Singing Sand Dunes

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One of the highly striking yet poorly understood natural phenomena is the *song of dunes*. Some sand dunes in deserts are capable of emitting a loud persistent sound with a characteristic audible low-frequency ($\approx 75–105$ Hz), that can sometimes be heard up to 10 km away. Scientific investigations suggest that the sustained low-frequency sound of sand dunes that resembles a pure note from a musical instrument, is due to the synchronized motion of well-sorted dry sand grains when they spontaneously avalanche under gravity. This article describes the underlying mechanism for sustained sound emission in singing sand dunes in light of recent physical experiments.

1. Introduction

_The desert spirits can do amazing and incredible things. Even in the daytime their voices can sometimes be heard, or there is a clash of arms, a roll of drums or the sound of different musical instruments. For these reasons, travelers go in large numbers and stay close to one another._

– Marco Polo (1295)

In 13th century, the Venetian explorer Marco Polo [1] on his journey through the Gobi desert witnessed mysterious noises which he solely attributed to the voices of evil spirits and goblins. He wrote that the singing sands

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**Keywords**

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“at times fill the air with the sounds of all kinds of musical instruments, and also of drums and the clash of arms.” Many explorers including Marco Polo, Charles Montagu Doughty [2], Ralph Bagnold [3], the Mughal emperor Babur [4], the viceroy of India Lord Curzon [4], and others [5, 6] have been mystified by the allure of desert’s music. Over the centuries, the legends and mystical beauty of singing sand dunes have occupied a special place in poetry, art, desert folklore, and writings.

Scientists started to unravel the mystery of sound generation in sands during the last two centuries [7-16]. Recently, through a number of ingenious experiments and direct field observations [17], physicists have worked very hard to understand the underlying dynamical mechanism of singing dunes [18–22]. Their in-depth investigations provide a physical picture of singing dunes on the basis of the dynamics of granular flow. It is interesting and, at the same time, quite hard to speak about the song of dunes as the singing mechanism is not as usual. Rather than entering into mathematical details, in this article, we make an attempt to visualize physical insights on the basis of the available scientific observations and explanations.

2. Sand Grains Under Shear

Sand is a granular material with astonishing physical behavior. While pouring freely under gravity, sands can act like a fluid with viscosity. The falling sand grains form a heap with rigidity, a characteristic of a solid. The windswept sand grains, temporarily suspended in the air like a gas, can travel long distances. There are some strange sand beaches in Japan (Kotobikihama beach [23]), Great Britain (the Isle of Eigg [24]), Canada (Basin Head, Prince Edward Island), and the United States (Barking sands of Kaua’i, Hawai [25]) which emit high frequency (∼ 1 KHz) sound when walked upon. While walking, the sand is displaced quickly underfoot.
and emits a high frequency squeak or whistle of short duration. In order to explain why some sands sing, scientists proposed during the last two centuries, explanations based on the characteristics of the grains. It was found that not all sands are musical; singing sands are composed of dry (free of humidity), rounded, and polished (free of dust and pollution) grains having a very narrow size distribution [7, 9, 10, 13, 24, 26, 15]. Carus-Wilson [7] ascribed the sound to friction between grains while Bolton and Julien [8] proposed the generation of sound in terms of an air film around the grains acting as a cushion capable of vibration. Poynting and Thompson [11, 12], on the other hand, pointed out that sound is produced by the relative motion between grains and that the frequency $f$ scales with the shear velocity $v$ and the characteristic length scale (the grain size) $d$, as $f \approx v/d$. Compressing sand grains by a pestle, Hidaka et al. [16] observed discrete shear bands and attributed it to the frictional properties of the sand. The frequency ($f_{sq}$) of the whistling of this compressed sand was found to depend on the width of the shear band $\delta h$, the penetration speed of the pestle $v_p$, and the total number of shear bands $n$, as

$$f_{sq} = \frac{n v_p}{\delta h}.$$  \hspace{1cm} (1)

Depending on the penetration speed $v_p$, the squeak frequency varies from 250 to 355 Hz. Laboratory experiments [27] also recorded frequencies ranging from 340 to 700 Hz while exciting whistling sand with a pestle in a glass pot. Nevertheless, the ‘squeaking’ sound on sand beaches, consisting of short acoustic bursts, differs fundamentally from the sustained acoustic emission from the singing dunes [28, 29]. In the following section, we shall discuss briefly the morphology of sand dunes, that might help the reader to follow the subsequent section.

3. An Overview of Sand Dunes

In deserts, wind-blown sand is important in shaping the

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$^1$ The differences in velocity (shearing) due to the frictional properties of the sand create discrete slip band known as shear band. The emergence of such shear banding in booming flows has been observed directly in the field [21]. The moving sand grains are separated from the static sand bed by a shear band whose thickness scales on the grain diameter $d$. Thus a localized shear band forms at the interface between the avalanche and static part of the dune. Inside a shear band, the energy of the colliding grains is transferred from the shearing motion to elastic deformations.
Figure 1. A sketch of a barchan dune showing its slip face and the morphological parameters, namely, the down-wind length $L$, cross-wind width $W$, and the cross-wind height $H$.

physical scenery. Wind lifts grains of sand, which are then blown and bounced forward. The wind piles up the sand to a single summit known as a dune. Sand grains start to cascade down (avalanche) naturally under the influence of gravity when the slope locally exceeds the static friction coefficient $\mu_s = \tan \theta_s$. In such a case, the gravity overcomes the frictional drag and triggers an avalanche down the surface. For a natural aeolian (wind driven) dune, $\theta_s$ is around $35^\circ$. Across the Earth’s dry sand deserts, there are several types of dunes with large slip faces (Figure 1). They display a wide variety of structures depending on the complex physical interactions between wind flow and the sand bed. The wind sets the sand grains into motion, controls the sand flux, and constructs a characteristic shape of the dune. In turn, the shape of the dune determines the velocity field around it and modifies the flow pattern of the wind. The equilibrium between these two processes leads to the selection of shape and dynamics of dunes. Accordingly, dunes are differentiated mainly as barchan (crescent-shaped dunes, horn downwind, and the slip face is on the concave side), linear (long, parallel ridges separated by corridors), parabolic (U-shaped with arms pointing downwind and crest pointing upwind), and star dunes (several radially symmetrical arms and slip faces).
The crescent-shaped barchans are visually striking enigmatic structures of many deserts [30, 31]. They are formed when the sand bed is driven by a unidirectional wind [32]. Trade winds driven by oceanic anticyclones are almost stable and unidirectional. Very few places in the world, namely, the Peruvian and Chilean coasts, coastal Namibia, Atlantic coast of the Sahara, Morocco, Senegal, northern shores of western Australia are swept out by trade winds. Morphologic measurements on these regions show the existence of a smooth ground surface in addition to a constantly prevailing wind direction. The wind continues to erode the back of the dune, and the sand, being transported in saltation, is deposited at the edge and redistributed on the slip face by avalanches. The barchans, when driven by an almost unidirectional wind, usually maintain a nearly invariant shape and size (3–10 m) for a very long time (1–30 years) [3, 6]. In Atlantic Sahara region there are more than 10,000 barchans [32]. They occur singly or in clusters and propagate on solid ground under unidirectional wind. When winds drive sand dunes forward, seif dunes are formed, named after an Arabic word meaning sword. Sometimes, advancing dunes bury farmland. To stop their advance, people plant trees and grasses to anchor the sand.

4. Physics of Singing Sand Dunes

Many desert sand dunes sing by emitting a persistent, low-frequency harmonious sound, characterized by a dominant audible frequency ($f = 70–105$ Hz) and several

**Figure 2.** Enigmatic structure of sand dunes in (a) Gobi desert and (b) Mongolia desert showing two distinct patterns.
Photo Credit: https://pixabay.com

Many desert sand dunes sing by emitting a persistent, low-frequency harmonious sound.
Figure 3. Sound-producing barchans in (a) Mongolia and (b) Morocco. Photo credit: https://pixabay.com

higher harmonics. This acoustic emission that resembles the sound of a drum, can last for several minutes and sometimes can be perceived up to 10 km away. The singing sand dunes are one of the great artistry of Nature captivating humans for centuries. This booming sound has been reported at latitudes on both the northern (47°N and 19°N) and the southern hemisphere (19°S and 29°S) covering desert climates in the subtropics and the mid-latitudes. Although star dunes are the most common dune type for booming, booming has also been found on barchans [17], on long linear dunes, and on mountains with extended sand drifts.

The singing dunes emit sound when wind blows over them. However, it is recognized that the harmonic sound is not due to the wind [3]. It is the grain motion during the slumping event or natural avalanche on their slip faces, that causes the sound. This has been proved by creating artificial avalanches in laboratory that have exactly the same acoustic emission. More recently, physicists have been interested in this fascinating problem and many interesting experimental results have been accumulated [18, 19, 20, 33, 22, 34]. Andreotti [18], one of the pioneer physicists in this field, performed a series of experiments in the Atlantic Sahara (Morocco) covering more than 10,000 barchans and observed that, in the absence of humidity, all the barchans produce sound [17]. Among them, there are three large mega-barchans,
the surfaces of which remain almost always dry and, as a consequence, they have the capability to emit sound nearly 350 days per year. The sound emitted by most of the other smaller dunes persists only a few tens of minutes per year during sunny weather. As we have already discussed in Section 3, the propagation of an almost unidirectional strong wind erodes the back of the dune and piles up sand at the edge of the slip face. When a critical slope is exceeded, a spontaneous avalanche nucleates and propagates down the dune, and sound is produced. Andreotti and his group demonstrated that, with a grain size 180 μm, a constant frequency $f$ of $100 \pm 5$ Hz was observed independent of the size of the dune and the location of the avalanche. Recently Douady et al. [19] during their field observations in Morocco, Chile, China, and Oman also observed a frequency range $75 - 105$ Hz depending on the grain size $(160 - 340 \, \text{µm})$.

The above-mentioned experimental studies and field observations, mainly aimed at elucidating the underlying physics of the booming sound in sand dunes in terms of the granular shear flow, can be summarized as follows. In singing dunes, all the well-sorted and rounded grains of nearly the same size $d$ share the same motion in the avalanche, making collisions at a rate $\Gamma$. During this process, the free surface of the sand bed moves up and down. Laboratory experiments [18] revealed that normal acceleration of the free surface is approximately in phase with the pressure time derivative and it is exactly the same for a loudspeaker whose membrane is covered by sand. Thus the free surface of the sand bed during avalanche vibrates like a membrane of a loudspeaker and excites elastic waves at the flowing layer. At the same time, a grain of size $d$ inside the avalanche moves at a mean speed $\Gamma d$ with respect to the grains beneath it. These collisions of the grains around the same frequency $\Gamma$, further excite the surface elastic waves. The sand layer thus oscillating at a frequency $f$ close to $\Gamma$, Andreotti and his group demonstrated that, with a grain size 180 μm, a constant frequency $f$ of $100 \pm 5$ Hz was observed independent of the size of the dune and the location of the avalanche.
stimulates a further oscillation with frequency $f$. This feedback mechanism synchronizes the collision process of the grain which, in turn, reinforces the oscillation. As a result, a number of grains move in synchrony and, both inside and outside the avalanche there exist surface elastic waves that are localized at few centimeters below the surface, just like Rayleigh waves [35]. The vibration of these resultant elastic waves produce the coherent acoustic emission in the air and the frequency $f$ of the emitted sound is controlled by the granular collision rate $\Gamma$ inside the avalanche.

In granular flow, the rate $\Gamma$ at which grains jump over their neighbours and make collisions, is a measure of the velocity gradient (or shear). Andreotti and his group [18] measured the average velocity profile $U(z)$ inside a small-scale avalanche of sound-producing grains and found a strong shear layer near the free surface. The velocity gradient $\Gamma = \frac{\partial U}{\partial z}$ is found to be independent of the flowing depth $H$ and is precisely equal to the spontaneous frequency $f (\approx 100 \pm 5 \text{ s}^{-1})$ of acoustic emission. This suggests that the acoustic emission of harmonic sound is induced by coherent elastic waves, localized in surface whose frequency $f$ is set by the shear rate $\Gamma$ inside the granular shear band separating the booming avalanche from the static part of the dune. In other words, the coherent oscillation of the sand bed tends to synchronize the collisions, which themselves excite the oscillation coherently.

The above experimental results clearly indicate that the produced harmonious sound in the air is neither due to any resonant condition nor due directly to the avalanche. It is the coherent vibration of the free surface that causes such a booming sound whose frequency depends on the size of the grains. Experiments and theory suggest that for a gravity-induced flow, the frequency $f$ roughly fol-
allows the scaling law

\[ f \approx 0.4 \sqrt{\frac{g}{d}}, \]  

(2)

where \( g \) is the acceleration due to gravity and \( d \) is the grain size. When the grains start taking off the surface, the normal acceleration of the free surface just balances gravity, giving an upper bound (~ 105 dB) to the amplitude of vibration (sound level). In fact, the scaling of the frequency \( f \sim d^{-1/2} \) was approximately verified by several researchers [26, 28] in the narrow range of diameters \( d \) [from 180 \( \mu \)m \( (f = 100 \) Hz) to 380 \( \mu \)m \( (f = 66 \) Hz)] of sounding grains across the world. This relation suggests that in a natural avalanche, the shear rate \( \Gamma \) is directly proportional to the acceleration due to gravity \( g \). By quickly pushing a small avalanche by hand or by releasing a large quantity of sand on a flat surface, the inertial effects can be added to gravity and thus modify the shear rate which, in turn, modifies the shock frequency. This corresponds to what is observed as squeaking sound with frequency of the order of 1 KHz as discussed earlier. Remarkably, this effect has been verified recently in laboratory [19] by plunging a blade into singing sand grains (collected from different locations across the world) at different depths and rotating it by a motor at different velocities. In this controlled laboratory set-up, shear is applied to the grains by pushing sand with the blade and thus sustained booming characterized by constant and well-defined frequencies is obtained, independent of the height of the sand and the velocity of the pushing blade. It was suggested [19] from this experiment that as the grains move, the coupling between each sheared layer of moving grains produces a synchronized motion of the grains, emitting a coherent audible sound whose frequency depends only on the mean shear applied to the grains.

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as discussed above, there are a number of controversial issues regarding the origin of sustained low-frequency sound in sand dunes. Among them, the description based on the resonance condition faced a serious debate in recent years. Some physicists believe that the booming sound in sand dunes originates due to resonance inside the dune just like the origin of musical sounds in a wind instrument [21, 36, 37]. Usually, the oscillations at which a system will oscillate when triggered by a short hit will occur at resonance frequencies. Most musical instruments, namely, the airflow instruments (flute, pipe organ), oscillating strings (guitar, piano, violin), membranes (kettledrum, snare drum), wooden blocks or steel bars (marimba, xylophone), have several resonance frequencies. The vibrations at a resonance frequency lead to large oscillation of the air and sound box in a guitar. In airflow instruments, such as the flute, the airflow is deflected at the sound-producing edge by the sound itself. Does a booming sand dune follow a similar mechanism to create its spontaneous harmonic sound?

It is believed that the dry sand layer of the dune sets up a resonant cavity [21, 36, 37]. The standing (resonant) modes cannot propagate and they accumulate energy in the cavity. The system thus acts like a passive resonator and the avalanche behaves like a source of noise injecting energy into the dune over a range of frequency. The dune thus acts like a passive filter reinforcing the resonance frequency $f_R$. It is also suggested [21, 36, 37] that the booming frequency does not correlate directly with the amplitude of the emission nor with the average particle size. If the booming occurs from the passive resonance of the dry surface layer of the dune, then the booming frequency $f$ should match with the resonant frequency $f_R$. The experiments on Atlantic Sahara [20], however, indicate a measurable difference between the resonance frequency and booming frequency. This is one of the reasons that led Andreotti
et al. [33] to argue that the surface propagation rather than the resonant mode at the meter scale is responsible for the song of dunes. In addition, the ingenious laboratory experiments performed by Douady et al. [19], suggest that the low-frequency booming sound can be produced without a dune and, therefore, the sound is not due to the resonance inside the dune, rather, it is imposed by the motion of the grains. Vriend et al. [36] argued that these brief acoustic emissions are due to a local process at the grain scale and are fundamentally different from the booming emission. They [36] showed via experiments that the frequency does not change with velocity and therefore shear rate.

The above conflicting experimental evidences constitute a great debate and the mystery of singing dunes still remains to be solved. Further experimental tests are required to understand the physics of singing dunes. A direct measurement of the velocity profile inside an avalanche would be helpful to identify the physical parameters involved. It can also be guessed that a continuum model for the acoustic propagation in the dune would provide insight into the elastic wave propagation in the layered structure found in a desert dune.

Conclusion

In this article, based on a number of existing standard scientific field observations and laboratory experiments, we describe the underlying physical principles for the singing sand dunes without any mathematical details. Indeed, the dynamics of granular surface flow during avalanche is governed by a set of nonlinear dynamical equations describing the nonlinear coupling between a moving layer and an erodible bed of static grains. In addition, fluctuations and inhomogeneities on the scale of the granular particles strongly influence their behavior. Thus, detailed numerical simulations are needed to unravel the underlying dynamical behavior of the granular
matter, particularly the spontaneous acoustic emission due to a granular shear flow. As suggested by experiments, the shear band, that leads to the exponential amplification of elastic waves inside an avalanche, occurs due to the friction between the granular flow and the static part of the dune. Inside any thick interface of granular matter, shear stress increases with pressure and acoustic modes get coupled to the mean flow. Consequently, the acoustic modes can be amplified when reflected by the diffusive shear band. In fact, the complex behavior of granular shear flow creates a formidable challenge in revealing the underlying physical mechanism for the song of dunes. However, we hope that the eternal beauty and musical magic of the singing sand dunes will promote human endeavor in uncovering this centuries old mystery.

Suggested Reading

[32] H Elbelchiti, B Andreotti and P Claudin, Barchan dune corridors: field characterization and investigation of control parameters,

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