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DEVELOPMENT AND VALIDATION OF TURBULENCE INGESTION PREDICTION CAPABILITY OF TONBROD

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ABSTRACT

With alternative energy becoming more prevalent the acoustic impact of machinery used to generate the energy is of interest. The noise produced from wind turbines is an important factor in the design as it can affect nearby communities. A numerical tool has been developed to predict the unsteady thrust and directly radiated noise from a single or multi-blade row turbomachine, which can easily be applied to a wind turbine.

The tool, called TONBROD, can predict blade rate and turbulence ingestion noise, however only the latter is of concern for this work. An asymptotic approach is used to quickly and efficiently predict the unsteady force on each blade from the chopping of incoming turbulence (e.g. turbulence ingestion noise). This force is then used to estimate the radiated noise. A user can prescribe the incoming turbulence intensity (circumferentially and radially varying) and integral length scale (circumferentially uniform but radially varying) that is then modified by the upstream blade row and advected to the downstream blade row through semi-empirical formulations. A prediction of the resulting unsteady force and noise is then made for either blade row. The asymptotic theory is briefly discussed and then the prediction of radiated noise for both homogeneous and inhomogeneous turbulence is compared to experimental data. It is shown that the method provides good results.

INTRODUCTION

Multiple blade row turbomachines have a wide variety of uses. The interaction of the turbomachine blades with the ingested flow can result in unwanted radiated noise and unsteady forces. For instance, the radiated noise from aircraft, automobile fans and wind turbines is a concern. The unsteady forces can drive other structural components that can radiate to the far field, as well as generate high vibration levels that can reduce the life cycle of the turbomachine or its supporting structure. Due to these undesirable attributes, there is a long history of the study of turbomachinery noise sources and propagation, focusing on their prediction and mitigation, Sharland [1], Kramer et al. [2], Sevik [3], and Blake [4], for example. The present paper considers the development and verification of a unique analytical approach for predicting the unsteady forces and noise due to turbulence ingested by a wind turbine. The ultimate use of this tool will be to aid in the design and analysis of wind turbines.

A numerical tool, TONBROD, was developed by Alion Science and Technology that predicts the unsteady forces and associated radiated noise from different physical mechanisms. Discrete tones are produced at the fundamental blade rate frequency and harmonics based on the flow velocity entering the wind turbine. For other cases, such as a water turbine, where there are multiple blade rows it will also estimate the incoming flow interaction with the wakes generated by the upstream blade row. The broadband noise includes turbulence ingestion noise and trailing edge noise due to the scattering of boundary layer turbulence passing over the blade trailing edge. This work documents the development and verification of the turbulence ingestion predictions. Future work is planned that will include the other noise mechanisms and provide validation calculations.

The TONBROD code is self contained and based on first principles, with minimal empiricism. The flow entering the wind turbine (both mean velocity and turbulence) is proscribed by the user. For a multiple blade row water turbine the wake entering the second blade row is calculated internally. The wake entering the second blade row is advected using semi-empirical formulations [5]. The unsteady forces generated by the ingestion of that turbulent flow, and the subsequent directly radiated noise, are determined by the operating conditions of the wind turbine, the geometry, the integral length scale of the turbulence, and the turbulence intensity. An inhomogeneous distribution of turbulence intensity in the circumferential and radial direction is allowed. The integral length scale can vary radially, but must be circumferentially uniform at each radius.

An asymptotic approach to turbulence ingestion noise is considered here, originally developed by Martinez [6, 7]. The advantages to this approach are significantly reduced run times. While the turbulence ingestion noise is considered a low frequency noise source the frequency range of interest is dependent on the rotor operating conditions and can have an upper bound in the kilohertz. Standard correlation approaches, which will be briefly discussed below, can have run times that do not allow for quick turnarounds. While TONBROD is capable of predicting the unsteady forces and radiated noise from a multi-stage water turbine the lack of publicly available data for validation results in a focus on single blade row predictions in this work.

NOMENCLATURE

B = Number of blades
d = Rotor diameter
dB = Decibel
J = Advance ratio
Re = Reynolds number
R_t = Rotor tip radius
Λ = Integral length scale

TECHNICAL APPROACH AND BACKGROUND

The phenomenon of turbulence ingestion can be attributed to two factors from the incoming turbulence: turbulence intensity and integral length scale. Both of these are features of any turbulent flow and can be measured. A typical response of a turbomachine to incoming turbulent flow is seen in Figure 1. There is an increase in the unsteady response near the fundamental blade rate frequency and its first multiple. This is broadband in nature. This hump is often referred to as a haystack, the shape of which is dependent on the incoming turbulence statistics and the geometry.

A wind turbine operating in turbulent flow, where there are eddies, is depicted in Figure 2, where the rotational speed of the blades and the mean speed of the wind determine how much the eddy is chopped. The larger the integral length scale, the larger the eddy and the more blades chop the same eddy. This correlates the blade-to-blade response and results in a sharper response around blade rate. The haystack becomes narrower, but with a lower peak amplitude. As the incoming length scale becomes smaller, a lower number of blades chop the same eddy, resulting in less correlation. This broadens the haystack around the blade rate frequency and increases the peak amplitude. The turbulence intensity is a measure of the velocity fluctuation about the mean and determines the magnitude of the unsteady lift. An increase in turbulence intensity leads directly to an increase in the unsteady thrust. The haystack that surrounds a peak is rightshifted (i.e. shifts to the right in frequency) based on the operating speed of the rotor and the inflow. For more information on the physics behind haystacking the reader is referred to Martinez [6].

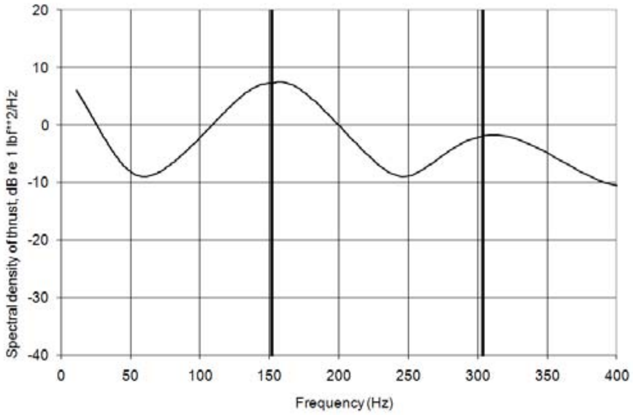


Figure 1. Typical unsteady thrust of a rotor operating in a turbulent inflow. Vertical lines delineate the first and second blade rate frequencies, where the haystacks are found.

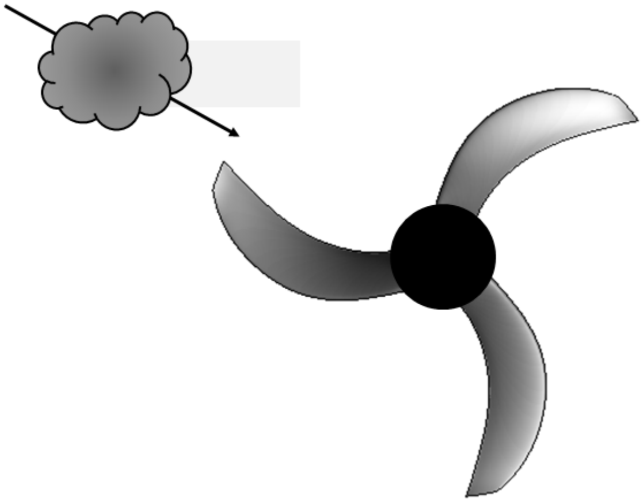


Figure 2. Notional wind turbine operating in turbulent flow.

Acousticians and hydrodynamists started to examine turbulence ingestion noise in the late 1960s. It was noticed that unsteady thrust measurements of rotors had a response that peaked around the blade rate frequencies. Investigators surmised that this peak, typically called a haystack, was related to the turbulent characteristics of the flow entering the rotor. There are some rotors that operate almost exclusive in the boundary layers (e.g. atmospheric boundary layer of wind turbines), and there the turbulence intensity could be much higher than the freestream, with increased unsteady thrust levels. A brief history of the genesis of the prediction methods will be discussed below, with the most common methods discussed. These have been improved upon since their inception and still see wide use today.

One seminal investigation was conducted by Sevik in 1970 [3], who developed a method to correlate the pressures acting on the surface of one blade that sum to the unsteady lift generated from operating in a turbulent inflow. This method is referred to as the *correlation method.* This method determines the unsteady force generated by the rotor by correlating the pressures on spanwise segments of one blade. The model, however, omits blade-to-blade effects for simplicity. Thus, implicit in the prediction is a lack of a haystack.

Jiang, Chang, and Liu [8] improved upon Sevik's original method by including blade-to-blade correlation effects. In this manner, the haystack characteristic in the turbulence ingestion noise spectrum is captured. Their method was compared to Sevik's measurements with good agreement.

Gavin [9] used the same correlation approach from Jiang et al but examined in detail the effect of varying turbulence characteristics. He provided an empirical function of turbulence using a two point correlation function based on his extensive measurements. Additionally, he enhanced the correlation method to apply it to blades of arbitrary (e.g. complex) geometries. A combination of strip theory (e.g. Sear's function) and a finite difference approximations to determine the local blade normal vectors permit the inclusion of blade geometry parameters such as rake and skew. A comparison to unsteady thrust measurements made by Jonson [10] had good results.

Another approach to turbulence ingestion noise is the *spectrum method*, which is detailed by Blake [4]. The turbulence ingested by the turbomachine is convected downstream assuming Taylor's Hypothesis (i.e. frozen). The characteristics of the turbulence are described with a function in wavenumber space. A significant portion of the detail revolves around the development of the wavenumber spectrum of the turbulence. A drawback of this approach is that the haystack does not smoothly transition to the "background" level, as is found in measured data.

An additional investigation was also conducted by Wojno, Mueller, and Blake [11, 12] that had both detailed measurements of incoming turbulence, as well as the directly radiated noise, but no measurements of the unsteady force response. The predictions were made using the spectrum approach. The groundwork for these references is the in-air measurements conducted by Wojno [13] that will be discussed in more detail below.

A third approach, and the one used in this paper, is an approach based on asymptotic theory. Martinez developed a "closed form" solution for turbulence ingestion noise by starting with the correlation method and applying various mathematical manipulations to arrive at a form suitable for an asymptotic analysis [1,14]. The end result is that Bessel functions are used to estimate the unsteady thrust generated by the turbomachine. The only requirement is that the number of blades must by large, with six typically taken to be sufficient. A subtle point should be made in that it is actually not the number of blades that must be larger, but rather the ratio $(\Lambda/R_t) * B$ must be much greater than one. One of the main advantages with the asymptotic method is the significant reduction in computational time. Comparison to another Alion turbulence ingestion code, PROPFORCES, which is based on the correlation method showed an order of magnitude reduction in run time for TONBROD. This is particularly important when a designer must examine a large range of operating conditions and rotor designs. The fast turnaround times allow for realistic guidance to be provided during the preliminary design.

TONBROD has both the Filotas [15] and Sear's [16] function available for determining the unsteady lift. The Sear's function is a lower-order model, compared to the Filotas function that ignores the spanwise variation of the driving gusts. For the relatively simplified cases considered herein that difference should not be of importance. For complex geometries or inflows that have a substantial radial or tangential velocity the Filotas function will provide more accurate predictions. For all cases presented in this work the Sear's function has been used.

The directly radiated noise from the unsteady thrust of the rotor is calculated assuming dipole radiation. It is assumed that the unsteady force at each spanwise section of the blade radiates to the far field as a dipole [17]. The radiated noise is then range corrected back to the standard distance of one yard from the center of the rotor.

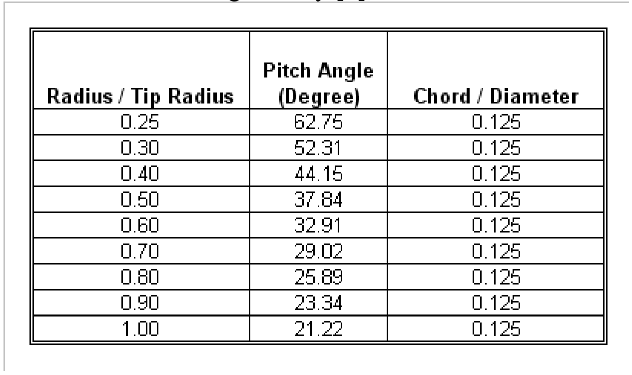
VALIDATION RESULTS

A series of calculations are performed to verify TONBROD's turbulence ingestion prediction capabilities. The comparison will be to experimental data, with the tests conducted both in-air and in-water. Even though most experiments conducted for this reason plan for, and measure, homogeneous turbulence statistics there is inherently some inhomogeneity that is seen by the rotor. To help quantify this effect a prediction is made against an inhomogeneous data set. While TONBROD has the capability to predict the turbulence ingestion noise from a multi-stage propulsor all results presented here are due to the ingestion of turbulence from a rotor. Unsteady thrust measurements, as well as the turbulence statistics required for the prediction of turbulence ingestion noise from a downstream blade row has not been found in the open literature.

ROTOR GEOMETRY

The propeller used for the present verification cases is the Sevik [3] subsonic rotor, a simple, notional unit designed specifically for conducting tests for code verification. It has ten unskewed, unraked blades with an eight inch diameter and has seen considerable use in many experiments due to its simplistic design. The salient features of the design are found in Table 1. A graphical representation of the subsonic rotor is given in Figure 3.

Table 1. Sevik rotor geometry [3].



Radius / Tip Radius	Pitch Angle (Degree)	Chord / Diameter
0.25	62.75	0.125
0.30	52.31	0.125
0.40	44.15	0.125
0.50	37.84	0.125
0.60	32.91	0.125
0.70	29.02	0.125
0.80	25.89	0.125
0.90	23.34	0.125
1.00	21.22	0.125

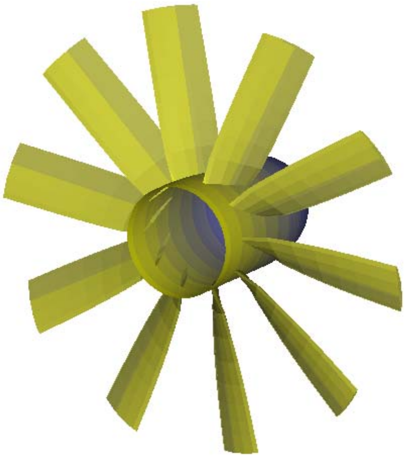


Figure 3. Graphical representation of Sevik's subsonic rotor.

IN-WATER MEASUREMENTS

Sevik was one of the pioneers in understanding the physical mechanisms behind turbulence ingestion noise [3]. As part of his theory development he also performed in-water experiments at the Applied Research Laboratory 48" diameter water tunnel at the Pennsylvania State University (ARL/PSU). Water was chosen as the test medium partly because the unsteady forces generated in water are much larger than those generated in air and are therefore easier to measure. The unsteady thrust produced by a subsonic rotor operating in grid generated turbulence was measured. The grids, comprised of a series of rods, were mounted a distance upstream of the rotor corresponding to 20 mesh sizes and had a grid-to-rod size ratio intended to generate homogeneous, isotropic turbulence.

The turbulence characteristics were not measured but estimated from experimental results from Naudascher and Farell [18]. The first grid has a spacing of 10.16 cm (4") and at the rotor produced a turbulence intensity (normalized to freestream speed) of 3.5% and an integral length scale of 2.81 cm. The second grid, with a larger mesh spacing of 15.24 cm (6") had the same turbulence intensity, 3.5%. However, the integral length scale was slightly larger at 4.24 cm. The tunnel speed and rotor RPM was set such that the rotor operated at an advance coefficient of 1.22. The test for the smaller grid had a tunnel speed of 4.69 m/s and a rotor RPM of 1136. The same parameters for the larger mesh were 4.60 m/s and 1114 RPM.

It must be remembered that while every effort was taken during the experiment to have a homogeneous turbulence inflow to the rotor that is not possible. There will always be some inhomogeneity, both circumferentially and radially. Discrepancies between the predicted and measured radiated noise could easily be attributed to this. Lastly, the turbulence intensity and integral length scales were *estimated,* as mentioned. There is certainly the possibility of an error between the estimated and actual turbulence characteristics.

One note must be made regarding the unsteady thrust measurements of Sevik. Due to an error made during the post processing of the experimental data the unsteady thrust amplitude is not correct in the original paper. While no erratum was ever issued to the authors' knowledge the error is well known in the marine community. Gavin [9] published the adjusted levels that were used for the comparisons in this work.

The prediction of the rotor response due to the inflow from the 10.16 cm grid spacing is shown in Figure 4. TONBROD under predicts the magnitude of the first haystack as well as over predicting the continuum levels above approximately 325 Hz. The under prediction of the first haystack could be due to the rotor responding to a resonance of the system in addition to the turbulence ingestion, but that cannot be confirmed. It is also surmised that the lower thrust amplitudes above 325 Hz is related to the experimental measurements and nonphysical. Of note is the almost step function between 325 Hz and 375 Hz, which is not representative of the smoothly varying turbulence ingestion noise spectrum that is expected.

The unsteady thrust prediction for the larger grid size is given in Figure 5. TONBROD captures the first haystack quite well but there is a large discrepancy for the second haystack. Based on the authors' experience with the Sevik subsonic rotor and its history at ARL/PSU it is known that the second haystack in the experimental data is not representative of turbulence ingestion noise. The first reason is that no previously published work that compared to this data has predicted a haystack of any magnitude near the second blade rate frequency. Additionally the haystack is left shifted in frequency from blade rate, not the expected right shift that should occur for turbulence ingestion noise. The hump could be a resonance of the rotor but then similar humps would be expected for both grid sizes. While it is not turbulence ingestion noise it cannot be said with any certainly on what the response is due to. The unsteady thrust predictions for the in-water measurements are within the bounds of experimental and numerical accuracy and are considered good.

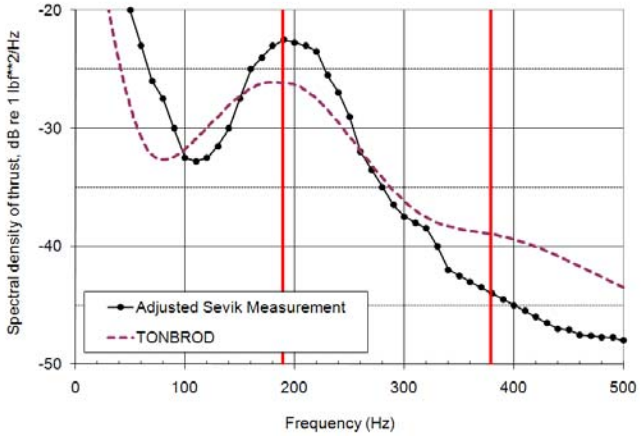


Figure 4. TONBROD prediction compared to the measured unsteady thrust for 10.16 cm mesh size. The vertical red lines represent blade rate frequencies.

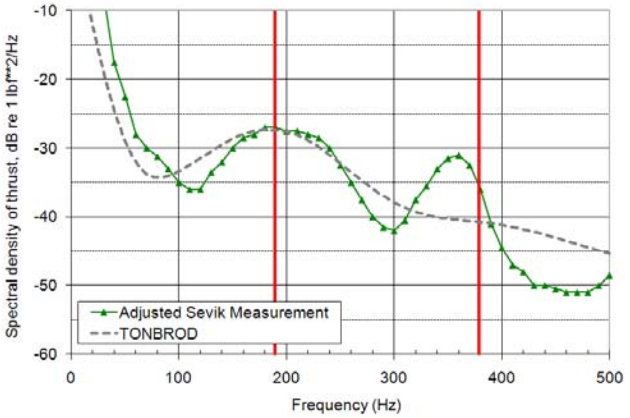


Figure 5. TONBROD prediction compared to the measured unsteady thrust for 15.24 cm mesh size. The vertical red lines represent blade rate frequencies.

IN-AIR MEASUREMENTS

The sound pressure level (SPL) of turbulence ingestion noise due to varying inflows was measured by Wojno as part of his PhD dissertation [13]. A series of experiments was conducted in-air using the ten bladed Sevik subsonic rotor to understand the effect of blade spacing on turbulence ingestion noise. The tests were performed in the Anechoic Wind Tunnel at Notre Dame. Detailed measurements were made of the turbulence intensity and integral length scale entering the rotor, with efforts made to ensure the distribution was as homogeneous as possible. The noise measurements were recorded at a 45° angle relative to the tunnel centerline. No unsteady force measurements were made.

The turbulence ingested by the rotor was generated by a grid placed approximately 0.61 m upstream of the rotor. Three different meshes were used for the experiment but the predictions concentrate on the 7.62 cm mesh spacing with a 1.27 cm diameter rod. This case is singled out as it has the most data published for it. The RMS turbulence intensity is 6.2% of the freestream and the integral length scale is 2.3 cm. This results in a ratio of 0.36 for the length scale to blade spacing, well within the limits imposed by the asymptotic theory for turbulence ingestion. The tunnel speed was set at 12.7 m/s and the rotor was at a RPM of 3300 for an advance ratio of 1.14. Other advance ratios were examined during the experiment but those will not be looked at for this work.

As with the in-water experiments steps were taken to produce homogeneous turbulence but there is most likely some inhomogeneity. Discrepancies between the predicted and measured radiated noise could easily be attributed to this.

The radiated noise prediction from TONBROD assumes a fore/aft aspect (i.e. along the rotor axis) but the measurements are at a 45° from fore aspect. As such, if a dipole radiation pattern is assumed then the TONBROD predictions should be 3 dB greater than the measurements. Thus, 3 dB are subtracted from the predictions. The comparison between the minimum and maximum radiated noise for the in-air data compared to the TONBROD prediction is found in Figure 6. Beyond a nondimensional blade rate frequency of three the trailing edge noise started to dominate the measurements [19]. Overall the agreement with the data is acceptable. It is noted that the prediction overestimates the haystack surrounding the first blade rate. It is unknown at this time why the discrepancy occurs. It could be related to the advance ratio at which the rotor is operating, as TONBROD assumes that each spanwise section of the rotor (e.g. from root to tip) is operating at zero angle of attack. To see the effect of a different advance ratio (even though the data is for J = 1.14) Figure 7 shows a prediction for a higher advance ratio. Overall the predictions provided by TONBROD are considered successful.

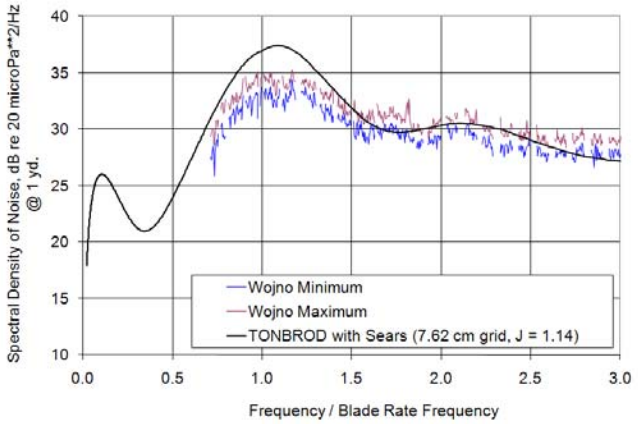


Figure 6. Turbulence ingestion prediction compared to experimental data for 7.62 cm grid with J = 1.14.

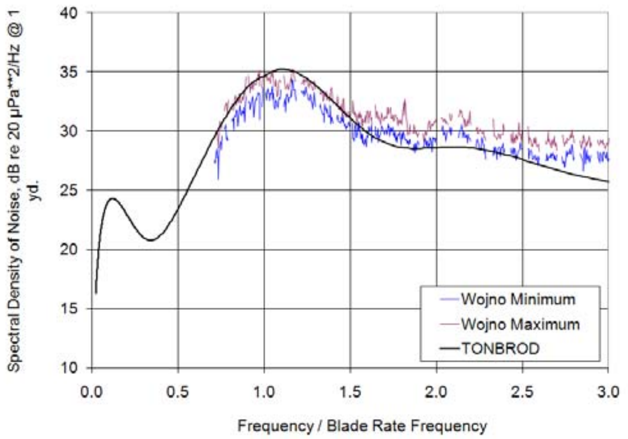


Figure 7. Turbulence ingestion prediction compared to experimental data for 7.62 cm grid with J = 1.31.

INHOMOGENEOUS TURBULENCE COMPARISON

Application of this tool to a real world situation requires the ability to handle inhomogeneous turbulence, both for the turbulence intensity and the integral length scale. As mentioned previously the experimental information available to perform these calculations is not available in the public literature. One of the few experiments that the authors' are aware of is that conducted by Lynch [20]. In the experiment he placed a strut upstream of the Sevik rotor to generate an inhomogeneous turbulent inflow.

A prediction using the theory on which TONBROD is based was made and provided by Lynch [21]. A prediction was made using the inhomogeneous turbulence as well as taking a spatial average to determine what the homogeneous turbulence would be. As can be seen in Figure 8 using the inhomogeneous turbulence provides a much better prediction. Many researchers will take an average of the turbulence (e.g. smearing it across the inflow plane) and this can be shown to under estimate the noise. For example, for this case shows a difference of up to 6 dB. Currently TONBROD has the capability to use inhomogeneous turbulence intensity in both the radial and circumferential directions but the integral length scale must be constant at each radial location. The length scale can vary at each spanwise location. Future work will allow for completely inhomogeneous integral length scales.

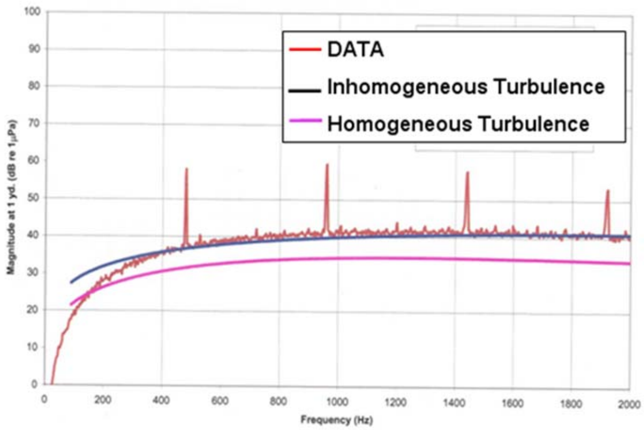


Figure 8. Comparison of TONBROD turbulence ingestion prediction for an inhomogeneous turbulence and an artificial homogeneous turbulence (via circumferential average).

CONCLUSIONS

A numerical tool to predict the unsteady forces and directly radiated noise associated with single and two blade row wind/water turbines operating in a turbulent inflow has been developed and verified. The asymptotic prediction method utilized in TONBROD has been exercised against the results of three experiments measurements. The comparisons of in-water and in-air measurement results to the predictions are sufficient to consider TONBROD verified for turbulence ingestion noise. The asymptotic nature of the calculations allows for at least an order of magnitude speed up over conventional, correlation based turbulence ingestion codes, without any loss in accuracy.

The most pressing enhancement to the turbulence ingestion prediction capability for TONBROD is to allow for a circumferentially varying distribution of integral length scales. The feature exists for the turbulence intensity, which few other codes have.

ACKNOWLEDGMENTS

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