Acoustic Simulation of Singing Sand Dunes using the Discrete Element Method

Introduction

Singing sand dunes, known for their characteristic low-frequency booming during avalanches, remain one of the most fascinating naturally occurring acoustic phenomena. Their sound, characterized by a low resonance ranging from 70–110 Hz, can persist for several seconds and reach high amplitudes (*citation*). Recent research (Dagois-Bohy et al., 2012; Vriend, 2010; Patitsas, 2008; Andreotti, 2004) has demonstrated that this sound arises from the synchronization of grain collisions within a well-sorted sand layer; collective oscillations propagate as a self-organized resonance, linking granular contact dynamics with overall dune motion and consequent acoustic emission.

Here, the acoustic qualities of granular avalanches are approximated using the Discrete Element Method (DEM) in the Yet Another Dynamic Engine (YADE) software. In a physical simulation, the mesoscopic kinematic interactions of sand grains is simulated for the purpose of recreating macroscopic oscillations directly related to the resonant sound heard in the field. The data collected from the simulation is then processed into an audio file. With these techniques, this work provides the basis for a new synthesis technique that generates sound based on the vibrational modes of a body of grains.

Related Works — Physical Modelling

The use of physical modelling in audio synthesis traditionally stems from linear systems (e.g., strings, plates, and membranes). However, granular physical modelling extends this paradigm to non-continuous, collision-based media. Studies by Bilbao (2009) and Perry Cook (2002) have explored physically-based synthesis using mass-spring systems and waveguides, yet few have addressed physical modelling emerging from granular media directly.

In computational acoustics, granular DEM has been employed to understand impact acoustics (Schwartz et al., 2019) and particulate friction noise (Howe & Kurbatskii, 2001 **dubious**). Translating such simulations into audio signals, however, is non-trivial, as the signal must represent acceleration fluctuations across the normal of a surface composed of grains. The present work expands upon this by sampling particle kinematics from DEM outputs and converting them into time-domain signals, establishing a data-driven approach to granular physical modelling synthesis.

Related Works — Mechanics of Singing Dunes

The mechanism of sound production in singing dunes has been investigated extensively. Dagois-Bohy et al. (2012) demonstrated that booming can occur in small laboratory avalanches, even in the absence of a full dune, suggesting that the sound arises from collective grain motion rather than only large-scale dune resonance. Patitsas (2008) proposed that sound generation occurs when surface grain collisions synchronize, forming standing waves through feedback within the moving layer.

Past experimental and numerical studies (Andreotti, 2004; Douady et al., 2006; Richard et al., 2008) identified the frequency of the emitted sound as inversely proportional to the average grain size, typically following the empirical relation:

(1) $f \approx \frac{v_c}{\lambda_g} \propto \sqrt{\frac{g}{d}}$

where (v_c) is the characteristic collision velocity, (λ_g) is the granular wavelength, (g) is gravity, and (d) is grain diameter. Dagois-Bohy et al. also established that resonant feedback within the flowing layer is possible when the layer thickness corresponds to half the acoustic wavelength, providing a self-sustained oscillation condition (**is this true?**).

These insights form the theoretical foundation of the present study, which aims to numerically reproduce this resonance using realistic singing sand parameters in YADE.

Methods

The simulation utilizes the Hertz–Mindlin contact model in YADE to compute forces during grain collisions. Material properties were derived for the sand, derived from the properties of quartz and experimentally measured values for singing sand (). A gravity-driven avalanche was triggered by releasing grains on an incline and allowing them to flow over time.

Python functions were integrated into YADE's simulation loop to measure surface velocity in defined sampling windows. These measurements represent the mesoscopic motion of grains along the inclined surface and can be used to model the booming found in natural dunes. The data collection functions calculate the normal velocity components of grains within bounded spatial windows using the plane equation $3x + 5.196z = 0$. Results were saved each iteration and saved into a text file formatted for future processing to a `numpy` array.

The collected data was then parsed from the text file to separate `numpy` arrays on which various processes were performed: normalization, resampling, then plotting and audio file generation. The generated audio files for each dataset was then aurally analyzed. Frequency content is also analyzed using a Short-Time Fourier Transform Spectrogram in Izotope's RX 10 Audio Editor.

Implementation

The simulation was implemented using Python 3.11.2 and YADE 2023.02a. The simulation itself made use of the `FrictMatCDM` material, which provides pressure-dependent friction simulation that ensures accuracy to the behavior of experimentally measured grains. The material parameters used are consistent with materials associated with sand measured experimentally, which is most commonly quartz (Leach 1995). Additionally, the Hertz-Mindlin contact model is employed to allow for more accurate modelling of the tangential force applied during frictional contact (Pandare 2025).

Various custom data collection methods are employed, the most notable of which being a class that can be instantiated using bounds of a particular window. The methods of this class allow for the collection of average normal distance, average normal velocity, average normal velocity above a given normal vector threshold, and the maximum normal velocity in a given spatial window. The data collected with this class is then plotted using YADE's `yade.plot` module, after which it is saved to a text file for later processing.

The processing in question is done using `numpy` and SciPy's `scipy.io.wavfile` module. Each array is first normalized to ensure consistent amplitude scaling.

```
sampleData = np.genfromtxt('../yade/sacred_data.txt',dtype=None,names=True)
data1 = sampleData['surfacevelocityabovethreshw1']
```

After normalizing each array between -0.5 and 0.5, each dataset's moving average is taken using `scipy`'s `uniform_filter1d` method and subtracted from the original dataset in order to capture the resonant details of each dataset.

```
windowdData1 = normalizedData1 - uniform_filter1d(normalizedData1)
```

The temporal resolution of the data is determined by the simulation’s time step, with the total duration calculated as the product of the time step and the number of data points. To convert the normalized time-series data into audio, the arrays are resampled at a sample rate of 44.1 kHz, preserving the temporal structure of the original simulation.

```
# set sample rate
sampleRate = 44100

# sample dataset at sampleRate Hz
def getDataAtSR(array):
    sampledArray = []
    interval = len(array) / (sampleRate * dataTimeLength)
    for i in range(sampleRate):
        sampledArray.append(array[int(i * interval)])
    return np.array(sampledArray, dtype=float)
```

The resulting datasets are saved in WAV format, enabling aural analysis of the collected data. Additionally, the normalized data is plotted using `numpy.plot`. Spectral characteristics are visualized using using a Short-Time Fourier Transform Spectrogram in Izotope's RX 10 audio editor.

Simulation Set-Up

The simulation scene is composed of **8000 grains** within a scaled domain representing a small sand ramp experiment.

Parameter	Symbol	Value
Grain radius	(r)	$1.5 \times 10^{-4} \times \kappa \, \mathrm{m}$
Grain density	(ρ_s)	$2650 \, \mathrm{kg/m^3}$
Young's modulus (sand)	(E_s)	$7.2 \times 10^{10} \, \mathrm{Pa}$
Poisson ratio	(ν_s)	0.17
Friction angle	(ϕ_s)	20°

Fig. 1: a table detailing the properties of each individual grain. κ represents the scaling factor applied globally to the simulation.

Boundary conditions included fixed ramp facets and a movable “door” element used to initiate grain flow. The ramp is approximately $2.1 \times \kappa$ meters. The simulation operated with a timestep defined by `O.dt = PWaveTimeStep()`, ensuring numerical stability under the Hertz–Mindlin regime.

Results

Spectral analysis of the post-processed data revealed dominant frequencies within the 70-80 Hz range, matching the approximation provided by the aforementioned equation

(2) $0.4\sqrt{\frac{g}{d}}$,

which provides a value of $72.3\mathrm{Hz}$.

Fig. 2 *A sporadic frequency spectrum is observed, reinforced aurally by a noisy, ill-defined sound.*

The datasets that produced audible resonance were the normal surface velocity datasets. This resonance appears to not be present in the initial audio file (*Fig. 2*). The reason for this is likely due to the fact that, when the average distance of a given group of grains is measured in a particular window, the comparably small amount of grains results in more variation in the average value.

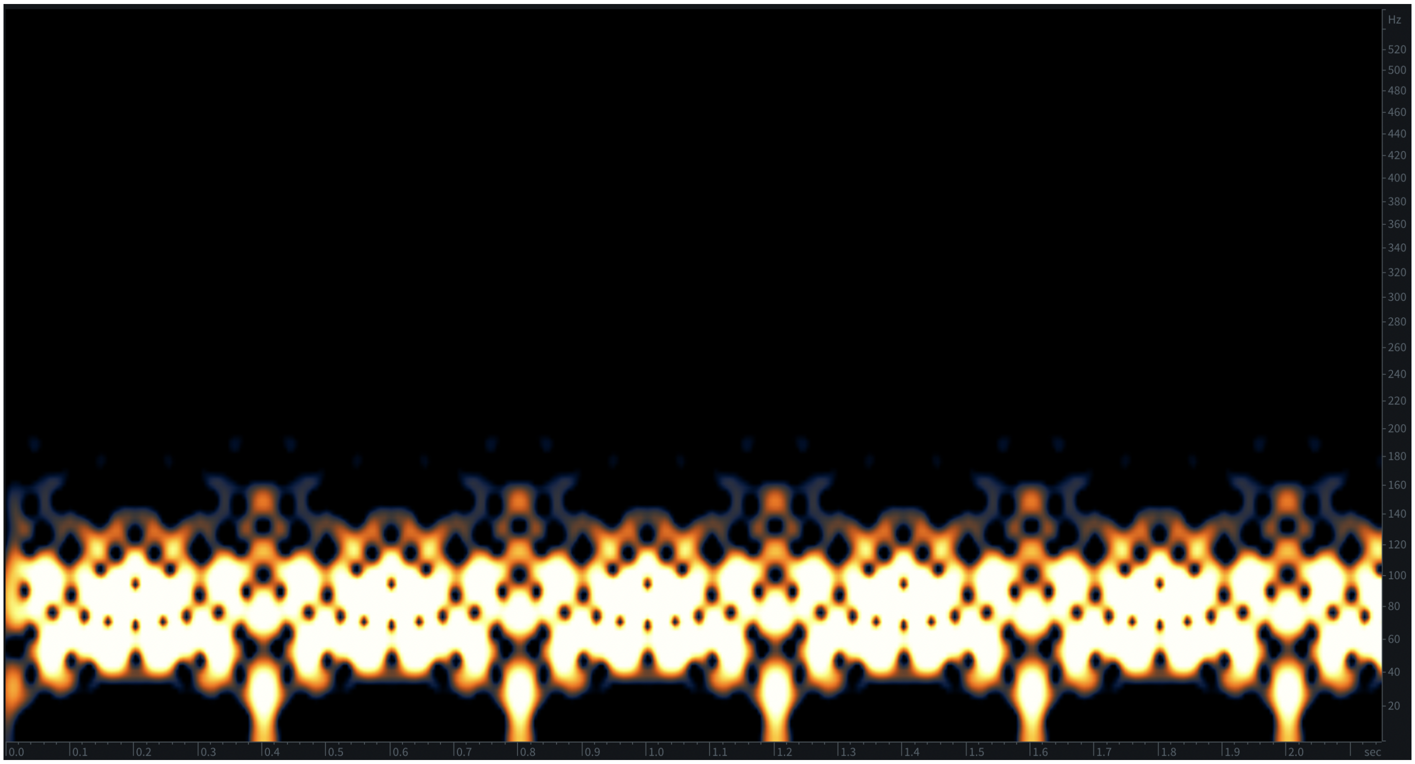

Fig. 3 *A portion of the original audio file processed from the average surface velocity in window 1 is filtered with a 12dB/oct Low Pass Filter at 500Hz and palindromically looped, resulting in a band of resonance centered around 70Hz*

With this in mind, a middle portion of the dataset can be palindromincally looped. The portion taken is approximately 400ms in length and results in a resonance that peaks at 70 Hz. This can be more precisely determined using a Welch Periodogram (*Fig. 4*). This is the only dataset that produces a value that is precisely consistent with (2). Despite these inconsistencies, though, the resonant frequencies of the other datasets are 93 Hz, which is within an acceptable range to be considered a result of the dune's resonance.

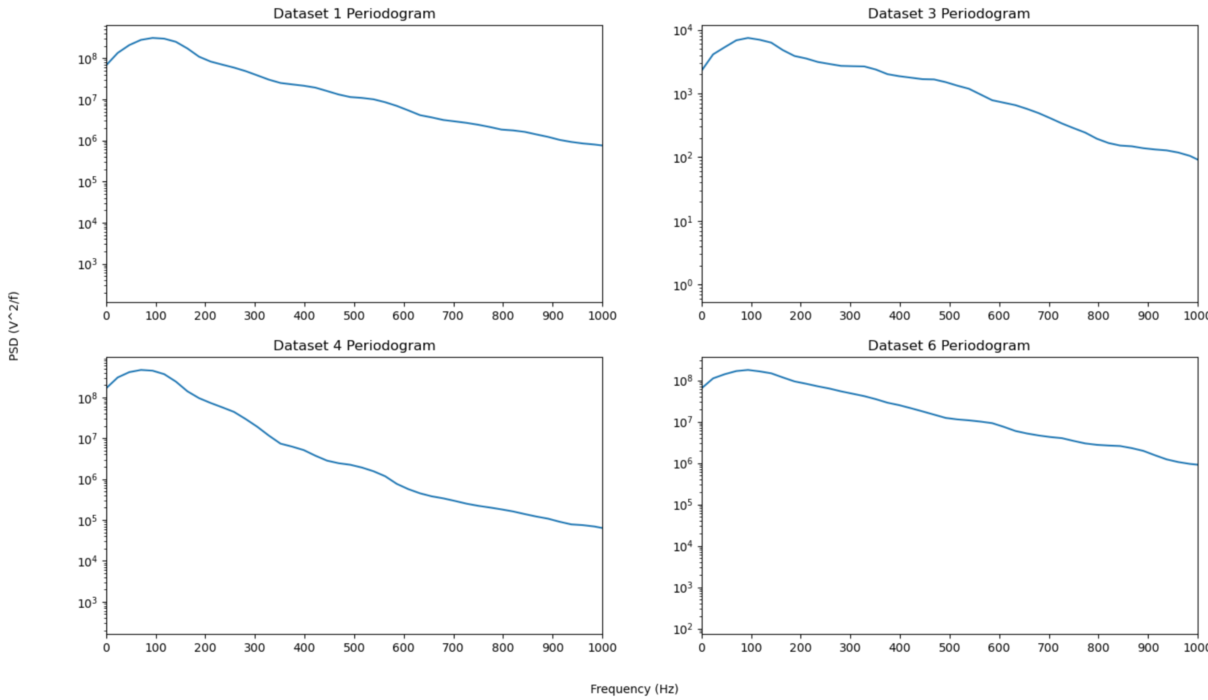

Fig. 4 *Welch Periodograms of each looped dataset.*

Therefore, though the simulation operates at a reduced scale, the relationships between grain size, gravity, and sound frequency remain somewhat consistent with the scaling laws established by Dagois-Bohy et al. (2012) and Andreotti (2004).

Conclusion

This study demonstrates that the booming dune phenomenon can be qualitatively reproduced using a physically faithful DEM-based granular simulation. By correlating microscopic particle dynamics with macroscopic vibrational modes, the simulation confirms that synchronized grain motion can yield sustained low-frequency oscillations.

While limited by computational performance and scale, this model establishes a framework for coupling granular physics and sound synthesis, forming a bridge between physical acoustics and computational music technology. Future work will focus on real-time parameterization, GPU acceleration, and direct audio synthesis from velocity data streams.

Discussion — Potential Applications

The implications of this study extend beyond geophysical research. In acoustic modelling, DEM-based granular simulations offer new avenues for synthesizing textures derived from real physical interactions — e.g., sand, gravel, and particulate friction sounds. In granular audio synthesis, such models provide microscopically accurate mappings between physical parameters (grain size, density, friction) and perceptual features (pitch, timbre).

As a plugin implementation, a simplified version of this model could be adapted into a physical modelling synthesizer for sound designers, allowing procedural control over granular material properties. Additionally, the ability to simulate self-organized oscillations introduces a new dimension to procedural sound generation and soundscape synthesis in media production.

References

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