundary layer thickness and turbulence intensity are important factors that explain the increase of TE noise due to surface roughness. It can also be seen in Table 5-1 that, for both cases, the turbulence intensity contribution is approximately twice that of the increase due to the displacement thickness. A conclusion can be drawn from this is that it is essential for any TE noise prediction model to take into consideration the turbulence intensity to predict the TE noise accurately, especially for blades with surface roughness. Furthermore, in the case of surface roughness due to ice accretion, both
the thickening of the turbulent boundary layer and the increase in turbulence intensity in the boundary layer lead to the increase in broadband noise (especially the high frequency broadband noise).

Table 5-1. Increased TE noise estimation

<table>
<thead>
<tr>
<th></th>
<th>noise increase due to displacement thickness $\delta_1$ (dB)</th>
<th>noise increase due to normalized integrated turbulence intensity $\hat{I}$ (dB)</th>
<th>total estimated noise increase (dB)</th>
<th>measured noise increase at 18 kHz (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>case 12 (large roughness)</td>
<td>2.05</td>
<td>4.09</td>
<td>6.15</td>
<td>5.8</td>
</tr>
<tr>
<td>case 15 (small roughness)</td>
<td>0.56</td>
<td>0.99</td>
<td>1.55</td>
<td>2.6</td>
</tr>
</tbody>
</table>

5.5 Spectral scaling

In the previous section, a consideration of the physical cause of the TE noise increase is:

1) Boundary layer thickness; 2) Turbulence intensity, due to the ice-induced surface roughness.

By implementing the predicted displacement thickness and the normalized integrated turbulence intensity into Howe’s TE noise scaling law, the estimated trailing noise increase matches well with the experimental results at high frequencies (18 KHz). One concern from that is the mean square sound pressure in Howe’s TE noise scaling law (LHS of Equation 4.1) is not a function of frequency, while TE noise does vary with frequency. The increase of the broadband noise due to surface roughness occurs at only high frequencies and its magnitude varies at different high frequencies. This indicates TE noise theories such as Howe’s TE noise scaling law are not adequate when studying the TE noise level at different frequencies. Therefore, to investigate how different SPL frequency component of TE noise scale with different rotor blade size, rotational speed, roughness height, etc., SPL spectral scaling must be performed.
In this section, the LBL-VS noise scaling results are presented first. This noise source is thought to be absent when relatively large ice-induced surface roughness features are present, which causes transition to a turbulent boundary layer. However, the LBL-VS noise could still contribute to the total rotor broadband noise to some extent (mainly at low frequencies where the quasi-tones exist) as seen in the result shown in the experiments (Fig 4-4). Rather than a detailed study of the LBL-VS noise mechanism, the intent of the current spectral scaling of the clean blade broadband noise results here is to confirm the noise source (LBL-VS noise) by scaling the quasi-tonal noise on a Strouhal number basis [29, 84, 87]. The scaling results would also help to identify the LBL-VS noise existing in the roughened blade rotor tests. For instance, in the following cases: 1) the inner part of the “paddle” blade where the blade is clean and the flow speed (Reynolds number) is low in the AERTS test, and 2) the inner blade of the rotor applied with texture paint in the UMAC test in which the flow speed is small and the roughness height might be too small to fully trigger the turbulent boundary. The LBL-VS noise would exist and contribute to the total measured broadband noise due to existence of the laminar boundary in the aforementioned locations.

For the TBL-TE noise, a detailed SPL spectral scaling study is conducted. A primary purpose is to assess the velocity scaling of the roughness generated noise (TE noise). Another scaling parameter investigated is the characteristic length. The intention is to study how the broadband noise due to surface roughness scales over different roughness heights.
5.5.1 LBL-VS noise spectral scaling

5.5.1.1 UMAC test clean blade results spectral scaling

The measured SPL results of the clean blade at different blade tip Mach numbers are shown in Fig. 5-10. The quasi-tonal nature of the LBL-VS noise can be clearly seen, for example, the spectra peak at about 20 kHZ of the tip Mach number 0.3 case. As the tip Mach number increases, the LBL-VS noise peak frequency shifts to higher frequencies. The peak level tends to increase in magnitude. Also the peak broadens to wider frequency ranges.

![clean blade measured SPL](image)

Figure 5-10. UMAC measured SPL of the clean blade.

There are no LBL-VS noise scaling methods established in the literature [29] because of the erratic behavior of the multiple tones in the narrow-band spectra and the general complexity of the mechanism. However, the initial scaling guidance provided by previous experimental and theoretical studies [29, 84, 87] is that the LBL-VS noise peak level could scale on a Strouhal basis with the relevant length scale being the laminar boundary thickness at the airfoil TE. The
scaling approach taken herein is the same as that used by Brooks et al. [29], which is Howe's TBL-TE noise scaling law. The Strouhal scaling was conducted, in which the displacement thickness from numerical simulations of the clean airfoil were used as the length scale. The values of the displacement thickness at TE are listed in Table 5-2. Fig. 5-11 shows the scaled SPL results of the clean blade. As can be seen, the frequency dependence of the LBL-VS noise quasi-tone with different tip Mach number coalesces around Strouhal number 0.8 - 1.0. The peak level coalesces within about 5 dB.

<table>
<thead>
<tr>
<th>Mach number</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement thickness $\delta_1 (10^{-3})$</td>
<td>2.83</td>
<td>2.72</td>
<td>2.65</td>
<td>2.81</td>
<td>3.01</td>
</tr>
</tbody>
</table>

Figure 5-11. UMAC scaled SPL of the clean blade.
For the case of blade tip Mach number at 0.7, as shown in the black line in Fig. 5-10 and 5-11, a high-frequency SPL peak is observed at about 80 KHz. The exact source mechanism of this peak is unknown. To try to understand the cause of this high frequency peak at this high tip Mach number, the SPL at every 0.01 Mach number of the clean blade was measured from Mach number 0.6 to 0.7 as shown in Fig. 5-12. The peak gradually forms around 65 KHz when the blade tip Mach number is larger than 0.6. As the blade tip Mach number increases from 0.6 to 0.7, the peak frequency increases.

![Clean blade measured SPL](image)

Figure 5-12. UMAC measured SPL of the clean blade at high tip Mach number.

5.5.1.2 AERTS test clean blade results spectral scaling

Fig. 5-13 shows the measured clean “paddle” blade SPL results. A similar trend is observed that the peak frequency and level increases with the blade RPM (tip velocity). Due to the small tested tip velocity range (tip Mach number from 0.13 to 0.2 corresponding to RPM from 300 to 450) tested in the AERTS, the noise peak is not broadened (due to the increased RPM) as much as that seen in the UMAC test.
Figure 5.13. AERTS measured SPL of the clean “paddle” blade.

Scaled results of the AERTS clean “paddle” blade are shown in Fig. 5.14. Due to the lack of the measured or numerical simulated boundary thickness, the same length scale was used in the Strouhal number calculation for cases with different RPM, which is 0.001 mm/chord length = 0.00187. Good frequency collapse is observed that the LBL-VS noise peaks from three different RPM coalesce well in a Strouhal number range 0.02 - 0.03.
5.5.2 TBL-TE noise spectral scaling

The fundamental scaling law of the TBL-TE noise is based on the analysis of Howe [36] as shown in Equation 4.1. It is obvious that the most important scaling parameters are the characteristic scales of velocity and length ($U$ and $l$). In this section, spectral scaling results based on the velocity and length are presented separately. The characteristic velocity used was the blade tip velocity and the characteristic length was the characterized roughness height. Due to the lack of the detailed 2-D roughened airfoil flow tests, other characteristic velocities (shear velocity, and turbulence velocity, etc.) and lengths (boundary thickness at TE) were not available for the scaling.
5.5.2.1 UMAC test results spectral scaling

Velocity scaling

As stated in Chapter 3, the primary motivation of the UMAC test was to study the scaling of the roughness generated noise. To investigate the effects of different velocity scales on the broadband noise due to surface roughness, a series of measurements were taken over a wide range of blade tip velocities (tip Mach number from 0.1 to 0.7). The measured SPL with different blade tip velocities for rotor with four different surface roughness types 0.1mm texture paint, 0.2 mm texture paint, 0.5 mm glass beads, and 1.02 mm sugar crystal are shown in Figs. 5-16 – 5-19 separately. The measured broadband noise results at blade tip Mach number 0.1 and 0.2 are not shown because of the electromagnetic interference. As can be seen in Figs. 5-16 – 5-19, for all four different types of surface roughness, one important behavior that results from changes in velocity is that the sound level rises significantly with increases in velocity. For example, each spectrum curve is separated by at least 4 dB from the next closest curve for the blade with 0.5 mm glass beads.

For rotor blade with 0.1 mm and 0.2 mm texture paint as shown in Fig 5-16 and 5-17, the spectral shape of each tip Mach number at high frequencies (frequencies larger than 60 kHz) looks similar to each other, while at low frequencies a SPL peak is seen for each tip Mach number whose shape changes with the tip Mach number. This low-frequency SPL peak was thought to be caused by the LBL-VS noise because it behaves like the LBL-VS noise peak as described in previous section: the tip Mach number increases, the peak frequency and level increases and the peak broadens. The existence of such LBL-VS noise peak indicates that the laminar boundary might persist even with the texture paint due to the relatively small roughness height. For the rotor blade with 0.5 mm glass bead and 1.02 mm sugar crystal as shown in Fig 5-18 and 5-19, no LBL-VS noise was noticed. SPL spectra from each tip Mach number show the
same spectral shape for the entire frequency range: 0 to 100 kHz. This illustrates the possibility of the velocity scaling based on the absolute frequency.

Figure 5-15. Measured SPL spectra of blade with 0.1 mm texture paint at different tip Mach numbers.

Figure 5-16. Measured SPL spectra of blade with 0.2 mm texture paint at different tip Mach numbers.
Figure 5-17. Measured SPL spectra of blade with 0.5 mm glass beads at different tip Mach numbers.

Figure 5-18. Measured SPL spectra of blade with 1.02 mm sugar crystal at different tip Mach numbers.

Scaled SPL spectra of the cases with 0.1 mm and 0.2 mm texture paint for different exponents of tip Mach number and on the absolute frequency are shown in Figs. 5-19 and 5-20. For both texture paint cases, the peaks do not coalesce on the absolute frequency. This result is as
expected because the peak was thought to be the LBL-VS noise and should be scaled on a Strouhal number base rather than the absolute frequency. The SPL at high frequencies (frequencies larger than 60 kHz), where the tonal LBL-VS noise disappears, was thought to be from the TBL-TE noise. Figs. 5-19 and 5-20 show that the TBL-TE noise (high-frequency SPL spectra) coalesces well on the absolute frequency. As can be seen in Fig. 5-19, for the blade with 0.1 mm texture paint, the TBL-TE noise coalesce the best on a 5.5 power of the tip Mach number. The SPL spectra from different tip Mach numbers coalesce to within about 3-4 dB at high frequencies as compared to a 25 dB scattering of the original SPL spectra in Fig. 5-15. Other tip Mach number scaling laws (4.5, 5, and 6) do not coalesce the measured SPL at high frequencies as well as the 5.5 power. For the blade with 0.2 mm texture paint as shown in Fig. 5-20, the high frequency TBL-TE noise coalesce the best (within 2-3 dB) on the 6th power of the tip Mach number. The 6th power scaling would indicate a dipole source rather than the TE noise. It might be because of the existence of the unsteady loading noise in this high-frequency range, which has a dipole nature that scales to the 6th power of the tip Mach number. Other reasons might be that, 1) the blade tip velocity used in the scaling is not as assumed (turbulence convection velocity) in the TE noise theory; 2) the existence of the LBL-VS noise may have some impacts on the high-frequency spectra which results in the this 6th power velocity scaling; 3) Different Reynolds numbers due to different spanwise velocities should have some impacts on the velocity scaling. For example, the single blade tip velocity (Mach number) used in the scaling may not be an ideal scaling velocity that could take all spanwise velocities into consideration.
Figure 5-19. Scaled SPL spectra of blade with 0.1mm texture paint based on different number of power law of flow velocities and absolute frequency.
Figure 5-20. Scaled SPL spectra of blade with 0.2mm texture paint based on different number of power law of flow velocities and absolute frequency.

To confirm that the peak discussed above is caused by the LBL-VS noise, a Strouhal number based scaling was conducted on the measured SPL of the blade with 0.1 mm and 0.2 mm texture paint as shown in Figs. 5-21 and 5-22. The scaling approach used here was the same as used in section 5.5.1 for the LBL-VS noise scaling. The length scaled used for different tip Mach numbers was the roughness height (0.1 mm and 0.2 mm) normalized by the blade chord due to the lack of the measured boundary layer thickness. For both texture paints, the peaks coalesce to a
similar extent as that shown in the clean blade LBL-VS noise scaling results in Fig. 5-11. This indicates that the LBL-VS noise is the source mechanism of the low frequencies peak of the blade with texture paint. Another point should be noticed from Fig. 5-21 and 5-22 is that the high-frequency part of the SPL spectra from different blade tip velocities do not collapse on the Strouhal basis.

Figure 5-21. Scaled SPL spectra of blade with 0.1 mm texture paint based on different number of power law of flow velocities and Strouhal scaling.
Scaled SPL spectra of blade with 0.2 mm texture paint based on different number of power law of flow velocities and Strouhal scaling.

Scaled SPL spectra of blade with 0.5 mm glass beads and 1.02 mm sugar crystals for different exponents of tip Mach number and on the absolute frequency are shown in Figs. 5-23 and 5-24. For the blade with 0.5 mm glass beads, the spectra scale the best on a fifth Mach number law, which coalesce within 3 to 4 dB in the frequency range from 0 to 60 kHz and within 6 to 7 dB at the high frequencies (larger than 60 kHz). A point to notice is that the spectra at high frequencies (larger than 50 kHz) coalesce well (within 5 dB) on the 6th power of the tip Mach number as shown in Fig. 5-23 (d). As discussed before, this could be because of the contribution of the unsteady loading noise, which has the dipole nature and scales to the 6th power of the tip Mach number, or due to that the blade tip velocity may not be the appropriate scaling velocity.

For the blade with 1.02 mm sugar crystal, the spectra at low frequencies (smaller than 50 kHz) show a better collapse on the 4.5 power of the tip Mach number as shown in Fig. 5-34 (a), and a better collapse on the 5th power for the spectra at high frequencies (larger than 50 kHz) as shown in Fig. 5-34 (b). The overall (all frequency range) spectra still scale the best on a fifth Mach
number law. Although for both cases with 0.5 mm glass beads and 1.02 sugar crystal, the overall (all frequency range) broadband noise SPL spectra scale the best on the 5th power of the tip Mach number compared to other exponents, the difference of how they scaled on low frequencies (smaller than 50 kHz) and high frequencies (larger than 50 kHz) separately should be noticed. The exact reason of this scaling behavior is unknown. A hypothesis is that the scaling velocity used, which is the blade tip velocity, is not proper. The turbulence convection velocity should be used for the scaling, but it is not available from the current test.

For both cases with glass beads and sugar crystal, no LBL-VS noise peak is observed at low frequencies as compared to the cases with texture paint. This indicates that the glass beads and sugar crystals (roughness height larger than 0.5 mm) are able to fully trip the blade boundary layer for all tip Mach numbers from 0.3 – 0.7 due to their relatively large roughness heights.
Figure 5-23. Scaled SPL spectra of blade with 0.5mm glass beads based on different number of power law of flow velocities and absolute frequency.
Figure 5-24. Scaled SPL spectra of blade with 1.02 mm sugar crystal based on different number of power law of flow velocities and absolute frequency.

Length scaling

As discussed in Chapter 4, the effect of the roughness height on rotor broadband noise is that the measured high-frequency broadband noise increases significantly with increasing surface roughness heights. In this subsection, an investigation of SPL spectral scaling based on the length scale is conducted. The purpose is to study if the broadband noise due to different surface roughness height would scale/coalesce for a particular characteristic length. Fig. 5-25 shows the
noise levels measured for each of the different roughness cases at different blade tip velocities. Generally the SPL levels increase as the roughness height is increased at frequencies larger than 40 kHz for all blade tip velocities.

Another interesting point is the transition of the LBL-VS noise to the TBL-TE noise as the blade tip velocity (Reynolds number) increases. As discussed early, for a blade with 0.1 mm and 0.2 mm texture paints, the SPL at low frequencies is dominated by the LBL-VS noise especially at low blade tip velocities. The low-frequency LBL-VS noise peak can be seen in most low blade tip Mach numbers: 0.3, 0.4, 0.5. As the blade tip Mach increases to 0.6 and 0.7, the LBL-VS noise peak SPL spectra of the blade with 0.1 mm and 0.2 mm texture paints disappears gradually. This results in a similar SPL spectral shape (TBL-TE noise spectra shape) as those of the blade with 0.5 mm glass beads and 1.02 mm sugar crystal. This transition from the LBL-VS noise to the TBL-TE noise is an acoustic indication to the transition of the flow from laminar to turbulent. A detailed examination of this property should be of interest in future work.

![Measured SPL at tip Mach number 0.3](image1.png)  ![Measured SPL at tip Mach number 0.4](image2.png)
Due to a lack of experimental measurements of the boundary layer thickness of different surface roughness, the characteristic length scale used in the current spectral scaling for the UMAC test is the absolute roughness height. Fig. 5-26 shows the SPL spectral scaling results based on the characteristic length at different blade tip velocities. The focus should be placed on the range larger than 40 kHz which is only dominated by the TBL-TE noise. Also it is where the SPL due to different roughness height separates from each other as shown in Fig 5-25. The first feature to notice in Fig 5-26 is the separation of the spectra of the blade with 0.1 mm and 0.2 mm
texture paints from that of the blade with 0.5 mm glass beads and 1.02 mm sugar crystals. This might be because of the difference of the noise source mechanism. For the blade with 0.1 mm and 0.2 mm texture paints, there are always contributions from the LBL-VS noise to the SPL spectra even if at high blade-tip velocities. As for the blade with 0.5 mm glass beads and 1.02 mm sugar crystals, no LBL-VS noise is observed in all blade tip velocities tested. Examination of the scaled spectra only from the blade with 0.5 mm glass beads and 1.02 mm sugar crystals, which is dominated by the TBL-TE noise, revealed the spectra coalesce well on the absolute roughness height.
Figure 5-26. Scaled SPL spectra at different blade tip Mach numbers based on length (roughness height).
5.5.2.2 AERTS icing test results spectral scaling

Velocity scaling

Two different ice-induced surface roughness (small roughness case 15 and large roughness case 12) were used for the velocity scaling of the SPL spectra. Velocity spectral scaling results of other testing cases are not shown here because they all show a similar scaling trend. Fig. 5-27 shows the measured SPL spectra of the rotor with small ice-induced roughness (case 15). As can be seen, higher RPM results a higher SPL over the entire frequency range. A low-frequency peak is observed in all three SPL spectra of different RPMs, which is thought to be the LBL-VS noise peak. As introduced in Chapter 3, during the broadband noise test, the ice-induced surface roughness generated on the inner part of the “paddle” blades, which has a NACA0015 airfoil with smaller chord length, has been removed. The clean blade surface and the relatively low flow speed at the inner part of the “paddle” blades would induce the LBL-VS noise. Consequently the measured broadband noise from all iced “paddle” blades could be composed of both the LBL-VS noise and the TBL-VS noise. The LBL-VS noise dominates the low-frequency peak, while the TBL-VS noise dominates the high-frequency part of the spectra.
Figure 5-27. Measured SPL spectra of rotor with small ice-induced roughness (AERTS case 15).

Scaled SPL spectra of blades with small ice-induced surface roughness for different exponents of tip Mach number and on the absolute frequency are shown in Fig. 5-28. The TBL-TE noise (high-frequency component) coalesces well on both 5.5 and 6 power of the blade tip Mach number. The middle frequency range (6 kHz – 15 kHz) coalesces better on a 5.5 power, while the high-frequency range (15 kHz – 24 kHz) coalesces better on a 6 power. The SPL spectra from different tip Mach coalesce within about 2 dB at high frequencies as compared to an about 11 dB scattering of the original SPL spectra in Fig. 5-27. Other tip Mach number scaling laws (4.5, 5) do not coalesce the measured SPL at high frequencies as well as the 5.5 power. For the LBL-VS noise peaks, a Strouhal scaling is performed as shown in Fig. 5-29. The same length scale was used in the Strouhal number calculation as for cases with different RPM, which is 0.001 mm/chord length = 0.00187. A good collapse of the LBL-VS noise peak around 0.02-0.03 is observed, which is the same as be seen in the clean blade scaling results shown in Fig. 5-14.
Figure 5-28. Scaled SPL spectra of rotor with small ice-induced roughness (AERTS case 15) based on different number of power law of flow velocities and absolute frequency.
Figure 5-29. Scaled SPL spectra of rotor with small ice-induced roughness (AERTS case 15) based on different number of power law of flow velocities and Strouhal scaling.

Another case used for studying the broadband noise velocity scaling is the rotor with large ice-induced surface roughness (case 12). Fig. 5-30 shows the measured SPL spectra of the rotor with large ice-induced roughness. Similar features are observed as for the case of small ice-induced surface roughness shown in Fig. 5-27; for example, 1) the broadband noise level increases with the rotor RPM; 2) the LBL-VS noise peaks are evident.

Figure 5-30. Measured SPL spectra of rotor with large ice-induced roughness (AERTS case 12).
Fig. 5-31 shows the scaled SPL spectra of blades with large ice-induced surface roughness for different exponents of tip Mach number and on the absolute frequency. The TBL-TE noise (high-frequency component) coalesces the best (within about 1 dB) on the 5.5 power of the blade tip Mach number. A Strouhal scaling is performed as shown in Fig. 5-32, to collapse the low-frequency LBL-VS noise peaks. A good collapse is achieved, which is similar to that of the rotor with small ice-induced surface roughness as shown in Fig. 5-29.

Figure 5-31. Scaled SPL spectra of rotor with large ice-induced roughness (AERTS case 12) based on different number of power law of flow velocities and absolute frequency.
Figure 5-32. Scaled SPL spectra of rotor with large ice-induced roughness (AERTS case 12) based on different number of power law of flow velocities and Strouhal scaling.

For both the small and big ice-induced surface roughness velocity scaling results in AERTS test, similar scaling results are observed as those cases in the UMAC test with 0.1 mm and 0.2 mm texture paint: velocity scales better on a larger exponent (5.5 or 6) of the tip Mach number rather than the 5\textsuperscript{th} power. The potential reasons, similar to the UMAC test, are: 1) the existence of the unsteady loading noise, which scales to the 6\textsuperscript{th} power of the tip Mach number; 2) the blade tip velocity used in the scaling is not as assumed (turbulence convection velocity) in the TE noise theory; 3) the existence of the LBL-VS noise may have some impacts on the overall velocity scaling; 4) Reynolds number effects on the scaling.

**Length scaling**

Fig. 5-33 shows the noise levels measured for the rotor with different ice-induced surface roughness at a rotor RPM equals to 450. The number of different roughness used here is 13,
which is the first 13 cases from Table 3-2. Two general trends that are clear in Fig. 5-33 is that sound level increases as the averaged roughness height (both the arithmetic average roughness height $Ra$ and the averaged roughness height based on area $aa$) is increased except below about 5 or 6 kHz where the LBL-VS noise and the background noise dominates. The TBL-TE noise from different ice-induced surface roughness separates more at high frequencies, for example, the SPL separates to about 6 dB at 20 kHz. The second trend is that as roughness height increases the lowest detectable frequency associated with the roughness-induced TBL-TE noise decreases.

![Measured SPL of 13 different ice roughness](image)

Figure 5-33. Measured SPL spectra of rotor with 13 different ice-induced surface roughness at RPM 450.

Both parameters developed in the current study to characterize the ice-induced surface roughness height, 1) the arithmetic average roughness height $Ra$, and 2) the averaged roughness height based on area, are used as the characteristic length for the spectral length scaling. Fig. 5-34 and 5-35 show the SPL spectral scaling results based on the arithmetic average roughness height $Ra$ and the averaged roughness height based on area $aa$ separately. Again here the focus should
be placed on the high frequency part (larger than 5 or 6 kHz), where SPL from different roughness separates from each other. For both length scales, the SPL coalesce within 2 dB except the case 7 which has large Ra and aa values as shown in Table 3-2 but with the lowest measured SPL at high frequencies as shown in Fig. 5-33. Upon examination of the ice-induced surface roughness shape of case 7, as shown in Fig. 5-36, a large bump in the smooth zone is observed around the leading edge, which could contribute significantly to both the average roughness height but not much to the rotor broadband noise. The roughness height in rough zone is relatively small compared to other cases, which is main cause of the increased TBL-TE noise. Consequently the use of the arithmetic average roughness height Ra and the averaged roughness height based on area aa as the characteristic length scaling parameter for case 7 may not be accurate in this case. A better choice of the TBL-TE noise characteristic length scale is the measured displacement thickness at the blade TE as discussed early in this chapter. However, it is not available in the current study.

Figure 5-34. Scaled SPL spectra based on the arithmetic averaged roughness height.
Figure 5-35. Scaled SPL spectra based on the averaged roughness height based on area.

Figure 5-36. Ice-induced surface roughness of case 7.
5.5.3 Spectral scaling summary

1. The scaling results of the LBL-VS noise of clean blades of both the UMAC and the AERTS tests showed that the relatively low-frequency peaks coalesce well on the Strouhal scaling. As for the LBL-VS noise magnitude scaling, although there are no LBL-VS noise scaling methods established because of the erratic behavior of the multiple tones in the narrow-band spectra and the general complexity of the mechanism, the BPM scaling model for the LBL-VS noise seems to work reasonably well on collapsing the magnitude. (UMAC test: about 12 dB divergence collapsed to 6 dB, AERTS test: about 8 dB to 3 dB)

2. For all the AERTS icing blade test and the blade with texture paints of the UMAC test, the low flow velocity and the low (UMAC texture paint) or zero (AERTS “paddle” blade clean inner part) roughness height at the inner part of the blade enables the LBL-VS noise to occur. Consequently, both mechanisms, the LBL-VS noise and the TBL-TE noise, exist. In such cases, scaling methods based on the Strouhal scaling and the absolute frequency must be used to scale the low-frequency LBL-VS noise peak and the high-frequency TBL-TE noise separately. The LBL-VS low-frequency peaks collapse well on the Strouhal basis, while the TBL-TE noise velocity scaling tends to scale to a 5.5th or 6th power of the tip Mach number, which is higher than the 5th power of the TBL-TE noise theory. The length scaling of the TBL-TE noise showed that the TBL-TE noise collapse well on the roughness height.

3. For the cases that only TBL-TE noise dominates (no LBL-VS noise is observed) – test cases with 0.5 mm glass beads and 1.02 mm sugar crystals in the UMAC test –
the TBL-TE noise collapses onto $M^5$ as predicted by the TE noise theory. As for the length scaling, the TBL-TE noise also collapses well on the roughness height (5 dB divergence collapsed to 1 or 2 dB).
Chapter 6

Conclusions

6.1 Summary

Experimental, theoretical, and numerical studies have been conducted to investigate the helicopter rotor noise change during ice accretion. As the acoustic part of a joint helicopter rotor icing physics, modeling, and detection project, the current research aims to provide acoustic insight into the understanding of the rotor icing physics and investigate the feasibility of detecting rotor icing through noise measurements, especially at the early stage of ice accretion. Different helicopter main rotor noise source mechanisms and their change during ice accretion are presented. Changes of the thickness noise, steady loading noise, and especially the TBL-TE noise due to ice accretion are identified and studied.

The change of thickness noise is calculated by comparing the thickness noise of iced and clean airfoils. Although a relatively large ice shape is used, the thickness noise only shows a small change. This is because the volume of the accreted ice is very small compared to that of the entire rotor blade. The calculated steady loading noise also shows a noticeably small change due to ice accretion. Two simplified methods are used to generate the loading on the rotor blades, which is then used as the input for PSU-WOPWOP to calculate the loading noise: 1) compact loading from the blade element momentum theory, icing effects are considered by increasing the drag coefficient; 2) pressure loading from the 2-D CFD simulation, icing effects are considered by using the iced airfoil shape. It is concluded that the discrete frequency noise is changed noticeably during ice accretion, but the change is too small to be used in icing detection.

Rotor broadband noise during ice accretion then becomes the main focus of the current study. Because of the importance of surface roughness to understand the icing physics, as well as
the need to detect the ice at the very beginning of ice accretion, the focus of the current broadband noise study is placed on the early stage of ice accretion, when the “ice” is essentially the ice-induced surface roughness. Due to the difficulties in obtaining the unsteady loading on the rotor blades, which is the input for direct calculation of the related broadband noise, rotor broadband noise measurements are conducted. Comprehensive broadband noise experimental data, in terms of different blade sizes and shapes, different roughness sizes (real ice-induced surface roughness and different synthetic roughness), different rotor rotational speeds, and a wide tip Mach number range, were obtained by conducting measurements in two facilities: the AERTS facility at The Pennsylvania State University, and the University of Maryland Acoustic Chamber (UMAC) at the University of Maryland.

Some proof-of-concept broadband noise measurements by using different sandpapers done at AERTS show that the measured high-frequency broadband noise increases significantly with increasing sandpaper grit size (surface roughness heights), which indicates that it is feasible to quantify helicopter rotor ice-induced surface roughness through acoustic measurements. More comprehensive broadband noise measurements based on the rotor blade accreted ice at the early stage of ice accretion were then conducted. Two roughness description parameters: 1) the arithmetic average roughness height, $R_a$; 2) the average roughness height based on the area under the digitized measurement of accreted ice height, are correlated to the broadband noise level. Strong correlations (absolute mean deviations of 9.3% and 11.2% for correlation using $R_a$ and the averaged roughness height separately) between the ice roughness and the broadband noise level are obtained, which can be used as a tool to quantify ice-induced surface roughness height in the AERTS facility through acoustic measurement. It might be possible to use a similar approach to develop an early ice accretion detection tool for helicopters, as well as to quantify the ice-induced roughness at the early stage of rotor ice accretion.
Rotor broadband noise measurements are then conducted at UMAC to further investigate the broadband noise change at different blade size, roughness height, and rotor RPM (blade tip velocity). Similar trends were observed as in the AERTS tests that the broadband noise at high frequencies increases with the increase of surface roughness heights. Rotor broadband noise source identification is conducted and the broadband noise related to ice accretion is thought to be primarily TBL-TE noise. Theory suggests TBL-TE noise scales with Mach number to the fifth power, which is also observed in the experimental data – supporting the hypothesis that the dominant broadband noise mechanism during ice accretion is trailing edge noise. The trailing edge noise theories developed by Ffowcs Williams and Hall, and Howe both identify two important parameters: boundary layer thickness and turbulence intensity. Numerical studies of 2-D airfoils with different ice-induced surface roughness heights were conducted to investigate the extent that surface roughness impacts the boundary layer thickness and turbulence intensity (and ultimately the TBL-TE noise). The results show that boundary layer thickness and turbulence intensity at the trailing edge increase with the increased roughness height. Using Howe’s trailing edge noise model, the increased sound pressure level (SPL) of the trailing edge noise due to the increased displacement thickness and normalized integrated turbulence intensity are 6.2 dB and 1.6 dB for large and small accreted ice roughness heights, respectively. The estimated increased SPL values agree reasonably well with the experimental results, which are 5.8 dB and 2.6 dB for large and small roughness height, respectively. Finally a comprehensive broadband noise (LBL-VS and TBL-TE noise) spectral scaling for all measured broadband noise in both AERTS and UMAC facilities is conducted. The magnitude and the frequency component of the measured broadband noise are scaled on characteristic velocity and length.
6.2 Concluding remarks

In the present work, the following conclusions can be drawn:

1. The rotor discrete frequency (thickness and steady loading noise) noise is changed noticeably during ice accretion, but the change is too small to be used in icing detection. The small thickness change is due to the small volume of the accreted ice compared to the volume of the blade.

2. The rotor broadband noise, especially in the high-frequency range, is sensitive to the blade surface roughness due to accreted ice, sandpaper, texture paints, sugar crystals, and glass beads. Higher roughness height results in a higher broadband noise level.

3. The ice-induced surface roughness measurements are correlated to the measured broadband noise level from 10 kHz to 24 kHz in the AERTS test. Strong correlations (absolute mean deviations of 9.3% and 11.2% for correlation using $R_a$ and the averaged roughness height separately) between the ice roughness and the broadband noise level are obtained, which can be used as a tool to determine the accreted ice roughness in the AERTS facility through acoustic measurement. It might be possible to use a similar approach to develop an early ice accretion detection tool for helicopters, as well as to quantify the ice-induced roughness at the early stage of rotor ice accretion.

4. Different rotor blade AOAs (from -2 degree to 4 degree) were not found to affect the broadband noise significantly (at most 1 dB) in the high-frequency range used for the correlation (10 kHz to 24 kHz), while the existence of roughness would increase the broadband noise by 4 to 5 dB.
5. The dominant broadband noise mechanism during ice accretion is the turbulent boundary layer – trailing edge (TBL-TE) noise, especially in high frequencies. This is supported by scaling the measured broadband noise, which scales with Mach number to the fifth power.

6. Two parameters are identified to explain the trailing edge noise increase due to surface roughness: 1) boundary layer (displacement) thickness, and 2) turbulence intensity. 2-D numerical simulations show that boundary layer thickness and turbulence intensity at the trailing edge increase with the increased roughness height. Using Howe’s trailing edge noise model, the increased sound pressure level (SPL) of the trailing edge noise due to the increased displacement thickness and normalized integrated turbulence intensity are 6.2 dB and 1.6 dB for large and small accreted ice roughness heights, respectively. The estimated increased SPL values agree reasonably well with the experimental results, which are 5.8 dB and 2.6 dB for large and small roughness height, respectively.

7. The effect of turbulence intensity on the trailing noise is greater than that from boundary layer thickness effects. Turbulence intensity should be considered in any trailing edge noise prediction model, especially for cases with surface roughness.

8. The laminar boundary layer – vortex shedding (LBL-VS) noise is observed in the measured noise results of clean blades, as well as such cases: 1) all AERTS “paddle” blade test results, 2) UMAC test with relatively small roughness height (0.1mm and 0.2 mm texture paint), especially at low RPMs (Reynolds numbers). This is due to the existence of a laminar boundary layer: for AERTS the inner part of the “paddle” blade is clean and the flow speed is low; and for UMAC the roughness height might be too small to fully trigger the turbulent boundary in the
operating conditions where flow speed is low. The low-frequency peak of the LBL-VS noise coalesces well on the Strouhal scaling in those cases.

9. For the measured results with relatively large roughness heights – 0.5 mm glass beads and 1.02 mm sugar crystals in the UMAC test – the TBL-TE noise dominates the broadband noise. No contribution of the LBL-VS noise is observed. The velocity scaling shows that the TBL-TE noise scales with Mach number to the fifth power on the absolute frequency. The length scaling shows that the TBL-TE noise scales well on the absolute roughness height based on Howe’s TE noise theory.

6.3 Significant original contributions

The following significant original contributions are achieved by the present work:

1. A comprehensive helicopter rotor noise investigation during ice accretion is first conducted. The icing effects on all rotor noise source mechanisms are studied.

2. The rotor discrete frequency (thickness and steady loading noise) noise during ice accretion is calculated. The physical causes are discussed. The change is noticeably small, and may not be used in icing detection.

3. Rotor broadband noise measurements due to early stage icing (surface roughness) are conducted in two facilities, the AERTS facility at The Pennsylvania State University, and the UMAC at the University of Maryland. Measured broadband noise results of various blades, surface roughness heights, and rotational speeds are presented. A strong correlation between the measured broadband noise and the surface roughness height is shown: higher roughness height results in a higher broadband noise level.
4. A correlation between the ice-induced surface roughness height and the broadband noise level is developed for the AERTS facility, which may be the basis for an early ice accretion detection tool for helicopters, as well as to quantify the ice-induced roughness at the early stage of rotor ice accretion.

5. The broadband noise source mechanism related to icing is identified to be the TBL-TE noise. The effect of surface roughness on the TBL-TE noise is physically explained.

6. Two important parameters: boundary layer thickness and turbulence intensity are identified to cause the TE noise increase based on the TE noise theory. Numerical simulations are conducted to investigate the effect of different surface roughness on these two parameters, and finally the TE noise. Simulation results show that boundary layer thickness and turbulence intensity at the trailing edge increase with the increased roughness height. The predicted TE noise increase due to the increase of the boundary layer thickness and turbulence intensity agrees well with the experimental results.

7. The velocity and length scalings of the measured TBL-TE noise are conducted. For the measured results with relatively large roughness heights – 0.5 mm glass beads and 1.02 mm sugar crystals in the UMAC test – the TBL-TE noise dominates the broadband noise. No contribution of the LBL-VS noise is observed. For velocity scaling, the TBL-TE noise scales with the fifth power of Mach number; for length scaling, the TBL-TE noise scales well with the absolute roughness height.

Although the present study originated from the helicopter icing problem, the experiment results and conclusions can also be applied to airfoil TE noise problems, especially for roughness cases.
6.4 Recommendations for future work

6.4.1 Full scale helicopter icing detection through acoustic measurements

The present work investigated the helicopter noise change during ice accretion, especially the change of rotor broadband noise at the early stage of ice accretion. A correlation between the ice-induced surface roughness height and the broadband noise level is developed for the AERTS facility, which may be the basis for an early ice accretion detection tool for helicopters. A main recommendation for the future work is to demonstrate the feasibility of detecting ice accretion through broadband noise measurements for full scale helicopters. It would be a very competitive icing detection method because it might use just a microphone which is light and inexpensive. However, quite a few related research topics must be conducted to demonstrate its feasibility:

1. Investigation of noise sources that generated from/related to the entire full scale helicopter.
   
   The main difference between a rotor in the test facility and a full scale helicopter is that a full scale helicopter has all types of noise sources besides the main rotor noise. For example, tail rotor noise, wind noise, and maneuver noise, etc. All these noise sources have the potential to contaminate the high-frequency noise where the TBL-TE noise increase to due to surface roughness is observed. So an investigation of all related noise source mechanisms must be conducted.

2. Microphone location determination
   
   The proper microphone location must be decided based on the noise source study in item 1. An ideal location would be where the TBL-TE noise is in its strong directivity while other sources are in their weak directivity. Microphone arrays, and putting a microphone in the rotational frame should also be considered as alternative ways to mount the microphone if a microphone in the fixed frame cannot detect increase of the TBL-TE noise.
3. Microphone mounting concerns

After the microphone location is determined, certain microphone mounting method must be considered to prevent the microphone from being damaged by the wind, ice, water, and cold temperature.

4. Roughness on the rotor blades

Different types of surface roughness, for example different materials, different roughness heights, need to be considered, as well as how they can be applied on the rotor blades.

6.4.2 General roughness height quantification through acoustic measurements

The present work focused on investigating the noise change due to the ice-induced surface roughness on an airfoil. However, noise change due to other surface roughnesses could be investigated on the same basis. The similar technique could be applied to quantify the roughness height through acoustic measurements. One point should be noticed for general surface roughness investigation is the roughness density effect on the generated noise. In the current study, the roughness density effect is not considered when developing the correlation between the broadband noise and the roughness height because it does not vary in the blade spanwise direction, and it is thought to be able to correlate with the roughness height. But for the general surface roughness investigation, the roughness density is an independent variable and its effect on noise should be studied.

Rather than the investigation on airfoil noise due to surface roughness, another interesting research topic is the sound generated from a roughened wall/airframe, which does not have a sharp trailing edge. Noise from the roughened wall is due to scattering of the turbulence into sound by roughness elements rather than by the trailing edge. A few published literatures [38-40] [87] are available which mainly focused on understanding and predicting the related noise source
mechanisms. However, the similar trend is observed in Grissom’s measurements [38] that higher wall surface roughness height would cause a higher broadband noise level at high frequencies. So it is thought to be valuable to investigate and apply the current technique to quantify the wall surface roughness height through acoustic measurements.

6.4.3 **Boundary layer transition investigation through acoustic measurements**

As described in Section 5.5.2 and showed in Fig. 5-25, the transition from the LBL-VS noise to the TBL-TE noise could be considered as an acoustic indication to the transition of the airfoil flow from laminar to turbulent. This could be used as a potential airfoil boundary layer transition detection method, which only uses a microphone instead of other flow measurement instruments. However, detailed experimental and theoretical studies are recommended be conducted in the future to demonstrate the feasibility.

6.4.4 **Reynolds number effects on rotor broadband noise velocity scaling**

Different Reynolds numbers due to different blade spanwise velocities may have certain impacts on the rotor broadband noise velocity scaling. As pointed out in Section 5.5, the single blade tip velocity (Mach number) used in the velocity scaling may not be an ideal scaling velocity, since it does not consider other spanwise velocities. To study the Reynolds number effects, a 2-D airfoil acoustic measurement is recommended.
References


[74] STAR-CCM+ user manual, CD-adapco Group.


Appendix A

Discontinuous data effects on frequency analysis

As described in Chapter 3, for each measurement in the UMAC test, the 4-second time-domain acoustic pressure saved by LabVIEW is not continuous, in which a random gap exists at every 5000 points or 0.025s based on the 200 kHz sampling rate that has been used. An example of this discontinuous data time history is shown in Fig. A-1. In this section, the effect of such gap in the acoustic data time history on the frequency-domain data analysis is investigated, the purpose is to prove that the high frequencies part (frequencies larger than a couple of thousands Hz) of the signal, which is of interest in the current research, would not be affected by those gaps in the data if appropriate FFT treatments are used, for example, using small segment length (less than 5000 points) without data overlapping.

Figure A-1. Velocity profile at trailing edge.
A.1 Synthetic noise sources

Synthetic acoustic pressure time histories are generated to investigate the gap effects on the frequency-domain data analysis. First, a discrete frequency noise is generated by adding sine waves with different frequency and magnitude together. Then a pink noise, which has a broadband nature similar to the measured rotor broadband noise, is used. For both discrete frequency noise and pink noise, the sampling rate is set to be the same as the UMAC measured data, which is 200 kHz. After the noise source (discrete frequency noise data or pink noise) is generated, a problematic acoustic pressure time history is generated from it by taking out a random length of data at every 0.025 second. This problematic data is used to represent the actual saved acoustic pressure time history (with gaps) by LabVIEW. Finally, different FFT treatments are applied on both generated noise source and the problematic data. The frequency-domain SPL results are compared and discussed.

A.1.1 Discrete frequency noise

Ten sine waves with different frequencies and magnitudes are added together to form the discrete frequency acoustic pressure time history. Frequencies and magnitudes of each sine wave are shown in Table A-1.

Table A-1. Sin wave components of the discrete frequency noise

<table>
<thead>
<tr>
<th>frequency (Hz)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>magnitude (Pa)</td>
<td>10</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Fig. A-2 shows the discrete frequency acoustic pressure time history (in red), as well as the problematic data generated from it (in green) by forming a random gap (zero acoustic
pressure) at every 0.025 second. The final problematic data time history is shown in Fig. A-3, which is formed by taking out the gaps of the green data in Fig. A-2.

Figure A-2. Time history of the discrete frequency noise and the problematic data with random gaps at every 0.025s.

Figure A-3. Time history of the problematic data.

Different FFT treatments are then applied on both the discrete frequency acoustic pressure time history and the problematic data. First, a pure FFT with a Hanning window is done,
which means the FFT is based on the entire length of the data (4 seconds), and no segment overlapping and averaging is done. The frequency-domain SPL results of both data are shown in Fig. A-4. Due to the existence of the random gaps in the data, the SPL from the problematic data at those 10 specific frequencies show a smaller magnitude, which is about 12 dB lower than that from the original data. Also, the problematic data main lobe width of each frequency component is much wider than that of the original data. This means those random gaps in the data contribute a lot of frequency components into the frequency-domain which should not exist in the original data, especially at lower frequencies as shown in Fig. A-4(b).

Generally, in order to get a smoother and clearer SPL trend, FFT is applied on small segments with overlapping along the acoustic pressure time history and an averaging process is done at last based on FFTs of all segments. Such a process is shown in Fig. A-5. The tradeoff by doing so is that the lowest frequency component $f_{\text{min}}$ that can be resolved and the frequency resolution $\Delta f$ (bin width) are limited by the segment length $N_{\text{seg}}$: (1) $f_{\text{min}} = f_s/2N_{\text{seg}}$; (2) $\Delta f = f_s/N_{\text{seg}}$. Where $f_s$ is the sampling rate. So the segment length should not be too small, otherwise low-frequency information would be lost and the frequency resolution would be too low.
Figure A-4. SPL comparison between the original discrete frequency data and the problematic data. FFT segment length: 800K (4 seconds), no overlap, no averaging.
Figure A-5. FFT procedure: windowing, overlapping and averaging.

For discontinuous time history data like the current research, it is obvious that the frequency-domain analysis won’t be accurate if the gap is introduced in any of a single segment, that is when a segment length is larger than 5000 points (0.025s) or overlapping is used. As
shown in Fig. A-6 (a) and (b), which are the SPL comparisons between the original data and the problematic data by using different FFT segment length (5000 and 8000) with overlapping, the SPL from the problematic data is as expected to deviate from the original SPL, which gives an about 2 dB discrepancy in magnitude. Also the main lobe width of each frequency component from the problematic data is wider.
Figure A-6. SPL comparison between the original discrete frequency data and the problematic data. FFT segment length: (a) 5000 (0.025 s); (b) 8000 (0.04s), with 50% segment overlapping and averaging.

To avoid the effect of gaps on the frequency-domain analysis, the segment, on which the FFT applies, must contain a piece of continuous acoustic pressure time history. For current research, this means a segment must be smaller than 5000 (0.025s) and without any overlapping. SPL comparison between the problematic data and the original data is made by using a 5000 segment length without overlapping FFT method, and the result is shown in Fig. A-7. Good agreement between the problematic data and the original data is achieved. A couple of small frequency peaks from problematic data can be seen in Fig. A-7 (a) which do not exist in the SPL from original data, however, the magnitudes of these small frequency peaks are about 35 dB lower than the main frequency component. These small frequency peaks are considered to be small (by 2 orders of magnitude in the linear scale) compared to the main frequency peaks and
can be neglected. For the comparison at low frequencies as shown in Fig. A-7 (b), a big
discrepancy occurs at about 200Hz to 300Hz. However, the frequency range interested in current
research is larger than a couple thousands Hz (based on different rotor RPM) where different
broadband noise from different surface roughness can be distinguished from each other as
described in Chapter 4. Consequently, we can conclude that by taking the FFT on a segment
length with 5000 points and no overlapping, which avoid introducing any gaps in a segment, the
discontinuous data would not affect the frequency-domain analysis for current research.
Figure A-7. SPL comparison between the original discrete frequency data and the problematic data. FFT segment length: 5000 (0.025s), no overlapping, with averaging.
A.1.2 Pink noise

Pink noise is known as a signal with a frequency spectrum such that the power spectral density is inversely proportional to the frequency of the signal. The broadband nature makes pink noise a better representation of the actual rotor broadband noise than the discrete frequency noise. In this subsection, a pink noise acoustic pressure time history is generated by using MATLAB as shown in Fig. A-8. The same sampling rate, 200 kHz, is used as the test in UMAC and the discrete frequency noise. A problematic time history data is also generated from the original pink noise acoustic pressure time history by taking out a gap with random length every 5000 points. The time history of the problematic data is shown in Fig. A-9.

![Pink noise time history and the problematic data with random gaps at every 0.025s.](image)

Figure A-8. Pink noise time history and the problematic data with random gaps at every 0.025s.
The same FFT treatments are applied on both the original pink noise acoustic pressure time history and the problematic data as that has been done on the discreet frequency noise: the segment length is chosen to be 5000 points and no overlapping is used. The purpose is to validate that such FFT treatment also works for a discontinuous pink noise acoustic pressure time history that the frequency analysis is not affected by those gaps in the time-domain data. Fig. A-10 shows the SPL comparison between the original pink noise data and the problematic data. The SPL from problematic data matches well to that from the original data for the entire frequency range, which indicates that current FFT treatment should be used for the frequency analysis of the discontinuous data.
Figure A-10. SPL comparison between the original pink noise data and the problematic data. FFT segment length: 5000 (0.025s), no overlapping, with averaging.

A.2 Real broadband noise from a RC helicopter

A measured broadband noise acoustic pressure time history of a RC helicopter is used in this section to further validate the FFT treatment (small segment length without overlapping) rather than the synthetic acoustic signal described in previous sections. The flight condition of the helicopter is in hover with a tip Mach number 0.32. In order to double-check that current FFT treatment works well for the discontinuous data, two sets of problematic data with different random gaps at every 5000 points are generated from the original acoustic data as shown in Figs. A-11 and A-12.
Figure A-11. Noise time history from the RC helicopter and the problematic data 1 with random gaps at every 0.025s.

Figure A-12. Noise time history from the RC helicopter and the problematic data 2 with random gaps at every 0.025s.
Fig. A-13 shows the SPL comparison between the two sets of problematic data and the original RC helicopter noise by using a 5000 segment length. Both problematic data match very well to the original acoustic data for the entire frequency range. A further validation is done by using a smaller length of the segment (1000 points), which then the SPL has a lower frequency resolution (200 Hz for a 1000 segment length vs. 40 Hz for a 5000 segment length) and more averaging times (800 times for a 1000 segment length vs. 160 times for a 1000 segment length). Although the SPL is much smoother as shown the Fig. A-14, the SPL from the two sets of problematic data still match perfectly to that from the original data. For a 1000 segment length, the lowest frequency that can be resolved is 100Hz and it is much smaller than the smallest frequency range interested in current research which is about a couple of thousands Hz depending on different rotor RPMs. The limitation of the low-frequency range caused by such FFT treatment would not affect the frequency-domain analysis of current research. Consequently, current FFT treatment (segment length smaller than 5000 without overlapping) can successfully take care of the frequency analysis of the UMAC measured data without worrying about the data discontinuity.
Figure A-13. SPL comparison between the original RC helicopter rotor noise data and two sets of problematic data. FFT segment length: 5000 (0.025s), no overlapping, with averaging.

Figure A-14. SPL comparison between the original RC helicopter rotor noise data and two sets of problematic data. FFT segment length: 1000 (0.025s), no overlapping, with averaging.
Appendix B

Additional test results

B.1 AERTS test sandpaper broadband noise results from different RPMs

Fig. 4-1 shows the averaged SPLs for “paddle” blades with sandpapers of different surface roughness heights and the clean blades for the 400 RPM rotational speed. A clear trend is seen in the frequencies higher than 12 kHz. The rougher surface (smaller grit size) gives a higher SPL value. SPL values from the other two rotational speeds – RPM 200 and 300 – are showed here in Figs. B-1 and B-2. The same trend is observed.

![RPM 200, tip Mach number 0.9](image)

Figure B-1. “Paddle” blades test results: SPL from different sandpaper roughness, clean blades, and background noise. RPM = 200.
Figure B-2. “Paddle” blades test results: SPL from different sandpaper roughness, clean blades, and background noise. RPM = 300.

For the modified QH-50 blades, SPL values from the other two rotational speeds – RPM 200 and 300 – are showed in Figs. B-3 and B-4.

Figure B-3. Truncated QH-50 blades test results: SPL from different sandpaper roughness, clean blades, and background noise. RPM = 200.
B.2 AERTS test broadband noise results of all ice-induced surface roughness

The SPL spectra comparison between clean blades and the complete 13 ice-induced roughness shapes is showed in Fig. B-5. The same trend as observed in the sandpaper test is seen: Higher iced roughness shows a higher SPL at high frequencies, even if the ice roughness elements are not as uniformly distributed as those of the sandpaper.
Figure B-5. “Paddle” blades test results: SPL from 13 different ice-induced surface roughnesses and their comparison with that from the clean blades.

B.3 UMAC test broadband noise results of different blade tip Mach numbers

A typical SPL comparison between roughened blades and the clean blade at tip Mach number equal to 0.4 is shown in Fig. 4-4. Measured broadband noise results at other tip Mach numbers (0.3, 0.5, 0.6, and 0.7) are shown in Figs. B-6 – B-9.
Figure B-6. UMAC test results: SPL from 4 different surface roughness and their comparison with that from the clean blade. Mach = 0.3.

Figure B-7. UMAC test results: SPL from 4 different surface roughness and their comparison with that from the clean blade. Mach = 0.5.
Figure B-8. UMAC test results: SPL from 4 different surface roughness and their comparison with that from the clean blade. Mach = 0.6.

Figure B-9. UMAC test results: SPL from 4 different surface roughness and their comparison with that from the clean blade. Mach = 0.7.
Vita

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