

Towards Identifying Contribution of Wake Turbulence to Inflow Noise from Wind Turbines

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Abstract. Downstream turbines in a wind farm often operate under the influence of wakes from upstream turbines. Aerodynamic losses and aeromechanical issues (stochastic loads) associated with such wake-turbine interactions have been investigated before. However, the role such interactions play in the generation of aerodynamic noise has not been looked into. This paper presents a two-step approach for predicting noise due to wake-turbine interaction. The first step involves aerodynamic simulation of a wind farm using the Simulator fOr Wind Farm Applications (SOWFA) software. Time accurate data and turbulence statistics in the turbine wakes are obtained from this simulation result just ahead of the downstream wind turbines. The second step uses the turbulence information with aeroacoustic models to predict radiated noise in the far field. Results from the solutions of two simplified model problems corresponding to these two steps are presented in this paper.

1 Introduction

Aerodynamic noise from wind turbines is generated at the rotor blades and is broadband in nature [1]. The turbulence in the incoming flow and the “self-generated” turbulence in the blade boundary layers are responsible for noise generation. These are referred to as “inflow turbulence” noise and “self” noise sources respectively. Recent research has focused predominantly on “self” noise from wind turbines, especially trailing edge noise. Relatively little work has been performed on inflow turbulence noise perhaps because of the community resigning to the belief that nothing can be done about it. An even less explored phenomenon is the acoustic impact of wake-turbine interaction and its contribution towards overall noise from wind turbines operating in a wind farm. This paper aims at assessing and quantifying the role of wake-turbulence in aerodynamic noise generation from wind turbines operating in a wind farm.

Aerodynamic interaction between turbines in wind farms is now relatively, though arguably, well understood. It is known that wakes from upstream turbines can significantly induce aerodynamic losses [2] and turbulent loads [3] on downstream turbines. These ‘wake turbulence’ induced aerodynamic losses and loads are prominent when “stable” atmospheric condition is established over the wind site. High wind shear and low atmospheric turbulence are characteristic of stable atmosphere [4]. In these conditions, turbine wakes persist for long distances and hence wake-turbine interactions become more prominent. Low free-stream turbulence and increased wake-turbine interactions

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associated with stable atmospheric condition enhance the role of wake turbulence in noise generation. Furthermore, high velocity shear is conducive to the generation of *other amplitude modulation* (OAM), which has recently gathered tremendous attention [5, 6]. Stable conditions also promote “channeling” of noise propagating in the downstream direction and hence cause more annoyance to wind farm neighbors.

2 Numerical Predictions

2.1 Approach

A schematic of the numerical noise prediction approach is shown in Fig. 1. It consists of two steps. In the first step, aerodynamics of a wind farm is simulated using a high-fidelity Large Eddy Simulation (LES) methodology. The Simulator fOr WindFarm Applications (SOWFA) software is selected to for this purpose. SOWFA can simulate aerodynamics of single or multiple turbines (windfarms) operating in uniform or atmospheric boundary layer flow. SOWFA uses the actuator line model [7] to parameterize the turbine rotors, which are represented by body force (sources) terms in the momentum equations. Time-accurate flow information and turbulence statistics are sampled from the LES simulations just ahead of the downstream turbines. The sampled data represents the flow that is ingested by the turbine.

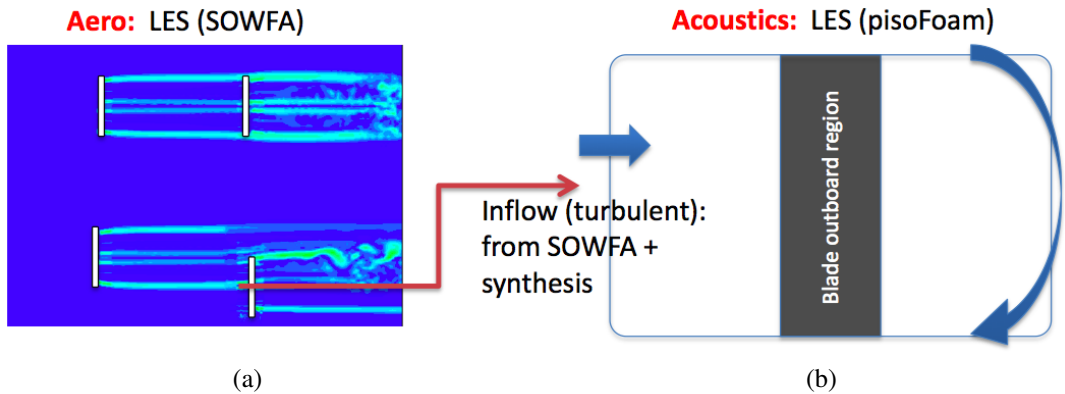


Figure 1: Envisioned approach for noise prediction: (a) Step 1, (b) Step 2.

The second step of the prediction approach can be performed using two methods. The first method is semi-analytical. It uses the inflow turbulence intensity and integral length scale (as computed in the first step) with the formulation by Lawson [8] to estimate the radiated noise. The second method involves another LES simulation where the interaction of wake turbulence with the rotor blade (part span) is numerically solved to compute noise. The inflow boundary condition for such LES simulations is set using the turbulence information extraction from the wind farm aerodynamics simulations performed in the first step. Since the aerodynamic noise source in wind turbines is known to be of dipole nature, where noise scales as velocity to the fifth power, only the outboard region of the rotor is important from noise perspective. Therefore, a part-span simulation is performed with periodic boundary conditions in the spanwise direction. The span length is carefully chosen to balance between computational power requirements and ensuring that the span length is larger than the coherence

length. These part-span, blade-resolved LES provide unsteady pressure on the blade and other near field data which is combined with two different acoustic solvers to compute far-field noise.

The following sections describe two model problems (and results) corresponding to the two steps of the process.

2.2 Wind Farm Aerodynamics

Simulator for Offshore Wind Farm Application (SOWFA) developed at the National Renewable Energy Laboratory (NREL) is used to carry out wind farm aerodynamics simulations. SOWFA uses an actuator line model (ALM) to parameterize wind turbines, so that the actual rotor blades are not modeled. SOWFA is built upon the flow solver PISOFOAM (OpenFOAM), which is a transient flow solver for incompressible flows capable of running with LES sub-grid scale models. The standard Smagorinsky model is used to model the sub-grid stresses.

Figure 2 (a) shows a schematic of the hypothetical wind farm for the first model problem. The wind farm has 4 wind turbines with two turbines (1 and 2) that experience freestream flow, and turbines 3 and 4 that operate in full and partial wakes of turbines 2 and 1 respectively. The simulation results shown here are for uniform inflow, instead of Atmospheric Boundary Layer (ABL) flow, thus turbines 1 and 2 have zero inflow turbulence. Figure 2 (b) shows iso-surfaces of vorticity magnitude. The iso surfaces are drawn for vorticity values such that the helical tip vortex structure (trailing vorticity) and the bound vorticity (around the blades) is visible.

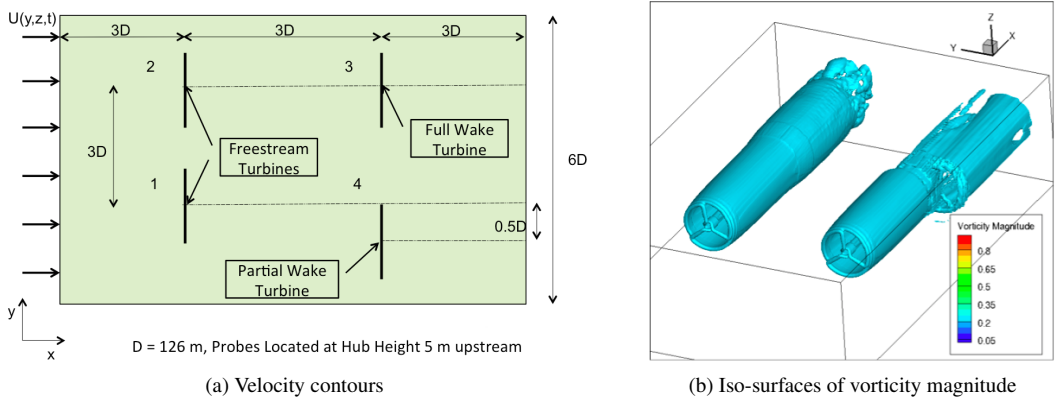


Figure 2: Wind farm aerodynamics problem setup and results: (a)wind farm layout, and (b) iso-surfaces of vorticity magnitude.

Flow (turbulence) data is extracted on a horizontal plane at the hub height. Figure 3 (a) and (b) show the contour plots for velocity magnitude and vorticity in this horizontal plane. It is seen that wake structure for turbines 3 and 4 differ significantly due to the difference in interactions with the upstream turbine wakes.

Complete time history of flow information at a point probe directly upstream of the hub of turbine 4 is also sampled. Figure 4 plots the streamwise velocity variation with time sampled at this point, and its autocorrelation function. The Autocorrelation function ($R_{uu}(\tau)$) is used to compute the integral time scale (T), which is subsequently used to compute the integral length scale (l_t) using Taylor's

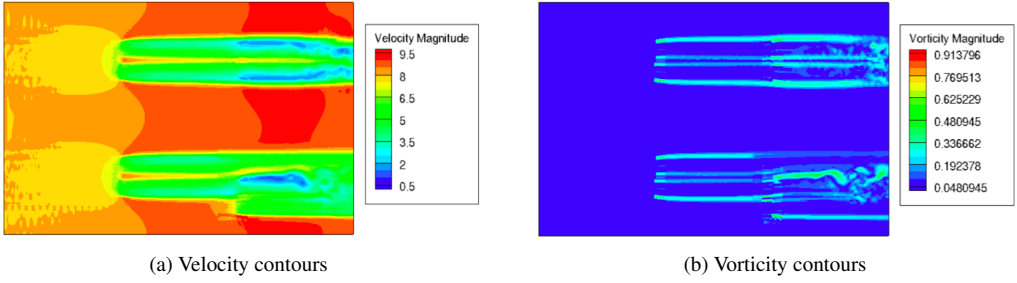


Figure 3: Wind farm results showing (a) velocity magnitude and (b) vorticity in the horizontal plane at turbine hub height.

frozen turbulence hypothesis.

$$\begin{aligned}
 R_{uu}(\tau) &= \frac{\langle u(t)u(t + \tau) \rangle}{\langle u^2(t) \rangle}, \\
 T &= \int_0^{\infty} R_{uu}(\tau) d\tau, \\
 l_t &= \langle U \rangle \times T
 \end{aligned} \tag{1}$$

where, $u = U - \langle U \rangle$ is the perturbation (mean-subtracted) stream-wise velocity.

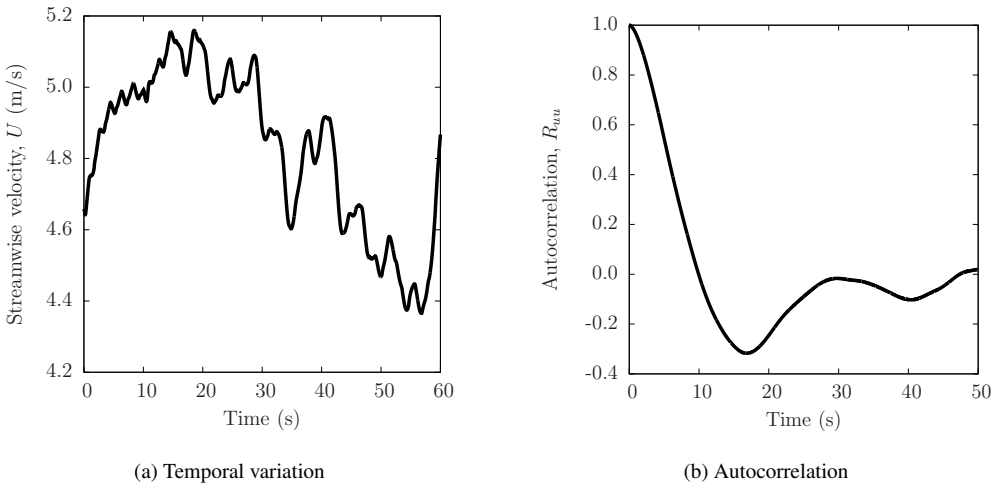


Figure 4: Streamwise velocity component in the wake: (a) time variation, and (b) its autocorrelation.

2.3 Noise Calculation: Semi-empirical approach

Using the integral scales computed above, the far-field noise spectrum is computed using Eq. 2 due to Lawson [8]. Lawson’s model (Eq. 2 is an extension of Amiet’s theory [9] with a correction for low

frequency noise estimation

$$\begin{aligned} \text{SPL}_{1/3}^H &= 10 \log_{10} \left[(\rho_0 c_0)^2 \frac{L}{2_0^2} I_t M^3 I^2 U_0^2 \frac{K^3}{(1 + K^2)^{-7/3}} \right] + 58.4 \\ \text{SPL}_{1/3}^L &= \text{SPL}_{1/3}^H + 10 \log_{10} \left(\underbrace{10S^2 MK^2 / (1 - M^2)}_{\text{low freq corr}} \right) \end{aligned} \quad (2)$$

where, I is turbulence intensity, U_0 is flow speed, L is airfoil span, $K = \omega c / (2U_{\text{rel}})$ is wavenumber based on semi-chord ($c/2$) and S^2 is the compressible Sears function. Figure 5 show the noise predictions for a few representative values of turbulent intensities and length scales. Spectra shows little variation in noise in higher frequencies however significant difference in low frequency noise.

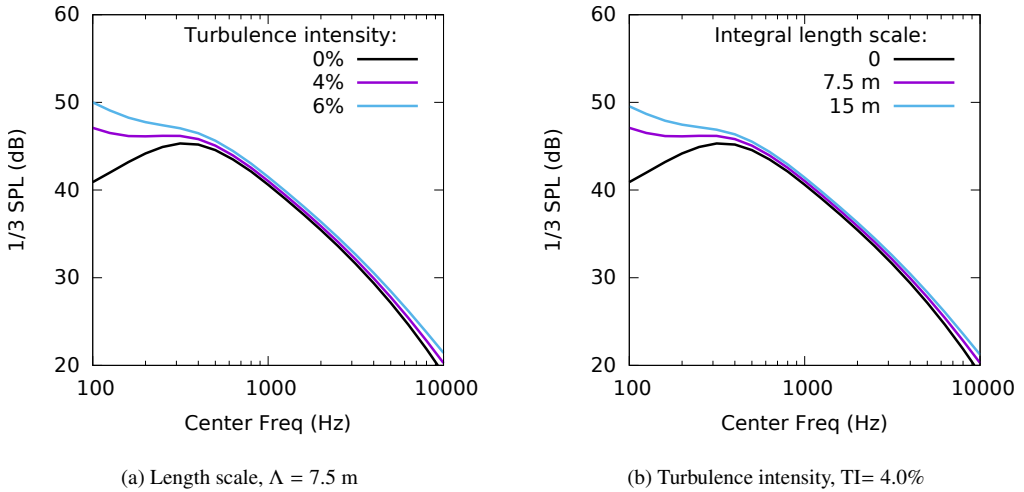


Figure 5: Noise spectra for different (a) turbulent intensities and (b) integral length scales (Λ).

2.4 Noise Calculation: LES approach

A second, higher-fidelity method for noise prediction is sought that uses LES to model turbulence-airfoil interaction. As explained in Sec. 2.1, this would require using turbulence information from windfarm aerodynamics calculations and prescribing them as inflow boundary conditions for noise computation. This framework is not yet ready. We instead demonstrate the LES-based noise prediction methodology on a model problem where the turbulence is generated by another body. This model problem consists of a cylindrical rod placed upstream (in tandem) of an airfoil (NACA 0012). Wake from the rod impinges on the airfoil and produces unsteady lift that then radiates as noise.

2.5 Rod-Airfoil Noise

The problem setup and details of the simulation procedure for the rod-airfoil problem have been described elsewhere [10, 11] and hence the description is kept brief. Figure 6 (a) show a snapshot

of the flowfield setup due to the rod-airfoil interaction. The rod wake comprises of quasi-periodic vortex shedding (peak Strouhal number, $St \sim 0.19$) and turbulence (due to vortex breakdown) which give tonal and broadband noise respectively. Two flow solvers are benchmarked against experiments: a compressible flow solver (Charles) by Cascade Technologies and an incompressible flow solver (PisoFOAM) from OpenFOAM. Flow Reynolds number based on the diameter of rod (Re_d) is 48,000 and Mach number is 0.2. Figure 6 (b) show the schematic along with the positions of point probes A and B in the near field chosen for near-field spectral analysis.

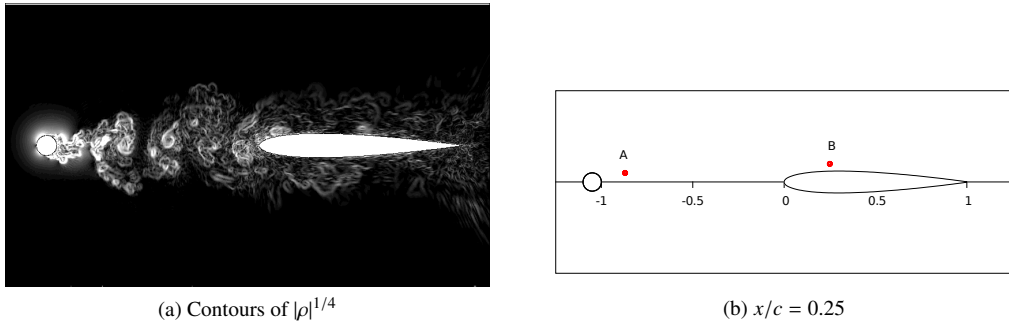


Figure 6: Contours of $|\rho|^{1/4}$ in the flow field around rod-airfoil configuration and near-field probe locations.

Figures 7 and 8 compare the power spectral density (PSD) in near field and far field with experimental results [12]. Figure 7 compares PSD of streamwise velocity at the point probes A and B for both simulations. Figure 8 compares the far-field noise PSD at a point transverse of flow direction from the leading edge of the airfoil. Far-field noise PSD is computed from the solution of Charles simulation using Ffowcs-Williams Hawkins Analogy [13] and Amiet's theory [9]. Spectral prediction using both approaches match well with the experiments for peak (vortex shedding) frequency and amplitude. Agreement in the spectral decay at high frequencies is also acceptable.

3 Conclusion and Future Work

An approach to assess the impact of turbine wake turbulence on wind turbine noise in wind farms is presented. Model problems are solved to assess the accuracy of the noise prediction methodology. Two LES solvers are benchmarked against experimental measurements for the rod-airfoil problem. Next set of simulations will involve more realistic effects such as atmospheric boundary layer (ABL) inflow for wind farm computations. Integrating the whole approach will create a framework to study the effects such as relative importance of wake versus atmospheric (freestream) turbulence.

4 Acknowledgment

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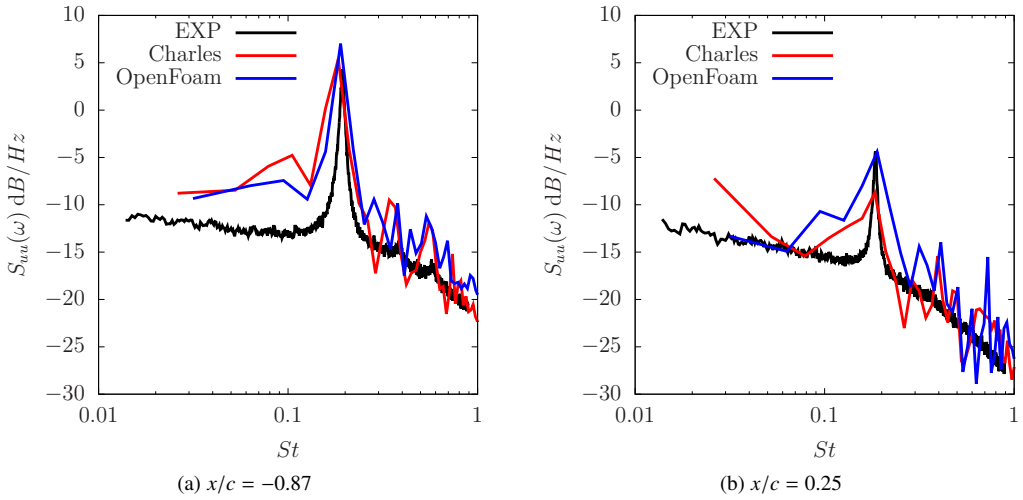


Figure 7: Velocity power spectral density, $S_{uu}(\omega)$ at the two near-field probes indicated by A and B in Fig. 6 (b).

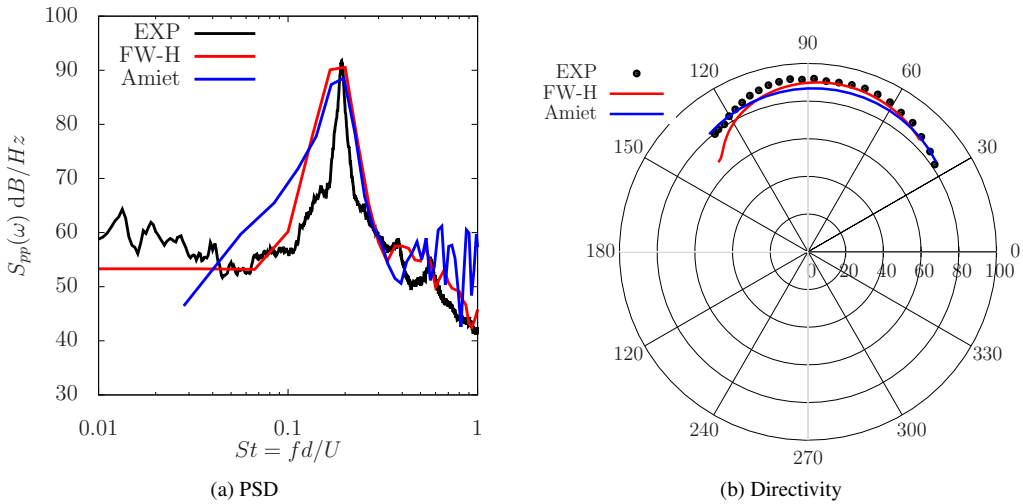


Figure 8: Far-field noise at a distance of 18.5 chords: (a) pressure spectral density (PSD) directly above the airfoil leading edge ($\theta = 90^\circ$) and (b) directivity. Predictions using the FW-H method [13] and Amiet’s theory [9] are compared with measured data.

References

[1] S. Wagner, R. Bareiß, G. Guidati, *Wind Turbine Noise* (Springer-Verlag, 1996)
 [2] F. Porté-Agel, Y. Wu, H. Lu, R.J. Conzemiuis, *Journal of Wind Engineering and Industrial Aerodynamics* **99** (2011)

- [3] M. Churchfield, S. Lee, J. Michalakes, P. Moriarty, *Journal of Turbulence* **13** (2012)
- [4] R.B. Stull, *An Introduction to Boundary Layer Meteorology*, Atmospheric and oceanographic sciences library (Kluwer Academic Publishers, 1988)
- [5] D. Bowdler, *Acoustic Bulletin of the Institute of Acoustics* **33** (2008)
- [6] S. Oerlemans, *Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause & Effect*, in *RenewableUK report: Work Package A1 - An Explanation for Enhanced Amplitude Modulation of Wind Turbine Noise* (2013)
- [7] J.N. Sørensen, W.Z. Shen, *Journal of Fluids Engineering* **124**, 393 (2002)
- [8] M.V. Lowson, *Assessment and Prediction of Wind Turbine Noise*, in *ETSU W/13/00284/REP* (Flow Solutions Report 92/19, Bristol, England, 1993)
- [9] R.K. Amiet, *Journal of Sound and Vibration* **41** (1975)
- [10] A. Sharma, *Large Eddy Simulations for Predicting Aerodynamic Noise due to Rod Wake-Airfoil Interaction*, in *Conference on Wind Energy Science and Technology* (Ankara, Turkey, 2013)
- [11] B. Agrawal, A. Sharma, *Aerodynamic Noise Prediction for a Rod-Airfoil Configuration using Large Eddy Simulations*, in *20th AIAA/CEAS Aeroacoustics Conference* (Atlanta, Georgia, USA, 2014)
- [12] M.C. Jacob, J. Boudet, D. Casalino, M. Michard, *Theoretical and Computational Fluid Dynamics* **19**, 171 (2005)
- [13] J.F. Williams, D.L. Hawkings, *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences* (The Royal Society, 1969), Vol. 264, chap. Sound generation by turbulence and surfaces in arbitrary motion, pp. 321–342