

Towards probing velocity distributions in dense granular fluids: Utilizing fiber Bragg gratings

Marlo Kunzner^{1,*}, Luis Henriques^{1,†}, Fahad Puthalath¹, Leonardo Facchini¹, Mohammadhossein Shahsavari¹, Léa Gommeringer¹, Martin Angelmahr², Peidong Yu¹, Matthias Sperl¹, Till Böhmer¹, and Jan Philipp Gabriel¹

¹*Institut für Materialphysik im Weltraum, Deutsches Zentrum für Luft- und Raumfahrt (DLR), 51170 Cologne, Germany*

²*Fraunhofer Heinrich Hertz Institute (HHI), 38640 Goslar, Germany*



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Granular gases are commonly characterized through their velocity distribution, which provides access to the granular temperature. In experiments, velocity distributions are typically obtained by particle tracking, which becomes, however, limited at moderate and high particle densities. As a way forward, we propose a new technique for measuring particle velocities *in situ* by using a fiber Bragg grating (FBG) sensor, which remains applicable at significantly higher particle densities. The FBG sensor detects strain pulses induced by particle-fiber collisions, from which the velocity of the impacting particle can be derived. Applying this method to an ensemble of granular particles allows us to extract its velocity distributions, as we present for a granular system excited by a vibrational shaker. We validate the extracted velocity distribution against conventional particle-tracking measurements, confirming the reliability of the FBG-based technique.

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I. INTRODUCTION

Granular matter, as encountered on Earth, appears both at rest and in motion—from the movement of dunes in the desert to the flow of tephra and plant seeds [1,2]. By contrast, granular matter in space is rarely at rest, as seen, for example, in accretion disks [3]. This naturally raises the question: What controls the flow of granular matter?

A central parameter is the volume fraction

$$\varphi = \frac{V_G}{V_T}, \quad (1)$$

quantifying the ratio of the volume occupied by the granular particles, V_G , with respect to the volume they are contained in, V_T , i.e., how densely the grains are packed [1,4–6].

However, volume fraction is not the only relevant parameter: External forces such as gravity, vibrations, shear, or introducing a permeating gas or fluid flow inject energy into the granular system and thereby modify the local packing dynamically, while even φ can be modified globally if the system is allowed to expand [1,7–9]. Thus, a dense granular system at rest (typically at $\varphi \gtrsim 55\%$ [6]) can be fluidized by

supplying sufficient energy [9]. The resulting motion depends on the excitation level: low excitations produce a rather dense fluid-like system, whereas strong excitations can create dilute gas-like systems [1,8].

However, the transition between a granular gas and liquid remains poorly defined, showing no clear difference in governing physics and, in theory, depending only on the volume fraction [1,10,11]. Investigating this open question experimentally is complicated by the opacity of granular matter, which prevents optical techniques from following the motion of individual particles: For a dilute granular system in three-dimensional space, physical properties of individual particles, such as position and velocity, are usually obtained by using direct imaging techniques paired with particle tracking [12–17]. However, already at volume fractions as low as $\varphi = 0.05$, most particles in motion are obscured by others located close to the camera. Thus, particle tracking can not be applied straightforwardly to denser systems, because particle velocities can only be probed close to the boundary where boundary effects are thought to dominate [1,18]. Approaches that can circumvent this issue, e.g., tomography techniques like CT or MRT, with a few exceptions, lack the necessary temporal resolution to access the relevant timescales of granular dynamics in such systems [19–21]. Therefore trade-off between time resolution and particles perceived by a technique needs to be made as soon as the system becomes opaque.

To provide a possible way forward, we introduce a method employing fiber-optical sensors based on fiber Bragg gratings (FBGs) [22–24], which enables the measurement of the velocity distribution in granular systems at previously inaccessible volume fractions. The principal idea is to employ the FBG sensor to monitor the mechanical deflection of an optical fiber during collisions with granular particles. As we derive, the amplitude of a deflection can be obtained from the wavelength

*Present address: Department for Theoretical Physics, University of Cologne.

†Contact author: Marlo.Kunzner@dlr.de

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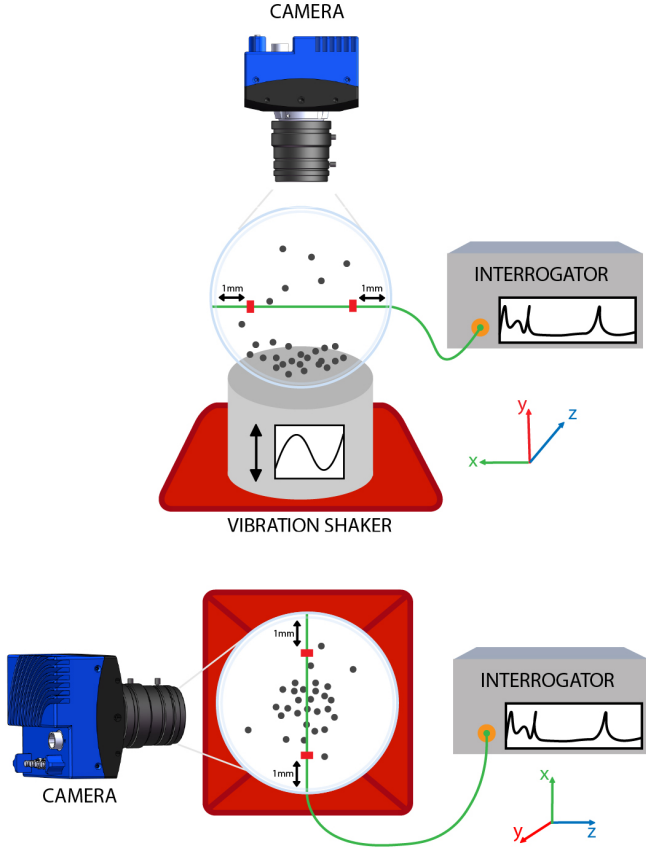


FIG. 1. Schematic illustration of the employed experimental set-up, with a side view in the top and a top view in the bottom panel of the figure. The vibration shaker sinusoidally excites a spherical sample cell filled with $\phi = 3\%$ MuMetal particles. A camera, positioned perpendicular to the fiber, records the particles in the vicinity of the fiber (green). Collision-induced wavelength shifts in the FBG sensors (red) are monitored using an interrogator.

shift probed in the FBG sensor and provides insights into the colliding particle's initial velocity. An exemplary experimental implementation is shown schematically in Fig. 1, where an optical fiber containing two FBG sensors is mounted to be surrounded by granular particles excited by a vibration shaker.

A unique characteristic of granular gases is that, according to kinetic theory, their velocity distribution can be described by a Maxwell-Boltzmann distribution with overpopulated tails [1,18,25,26]. Additionally, due to granular particles colliding inelastically, the restitution coefficient ε_R , indicating the degree of elasticity, is introduced [1,18,27]. Since only the exponents are of interest, the distribution can be simplified to $P(v) \propto \exp(-kv^{3/2})$ for $v > \langle v \rangle / \varepsilon_R$, where $k = m/(2k_B T)$, T the granular temperature, m the particles' mass, and $\langle v \rangle$ their average velocity.

Below, we begin by discussing the principles of FBG sensors and the considerations required to employ them to probe a granular system's velocity distribution. Afterward, we present the first experimental results, beginning with a careful evaluation of single-particle collisions with known initial velocities and contact angle. Finally, we employ an FBG sensor to probe the velocity distribution of a granular system at 3% volume fraction and show that the results conform to simultaneous

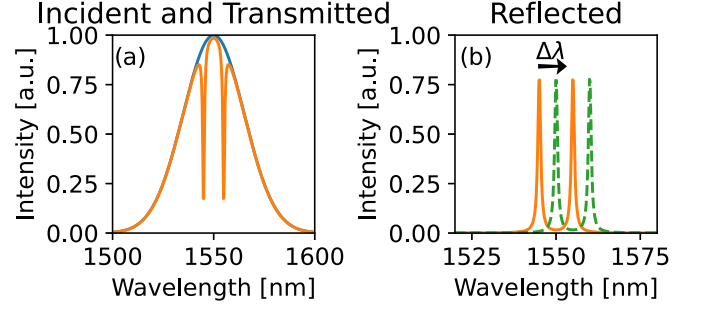


FIG. 2. Schematic illustration of the incident, transmitted and reflected light's spectrum in a FBG sensor. The left panel shows the normalized incident spectrum before passing the grating (blue) and the light transmitted through the grating (orange). The reflected light, which is the one detected by the interrogator, is shown in the right panel. The reflected signal shows a wavelength shift $\Delta\lambda$ once the FBG is strained (dashed green).

particle-tracking measurements and to previous experiments on granular gases [18,28,29].

II. EXPERIMENTAL PRINCIPLE

FBG sensors are optical sensors that use the principle of Bragg reflection to measure various physical parameters such as strain, temperature, and pressure [22,23,30]. They are produced by inscribing a periodic variation of the refractive index (e.g. by femtosecond laser technology) within the core of an optical fiber. When light is transmitted through the fiber, specific wavelengths are reflected by each segment and any changes in the reflected wavelengths can be correlated to local changes in the physical deformation of the grating. For the measurement, the fiber is connected to a fiber optical readout unit referred to as an FBG interrogator. The readout unit consists of a broadband light source, e.g., a superluminescent diode, as well as a spectrometer or a photodiode employed to analyze the reflected light [31,32]. Following this, as illustrated in Fig. 2(a), the intensity spectrum of light transmitted through the FBG sensor (depicted in orange) features a valley in intensity at the Bragg wavelength compared to the incident light (blue). Thus, the reflected light contains the reflected Bragg wavelengths of the FBG sensors, as shown in Fig. 2(b).

When a strain is applied to the fiber, it induces a shift $\Delta\lambda$ to the reflected wavelengths (depicted in green), which is the quantity monitored as a function of time in a typical FBG measurement. As the fiber temperature in our measurements is assumed to be stationary on the timescale relevant for the experiment, changes of $\Delta\lambda$ mostly reflect changes of mechanical strain ε , which is the ratio of change in length of the fiber, ΔL , to original length, L , due to a tensile force, i.e., [33]

$$\varepsilon = \frac{\Delta L}{L}. \quad (2)$$

While neglecting temperature-induced effects, $\Delta\lambda$ caused by this strain can be calculated as

$$\Delta\lambda = \lambda_{B_0}(1 - c_{\text{Photo}})\varepsilon, \quad (3)$$

where λ_{B_0} is the Bragg wavelength and c_{photo} the material-dependent photo-elastic constant, which for the FBG sensor

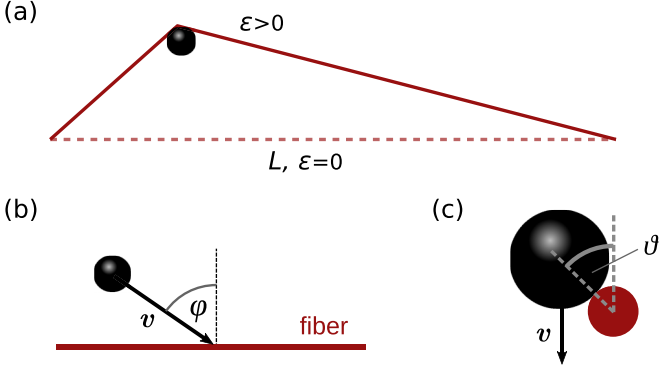


FIG. 3. (a) Upon impact, a particle deflects the fiber of length L , inducing a strain ε (deflection not to scale; actual deflections are orders of magnitude smaller than L). The lower panels illustrate the definition of (b) polar angle φ and (c) contact angle ϑ that characterize the energy transfer to the fiber (red) during collisions with a particle (black).

used in this study is ~ 0.22 [24,33]. Considering the commonly available accuracy of this measurement technique of $\Delta\lambda \approx 1$ pm, strains can be detected with an accuracy of $0.83 \mu\text{m/m}$ at $\lambda_{\text{B0}} = 1555$ nm.

When the FBG sensor is implemented in a granular system, collisions of particles with the fiber lead to deflection of the latter and, thus, induce a distinct strain. In the following, we derive a relation between the velocity v of the particle hitting the fiber and the observed wavelength shift $\Delta\lambda$. To start, we consider direct collisions with vanishing contact angle and with the velocity vector perpendicular to the direction of the fiber. Deviations from these conditions are treated below.

Figure 3(a) illustrates the deflection of the fiber after collision with a particle with velocity v and mass m . The impact and the deflection of the fiber occur on a much longer timescale (~ 3 ms) than the time required for longitudinal sound waves to travel through the entire fiber ($\leq 20 \mu\text{s}$). Therefore, we treat the problem quasistatically, meaning that we assume that at any given point, the fiber has had sufficient time to equalize the tension between the two sides of the fiber; thus, we treat ε as uniform throughout the entire length of the fiber.

Neglecting dissipation, the work $W(\varepsilon)$ required to deflect the fiber equals the colliding particle's initial kinetic energy,

$$W(\varepsilon) = \frac{1}{2}mv^2. \quad (4)$$

To obtain an explicit expression for $W(\varepsilon)$, we consider the total tension on the fiber, given by

$$F(\varepsilon) = EA\varepsilon + T, \quad (5)$$

where E is Young's modulus, A is the cross-sectional area of the fiber, and T is the applied pretension. The total work required to deform the fiber of length L to a strain ε is then given by

$$W(\varepsilon) = \int_0^\varepsilon F(\varepsilon')L d\varepsilon' = \frac{EAL}{2}\varepsilon^2 + TL\varepsilon. \quad (6)$$

Upon combining this relation with the energy conservation condition equation (4), we obtain

$$v^2 = \frac{L}{m}(EA\varepsilon^2 + 2T\varepsilon). \quad (7)$$

This expression links the particle's initial velocity to the resulting maximum strain in the fiber. Considering Eq. (3), a similar relation holds for the particle velocity and the probed wavelength shift, i.e.,

$$v^2 = \frac{L}{m\kappa} \left(\frac{EA}{\kappa} \Delta\lambda^2 + 2T\Delta\lambda \right), \quad (8)$$

where the constant $\kappa = \lambda_{\text{B0}}(1 - c_{\text{photo}})$ relates strain and wavelength shift.

For each detected collision event probed by the FBG, the derived relation allows us to determine the initial velocity of the colliding particle. Notably, the relation, for now, is only valid for direct collisions with vanishing polar angle φ and contact angle ϑ —see Figs. 3(b) and 3(c) for an illustration of both angles. Utilizing the FBG sensor to probe the velocity distribution of a granular system requires us to explicitly take into account collisions with nonvanishing φ and ϑ . Thus, in the following, we treat how the distribution of particle velocities is modulated when both angles are considered.

Following arguments of classical mechanics and neglecting frictional effects, the particle's velocity component u relevant for the deflection of the fiber is given by

$$u = v \cos(\vartheta) \cos(\varphi). \quad (9)$$

When a large number of collisions from an ensemble of granular particles is probed, v , ϑ , and φ are random variables distributed as probability densities $P_V(v)$, $P_\Theta(\vartheta)$, and $P_\Phi(\varphi)$, respectively. P_V is the velocity distribution of interest, while we determine $P_\Theta(\vartheta)$ and $P_\Phi(\varphi)$ using the following geometrical arguments:

In an isotropic granular system, no direction of particle velocity is favored, such that φ is uniformly distributed as $P_\Phi(\varphi) = 1/\pi$ for $\varphi \in [-\pi/2, \pi/2]$.

Considering translational invariance, the impact parameter $b = (R + r) \sin \vartheta$ of particle-fiber collisions is uniformly distributed for $b \in [-(R + r), R + r]$, where R and r are the fiber's and the particle's radius, respectively. Variable transformation yields for the contact angle distribution

$$P_\Theta(\vartheta) = P_B(b(\vartheta)) \left| \frac{db}{d\vartheta} \right| = \frac{1}{2} \cos(\vartheta). \quad (10)$$

Combining these ideas, we obtain for the probability density $P_U(u)$ of the reduced velocity

$$P_U(u) = \frac{1}{m} \int_{-\pi/2}^{\pi/2} \int_{-\pi/2}^{\pi/2} P_V\left(\frac{p}{\cos \vartheta \cos \varphi}\right) \frac{P_\Phi(\varphi) P_\Theta(\vartheta)}{\cos \vartheta \cos \varphi} \times d\varphi d\vartheta. \quad (11)$$

To visualize the difference between $P_U(u)$ and $P_V(v_p)$, we choose $P_V(v)$ to be Maxwell-Boltzmann distributed and calculate $P_U(u)$ numerically using Eq. (11). The results are illustrated in Fig. 4, where the blue and green data represent $P_V(v)$ and $P_U(u)$, respectively. In addition, we include the orange curve that assumes the polar angle to be zero, i.e.,

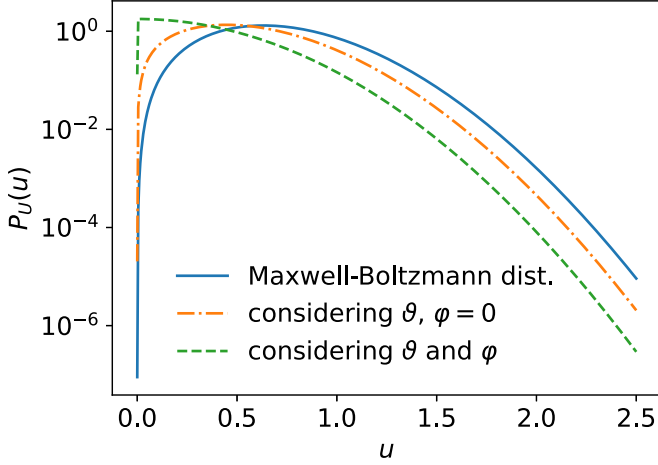


FIG. 4. Velocity distribution functions for a Maxwell-Boltzmann distribution ($P_V(v_p)$) and the angle-dependent skewed versions.

the case where particles only have velocities that are perpendicular to the fiber. Evidently, considering the distribution of contact and polar angle shifts the maximum of the probability density toward smaller velocities and distorts the shape of the velocity distribution at small velocities. However, its shape remains virtually unchanged at larger velocities, which is particularly advantageous as it enables extracting the nature of the overpopulated high-velocity tail present in dense granular gases.

We note that, at least in principle, $P_V(v)$ can be recovered from $P_U(u)$ by inverting Eq. (11)—though, in practice, such an inversion is highly sensitive to noise and is therefore unlikely to be feasible with experimental data. However, it is possible to obtain expressions relating the average velocities of both distributions, which reads

$$\langle u \rangle = \langle v \cos \vartheta \cos \varphi \rangle = \langle v \rangle \langle \cos \vartheta \rangle \langle \cos \varphi \rangle, \quad (12)$$

since for an isotropic system, v , ϑ , and φ are statistically independent, and thus the averages of their respective distributions factorize.

Equation (12) enables comparison to results from particle-tracking approaches that can extract the absolute value of the velocity without any modulation by polar and contact angle. Considering the distributions derived above, $\langle \cos \vartheta \rangle = \pi/4 = 0.785$ and $\langle \cos \varphi \rangle = 2/\pi = 0.637$. We conclude that analyzing $P_U(u)$ instead of $P_V(v_p)$ allows us to draw qualitative conclusions about the shape of the velocity distribution in granular systems, especially at large velocities, and yields a quantitative expression for the respective average velocities.

Finally, we briefly discuss the expected evolution of $\Delta\lambda$ as a function of time once the fiber is hit by a granular particle. The considerations for obtaining the work required to deflect the fiber can be employed to calculate the equation of motion for a particle-fiber collision and, thus, the temporal evolution of the wavelength shift. While the exact solution is only available numerically, for describing the probed signals we consider the analytical expression

$$\Delta\lambda(t) = A \cos(\omega(t - t_0))^2, \quad (13)$$

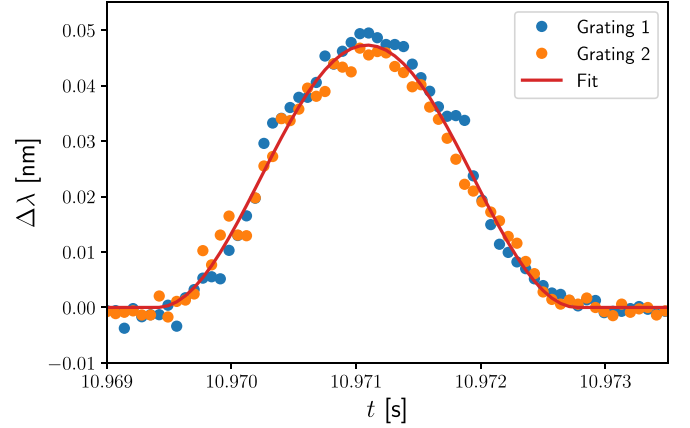


FIG. 5. Wavelength shift versus time for two gratings in a 5 ms time interval. The red line is the fit by Eq. (13) while the blue and orange dots represent gratings 1 and 2, respectively.

obtained by first-order Taylor expansion (see the Appendix A). Figure 5 shows typical data for the wavelength shift probed in both gratings and a fit by Eq. (13). Notably, both gratings are found to probe the same strain for all analyzed collision events. This observation supports our previous assumption of treating the strain as being uniform along the fiber. Below, we always consider the average of both gratings and analyze collision events through fits by Eq. (13).

III. EXPERIMENTAL RESULTS

To confirm the applicability of FBG sensors for measuring granular velocity distributions, we conduct two type of benchmark experiments: First, we verify the theoretically derived relationship between a particle's initial velocity and the corresponding FBG wavelength shift $\Delta\lambda$ derived in Eq. (8). This is achieved by monitoring individual particle-fiber collisions using a high-speed camera to extract initial velocity and contact angle, and correlating the result to the amplitude of the FBG signal. The results allow us to calibrate the FBG sensor for determining absolute particle velocities. Second, we measure the velocity distribution of an ensemble of granular particles excited by a vibration shaker using the FBG signal, and confirm that it agrees with the distribution obtained via particle tracking.

Both experiments were conducted inside a sample cell consisting of a glass sphere with a radius of $r = 2$ cm. The glass fiber (SMF-28 Ultra 200 Optical Fiber from Corning, with a cladding diameter of $d_{\text{clad}} = 125 \mu\text{m}$ and a coating diameter of $d_{\text{coat}} = 242 \mu\text{m}$ [24,34,35]) equipped with two FBG sensors, was inserted into the cell through two small openings at opposite sides. The fiber was positioned such that the distance between each FBG and the corresponding cell wall was approximately 1 mm (marked red in Fig. 1). Subsequently, the fiber was glued to one side of the cell with a structural adhesive (Uhu Plus Schnellfest), after which a mass of 50 g was attached to the fiber to apply a fixed tension force T . The fiber was glued to the opposite opening while the mass remained attached, which yields a total length of the fiber of $L = 42$ mm. After curing the glue and removing the weight, the relaxation of the glue most likely led to a reduction of the

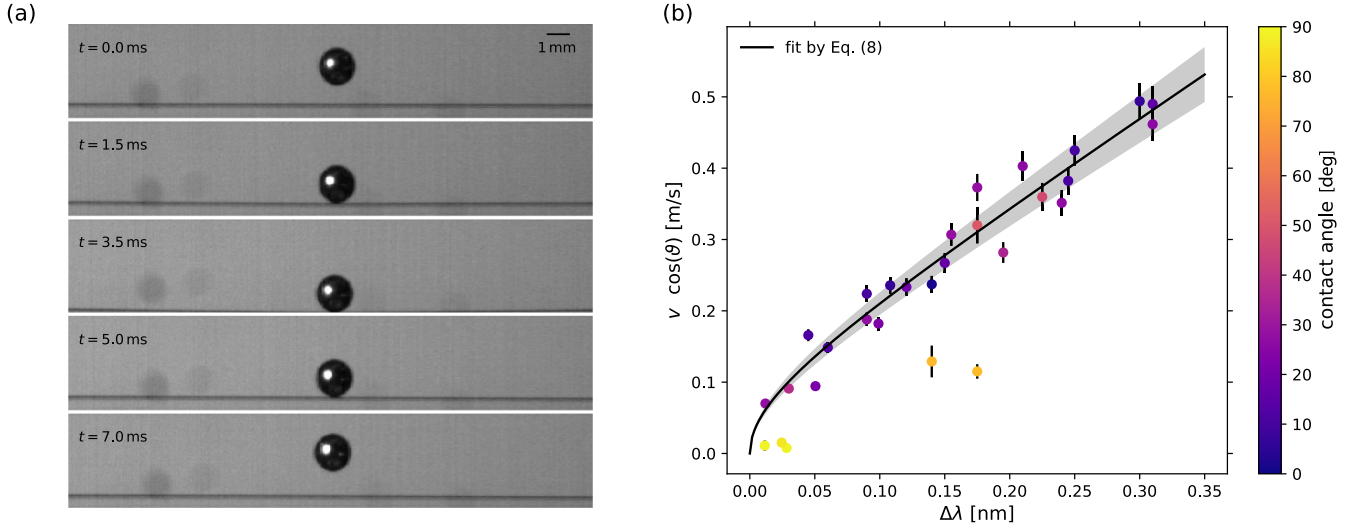


FIG. 6. Interaction of a single particle with the fiber. Panel (a) shows an orthogonal collision event of the particle and the fiber. The collision takes roughly 3.5 ms from frames two to four. Panel (b) shows the reduced velocity $u = v \cos \vartheta$ of the particles plotted against wavelength shift $\Delta\lambda$ observed with the FBG. The contact angle of each data point is indicated by its color. The solid black line indicates a fit based on Eq. (8); for details, see text.

tension to a fraction of its initial value, as will be discussed below. The fiber was connected to the Interrogator (model SPK-155 from Miopas) operated at $1/7 \times 10^5$ Hz and set to monitor both gratings simultaneously. We note that using a fiber with polyimide coating is necessary for these types of measurements, as the acrylate coating created artifacts in the signal. These were most likely caused by the core moving against the coating, as the acrylate coating is less firmly attached to the core than polyimide.

In both experiments, Mu-metal particles with a diameter of 1.6×10^{-3} m, a density of 8.7×10^3 kg/m³, and a mass per particle of $m = 1.87 \times 10^{-5}$ kg were used. These were chosen to match previous experiments on magnetically agitated granular gases in weightlessness [17].

A. Single particle drops

To verify the relationship between $\Delta\lambda$ and u [see Eq. (8)], single particles were dropped onto the fiber from different heights, while their velocity v and contact angle ϑ were monitored using cameras. As dropping the particles from above ensures their velocity is perpendicular to the orientation of the fiber, the polar angle φ is zero and was not monitored during the experiment. To obtain accurate velocity data, a MotionBLITZ Cube 4 high-speed camera, operated at 10 000 frames per second, was used to track the particles' position relative to the fiber. The contact angle was obtained as half the angle of deflection of the particles after collision with the fiber, which was monitored using a Basler acA800-510um camera operated at 510 frames per second and positioned to monitor the particles' position within the scattering plane. Exemplary images showing a particle colliding with the fiber are shown in Fig. 6(a).

The particle velocities were determined using particle tracking and ranged from 0.07 to 0.54 m/s with contact angles between 2 and 88°. Figure 6(b) summarizes the results from the single-particle drop experiments by plotting the particles'

reduced initial velocity $u = v \cos(\vartheta)$ against $\Delta\lambda$. The color of each symbol indicates the contact angle according to the color bar, while the error bars represent the uncertainty of the measured velocity due to the camera resolution.

The solid black line shows a fit using Eq. (8), where E and T were treated as free parameters, yielding $E_{\text{fit}} = (19.49 \pm 3.84)$ GPa and $T_{\text{fit}} = (7.97 \pm 1.61)$ N. All other parameters contributing to Eq. (8) are constants defined by the experimental setup, with parameters that characterize the fiber referring to the composite of core and coating. The fit describes the data well, except for collisions at the largest contact angles, where frictional effects rather than momentum transfer likely dominate the particle-fiber interaction. In the following, Eq. (8) with the parameters determined by the fit is used to extract the absolute particle velocity from measured values of $\Delta\lambda$.

To verify the obtained fitting parameters, we estimate the fiber's expected Young's modulus by modeling it as a two-component composite consisting of silica and polyimide, with Young's moduli of 68.56 GPa and 2.5 GPa, respectively [35,36]. Taking into account the cladding and coating diameters, we obtain an expected value of $E_{\text{theo}} = 20.1$ GPa, which agrees with E_{fit} within the uncertainty. At the same time, the fitted tension is approximately one third of the initially applied tension during gluing, confirming the expectation that part of the tension relaxed due to adhesive relaxation. In the future, a more controlled procedure for implementing a well-defined tension to the fiber could eliminate the need for a comprehensive calibration using single-particle collisions monitored by high-speed cameras.

B. Shaker experiment

The experimental setup employed for the shaker experiment is depicted schematically in Fig. 1. The particles were filled into the sample cell until a volume fraction of $\varphi = 3\%$ was reached. During shaking, the local volume fraction of the granular gas phase was slightly lower than 3%, as some particles remained at the bottom of the sample cell.

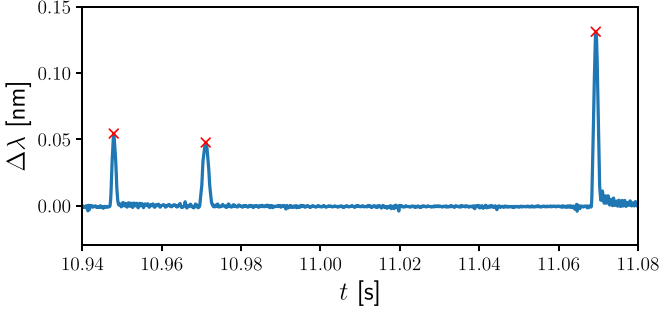


FIG. 7. Wavelength shift versus time showing three collision events during a 140 ms time interval. The red symbols indicate a detected collision event. The subtle background noise is caused by the 40 Hz excitation the shaker operates at.

The shaker, model LSD V721 by Brüel & Kjaer, is operated at a sinusoidal frequency of 40 Hz and with an amplitude of 1 mm. Data were collected for a total of 30 min to reach sufficient statistics.

Since the strain pulses probed by both gratings are found to be identical, we consider their average to reduce measurement noise. Prior to peak detection, a baseline is extracted from the signal using morphological operations, a method that is robust against nonstationary baseline drift and abrupt jumps [37]. Such jumps are present in the data and are attributed to the experimental setup. Peak detection is then performed using the `signal.find_peaks` function from the SciPy library [38] using the following heuristic criteria: a minimum height of 0.008 nm, a full width at half maximum (FWHM) between 0.5 and 5 ms, and a distance from any other detected peak of at least 15 ms. Subsequently, the detected peaks are fitted using Eq. (13) to extract their amplitude $\Delta\lambda$ (see Fig. 5). Fits are retained only if the uncertainty returned by the orthogonal distance regression remains below a prescribed threshold, ensuring that only single-particle fiber collisions contribute to the analysis. An exemplary time series of the FBG signal is shown in Fig. 7, displaying three distinct collision events marked by the red symbols. Using Eq. (8), the particle's reduced velocity is calculated for each impact, which finally yields the velocity distribution of the granular system.

To compare the obtained velocity distribution to results obtained from an established technique, we also determine the velocity distribution from the video recordings of the shaker experiment (with 5000 frames per second) using particle tracking. For the studied system, we did not face any significant issues of overlapping particles. We note that the particle-tracking data correspond to an experiment shaken at 50 Hz.

We compare the velocity distributions obtained using the FBG sensor (orange symbols) and particle tracking (blue symbols) in Fig. 8. Panel (a) reports the distributions as functions of the absolute velocity, while panel (b) shows them normalized with regard to their respective average velocities, which correspond to $\langle u_{\text{int}} \rangle = 0.1244$ m/s and $\langle v_{\text{PT}} \rangle = 0.2143$ m/s, respectively. We note that $\langle v_{\text{PT}} \rangle$ includes a factor of $4/\pi$ that compensates for the fact that the technique probes a 2D projection of the 3D particle dynamics.

The shapes of both velocity distributions are very similar, which is emphasized when comparing both distributions as a function of the normalized velocities, showing almost perfect collapse. As functions of the absolute velocities, the velocity distribution obtained from the FBG sensor is shifted to lower velocities, as it is expected considering that the technique probes $u = v \cos \vartheta \cos \varphi$ instead of v . Comparing the quotient of the respective average velocities yields

$$\frac{\langle u_{\text{int}} \rangle}{\langle v_{\text{PT}} \rangle} = 0.581, \quad (14)$$

which is slightly larger than the factor of $\langle \cos \vartheta \rangle \langle \cos \varphi \rangle = 0.5$ derived in Eq. (12). This is expected, though, considering that collisions at large polar and contact angles close to $\pi/2$ induce very small $\Delta\lambda$ and, therefore, tend to fall below the detection threshold of the technique. As a result, $\langle \cos \varphi \rangle \langle \cos \vartheta \rangle$ is expected to be slightly larger than what would be expected for an isotropic velocity distribution from theory.

IV. DISCUSSION

We begin by discussing the conclusions that can be drawn from the shape of the velocity distributions presented in Fig. 8(b). Both employed experimental techniques reveal an

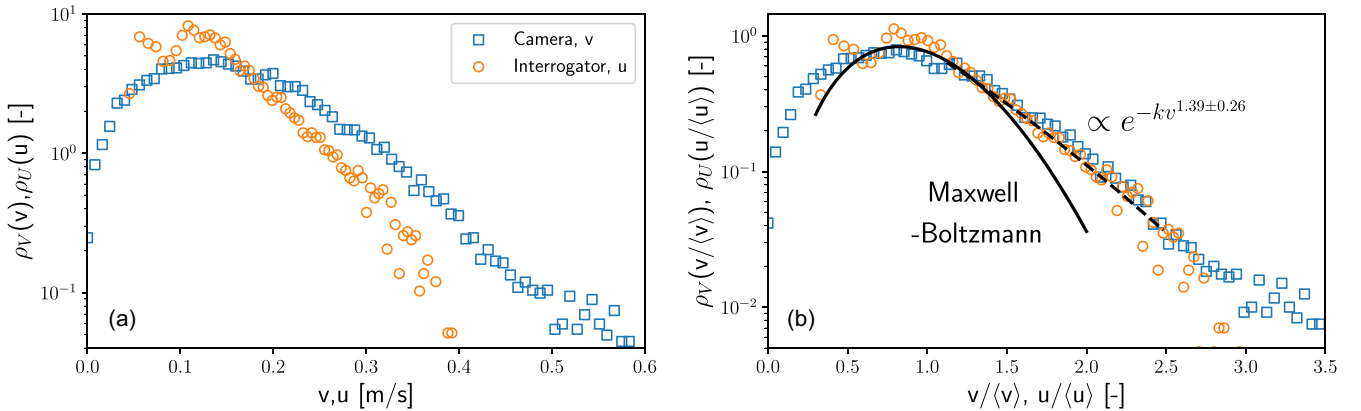


FIG. 8. Velocity distribution of the recorded impacts via FBGs and particle tracking in absolute, panel (a), and normalized, panel (b), velocity. The orange circles show FBG data and blue squares show particle tracking data. The solid black line is a Maxwell-Boltzmann fit for low velocities and the dashed black line an exponential fit with an exponent of $\alpha = 1.39 \pm 0.26$, indicative of the overpopulation at high velocities.

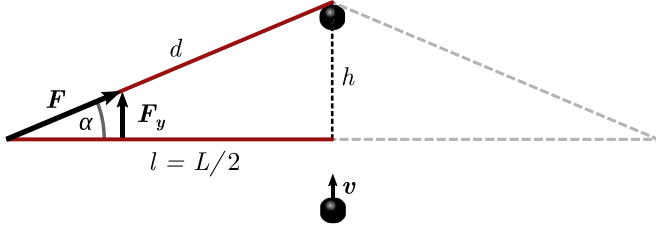


FIG. 9. Illustration of the definitions required to determine the time evolution of the axial stress in the fiber during a particle-fiber collision.

overpopulation at large velocities, which becomes evident when comparing the experimental results to the solid black curve representing a Maxwell-Boltzmann distribution that is unable to describe the data at larger-than-average velocities. Instead, the data follow the dashed black line, which is a maximum likelihood estimation of the slope of the overpopulated high-velocity tail by $\propto \exp(B \cdot v^\alpha)$, where the exponent is $\alpha = 1.39 \pm 0.26$. This exponent is close to what is found for constantly heated granular gases, where typically $\alpha = 1.5$ [25]. However, due to the relatively large uncertainty of α , we cannot fully rule out a freely cooling gas or even granular fluid-like behavior, which would correspond to values of α between 1.5 and 2 [29,39,40]. We furthermore note that, while the fiber intrudes into the system, its influence on the velocity distribution is negligible and it does not act as a nucleation site for particles, as we demonstrate in simulations in Appendix D.

A precise characterization of the studied granular system's nature is further complicated considering that excitation with a shaker under gravity conditions does not create a true granular gas, due to introducing anisotropic particle velocities [1,29,41,42]. Additionally, using a shaker for exciting the entire sample cell introduces motion of the fiber, such that the fiber probes particle velocities in the moving reference frame of the sample cell, instead of a fixed reference frame. Both shaker-related issues could be resolved by using another mechanism of excitation in a microgravity environment as done in previous experiments studying spherical particles, e.g., by Yu *et al.* [18] and Sata *et al.* [43], or rod-like particles, e.g., by Aumaitre *et al.* [12] and Harth *et al.* [15] during parabolic flights. We expect that future implementation of the FBG technique into similar experimental scenarios involving microgravity will unfold its full potential.

Finally, we discuss the applicability of FBG sensors for probing velocity distributions in more dense granular systems. At the studied volume fraction of $\phi = 3\%$, 9939 collision events were probed by the FBG sensor during the 30 min of the experiment, which corresponds to 5.5 collisions per second. Considering that the duration of a single collision is approximately 3–4 ms (see Fig. 10), it should be possible to resolve up to 250 collision events per second, which implies that the FBG sensor remains applicable for investigating granular systems at significantly larger volume fractions. By contrast, particle-tracking techniques have been shown to struggle with the overlapping of particles in the camera recording at packing fractions beyond 5% [18]. While camera particle tracking is thus limited to observing mostly boundary effects at $\phi > 5\%$, FBG sensors can resolve bulk behavior

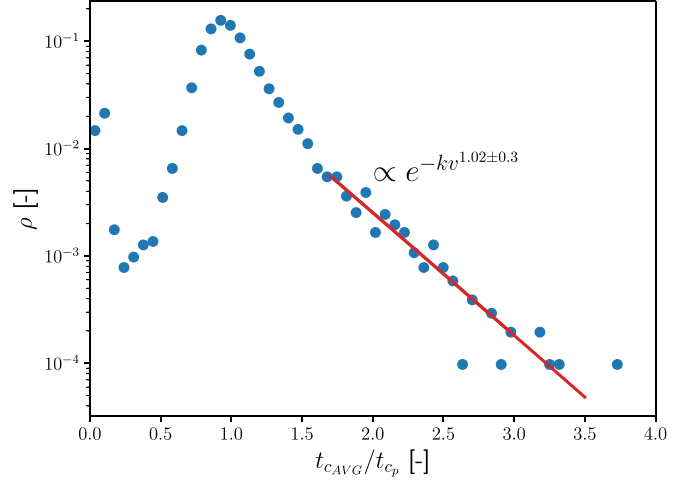


FIG. 10. Contact time distribution of the recorded impacts via FBGs. The solid red line is an exponential fit with an exponent of 1.02 ± 0.3 , at low impact velocities.

of the granular system, since signals from all along the fiber are recorded. Experiments performed with particle tracking in conjunction with FBGs should be able to record boundary and bulk behavior at desired timescales, thereby supplementing each other well. This gives FBGs a significant advantage over tomography techniques, which operate at low frequencies and are usually spatially demanding, requiring large experimental set-ups. Furthermore, their tracking data, thousands of frames, are difficult to save and store and would be reduced to a velocity distribution [19–21]. The required duration of a measurement to extract sufficiently statistically backed-up velocity distributions with FBGs at below and slightly above $\phi = 3\%$ is longer than for particle tracking. However, since the measurement timescales with the collision frequency, the measurement duration should decrease with increasing density. Strengthening the application for high volume fractions.

V. CONCLUSION

We introduced an experimental technique for determining velocity distributions of granular systems based on monitoring the deflection of an optical fiber equipped with FBG sensors upon collisions with granular particles. Using classical mechanics, we derived an expression for the strain-induced wavelength shift $\Delta\lambda$ induced in the FBG when the fiber collides with a granular particle with velocity v . With this, evaluating the distribution of $\Delta\lambda$ obtained by analyzing numerous collision events allows us to determine the velocity distribution of the granular system—which on top requires considering how it is modulated by the polar—and contact-angle distribution of the collisions.

By performing controlled particle-fiber collisions monitored by a high-speed camera, we experimentally confirmed the derived relation between $\Delta\lambda$ and v and obtained a quantitative calibration to extract absolute particle velocities from the FBG signal.

Building on this, we applied the technique to a granular ensemble excited by a vibrational shaker. Parallel particle-tracking experiments allowed us to confirm that both

techniques effectively probe the same velocity distribution. The extracted velocity distribution displays characteristic features of a constantly heated granular gas, namely an exponential deviation from Maxwell-Boltzmann statistics at high velocities with an exponential exponent of $\alpha = 1.39 \pm 0.26$, thus resembling previous results [18,39,42]. Finally, we inferred that the technique applies to granular systems at higher volume fractions where particle-tracking techniques start to fail due to particles overlapping in the recorded videos.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available because of legal restrictions preventing unrestricted public distribution. The data are available from the authors upon reasonable request.

APPENDIX A: EQUATION OF MOTION AND A CANDIDATE FIT FUNCTION

To characterize the time evolution of the fiber deflection, we study the differential equation given by the forces acting on the particle. For simplicity, we consider a central impact, see Fig. 9. The force decelerating the particle is given by the vertical part of the tension, i.e.,

$$F_y = F \sin \alpha = \frac{h}{d} F = h + \frac{h}{\sqrt{h^2 + l^2}} \left(\frac{T}{2} - kl \right), \quad (\text{A1})$$

where $k = EA/L$ is the fiber's axial spring constant, T is the applied pretension, $l = L/2$ is half the nondeflected length, h is the amplitude of the deflection, and d is half the deflected length.

To derive an analytic solution, we approximate the restitution force by retaining only the linear term in h . This is justified because $h \ll l$,

$$\begin{aligned} m\ddot{h} &= F = 2 \left(kh + \left(\frac{T}{2} - kl \right) \frac{h}{\sqrt{h^2 + l^2}} \right) \\ &= 2kh + \left(T - 2kl \right) \left(\frac{h}{l} - \frac{h^3}{2l^3} + \dots \right) \\ &= \frac{T}{l} h + \mathcal{O}(h^3). \end{aligned} \quad (\text{A2})$$

The time evolution of the impact may therefore be approximated with the harmonic oscillation

$$h(t) = \frac{v_0}{\sqrt{T/lm}} \cos \left(\sqrt{\frac{T}{lm}} (t - t_0) \right). \quad (\text{A3})$$

Using Eqs. (2) and (3), the time dependence of the measured wavelength shift is of the form

$$\Delta\lambda(t) = \kappa \left(\sqrt{1 + A^2 \cos^2(\omega(t - t_0))} - 1 \right), \quad (\text{A4})$$

where $A = v_0/(l^2 \sqrt{T/lm})$ and $\omega = \sqrt{T/lm}$. This first-order approximation shows no velocity dependence of the contact times, while higher-order terms show a strong velocity dependence of the contact time. Since the amplitudes are very small, we can further approximate the function as

$$\Delta\lambda(t) = A^2 \sin^2(\omega t) + \mathcal{O}(A^4), \quad (\text{A5})$$

which we use to fit the experimentally probed wavelength-shift pulses.

APPENDIX B: CONTACT TIME DISTRIBUTION

The distribution of contact times is normalized and shown in Fig. 10. We can not apply the same statistics to the time we used for the velocities. Furthermore, low values in normalized time correspond to high velocities.

APPENDIX C: WAVELENGTH SHIFT VS CONTACT TIME

The distribution of contact times for the single particle drop experiment is shown in Fig. 11.

APPENDIX D: FIBER INTRUSION TO THE SYSTEM

Our FBG measurement is an intrusive method since a physical object is introduced to the granular system and collisions between the particles and the fiber may affect the statistics of the system, especially when the density of the particles is relatively high. To investigate the impact of this intrusion, we have carried out DEM simulation using the method described in Ref. [44]. The purpose of the simulation is to evaluate the role played by the fiber in a real application scenario of the FBG method, i.e., a homogeneously excited granular fluid system with a relatively high packing fraction $\varphi = 0.25$. The

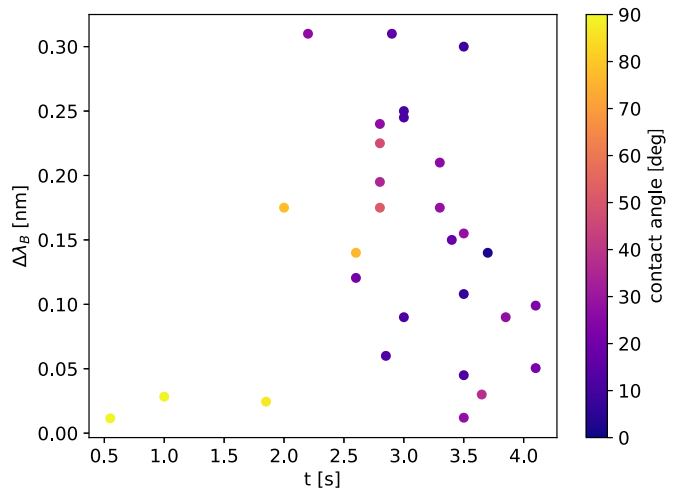


FIG. 11. The contact time of the particles plotted against wavelength shift $\Delta\lambda$ measured by the interrogator. The angle dependence is indicated by the color of each symbol.

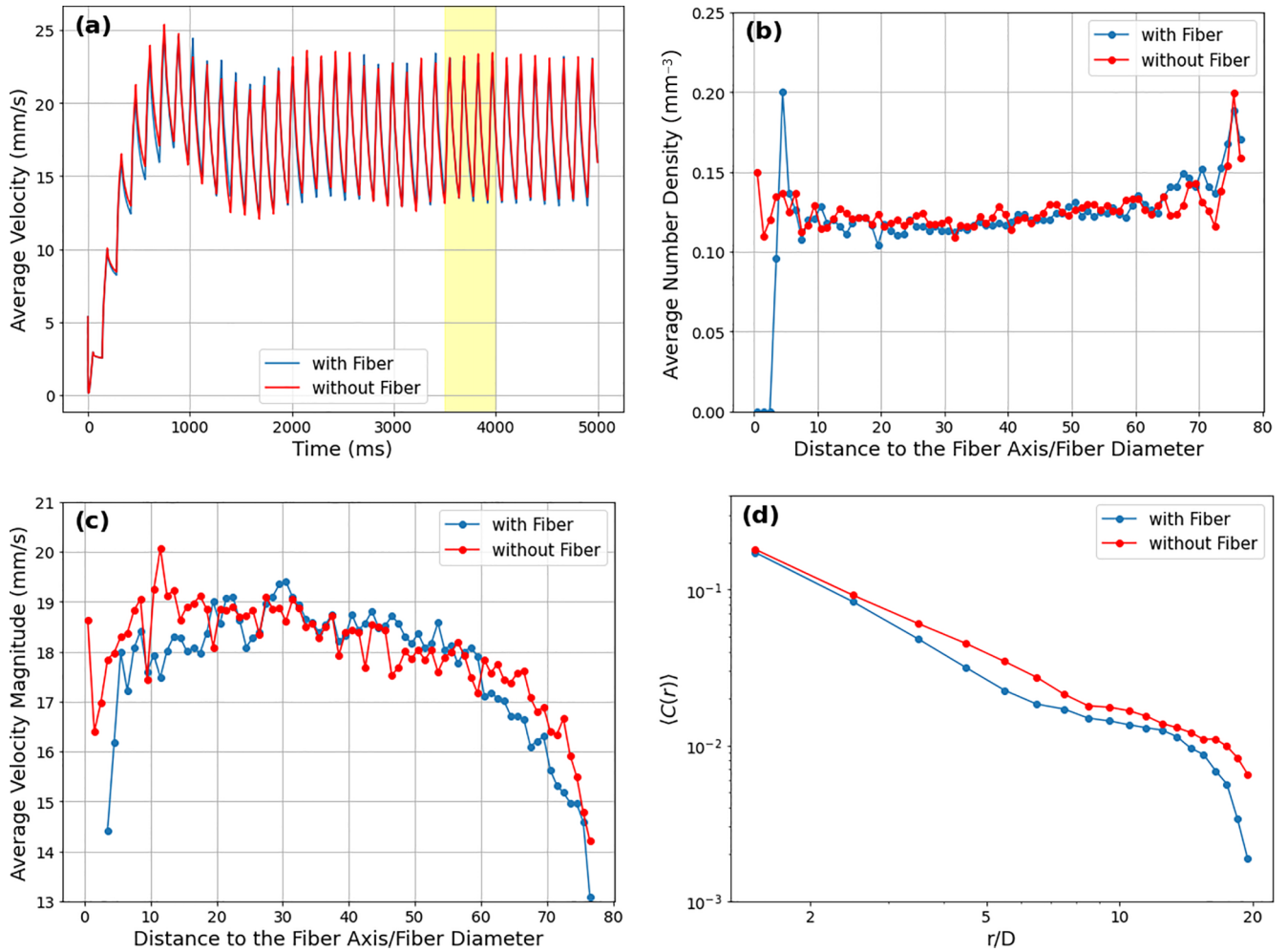


FIG. 12. Comparison of a relatively dense system ($\phi = 25\%$) under low-gravity with and without fiber from DEM simulation. (a) Average particle velocity magnitude over 5 s of simulation. The segment from 3.5 s to 4 s, after the system reaches steady state, is used for analyzing (b)–(d). (b) Average number density of the particles with regard to the distance from the fiber axis. (c) Average particle velocity magnitude with regard to the distance from the fiber axis. (d) Velocity correlation functions of two particles separated by a distance r (scaled by the particle diameter D).

corresponding experimental conditions must include a low-gravity condition, which is easily implemented in the simulation, while the excitation method is chosen to be, instead of the shaker excitation used in our ground experiment, a varying magnetic field, which, in our past low-gravity experiments, has shown great potential for homogeneous excitation [17]. Other than these parameters, the sample cell geometry and the particle shape and material remain the same as those used in our ground shaker experiments. The simulation has proven to reproduce and explain the homogeneously excited dilute system from the experiment.

Figure 12 compares several statistical properties of two simulated systems magnetically excited with and without the fiber, respectively. Figure 12(a) shows the behavior of the average velocity over time during excitation. The excitation is applied intermittently, simulating the real low-gravity experiment condition [17], causing the regular up-and-down of the average velocity. The two curves largely overlap with

each other, and the fiber causes very little variation. The segment from 3.5 s to 4 s, marked in yellow, after the system reaches steady state, is used for other analysis. The number density distribution with regard to the distance to the fiber axis [Fig. 12(b)] shows an obvious difference near the fiber because of the volume exclusion introduced by the fiber object. But elsewhere, the difference is insignificant. A similar observation applies to the average velocity distribution [Fig. 12(c)].

When an intrusive measurement component is introduced, one disruptive effect is the introduction of long-range correlation of the particle motions. We therefore also investigate the velocity correlation function of any pair of particles in the simulated excited system: $C(r) = \langle \hat{v}_i(0) \cdot \hat{v}_j(r) \rangle$, where $\hat{v}_i$ and $\hat{v}_j$ are the unit vectors of the velocities of particle i and particle j that are separated by a distance r . As shown in Fig. 12(d), the correlation decreases as r increases, and no significant difference is introduced by the fiber.

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