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An Exergy Based Approach to Noise Prevention in Wind Turbines: Concept and Preliminary Assessment

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Abstract: Unsustainable human activities and practices are polluting water supplies and emitting to the atmosphere greenhouse gases as well as compounds that erode the earth's protective ozone layer. The potential impact on human health and economic costs associated with global warming have motivated scientists and engineers to seek sustainable technologies. One such technology is the wind turbine, which harnesses energy from the wind. However, a significant hindrance preventing the widespread use of wind turbines is the noise they produce. This study examines flow over an object and the consequent noise generation produced by this flow-structure interaction. Flow over a cylinder has been chosen as the benchmark. The aim of this study is to correlate three main characteristic parameters of the system, namely, the generated sound pressure level, the exergy destroyed, and the normal flow velocity). The main motivation for this work is to relate the exergy destruction to the noise generated in the flow to improve understanding and to provide a correlation can be utilized to reduce or minimize the noise of wind turbines.

Keywords: wind energy; wind turbine; noise reduction; aerodynamic noise, sound pressure level, exergy destruction.

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1. Introduction

Concerns about global warming have fostered a global trend towards cleaner energy sources. Promising alternatives to coal and other fossil fuels include nuclear power and renewable energy sources, one of the most promising of which is wind energy. However, some concerns exist with wind turbine technology, and one of the main ones is in the noise that occurs during operation. Efforts are being expended by researchers to reduce or prevent the noise.

Two major sources of noise are present during wind turbine operation: mechanical and aerodynamic. Mechanical noise generally originates from the many different components within the wind turbine, such as the generator, the hydraulic systems and the gearbox. Aerodynamic noise is the dominant source of noise from wind turbines, and the largest contribution to aerodynamic noise originates at the trailing edge of wind turbine blades. The noise generated can be modeled in terms of exergy destruction: a useful quantity describing the mutual equilibrium of a system and its surroundings. Exergy destruction represents a loss in energy quality or usefulness. Therefore, in order to increase system's usefulness and ultimately decrease the noise generated, it may be useful to reduce exergy destruction. The objective of this paper it to examine the noise produced by wind turbines is the noise they produce and to correlate the exergy destroyed with relevant characteristic parameters like the generated sound pressure level and the normal flow velocity so as to improve understanding and to provide a correlation can be utilized to reduce or minimize wind turbine noise.

This paper is organized as follows: relevant background is provided on wind turbine noise sources and prevention and on exergy methods in Section 2, the approach and methodology are discussed in Section 3, the results are presented and discussed in Section 4 and conclusions are given in Section 5.

2. Background

2.1 Sources and Prevention of Wind Turbine Noise

The noise disturbances by wind turbines are related to such factors as distance between the wind turbine and populated areas as well as the background noise where the wind turbine is operating [1]. Operating conditions and maintenance of the wind turbine also affect noise production [1], for both main categories of noise sources for wind turbines (mechanical and aerodynamic). The type of noise produced by mechanical components tends to be more tonal and narrowband in nature, which is more irritating for humans than broadband sound [1]. There are two ways in which mechanical noise is transmitted: airborne or structural. Airborne noise is directly emitted to the surroundings. Structural noise is more complex as it can be transmitted along the structure of the turbine and then into the surroundings through different surfaces, such as the casing, the nacelle cover, and the rotor blades. Aerodynamic noise is more complex and it is the dominant source of noise from wind turbines [2].

In general, there are six main regions along a wind turbine blade [1–9]. In terms of noise, the six regions are classified into turbulent boundary layer trailing edge noise (TBL TE), laminar boundary layer vortex shedding noise (LBL VS), separation stall noise, trailing edge bluntness vortex shedding noise (TEB VS), tip vortex formation noise and noise due to turbulent inflow. Brooks and Hodgson [10] developed a predictor for TBL TE using measured surface pressures. Schlinker and Amiet [11] employed a generalized empirical description of surface pressure to predict measured noise. Ffowcs and Hall [12] present a simpler approach to the TBL TE noise problem, based on an edge-scatter formulation. Also, the Reynolds number and angle of attack have been shown to influence the turbulent structure [11,13]. It has also been determined through far-field cross correlations that the noise is emitted from the trailing edge for mildly separated flow and from the chord for large-scale separation [13]. The noise from this source (LBL VS) is coupled to acoustically excited feedback loops taken between the trailing edge and instability waves (Tolmien-Schlichting waves) upstream of the trailing edge [6,7,14–19]. A relation for an untwisted, constant chord blade was also developed by Brooks, Pope and Marcolini [6,12,20] in order to predict tip vortex formation noise whereas Lowson [21] developed empirical relations for turbulent inflow noise for both low and high frequencies, based on the experimental results of Amiet [22]. There are many ways in which sound can be reduced. One is to design the wind turbine with acoustic behaviors in mind. Researchers are focused on reducing noise without affecting the power generated by the wind turbine [23-33].

The present investigation seeks to correlate the noise pollution to exergy, a factor not normally used to design wind turbine airfoils, with the objective of determining a correlation between the sound pressure level resulting from flow over a solid object and the exergy destroyed within the fluid medium. Such a correlation has the potential to reveal relationships between noise pollution and exergy destruction, and may be useful in efforts to reduce or minimize noise pollution in wind turbines.

2.2 Exergy Methods

In a two-dimensional study, the exergy destroyed (Ex_d) can be obtained using an exergy balance over a plane situated downstream of the fluid domain. This is given by [34]:

$$Ex_d = \int_2 \rho u_2 \left[(h_2 - h_0) - T_0 (s_2 - s_0) + \frac{u_2^2 + v_2^2}{2} \right] dS - \int_3 \rho u_3 \left[(h_3 - h_0) - T_0 (s_3 - s_0) + \frac{u_3^2 + v_3^2}{2} \right] \quad (1)$$

where surface 2 is the entrance of the control surface and surface 3 is the exit of the control surface (denoted by subscripts 2 and 3 respectively), h_i and s_i are the specific enthalpies and entropies, respectively, at the entrance $(i = 2)$, the exit $(i = 3)$, and the reference environment $(i = 0)$, T_0 is the temperature of the reference environment, u_i and v_i are the velocities in x and y directions, respectively, and ρ is the density of air.

The following simplifications can be made for Eq. (4.1):

1. Constant properties, therefore $h_0 = h_2 = h_3$, and $s_0 = s_2 = s_3$.

2. Surface 3 is far enough from the object that it approaches the freestream velocity, i.e. $u_3 \to U_\infty$ and $v_3 \to 0$ as $x \to \infty$.

3. The boundaries of the control surface are far enough from the object that negligible flow leaves through any boundaries other than the input and output boundaries.

4. Surfaces 2 and 3 are equal in size.

Taking into account the above assumptions, Eq. (1) becomes:

$$Ex_d = \int_2 \rho \left(\frac{u_2^3 - U_\infty^3 + u_2 v_2^2}{2} \right) \quad (2)$$

3. Approach and Methodology

3.1 Correlating Sound Pressure Level and Exergy Destruction

We now develop a correlation between sound pressure level (SPL) resulting from flow over a solid object and the exergy destroyed within the fluid medium. This correlation has the potential to reveal relationships between noise pollution and exergy destruction which may be utilizable to minimize noise while increasing efficiency in commercial wind turbines. Eq. 2 is programmed into the computational software utilized in this study and integrated over the boundary. The SPL is obtained using Comsol Multiphysics. Matlab's Curve Fitting Toolbox is used to generate a relationship between the SPL and Ex_d as well as between SPL and U_∞. Several "types of fit" are performed and the ones returning the lowest root mean square error (RMSE) are chosen. For both SPL vs. Ex_d and SPL vs. U_∞, an exponential function of the following form yields the best approximation:

$$f(x) = ax^b + c \quad (3)$$

3.2 Methodology

The methodology in this study focuses on finding a correlation between the noise pollution and the exergy destroyed over a cylindrical object using computational methods. The structure of the problem is initially formulated by creating a fluid domain consisting of air. The object that the air is to interact with is created and modeled directly in the center of the vertical axis of the fluid domain [35]. The interaction of two physic aspects, namely the fluid flow and the acoustic sound pressure, is modeled using the two fundamental partial differential equations representing each of the aspects: the Navier-Stokes (NS) equation [36, 37] and the acoustic wave (AW) equation [38], respectively. Importantly, these two physical aspects are coupled, e.g. the pressure solved for in the NS equation and is coupled to the pressure in the AW equation. These equations are then solved simultaneously using Comsol Multiphysics, as it is specifically designed to couple finite element method analysis [39]. The result is an interaction between two predetermined physical aspects that can reveal interesting and useful traits via a parametric study.

The boundary conditions when setting up the problem are given as follows [35]:

- A normal velocity is used at the inlet of the control surface.
- The outlet condition is that of atmospheric pressure, with no viscous stress.
- The boundaries parallel to the flow are assumed to be far enough from the object that no flow leaves the boundaries. As a result, a "wall" boundary condition is imposed.

The inlet normal velocity, U_∞, is varied from 1.5 m/s to 9 m/s. The results shown pertain to a velocity, U_∞, of 7 m/s, which is chosen based on energy and exergy efficiency maps generated by Dincer and Rosen [40].

Although the present study is a preliminary, it can be straightforwardly expanded to analyze the sound in wind turbines by analyzing the individual airfoils themselves. This is a problem of interest among researchers today.

4. Results and Discussion

4.1 Sound Pressure Level

The solution of the problem is conducted in a time dependent domain. This is done so as to reveal any time dependent properties of the system. One of these time dependent properties is vortex shedding. Physically, vortex shedding in the wake of the solid object gives rise to pressure variations in the medium of the fluid. These pressure variations generate fluctuations in noise. Vortex shedding is represented by a complex mathematical model for which an analytical solution is difficult to obtain. As a result, the Computational Fluid Dynamics (CFD) software described above is employed to obtain a solution.

The creation of the vortex can be observed clearly in Figure 1.

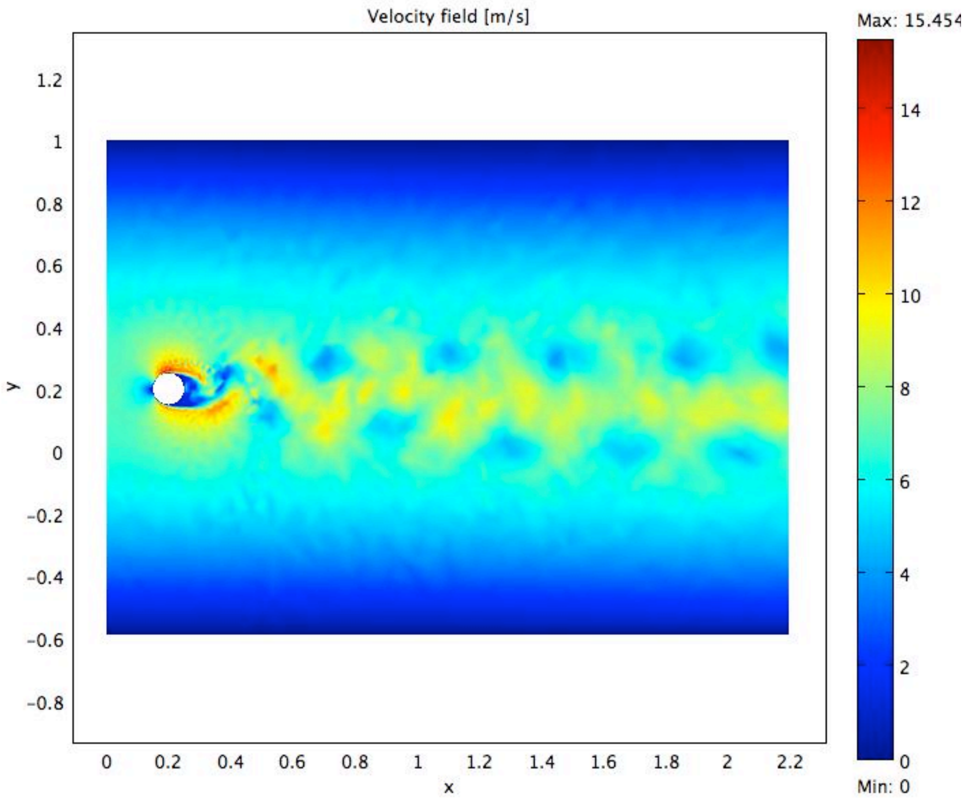

Figure 1. Velocity field and vortex shedding

Note that the vortex is generated periodically: the counter-clockwise rotating vortex from the bottom and the clockwise from the top of the cylinder. The position of the vortices is almost equidistant along the horizontal distance, indicating a cycling nature of the vortex shedding behind the cylinder [41]. It is to be noted that the frequency of vortex shedding matches the frequency of the fluctuation of the SPL also solved for in this model.

4.2 Correlation of Exergy Destruction with Sound Pressure Level

Since an aim of the study is to relate the SPL to Ex_d and Ex_d is a function of the velocity, it is suggested that the Ex_d increases as the SPL increases. Eq. 2 is utilized to determine Ex_d. Correspondingly, the SPL is obtained from simulations. The results are tabulated in Table 1.

Exd	V	Sound pressure
0.55	1.50	69.52
1.34	2.00	75.07
3.11	2.50	79.82
5.07	3.00	82.82
8.23	3.50	85.43
12.24	4.00	87.83
16.94	4.50	90.50
20.50	5.00	91.51
30.89	5.50	93.75
36.15	6.00	95.50
42.16	6.50	96.20
57.10	7.00	98.49
74.23	7.50	98.74
89.85	8.00	100.40
105.42	8.50	102.06
123.06	9.00	102.24

Table 1. Values of sound pressure level (SPL) and exergy destruction rate Ex_d obtained from COMSOL.

Based on the tabulated results, a curve relating SPL to Ex_d was obtained. The form of the function is given in Eq. 3 whereas the fit can be observed in Figure 2. Accordingly, a relationship between SPL and Ex_d can be written as:

$$SPL = 500.2\left(Ex_d\right)^{0.01192} - 427.1 \tag{4}$$

Such a fit returned an RMSE of 0.4172. Note from Eq. 4 as well as Figure 2 that SPL is a positive function of Ex_d and that, as Ex_d increases, SPL rapidly increases for low values of U_∞. As U_∞ further increases, so does Ex_d whereas the SPL converges to a value of about 105 dB.

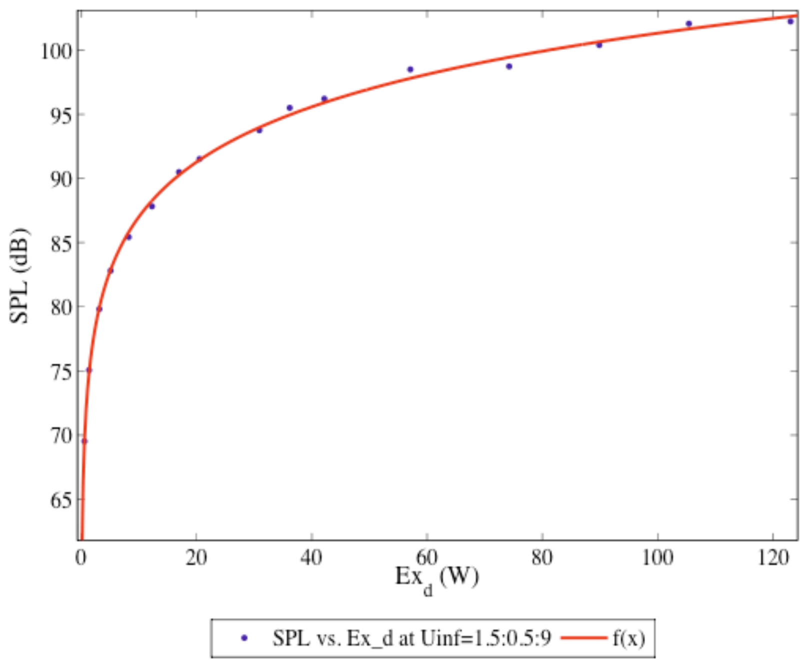

Figure 2. SPL vs. Ex_d curve fit.

A similar fit was performed in order to express SPL in terms of U_∞. An exponential function of the form in Eq. 3 was also chosen based on the RMSE. The SPL as a function of U_∞ can be expressed as:

$$SPL = -359.2\left(U_\infty\right)^{-0.05463} + 421 \quad (5)$$

Correspondingly, the RMSE is 0.3856. The fitted function can be observed in Figure 3. Similar to the above findings, the SPL increases as U_∞ increases. This observation is expected since Ex_d is a function of U_∞. However, the function increases more gradually and the convergence is not as noticable as in the above findings. This is attributed to the fact that Ex_d is not a linear function of velocity.

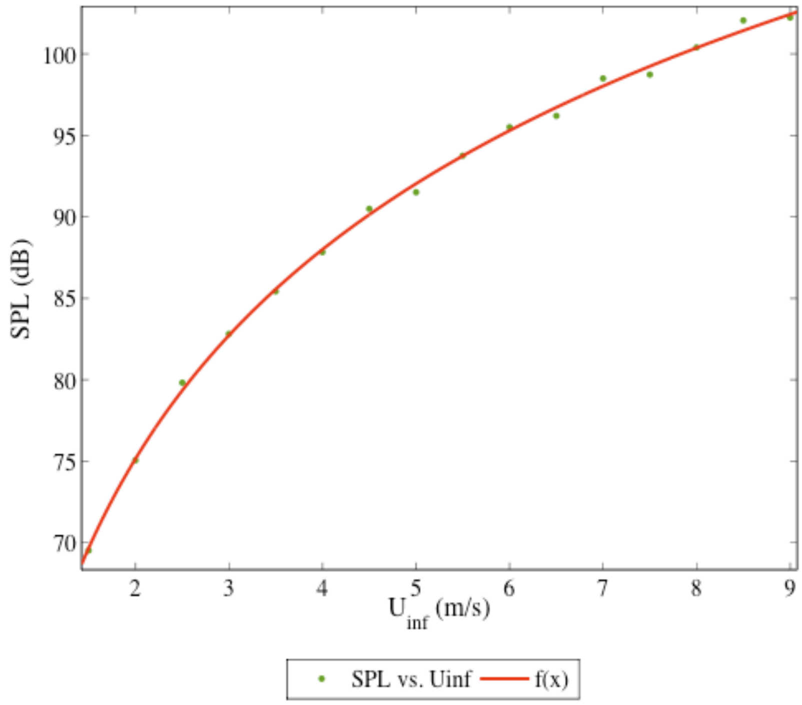

Figure 3. SPL vs. U_∞ curve fit.

Given the above results, one can observe that there is a positive correlation between the sound pressure level and the exergy destruction. That is, with an increase of exergy destruction an increase in noise pollution also occurs. This relationship follows the nonlinear relationship given in Figure 3. For lower values of exergy destruction it is shown that the noise is significantly affected by any increase in exergy destruction. This strong correlation suggests that, by keeping the exergy destruction small, the noise generated may become a global minimal. It is expected that this type of correlation can be expanded upon and applied to wind turbine airfoils.

4.3 Limitations and Needs

The SPL produced as a result of flow over a two-dimensional and three-dimensional airfoil models requires further investigation. Future work appears to be merited to consider turbulent $k-\varepsilon$ models, and to develop relationships between the SPL and Ex_d as well as SPL and U_∞. Shape optimization for noise reduction based on U_∞ and Ex_d of the airfoil also appears to be meritted.

5. Conclusions

The sound pressure level produced as a result of flow over a two dimensional cylindrical model was investigated. CFD simulations in COMSOL Multiphysics were performed in order to estimate the SPL. The SPL was then related to the exergy destruction Ex_d as well as the velocity U_∞. Matlab Curve Fitting Toolbox was employed to obtain a relationship between the SPL and Ex_d as well as SPL and U_∞. It was found that both could be represented by exponential functions of the same form. Further investigation showed that although Ex_d increases as U_∞ increases, the SPL tend to settle at around 105 dB. As expected, a lower SPL can be obtained when the Ex_d is minimized.

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Conflict of Interest

The authors declare no conflict of interest.

References and Notes

1. Klug, H. Noise from Wind Turbines: Standards and Noise Reduction Procedures. Paper presented on the Forum Acusticum, 2002, Sevilla, Spain.
2. Romero-Sanz, I.; Matesanz, A. Noise management on modern wind turbines. *Wind Engineering*, **2008**, 32, 27-44.
3. Oerlemans, S.; Sijtsma, P.; Mendez Lopez, B. Location and quantification of noise sources on a wind turbine. *Journal of Sound and Vibration*, **2007**, 299, 869-883.
4. Moriarty, P.; Migliore, P. Semi-Empirical Aeroacoustic Noise Prediction Code for Wind Turbines. National Renewable Energy Laboratory, **2003**, USA.
5. Schepers, J.G.; Curvers, A.; Oerlemans, S.; Braun, K.; Lutz. T.; Herrig, A.; Wuerz, W.; Mantesanz, A.; Garcillan, L.; Fischer, M.; Koegler, K.; Maeder, T. SIROCCO: Silent Rotors by Acoustic Optimization. Energy Research Center of the Netherlands, ECN-M-07-064, **2007.**
6. Brooks, T.F.; Pope, D.S.; Marcolini, M.A. Airfoil Self-noise and Prediction. NASA Reference Publication 1218, National Aeronautics and Space Administration, **1989**, USA.
7. Leloudas, G.; Zhu, W.J.; Sorensen, J.N.; Shen, W.Z.; Hjort, S. Prediction and reduction of noise from 2.3 MW wind turbine. *Journal of Physics: Conference Series 75*, **2007**.
8. Oerlemans, S.; Schepers, J.G. Prediction of wind turbine noise and validation against experiment. *International Journal of Aeroacoustics*, **2009**, 8, 555-584.
9. Jianu, O.; Rosen, M.A.; Naterer, G. Noise Pollution Prevention in Wind Turbines: Status and Recent Advances. *Sustainability* **2012**, 4, 1104-1117.
10. Brooks, T.F.; Hodgson, T.H. Trailing edge noise prediction from measured surface pressures. *Journal of Sound and Vibration,* **1981**, 78, 69-117.
11. Schlinker, R.H.; Amiet, R.K. Helicopter Rotor Trailing Edge Noise. NASA CR-3470, **1981**.

12. Ffowcs Williams, J.E.; Hall, L.H. Aerodynamic sound generation by turbulent flow in the vicinity of a scattering half plane. *Journal of Fluid Mech.,* **1970**, 40, 657-670.
13. Chou, S. T.; George, A.R. Effect of angle of attack on rotor trailing-edge noise. *American Institute of Aeronautics and Astronautics Journal,* **1984**, 22, 1821-1823.
14. Paterson, R.W.; Amiet, R.K.; Munch, C.L. Isolated airfoil-tip vortex interaction noise. *American Institute of Aeronautics and Astronautics Journal,* **1974**, Paper No. 74-194.
15. George, A.R.; Najjar, F.E.; Kim, Y.N. Noise Due to Tip Vortex Formation on Lifting Rotors. *American Institute of Aeronautics and Astronautics Journal,* **1980**.
16. Arakawa, C.; Fleig, O.; Iida, M.; Shimooka, M. Numerical approach for noise reduction of wind turbine blade tip with earth simulator. *Journal of the Earth Simulator*, **2005**, 2, 11-33.
17. Tam, C.K.W. Discrete tones of isolated air-foils. *J. Acoust. Soc. America*, **1974**, 55, 1173-1177.
18. Fink, M.R. Fine Structure of Airfoil Tone Frequency. UTRC78-10, United Technologies Research Center, **1978**.
19. Wright, S.E. The acoustic spectrum of axial flow machines. *J. Sound* and *Vibration*, **1976**, 45, 165-223.
20. Brooks, T.F.; Marcolini, M.A. Airfoil tip vortex formation noise. American Institute of Aeronautics and Astronautics Journal, **1986**, 24, 246-252.
21. Lowson, M. Assessment and Prediction of Wind Turbine Noise, ETSU W/13/00284/REP Energy Technology Support Unit, Harwell, United Kingdom **1992**.
22. Amiet, R. Acoustic radiation from an airfoil in a turbulent stream. *Journal of Sound and Vibration*, **1975**, 41(4), 407–420.
23. Kelly, S.G. *Fundamentals of Mechanical Vibrations*. 2nd Edition, McGraw Hill, 2000.
24. Wang, F.; Zhang, L.; Zhang, B.; Zhang, Y, He, L. Development of wind turbine gearbox data analysis and fault diagnosis system. *Power and Energy Engineering Conference (APPEEC)*, **2011**, Asia-Pacific.
25. Angelov, P.; Filev, D. An approach to online identification of Takagi-Sugeno fuzzy models. *IEEE Transactions on Systems, Man and Cybernetics - Part B: Cybernetics*, **2004**, 34, 484-498.
26. Song, Q.; Kasabov, N. NFI - neuro-fuzzy inference method for transductive reasoning and applications for prognostic systems. *IEEE Trans. Fuzzy Systems*, **2005**, 13, 799-808.
27. Kasabov, N.; Song, Q. DENFIS: dynamic, evolving neural-fuzzy inference systems and its application for time-series prediction, *IEEE Transactions on Fuzzy Systems,* **2002**, 10, 144–154.
28. Wang W.; Ismail F.; Golnaraghi, F. A neuro-fuzzy approach for gear system monitoring. *IEEE Transactions on Fuzzy Systems*, **2004**, 12, 710-723.
29. Jianu, O. An Evolving Neural Fuzzy Classifier for Machinery Diagnostics. M.Sc. Thesis, **2010**, Lakehead University, Canada.
30. Oerlemans, S.; Schepers, J.G.; Guidati, G.; Wagner, S. Experimental demonstration of wind turbine noise reduction through optimized airfoil shape and trailing edge serrations. *Proceedings of the European Wind Energy Conference and Exhibition*, **2001**, Copenhagen, Sweden.
31. Oerlemans, S. Reduction of wind turbine noise using optimized airfoils and trailing-edge serrations. *14th AIAA/CEAS Aeroacoustics Conference*, **2008**, Vancouver, Canada.
32. Kamruzzaman, M.; Lutz, T.; Wurtz, W.; Shen, W. Z.; Zhu, W.J.; Hansen, M. O. L.; Bertagnolio, F.; Madsen, H. A. Validations and improvements of airfoil trailing-edge noise prediction models using detailed experimental data. *Wind Energy*, **2012**, 15, 45-61.

33. Herr, M. Experimental study on noise reduction through trailing edge brushes. *New Results in Numerical and Experimental Fluid Mechanics V, Notes on Numerical Fluid Mechanics and Multidisciplinary Design*, **2006**, 92, 365-372.
34. Li, H.; Stewart, J.; Figliola, R. Exergy Based Design Methodology for Airfoil Shape Optimization and Wing Analysis. *25th International Congress of the Aeronautical Sciences*, **2006**.
35. Zhu, W.J. Aero-Acoustic Computations of Wind Turbines. Doctor of Philosophy Thesis. Department of Mechanical Engineering, Technical University of Denmark, **2007**.
36. Marcus, R.; Brenner, M. P. A nonperturbative approximation for the moderate Reynolds number Navier–Stokes equations. *Proceedings of the National Academy of Sciences,* **2009,** 106, 2977-2982.
37. Djojodihardjo, H.; Abdulhamid, M.F.; Basri, S.; Romli, F.I.; Abdul Majid, D.L.A. Numerical Simulation and Analysis of Coanda Effect Circulation Control for Wind-Turbine Application Considerations. *IIUM Engineering Journal, Special Issue, Mechanical Engineering*, **2011.**
38. Arnaout, M.; Berquez, L.; Baudoin, F.; Payan, D.; Contribution to improving the spatial resolution of a pulsed electro acoustic cell measurement: An analysis of acoustics waves propagation. 10th IEEE International Conference on Solid Dielectrics (ICSD), vol., no., pp.1-4, 4-9 July **2010.**
39. Marignetti, F.; Delli Colli, V.; Coia, Y. Design of axial flux PM synchronous machines through 3-D coupled electromagnetic thermal and fluid-dynamical finite-element analysis. *IEEE Transactions on Industrial Electronics,* **2008**, 55: 3591-3601.
40. Dincer, I.; Rosen, M.A. *Exergy Energy, Environment and Sustainable Development*. Elsevier: Oxford, UK, 2007; 195-199.
41. Tomimatsu, S.; Fujisawa, N. Measurement of aerodynamic noise and unsteady flow field around a symmetrical airfoil. *Journal of Visualization*, **2002**, 5, 381-388.