WIND TURBINE NOISE: A NEED FOR REGULATION TO KEEP OUR COUNTRY SAFE

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By

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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THE RISE OF WIND TURBINES IN THE UNITED STATES

Since 2008, the United States has doubled its renewable electricity generation with wind energy serving as a prime stepping stone in the path to weaning off fossil fuels. Of the total electricity generated by our country, wind energy systems comprise of 300 million megawatt-hours, or 6.5% of the total grid supply (Marcy, 2019). Although a reliable source of clean energy production, turbines produce a loud, repetitive "wooshing" sound while in operation known as amplitude modulation. Current experimentation with blade design shows promise in mitigating the annoyance associated with loud, repetitive aerodynamic noise created by turbines.

The Technical project associated with this research paper explores potential turbine blade modifications that reduce the total decibel output of wind turbines in operation whilst not over impeding on their efficiency. Currently, an experiment is being prepared to measure the decibel output and electricity generation of a noded, serrated trailing edge, folded wingtip, and standard scaled turbine system when subjected to a constant, laminar wind flow. The data collected will determine the effectiveness of each blade variation and help draw conclusions as to which modifications have the potential for implementation in future wind energy systems, in hopes of reducing annoyance among surrounding dwelling areas.

As the installation of turbine farms continues to rise in the U.S., so does the need for a coherent and research-backed policy limiting the total decibel output of wind farms to protect citizens in the immediate vicinity from adverse health effects. The STS portion of the project explores the negative health effects associated with long-term exposure to wind turbine noise and examines potential technical and policy solutions through the lens of a SCOT framework. The SCOT framework examines how social factors and societal influences mold technology overtime (Klein & Kleinman, 2002), which will become crucial as complaints associated with turbine noise continue to increase and raise concern. In Ontario Canada, a province with noise regulations more stringent than the U.S., the government noise pollution hotline documented 4,575 incident reports related to turbine noise between 2006 and 2016 (Krough et al., 2019.) According to Poulsen et al. (2019), exposure to the repeated noise experienced by the Ontario residents can lead to serious adverse health effects such as sleep loss, stress, and risk of myocardial infarction, augmenting the importance of proper government regulation.

By conducting experimentation of blade design modifications and researching current turbine noise regulations around the world, one could hope to answer the question of how can turbines be designed to reduce their overall noise pollution, and what codes should governments establish and enforce to protect U.S. citizens from the noise pollution turbine farms generate.

THE DANGERS OF WIND TURBINE NOISE EXPOSURE AND LACK OF REGULATION

INCREASE OF WIND TURBINES AND SPREAD OF MISINFORMATION

Cementing their place in the country's plan to wean off of fossil fuels, wind turbines serve as a key component in creating enough clean electricity to meet consumer demand in the future. According to Raman et al. (2016), "The U.S. Department of Energy has examined a scenario that has wind turbine technology providing 20% of the electricity for the United States by 2030" (p.1). If this scenario were to come true, the presence of wind turbines would approximately triple within the next ten years, amplifying the importance of understanding potential long-term health consequences and subduing misinformation.

Misrepresentation of turbine noise safety concerns has spread on the internet convincing citizens that wind turbines cause little to no noise damage when placed at an "adequate" distance away from dwellings. In 2014, GE, the worlds largest turbine manufacturer (Marcy, 2016), published a study stating that turbines only produce 43 decibels at a range of 300 meters and 38 decibels at a range of 500 meters, both of these noise levels being relatively safe for human consumption ("How loud is a wind turbine", 2014, para. 3). However, the study only considers ideologic scenarios and does not take into account real-world variables.

General Electric merely used mathematical models to calculate the decibel outputs of wind turbines at particular distances in their experiment, as opposed to taking field measurements and discovering how much noise currently installed turbines create at the listed distances. Turbine noise output can vary by ten or more decibels when subjected to true meteorological conditions (increased wind speed, turbulent flow near the blades, rain) (Stigwood et al., 2013), meaning turbines placed at a distance of 500 meters from residential areas could reach up to fifty decibels which would be a level unsafe for human consumption, contradicting GE's safety claim. Government regulation and policy stands as the last line of defense in protecting citizens from the potential dangers of high decibel turbine output consumption.

UNREGULATED TURBINE NOISE CAUSING SIGNIFICANT SOCIETAL HARM

In the United States, wind energy noise regulations stand to be improved, as limits vary across the country with little to no scientific backing. To quote from Duncan et al. (2011), "Unlike countries such as the UK and Denmark, the United States does not have a quantitative national noise standard or guideline for wind turbines. Some state regulations are in place, but these vary significantly" (Abstract). Even of the sparse ordinances that do exist, many do not explain their intent or rationale, drawing their threshold numbers from what seems like thin air. Some regulations, such as Michigan's statewide standard, allow turbines to emit up to 55 dBA at property lines. Although this level does not interfere with speech between two people, the decibel limit does not protect against sleep loss when cross-referenced with WHO sound level limits (Duncan et al., 2011), causing potential annoyance amongst citizens who live near these turbine farms.

Many citizens around the world view turbine noise as a nuisance and report negative side effects such as sleep loss and annoyance due to amplitude modulation. A study that examined two semi-rural areas in New Zealand found residents living within two kilometers of wind turbines producing between 24 – 50 dBA scored significantly lower in a health and quality of life survey when compared to residents living more than two kilometers away from a wind turbine. Participants in the study that comprised of the turbine group, or the individuals within two kilometers of the nearest turbine, also submitted many complaints of turbine noise causing general annoyance and contributing to a loss of sleep (Shepherd et al., 2011). Summary statistics for the health and quality of life survey can be see seen in the figure below.

Measure	Turbine group		Comparison group	
	M	*SD*	*M*	*SD*
Physical	27.38	3.14	29.14	3.89
Psychological	22.36	2.67	23.29	2.91
Social	12.53	1.83	12.54	2.13
Environmental	29.92	3.76	32.76	4.41
Amenity	7.46	1.42	8.91	2.64

Figure 1: Results of New Zealand HQOL survey: The turbine group reported lower scores in every category of the survey, indicating that turbine noise was perceived as extremely annoying amongst affected residents. From "Evaluating the impact of wind turbine noise on health-related quality of life", by Shepherd et al., 2011, *Noise and Health, 13(54),* p.336. Copyright 2011 by Noise and Health.

Reports of turbine annoyance are not strictly concentrated in New Zealand but extend to other parts of the world as well. Citizens living near turbine farms in the province of Ontario, Canada filed 4,575 incident reports to the government hotline directly relating to wind turbine noise, with only one percent of reports receiving a priority response (Krough et al., 2019). Residents complained of experiencing headaches, ringing or pressure sensations in the head, general annoyance, and sleep deprivation due to turbine noise. Lack of government attention to the reported complaints raises worry, as the aforementioned symptoms can lead to the formation of unfavorable medical conditions later on in life.

Long-term exposure to repetitive noise produced by wind turbines not only causes annoyance among nearby inhabitants but puts their health and safety in serious danger, increasing their risk of experiencing myocardial infarction and stroke later in life. In the above sections, many people complained of stress and loss of sleep due to turbine noise, both of which are common in heart attack victims. When examining symptoms of patients who had experienced a myocardial infarction, 45.5% reported high-stress levels and 27.7% reported sleep loss prior to their health scare (Singh et al., 2004). A study conducted on the Danish population living within twenty turbine lengths away from a turbine farm between 1983-2013 found that "the rate of experiencing myocardial infarction was higher in groups of people exposed to wind turbine noise of 42dB(A) 7 when compared to those exposed to only 24 dB(A) for both 1 and 5 year exposure times" (Poulsen et al., 2019, p. 7). Without proper government regulation, similar instances could become commonplace in the United States as we begin to install more turbine farms across the country.

THE SOCIAL IMPLICATIONS OF WIND TURBINE NOISE AND FUTURE POLICY

ANALYSIS THROUGH AN STS LENS

The Social Construction of Technology framework focuses on how social factors and forces shape the way in which technological design ensues in the future (Klein & Kleinman, 2002). In the scope of wind energy systems, social factors include the potential long-term effects of turbine noise pushing designers to develop quieter designs for future implementation. By examining the framework's four main tenants of interpretive flexibility, relative social groups, closure and stabilization, and the wider context, an outline of how design strategy and government policy must change over time can be constructed.

Interpretive flexibility focuses on the technical design being an open process that produces different outcomes based on the social circumstances of development (Klein & Kleinman, 2002). Original turbine blade designs consisted of long, smooth blades that produced high levels of amplitude modulation offered little to no noise reduction mechanisms. During their inception, turbine manufacturers focused primarily on blade efficiency or generating the most electricity possible. Noise pollution most likely did not occur to many engineers, since little to no turbines were operating, providing no annoyance for citizens to complain about.

Relative social groups consist of all the members of a particular social unit that share the same meanings attached to a specific artifact (Klein & Kleinman, 2002). When considering the manufacturing and implementation of turbine farms, the three key social groups consist of turbine manufacturing companies, government regulators, and citizens in dwelling areas sufficiently near (roughly 500 meters or closer) to wind turbines. Turbine manufacturing companies possess the upper hand out of all three groups, as our society desperately needs their green energy systems. They ultimately determine the effectiveness and noise production of turbines themselves through the designs they create. Government officials offer companies contracts based on the performance of their wind energy systems and give companies permission to install turbines in certain areas. Regular citizens both benefit and reap the negative effects of wind farms, as they consume the electricity they generate to go about their daily lives, but must also put up with the noise pollution they emit.

Closure and stabilization refers to the evolution of the design process until conflicts between social groups become quelled (Klein & Kleinman, 2002). As complaints among people living near turbine farms continue to increase, one could hope blade designers consider the concerns of the public and incorporate design techniques that aim to reduce the total decibel output emitted by wind turbines. Blades that integrate relatively simple modifications such as angle of attack adjustments and trailing edge serrations show promise in the reduction of total turbine decibel output without impeding on turbine efficiency (Oerlemans et al., 2009). Once turbines no longer cause mass annoyance among the general public but still generate sufficient electricity to please manufacturers and government officials, the conflict of annoyance with amplitude modulation could be considered closed.

The wider context consists of the way an artifact affects personal and political environments beyond its original function (Klein & Kleinman, 2002). Unforeseen consequences of turbine noise do not only consist of sleep disruption and stress amongst adjacent residences but policy formation as well. Lackluster turbine noise ordinances in the United States exist few and far between and invite much criticism (Duncan et al., 2011). With the rise of evidence supporting negative health effects associated with turbine noise exposure, policymakers may face pressure in the future to implement stricter policies to protect citizens as the installation of wind energy systems continues to increase.

RESEARCH RECOMMENDATIONS FOR U.S. POLICYMAKERS TO FOLLOW

With scattered and unsafe noise ordinances littered around the country, the U.S. desperately needs a uniform, national policy with a scientific basis to limit turbine noise output at the property line of human dwelling areas for the sake of health and human safety. Citizens simply cannot rely on falsified studies and outdated, scattered state/local turbine noise edicts to protect themselves from developing serious medical conditions caused by overexposure to amplitude modulation. Luckily, examples of proper regulation exist and can serve as models for our federal government lawmakers to build off of.

In Centerville Township, Michigan a subcommittee dedicated four years to studying academic literature, interviewing residents living in close proximity to turbines, and consulting with experts to form a cohesive policy backed by scientific basis and concern for human safety and welfare. The policy limited turbine noise at property lines to 35 dBA or the ambient background noise plus 5 dBA (whichever was lower), from the hours of 6 am to 10 pm, and permitted turbines to produce a maximum of 5dBA above the background noise during the night time hours (Duncan et al., 2011). The ordinance makes it so citizens of Centerville Township cannot hear turbines while on their property, protecting them from hearing loss, sleep loss, speech interference, annoyance, and any other potential negative adverse health effects associated with amplitude modulation.

The Michigan policy runs consistent with findings from other research groups working on finding the absolute limit of turbine noise consumption that results in no negative health or well-being consequences. In 2011, an acoustic consulting firm funded by the United States Department of Energy stated, "As an ideal design goal, it is advisable for new projects to attempt to maintain a mean SPLs of 40 dBA or less outside all neighboring residences" (Raman et al., 2016, p.325). Similarly, in 2013, a group of acoustical consultants in the U.K called for the limitation of turbine noise to be no more than 5 dBA above the ambient background noise, and in areas with low background noise, the output should be limited to 35-40dBA (Raman et al., 2016). With multiple instances of researchers and successful policies providing similar insight, U.S. lawmakers should have no trouble creating a national policy limiting turbine noise based on the findings of acoustical firms and current successful policy.

VISUALIZING HOW NOISE LIMITATIONS AND BLADE DESIGN CURB A FUTURE HEALTH CRISIS

After examining the broad scope and many variables associated with turbine noise and citizen annoyance, an overall picture of the problem can be understood. The pictorial below displays the domino effect of how noise sensitivity to amplitude modulation snowballs into serious health consequences and overall lower quality of life for residents who experience this problem.

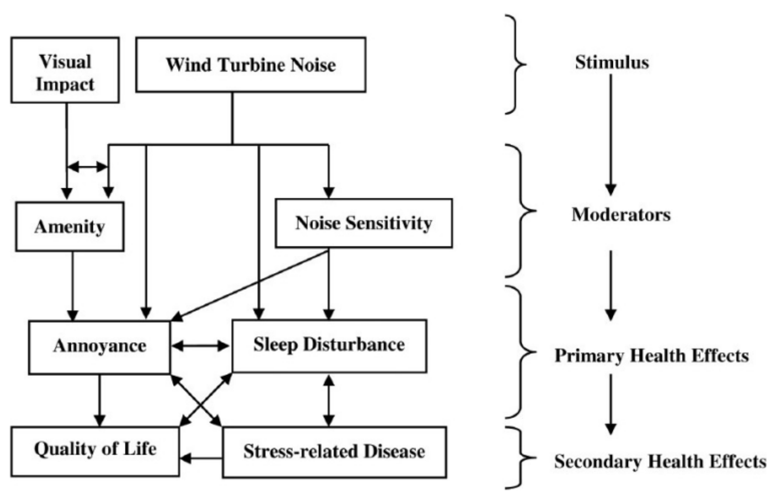

Figure 2: Turbine Noise Consequences: The costs of turbine noise on society have been illustrated and show how minor symptoms lead to more serious health consequences. (Shepherd et al., 2011, Introduction).

Fortunately for Americans, many of these issues prove to be easily mitigated through government and design engineer action. The graphic below illustrates how a combination of policy and alterations to the turbine blade design process help reduce and protect citizens from the adverse health effects associated with long-term exposure to wind turbine noise.

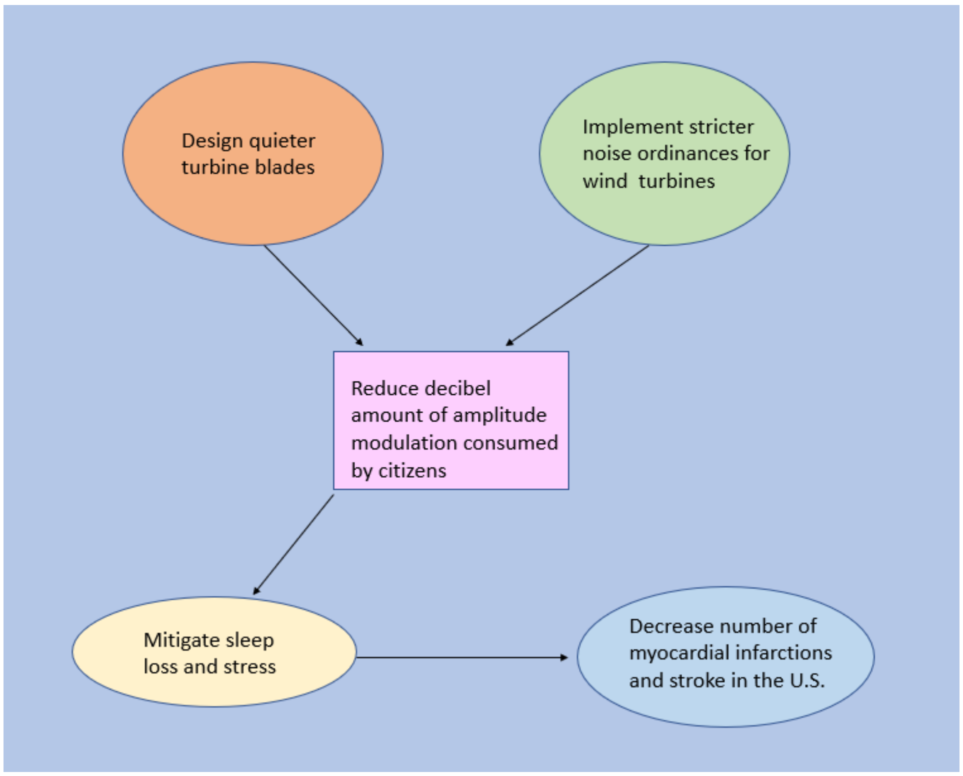

Figure 3: Mitigating Turbine Noise Damage: Image displays how a combination of proper policy and blade design improvements ultimately help reduce U.S. citizen's risk of myocardial infarction and stroke. (Jacobson, 2021).

The call to action for members of the U.S. worried about the dangers associated with wind turbines remains clear cut: urge turbine companies to reduce overall noise output through intelligent design and pressure lawmakers to protect citizens from amplitude modulation through strict regulation on overall noise consumption at property lines within the vicinities of turbine farms.

MOVING FORWARD

With the United States aiming to generate 30% of the total grid supply from wind energy by 2030 (Raman et al., 2016), engineers designing turbine blades have an ethical responsibility to develop aerodynamic noise reduction techniques in both currently operating and future turbine systems. Our ability to design quieter turbine blades shows promise with many simple modifications resulting in a significant amount of noise reduction without disrupting the system's overall electricity generation. Experimental data collected in the technical report contributes to the effort of reducing amplitude modulation.

In addition to developing quieter turbines, the government must look to other nations and certain homeland localities to formulate a universal noise ordinance for wind energy systems, protecting citizens from health consequences such as sleep loss and stress which in turn increases risk for stroke and myocardial infarction in the future. Duncan et al. (2011) provide a brilliant list of demands for the government moving forward, stating the need for a cohesive federal policy that shows:

> A clear understanding of what the legislation is made to protect, an understanding of the fundamentals of noise and the literature on noise impacts and wind turbine-specific issues, and an intention to protect against hearing loss, long-term health impacts, and sleep deprivation through quantitative limits, whether absolute or relative. (Conclusion)

Supporting research and policy calls for turbines to emit no more than 35-40 dBA at property lines during daytime hours, and no more than 5 dBA above the background noise during the night. Implementing this restriction across the country would provide a safe environment for all Americans and give turbine manufacturing companies a clear-cut goal to strive for in future design processes.

WORKS CITED

Duncan, E. C., Eros, E. J., & Old, I. H., P. 161st Acoustical Society of America Meeting.

How loud is a wind turbine? (2014, August 2). https://www.ge.com/news/reports/how-loud-is-a-wind-turbine#:~:text=The%20closest%20that%20a%20wind,run%20at%20around%2040%20decibels.

Jacobson, N. (2021). *Mitigating Turbine Noise Damage*. [Figure 3]. *STS Research Paper:Wind Turbine Noise: A Need For Regulation To Keep Our Country Safe* (Unpublished undergraduate thesis). School of Engineering and Applied Science, University of Virginia. Charlottesville, VA.

Klein, H. K., & Kleinman, D. L. (2002). The social construction of technology: Structural considerations. *Science, Technology, & Human Values*, *27*(1), 28-52.

Krogh, C. M., & Magentica Research Group. (2019). Wind Turbine Incident/Complaint Reports in Ontario, Canada: A Review—Why Are They Important?. *Open Access Library Journal*, *6*(02), 1.

Marcy, C. (2016, November 28). *Three turbine manufacturers provide more than 75% of U.S. wind capacity*. US Energy Information Administration. https://www.eia.gov/todayinenergy/detail.php?id=28912

Marcy, C. (2019, March 19). *US renewable electricity generation has doubled since 2008*. US Energy Information Administration. https://www.eia.gov/todayinenergy/detail.php?id=38752

Oerlemans, S., Fisher, M., Maeder, T., & Kögler, K. (2009). Reduction of wind turbine noise using optimized airfoils and trailing-edge serrations. *AIAA journal*, *47*(6), 1470-1481.

Poulsen, A. H., Raaschou-Nielsen, O., Peña, A., Hahmann, A. N., Nordsborg, R. B., Ketzel, M., ... & Sørensen, M. (2019). Long-term exposure to wind turbine noise and risk for myocardial infarction and stroke: a nationwide cohort study. *Environmental health perspectives*, *2019*(3), 037004.

Raman, G., Ramachandran, R. C., & Aldeman, M. R. (2016). A review of wind turbine noise measurements and regulations. *Wind engineering*, *40*(4), 319-342.

Shepherd, D., McBride, D., Welch, D., Dirks, K. N., & Hill, E. M. (2011). Evaluating the impact of wind turbine noise on health-related quality of life. *Noise and Health*, *13*(54), 333-339.

Singh, R. B., Pella, D., Neki, N. S., Chandel, J. P., Rastogi, S., Mori, H., ... & Gupta, P. (2004). Mechanisms of acute myocardial infarction study (MAMIS). *Biomedicine & pharmacotherapy*, *58*, S111-S115.

Stigwood, M., Large, S., & Stigwood, D. (2013, August). Audible amplitude modulation—results of field measurements and investigations compared to psychoacoustical assessment and theoretical research. In *Fifth International Conference on Wind Turbine Noise*.

BIBLIOGRAPHY

Duncan, E. C., Eros, E. J., & Old, I. H., P. 161st Acoustical Society of America Meeting.

How loud is a wind turbine? (2014, August 2). https://www.ge.com/news/reports/how-loud-is-a-wind-turbine#:~:text=The%20closest%20that%20a%20wind,run%20at%20around%2040%20decibels.

Jacobson, N. (2021). *Mitigating Turbine Noise Damage*. [Figure 3]. *STS Research Paper:Wind Turbine Noise: A Need For Regulation To Keep Our Country Safe* (Unpublished undergraduate thesis). School of Engineering and Applied Science, University of Virginia. Charlottesville, VA.

Jianu O, Rosen MA, Naterer G. Noise Pollution Prevention in Wind Turbines: Status and Recent Advances. *Sustainability*. 2012; 4(6):1104-1117.

Klein, H. K., & Kleinman, D. L. (2002). The social construction of technology: Structural considerations. *Science, Technology, & Human Values*, *27*(1), 28-52.

Krogh, C. M., & Magentica Research Group. (2019). Wind Turbine Incident/Complaint Reports in Ontario, Canada: A Review—Why Are They Important?. *Open Access Library Journal*, *6*(02), 1.

Marcy, C. (2016, November 28). *Three turbine manufacturers provide more than 75% of U.S. wind capacity*. US Energy Information Administration. https://www.eia.gov/todayinenergy/detail.php?id=28912

Marcy, C. (2019, March 19). *US renewable electricity generation has doubled since 2008*. US Energy Information Administration. https://www.eia.gov/todayinenergy/detail.php?id=38752

Oerlemans, S., Fisher, M., Maeder, T., & Kögler, K. (2009). Reduction of wind turbine noise using optimized airfoils and trailing-edge serrations. *AIAA journal*, *47*(6), 1470-1481.

Poulsen, A. H., Raaschou-Nielsen, O., Peña, A., Hahmann, A. N., Nordsborg, R. B., Ketzel, M., ... & Sørensen, M. (2019). Long-term exposure to wind turbine noise and risk for myocardial infarction and stroke: a nationwide cohort study. *Environmental health perspectives*, *2019*(3), 037004.

Raman, G., Ramachandran, R. C., & Aldeman, M. R. (2016). A review of wind turbine noise measurements and regulations. *Wind engineering*, *40*(4), 319-342.

Shepherd, D., McBride, D., Welch, D., Dirks, K. N., & Hill, E. M. (2011). Evaluating the impact of wind turbine noise on health-related quality of life. *Noise and Health*, *13*(54), 333-339.

Singh, R. B., Pella, D., Neki, N. S., Chandel, J. P., Rastogi, S., Mori, H., ... & Gupta, P. (2004). Mechanisms of acute myocardial infarction study (MAMIS). *Biomedicine & pharmacotherapy*, *58*, S111-S115.

Stigwood, M., Large, S., & Stigwood, D. (2013, August). Audible amplitude modulation—results of field measurements and investigations compared to psychoacoustical assessment and theoretical research. In *Fifth International Conference on Wind Turbine Noise*