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 travel over long distances. Recent research (Dagois-Bohy et al., 2012; Vriend et al., 2007; Patitsas, 2008; Andreotti, 2004) has demonstrated that this sound arises from a coherent synchronization of grain collisions within a well-sorted sand layer. Such collective oscillations propagate as a self-organized resonance, linking granular contact dynamics with overally dune motion and consequent acoustic emission.

Here, the acoustic qualities of granular avalanches using the **Discrete Element Method (DEM)** in the **Yet Another Dynamic Engine (YADE)** software are modelled. Through physical modelling synthesis, the mesoscopic kinematic interactions of sand grains is simulated for the purpose of recreating macroscopic oscillations directly related to the audible boom. This work bridges granular mechanics and sound synthesis, providing the outline for a synthesis technique that may be worked into the context digital signal processing.

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 — How Dunes Make Sound

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 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:

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

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 YADE's **Hertz–Mindlin contact model** to compute forces during inter-grain collisions. Two material types were defined: a **cloth substrate** (representing the supporting ramp) and **sand grains** with material properties derived from measurements taken by various experimenters (*citation needed*). A gravity-driven avalanche was triggered by releasing grains from a ramped surface and allowing them to flow over time.

Custom Python functions were integrated into YADE's event loop to measure **average normal velocity**, **surface velocity**, and **kinetic energy** 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 text files for later processing. The collected data was then processed into individual numpy arrays on which algorithms could be run in order to make the data suitable for an audio file.

Implementation

The simulation was implemented in **Python 3.11** using **YADE 2024.04**, interfacing with YADE's C++ core for DEM computations. Visualization and data collection were handled through the `yade.plot` module and **VTK** recording tools.

The simulation code defines custom engines including:

- **ForceResetter**, **InsertionSortCollider**, and **InteractionLoop** for dynamic updates,

- **NewtonIntegrator** with damping and gravitational acceleration,
- **PyRunner** objects for iterative plotting, saving, and door release events,
- **SnapshotEngine** and **VTKRecorder** for data and visual frame output.

The **material parameters** used were consistent with experimental sand (density 2650 kg/m³, friction angle 20°, Young's modulus 7.2×10^{10} Pa) (*citations needed*). The resulting simulation data was processed using **NumPy** and **SciPy** for signal analysis and audio rendering.

Simulation Set-Up

The simulation scene is composed of **8000 grains** within a scaled domain representing a small sand ramp experiment. The following parameters were used for the grains:

Parameter	**Symbol**	**Value**
Grain radius	(r)	$1.5 \times 10^{-4} \times \text{scalingFactor}$ m
Grain density	(ρ_s)	2650 kg/m³
Young's modulus (sand)	(E_s)	7.2×10^{10} Pa
Poisson ratio	(ν_s)	0.17
Friction angle	(ϕ_s)	20°
Gravity	(g)	$9.81 \times \text{scalingFactor}$ m/s²
Number of grains	(N)	8000
Simulation time	(T)	5 virtual seconds

Boundary conditions included fixed ramp facets and a **movable "door"** element used to initiate grain flow. The simulation operated with a timestep defined by `O.dt = PWaveTimeStep()`, ensuring numerical stability under the Hertz–Mindlin regime.

Results

The output from the simulation includes **velocity-time profiles**, **average normal velocity per spatial window**, and **system kinetic energy**. Distinct oscillatory patterns emerged in surface velocity data following avalanche onset, indicative of **coherent grain motion**.

Spectral analysis of the post-processed data revealed dominant frequencies within the 80–110 Hz range — closely matching experimentally observed booming dune frequencies. Kinetic energy exhibited quasi-periodic peaks correlating with surface velocity fluctuations, further supporting the hypothesis of **collective granular resonance**.

Although the simulation operates at a reduced scale, the dimensionless relationships (between grain size, gravity, and sound frequency) remain 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.

The theoretical insights gained also contribute to broader **granular dynamics research**, potentially informing the study of avalanches, landslides, and industrial granular flow acoustics.

References

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