THE EFFECT OF AIR TURBULENCE ON SOUND AND ITS APPLICATION TO MUSICAL SIGNAL PROCESSING

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ABSTRACT

The effect of atmospheric air turbulence on acoustic signals is modeled with the goal of producing a novel DSP technique for music and sound production. The building block of the turbulence model is called a 'turbule', a localized eddy with spherical symmetry. At the current stage of development, an operational model of a turbule is implemented in Matlab, and the effect of the turbule has been evaluated for a variety of atmospheric conditions. Analysis of the results from this model will pave the way for the creation of a digital effects module built on a network of turbules, one that can exaggerate the effect of air turbulence when needed for expressive purposes.

1. INTRODUCTION

We all encounter air turbulence in everyday life and we all have many associations with the experience of wind whether it be a light breeze or a dangerous gale. Turbulence affects the propagation of the sound waves through the medium of air and produces characteristic kinds of changes to the acoustic signal. Within the field of acoustic research there have been several studies that have examined the effect of atmospheric air turbulence in specific situations. For example, while one study modelled sonic boom propagation [1] through turbulence, another considered the effects of turbulence on steady-state sounds [2]. Furthermore, some studies considered sound propagation through turbulent fields over listener-receiver distances greater than 100 m [3] while others observed the effects at close distances of less than 16 m [4]. Despite the wide range of these studies, none of them considered how air turbulence might affect common acoustic signals such as music.

As pointed out by Wilson, *et al.* [5], air turbulence functions as an acoustic filter as sounds of certain wavelengths scatter from the turbulence in the path of sound propagation. If one can determine the effects of air turbulence on each part of the aural spectrum, it is possible to create a digital signal-processing system that simulates the acoustic properties of air turbulence. Because of its chaotic nature, it is difficult to develop a model of air turbulence that consistently accounts for the effects for a wide range of frequencies and listener-receiver geometries. First, there is a broad range of energies and length-scales involved in turbulence, making it necessary to determine the scale of turbulence that is most relevant to sound propagation near the ground [5]. Second, it is challenging to obtain consistent field measurements since turbulence is dynamic and hard to isolate. Hallberg *et al.* [6] outline some of these difficulties, focusing on issues such as microphones, anemometers, and the ground effect for turbulence near the ground.

The simulation of turbulent sound fields can be achieved with a computer simulation of sound propagating through a 'turbule'. Goedecke and Auvermann [3] suggest the idea of a turbule, or localized eddy with spherical symmetry, as a means of representing turbulence. In other words, they treat turbulence as discrete pockets of temperature and wind velocity variations, enabling them to generate specific geometries between sound propagation and turbulence. In support of this method, Mcleod, *et al.* [4] use a single turbule to model the interaction of an acoustic pulse with turbulence. They are able to validate most of their predictions with outdoor measurements.

There are several advantages to using the turbule model. Because of the discreteness of the turbule as well as the spherical symmetry, it is possible to scale the turbule to different sizes, accounting for the different length-scales of atmospheric turbulence. Furthermore, one can account for the wide range of energies involved in turbulence by adjusting the meteorological parameters within the turbule. Finally, one can arrange several turbules in a series to create more complicated interactions between sound and turbulence.

This study employs the turbule model in order to create a controllable simulation of turbulence. The goal is to produce a novel effect that may be useful in music and sound processing. At this stage, the system consists of a computer simulation of the propagation of an impulse through a turbule. The architecture of this simulation is discussed in section 2 while the specific conditions of the test simulations are summarized in section 3. After calculating the impulse response for a variety of turbules, the musically relevant effects of turbulence are discussed in section 4, while section 5 covers the implementation of musical signal-processing modules that can be used with current music software.

2. SYSTEM DESCRIPTION

The computer simulation of sound propagation through a turbule is accomplished with a Matlab simulation that creates a model of a three-dimensional, virtual environment. This virtual environment is supposed to approximate outdoor conditions close to the surface of the earth but far enough away from the ground to neglect ground reflections. It is assumed that atmospheric air is the sole medium of sound conduction with the following relation for the speed of sound as suggested by Kuttruff [7]:

$$c = 331.4 + 0.6 \bullet T \qquad (1)$$

where c is the speed of sound in m/sec and T is the air temperature in centigrade. In order to account for the effects of wind, the speed of the wind is simply added to the speed of sound.

As with any digital representation of continuous conditions, it is necessary to discretize the virtual environment, which is divided into a grid of equally spaced points. The smallest separation in the simulation is equivalent to 0.0148 meters in a real environment, providing enough spatial resolution to allow two samples per wavelength of a tone at 12 kHz under the coldest and windiest conditions. Ideally the spatial resolution would accommodate the wavelength of a 20 kHz tone, but limitations of computer power and memory limit the resolution.

2.1. 3D Finite Difference Wave Equation

Although Goedecke and Auvermann [3] use ray tracing techniques in their implementation of the turbule model, the three-dimensional, finite difference approximation of the acoustic wave equation was judged more appropriate for this simulation. This approach offers several advantages such as the ability to account for diffraction, the ability to account for all angles of incidence, and the ability to sample the wave front at any point in the virtual environment.

In the finite difference approximation, the acoustic pressure at a particular point in space is determined by the pressure values at surrounding spatial samples and from the current and previous time samples. The following equation shows the form used to calculate the pressure at a particular point:

$$\begin{aligned} P^{t+1}_{x,y,z} = {} & \frac{c_x^2 \bullet \Delta t^2}{\Delta x^2} \bullet \left(P^t_{x+1,y,z} - 2 \bullet P^t_{x,y,z} + P^t_{x-1,y,z}\right) \\ & + \frac{c_y^2 \bullet \Delta t^2}{\Delta x^2} \bullet \left(P^t_{x,y+1,z} - 2 \bullet P^t_{x,y,z} + P^t_{x,y-1,z}\right) \\ & + \frac{c_z^2 \bullet \Delta t^2}{\Delta x^2} \bullet \left(P^t_{x,y,z+1} - 2 \bullet P^t_{x,y,z} + P^t_{x,y,z-1}\right) \\ & + 2 \bullet P^t_{x,y,z} - P^{t-1}_{x,y,z} - c^2_{x,y,z} \bullet \Delta t^2 \bullet S^t_{x,y,z} \end{aligned} \tag{2}$$

where x, y, and z are the spatial indices, t is the time index, P is the acoustic pressure in N/m^2, S is the pressure of the initial sound source, Δt is the finite time difference equal to our sampling period (1/44100 sec.), Δx, Δy, and Δz are the finite spatial differences equal to our spatial resolution (0.0148 meters), and c is the speed of sound in m/sec. One will notice that we treat the speed of sound as a three-dimensional vector rather than a scalar. While the dependence of c on temperature as represented in (1) is direction independent, the directional effects of wind velocity force us to consider c in terms of spatial components.

After deriving the finite difference approximation of the wave equation, it is important to establish boundary conditions. In order to simulate outdoor conditions, the sound energy should dissipate completely at infinity. Since the virtual environment is finite in extent, total absorption is required at the boundaries. In practice, it is not possible to achieve perfect absorption when using the finite difference equation. Robert L. Higdon [8], however, suggests methods that approach near perfect absorption at the boundaries. This simulation utilizes an averaging method that incorporates the following relationship for the boundaries of the cubical simulation space (here for one boundary):

$$P^{t+1}_{0,y,z} = \frac{1}{3} \bullet \left(P^{t+1}_{1,y,z} + P^t_{0,y,z} + P^t_{1,y,z}\right) \tag{3}$$

where P is the pressure magnitude with spatial indices x, y, and z and temporal index t. Similar relationships follow for the other five boundaries when substituting the appropriate values for the indices.

Due to the nature of the finite difference equation, there are certain values of the constants that can result in an unstable output. Lines, Slawinski, and Bording [9] suggest applying the following constraint:

$$\frac{c \bullet \Delta t}{\Delta x} \le \frac{1}{\sqrt{3}} \tag{4}$$

where c is the speed of sound in m/sec, Δt is the period between samples in seconds, and Δx is the finite difference in meters.

2.1. Constructing the Turbule

As suggested by Goedecke and Auvermann, the turbule is spherically symmetric with temperature and wind velocities differing from ambient atmospheric conditions. For simplicity, the turbule remains fixed in space, and there is no ambient wind. Inside the turbule, the temperature is homogeneous. As an initial approximation of a circular eddy of wind, the wind geometry depicted in Figure 1 is applied to the turbule. In this particular arrangement, only the x-components and z-components of the wind velocity have nonzero amplitude, and their amplitudes are uniform throughout the turbule. While there are several other geometries possible, those are left for future experiments.

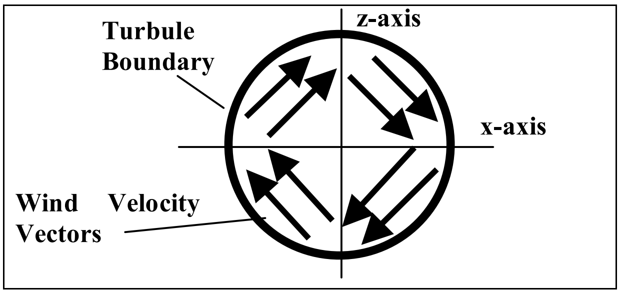

Figure 1. Sample structure of the wind velocity components inside the turbule with the y-axis coming out of the page. The wind has x-components and z-components but no y-components. The vectors are arranged to roughly approximate a circular eddy.

2.3. Choosing the Sound Source

Both the temporal and spectral effects of turbulence are important to this work; therefore, the sound sources must have transients that account for all frequencies in the audible range. In this regard, an acoustic impulse provides the ideal source because it occurs over a short interval of time and includes all frequencies. But, because of the finite sampling rate, the impulse must be band-limited to avoid energy above 12 kHz, the cutoff of the simulation. Matlab is used to create a sinc function of amplitude 1 with a Gaussian envelope to ensure a more finite duration.

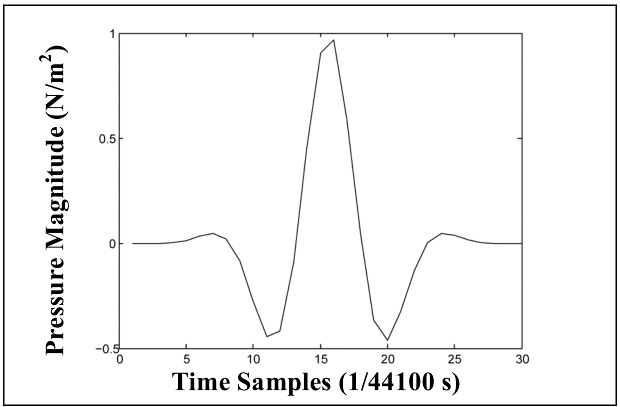

Figure 2. The acoustic impulse used as the sound source in the turbulence simulation. It is constructed from a sinc function with a Gaussian envelope.

2.4. Propagation Geometry

In this simulation, the center of the turbule coincides with the center of the virtual environment. The left most point on the radius is defined to be 0^o (opposite of unit circle). The impulse propagates from the left such that it enters the turbule at 0^o. See Figure 3.

3. RUNNING THE SIMULATION

After creating a robust and flexible simulation environment, the effects of turbulence can be tested in a variety of contexts. This section discusses the parameterization and measurement of the effect of turbulence on sound. All computations were performed on a MacBook Pro laptop running OS X.

sim #	turbule radius (fin diff)	x-comp wind (m/s)	y-comp wind (m/s)	z-comp wind (m/s)	temp diff. (C^o)
1	20	10	0	5	5
2	40	10	0	5	5
3	60	10	0	5	5
4	80	10	0	5	5
5	100	10	0	5	5

Table 1. Parameters for each simulation: radius of turbule in finite differences, components of wind velocity in m/sec, and temperature difference between turbule and ambient conditions in degrees centigrade.

3.1. Turbule Variations

It is possible to simulate a variety of turbulent conditions by manipulating three parameters: the radius of the turbule, the air temperature inside the turbule, and the magnitude of the wind velocity vectors inside the turbule. It is the radius of the turbule that will most likely have a direct correlation with the spectrum of sound; therefore, the other parameters remain constant while the radius varies from simulation to simulation. Table 1 shows the parameters for each simulation.

3.2. Impulse Responses

The effects of air turbulence on the acoustic impulse are measured by sampling the data both before and after the propagation through the turbule. Because the finite difference equation has its own impulse response without turbulence, it is important to compare post-turbule responses with pre-turbule responses rather than with the isolated waveform of the impulse. The first sample point lies just outside the turbule at the 0^o angle of incidence. The other sample points lie just outside the turbule at 120^o, 180^o, and 240^o as shown in Figure 3.

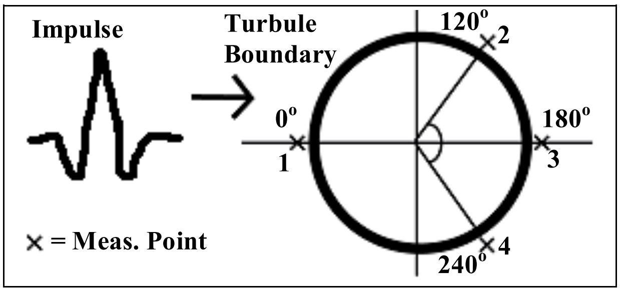

Figure 3. Geometry of four sample points. Point 1 at 0^o samples pre-turbule propagation while points 2, 3, and 4 at 120^o, 180^o, and 240^o, respectively, sample post-turbule propagation.

4. RESULTS

4.1. Distortion of the Wave Form

Figure 4 shows the impulse responses of simulation #4 with the pre-turbule impulse in the top left. Due to the variations in wind speed and temperature, one should notice distortions in the waveform of the impulse. These distortions result in three types of effects: an increase or decrease in the peak energy of the impulse, a change in frequency content, and a phase delay.

4.2. Phase Delay

While the changes in peak energy and frequency content are relevant to music, the phase delay is the most significant effect since it can determine the filter coefficients in a module that would emulate the effects of turbulence in real time. The phase delay of the turbule is calculated by taking the difference between the phase delay of the pre-turbule impulse response and the phase delay of the post-turbule impulse response.

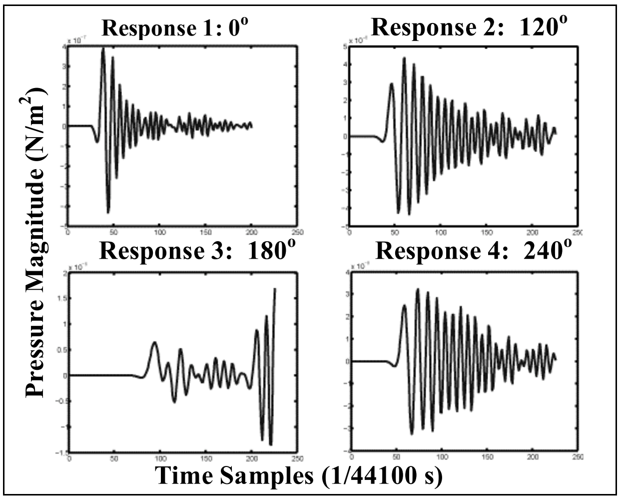

Figure 4. Impulse responses from simulation #4 with the pre-turbule response at the top left. Notice the amount of delay and distortion of the post-turbule responses compared to the pre-turbule response.

Figure 5 shows the phase delay of the four turbule sizes from simulations 1-4. From Figure 5 it is evident that increasing the radius of the turbule increases the phase delay of the lower frequencies. This proves that the radius of the turbule directly correlates with the spectrum of sound.

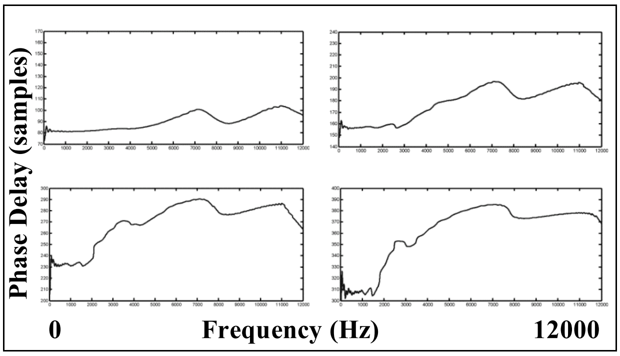

Figure 5. Phase delay of five turbule radiuses from simulations 1-4. In this particular example, the 0^o and 180^o impulse responses are used.

5. CONCLUSIONS

We have successfully implemented the turbule model and demonstrated its effect on acoustic signals. The impulse responses of simulated turbules have been calculated and examined. In the next stage of the project a library of turbule responses will be created, each representing a unique size and unique atmospheric condition. This data will be used to re-implement turbules for audio signal processing by simulating the turbule's properties through digital filtering. The easiest approach would be to implement convolution with the turbule response.

For a digital effects module to be practical, it must allow the user to control and scale the magnitude and quality of the turbulence. This will be accomplished by building a dynamic network of turbules, a network that includes turbules of different sizes, air velocities and temperatures. The user of such a module will be able to simulate air turbulence through a variety of atmospheric conditions and over a variety of distances. Most importantly, there is no restriction that the network simulate real-world conditions. The magnitude of air turbulence can be exaggerated to whatever extent is useful in order to convey the impression of air turbulence. A digital effect does not necessarily depend on realism to be practical. We anticipate the potential that a sound effects idiom representing air turbulence can be established through a model that is built on physical modelling but can be extended to simulate exaggerated conditions.

6. REFERENCES

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