

Feedback-Controlled Linear Actuator System to Simulate Laboratory Analogues of Landslides

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This study describes a scientific apparatus that induces granular flow by tilting an acrylic sample container under user-prescribed constant angular velocity and acceleration profiles. The system consists of a transparent sample container mounted within a motorized frame driven by a linear actuator that we control using pulse-width modulation with feed-forward compensation. Additional components of the device enable control of the sample volume fraction, image acquisition to determine the onset of failure, measurement of the spatiotemporal evolution of traction shear stress, and acoustic monitoring of the granular material. Mechanical testing demonstrates low noise levels and reliable reproduction of reference tilt profiles, with constant angular velocity and acceleration maintained to within 1 degree. The device can achieve a set target angle within 2 degrees, with this overshoot being related to the inertia of the device. We demonstrate the capabilities of the device using two experiments that show [1] slide initiation angle varies systematically with volume fraction and decreases with increasing angular velocity and angular acceleration and [2] that the magnitude and size traction shear stress clusters increase leading up to failure. The device is therefore well suited for fundamental studies of what controls whether, when, and how failure occurs in granular materials, particularly in the context of landslide modeling.

I. INTRODUCTION

Granular materials exist and are widely used and or manipulated in natural and industrial settings^{1–3}. In nature, their rapid flow lead to geohazards that threaten lives and infrastructure, for example, landslides, submarine slides, pyroclastic density currents, liquefaction, and lateral spreads^{4–6}. In industrial settings, challenges exist in optimizing their storage, transport, and handling⁷. The difficulties in predicting the initiation, cessation, and patterns of granular flow partly stem from dynamic interactions among grains, interstitial fluids, and pores of varying geometries^{8–14}. These interactions can lead to mesoscale clusters of varying rigidities within the same material^{9–14}. Granular flow initiates from structural instabilities within regions of relatively low rigidity, and mass flow events occur when these instabilities become system-spanning^{9,14–17}. Some of the properties that control the development of mesoscale structures that influence granular flow are known (e.g., volume fraction, applied forcings, granular temperature, coordination number, and friction, force networks^{14,18,19}); however, a constitutive theory that captures the full range of observed granular flow behaviors in laboratory settings and in natural systems remains elusive^{2,4,5,20}.

Laboratory analog studies have been instrumental in identifying the key controls on granular flow patterns⁸. Many laboratory experiments have done this by constraining, and then relating, the spatiotemporal evolution of stress, strain gradients, grain-pore properties, and granular flow velocity and patterns^{8,21–24}. The choice of experimental setups used depends on the specific goals of the investigations, with each device having its own strengths and limitations⁸. Popular experimental set-ups include rotating drums, inclined chutes, oedometers, silos, rheometers equipped with parallel plates, annular shear cells, or Couette cells, hopper and hopper-orifice

systems, vibration tables, air- and water-fluidized beds, triaxial cells, and flumes^{8,24–27}. To our knowledge, no existing device allows controlled, tilt-induced granular flow driven by constant angular velocity and acceleration reference profiles while simultaneously enabling in-situ controls on volume fraction as well as imaging that captures particle displacements at the base and/or sides of the granular material. With such capabilities, quantities such as traction shear stress τ_s , inertial number I , friction angle, and the timing of and conditions leading to granular flow initiation and cessation would be derivable from the collected images and could then be related to volume fraction, grain-pore properties, and the tilt-displacement profiles. These improved understanding would also be particularly relevant to the study of landslides, where natural processes such as rain, fire, deposition, erosion, uplift, and ambient noise can lead to spatiotemporal changes in the slope of the free surface or in the rate of subcritical yielding (i.e., “creep”) that often precedes mass failure^{4,28}. Such real-world changes in slope and/or creep rates can be modeled in the lab via controlled tilting of the material.

Our study contributes to granular flow research, and particularly landslides, by introducing a device that allows simultaneous constraints on two-dimensional traction shear stress and granular flow properties under controlled angular velocity and acceleration profiles. The device, named the ‘lab-slide generator’, induces granular flow by tilting an acrylic cuboid-shaped sample container filled with grains (Fig. 1). Tilting of the device occurs via a linear actuator system controlled by pulse-width modulation (PWM). A high-speed camera positioned directly below the container records particle displacement at the base and one side of the container. Tilting the sample container at constant angular velocity and acceleration while maintaining a constant imaging plane is achievable after a brief period of initial acceleration. We provide examples of how this equipment may be used to investigate how ϕ and

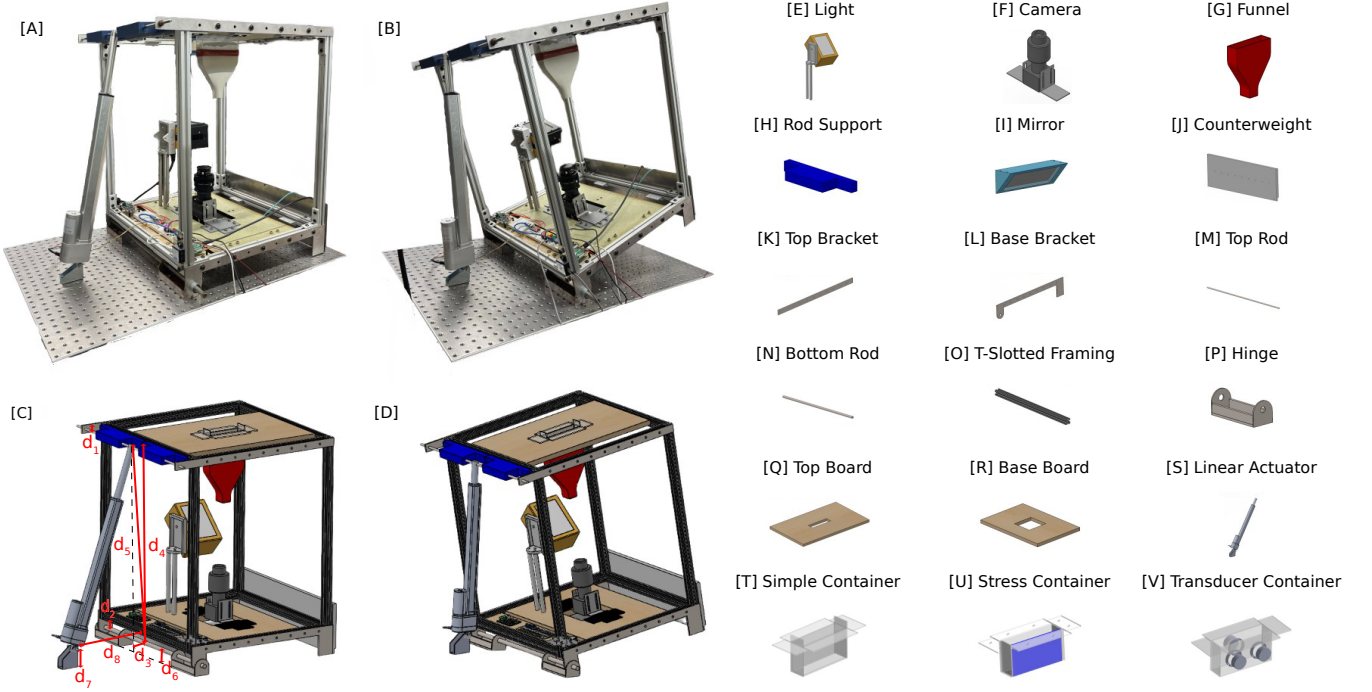


FIG. 1. Images are the lab-slide generation device [A] flat versus [2] tilted on the vibration-isolation table. CAD assembly images of the lab-slide generation device [C] flat versus [D] tilted. Quantities d1-d8 on [C] refer to the distance variables in Table I. [E]–[V] components of the lab-slide generation device. In [U], the PDMS walls are illustrated as transparent and tracer particles illustrated in blue.

reference constant angular velocity and acceleration profiles influence τ_s distribution and the angle that mass flow events initiates.

II. DESCRIPTION OF EQUIPMENT

A. Lab-Slide Generation Device

The main structure of the lab-slide generator is an open-faced cuboid frame that we construct using T-slotted aluminum rails with length $l = 51$ cm, width $w = 51$ cm, and height $h = 61$ cm (Fig. 1). The rails support two wooden platforms (Fig. 1Q–R) that span the width of the frame; one platform is at the top (Fig. 1Q), and the other is at the bottom (Fig. 1R). We secure the sample container (Fig. 1T–V) and a mirror (Fig. 1I) angled 45° towards the container to the top platform and mount a camera (Fig. 1F), a light (Fig. 1E), and the electronics to the bottom platform (Fig. 1). A Bluetooth-enabled inclinometer (Witmotion WT901 sensor), mounted on the right rail of the face closest to the actuator, provides real-time angular measurements.

The shaft of the actuator (Fig. 1S) connects to the top of the aluminum frames via steel brackets (Fig. 1K). We integrate 3D-printed rod (Fig. 1H) supports on the top of the frame for alignment and mechanical support. The entire apparatus at-

taches to a vibration-isolation table (Fig. 1A–B) via a second bracket (Fig. 1L) and welded hinges (Fig. 1P). The welded-steel hinge components at the base of the structure act as the device’s pivot axis, with a steel rod (Fig. 1N) that enables rotation of the device. Initial tests and modeling in simple Desmos²⁹ reveal that the linear actuator produces its largest acceleration between ~ 33 – 35° , coinciding with the transition from pulling to pushing the frame when the device’s center of mass crosses the vertical plane of the pivot axis, inverting the device’s gravitational torque. Stacked steel plates attached to the bottom of the non-pivot side of the aluminum frame (i.e., the side opposite the linear actuator) act as a counterweight (Fig. 1J) to prevent this acceleration. We install a limit switch near the base of the counterweight as a second safeguard for halting motion when the frame of the device contacts the table. Together, these design choices ensure structural stability during tilting while maintaining a constant focal distance to acquire high-resolution images of the particles within the container.

1. Linear actuator selection

We select the linear actuator model 0041668 from Wireless Remote SwitchesTM (Fig. 1A) based on four criteria. The actuator must (1) be long enough to tilt the lab-slide generator

TABLE I. Distance variables used during Linear actuator selection and their descriptions.

d_1	distance between top edge of device frame and top bracket	0.5 in
d_2	distance between bottom edge of frame and device pivot point	1.25 in
d_3	x-component of distance between device pivot point and tip of actuator	2.63 in
d_4	y-component of distance between device pivot point and tip of actuator	$d_2 + h - d_1$
d_5	distance between device pivot point and tip of actuator	$\sqrt{(d_2 + h - d_1)^2 + d_3^2}$
d_6	distance between ground and device pivot point	1.25 in
d_7	distance between ground and actuator pivot point	3725.4 in
d_8	distance between base of frame and base of actuator	$(10 - 3525.4)$ in

beyond the angle of repose for granular materials, preferably to at least 40° , (2) have a force rating larger than required to tilt the device, (3) produce shaft linear speeds that generate the desired tilt angular velocities ω ($< 1.1^\circ/\text{s}$) and accelerations ($< 0.03^\circ/\text{s}^2$), and (4) include screw-mounting holes compatible with those in the vibration-isolation table (Fig. 1A). We analytically derive expressions for the required actuator length and force rating, and use Desmos²⁹ to model and visualize the spatiotemporal relationships between the apparatus and the linear actuator during tilting. We also use calculations in Desmos to identify the fastest achievable angular velocities given the actuator's linear shaft speed.

The required actuator length x as a function of time t and angular velocity β is

$$x(\beta_t) = \sqrt{l_x^2 + l_y^2}, \quad (1)$$

where l_x and l_y are the horizontal and vertical distances between the base of the actuator (i.e., the actuator's lower pivot point) and the point where the actuator attaches to the top of the lab-slide generator (i.e., the actuator tip).

$$l_x = d_8 - \psi_h, \quad (2)$$

where

$$\psi_h = d_5 \sin\left(\beta_t + \tan^{-1}\left(\frac{d_3}{d_4}\right)\right) \quad (3)$$

is the horizontal distance between the actuator tip and the device's pivot axis on the vibration isolation table. Quantities d_3, d_4, d_5 , and d_8 are fixed apparatus dimensions (Table I), and $\tan^{-1}(d_3/d_4)$ represents the constant angle that the top bracket makes with the right edge of the frame of the apparatus.

$$l_y = \psi_v + d_6 - d_7, \quad (4)$$

where

$$\psi_v = d_5 \cos\left(\beta_t + \tan^{-1}\left(\frac{d_3}{d_4}\right)\right) \quad (5)$$

is the vertical distance between the actuator's lower pivot point and tip, and $d_6 - d_7$ is the fixed vertical offset between the actuator pivot point and the device pivot point.

The moment m_l generated by the device's weight W is

$$m_l = W r_{cm} \sin(\text{atan2}(x_{cm}, y_{cm} + d_2) - \beta), \quad (6)$$

where r_{cm} represents the distance between the device's pivot point and the center of mass,

$$r_{cm} = \sqrt{x_{cm}^2 + (y_{cm} + d_2)^2}. \quad (7)$$

Here, $x_{cm} = 28.24$ cm and $y_{cm} = 23.22$ cm are the x and y coordinates of the center of mass of the device, which we derive from our models of the device in SOLIDWORKS³⁰. The constant angle $\text{atan2}(x_{cm}, y_{cm} + d_2)$ gives the orientation of the center of mass vector measured from the right edge of the frame of the apparatus. If this angle is $> 40^\circ$, then the center of mass will stay on one side of the vertical plane of the device's pivot axis, preventing the actuator from transitioning from pulling to pushing the device.

The actuator applies force $F(\beta)$ along its line of action at angle α_β relative to the horizontal. The force components are $F \cos(\alpha_\beta)$ (horizontal) and $F \sin(\alpha_\beta)$ (vertical), acting with lever arms ψ_v and ψ_h , respectively. Thus, the actuator moment is

$$F \cos(\alpha_\beta) \psi_v + F \sin(\alpha_\beta) \psi_h. \quad (8)$$

Balancing moments and solving for F gives

$$F(\beta) = \frac{W r_{cm} \sin(\text{atan2}(x_{cm}, y_{cm} + d_2) - \beta)}{\cos(\alpha_\beta) \psi_v + \sin(\alpha_\beta) \psi_h}, \quad (9)$$

where ψ_h and ψ_v jointly determine the torque the actuator produces at each β .

Dynamically simulating $x(\beta_t)$ and $F(\beta)$ can be done by solving Eqs. (1) and (9) iteratively. Desmos does not have a built-in function to determine the index n of an object in an array, so we implemented our own method using Desmos' one-based indexing to identify the fastest achievable angular velocities. Specifically, the expression

$$A[n] = O : 1, 0 \quad (10)$$

returns 1 if the n th element of the array A matches the object O , and 0 otherwise. By multiplying this output value by b^n , where b is our chosen base (1.01), and summing over all n , we obtain $b^{n_1} + b^{n_2} + \dots + b^{n_{\text{crit}}-1} + \dots + b^{\text{length}(A)} \cdot 0$, where n_{crit} is the index of the input object. All terms except $b^{n_{\text{crit}}}$ are

TABLE II. Input and output devices for the lab-slide generator.

I/O Devices		
Device	Type	Connection
Start Button	Input	RPi via GPIO
Stop Button	Input	RPi via GPIO
Reverse Button	Input	RPi via GPIO
Active LED	Output	RPi via GPIO
Idle LED	Output	RPi via GPIO
Reverse LED	Output	RPi via GPIO
WT901	Input	RPi via Bluetooth Low Energy
Arduino Nano	Both	RPi via USB Serial
MD10C Motor Driver	Output	Nano via PWM, Digital
Linear Actuator	Output	MD10C
Monitor	Output	RPi via micro HDMI
Keyboard	Input	RPi via USB
Mouse	Input	RPi via USB

multiplied by 0, so the sum simplifies to $b^{n_{\text{crit}}}$. By taking the logarithm base b ,

$$\log_b(b^{n_{\text{crit}}}) = n_{\text{crit}}, \quad (11)$$

we recover the index of the object.

The choice of b is arbitrary, as long as $b \neq 1$ and $b > 0$. We selected a value close to 1 to avoid overflow or rounding-to-zero errors when computing $b^{n_{\text{crit}}}$ prior to taking the logarithm.

2. Electrical setup

The electrical system that we use to tilt the lab-slide generator consists of a Raspberry Pi 4 Model B, a digital inclinometer (WT901), an Arduino Nano, a DC motor driver, and a limit switch (Fig. 2). We provide physical control and monitoring through buttons and light-emitting diodes (LEDs): green, red, and yellow buttons start, stop, and reverse tilt of the apparatus, while green, red, and blue LEDs indicate whether the actuator is retracting, idle, or extending (Fig. 2). We list the devices, whether they are input or output devices, and how they connect to each other in Table II. Software and hardware specifications and system requirements for the Raspberry Pi and Arduino Nano are in Table III.

We operate the system using a proportional feedback controller with feedforward compensation³¹ that calculate the PWM value required to tilt the apparatus at a reference constant angular velocity or acceleration. This PWM value corresponds to a duty cycle that modulates the 24 V supply to the linear actuator³², which in turn controls the extension and retraction of the actuator shaft and, consequently, the angular velocity and acceleration of the apparatus during tilting. We transmit the PWM value via Serial to the Arduino, which then applies the corresponding PWM signal to the motor driver powering the linear actuator. We use the Arduino rather than the Raspberry Pi to generate the PWM signal because the Arduino has lower PWM-period jitter than the Raspberry Pi (6 μs versus 50 μs), making the Arduino-based commands more reliable for driving the actuator^{33–37}. Our PWM signal range is thus based on the Arduino's 8-bit PWM resolution, which

allows 256 discrete levels from 0 to 255³³. We reserve the value 255 as a command to initiate reverse tilting at the end of an experimental run.

The controller uses the difference between the reference angle θ_r and the measured angle θ_m from the WT901 (the tracking error) to determine the PWM values required to produce constant angular velocity or acceleration profiles³¹. We calculate θ_r through single or double integration of the reference angular velocity and angular acceleration profiles, respectively, with the initial angle being the one measured by the WT901 while the apparatus is at rest. We begin motion by applying the PWM signal required to lift the device, a value we find by applying increasingly higher PWM signals until the device begins motion from rest. After applying this initial PWM signal, the controller waits a fixed interval, 30 ms for constant angular velocity profiles and 5 ms for constant angular acceleration profiles, before calculating a tracking error and its associated PWM value. The controller repeats this process until the apparatus stops tilting, either when it reaches the final reference angle or the user presses the red button. If the user wants to reverse the tilt, they can press the yellow button, turning on the blue LED. Then, the next time the user presses the green button, the actuator will extend rather than retract until the limit switch contacts the table or the user presses the red button. If the limit switch contacts the table, the blue LED automatically turns off, indicating that the actuator will retract the next time the user presses the green button. Otherwise, the user must manually toggle the linear actuator for retraction and extension.

For constant angular velocity profiles, we found that making the controller dependent only on the tracking error, which we multiply by the proportional gain, K_p , was sufficient to achieve near-constant angular velocity across a range of angles prior to failure. In this proportional controller (P-controller)³¹, the proportional term (K_p) directly determines the PWM value supplied to the actuator. This means that the voltage supplied to the actuator increases linearly with the tracking error. Because the P-controller only tilts the device when a tracking error exists, a residual tracking error always remains³¹. However, because of the constant angular velocity profile and decreasing force required to tilt the device as the angle increases, the voltage required, and hence the tracking error, stays bounded³¹. Increasing K_p reduces this tracking error as well as the duration of initial acceleration required to achieve the reference angular velocity³¹. However, it also increases vibrations in the system since the controller responds more aggressively to the tracking error as well as error due to sensor noise³¹. Therefore, K_p must be increased while the magnitude of vibrations is within tolerance so that the device accelerates to its reference angular velocity in the shortest duration possible. Through experimental tuning, we determine that $K_p = 42$ is a satisfactory value for all constant angular velocity profiles since vibration amplitudes remain similar across profiles.

When a P-controller tracks constant angular acceleration profiles, unlike for constant angular velocity profiles, the tracking error grows unbounded³¹. This is because the velocity continuously increases, so the voltage required continu-

TABLE III. Software and system requirements for the lab-slide generator.

Item	Raspberry Pi (RPi)		Arduino Nano	
	Min Required	Recommended	Min Required	Recommended
Model	3B+	4	N/A	N/A
OS / Version	Buster	Bullseye, Bookworm	Arduino IDE 1.6.0	Arduino IDE 1.8.13
CPU Headroom	4%	10%	N/A	N/A
RAM	1 GB	2–4 GB	2 KB	2 KB
Disk Space	8 GB	16–32 GB	32 KB	32 KB
Python Libraries	asyncio, threading, struct, bleak, RPi.GPIO, time, serial	Min Required + matplotlib.pyplot	N/A	N/A
Programming Language	Python 3.7	Python 3.9+	C++	C++

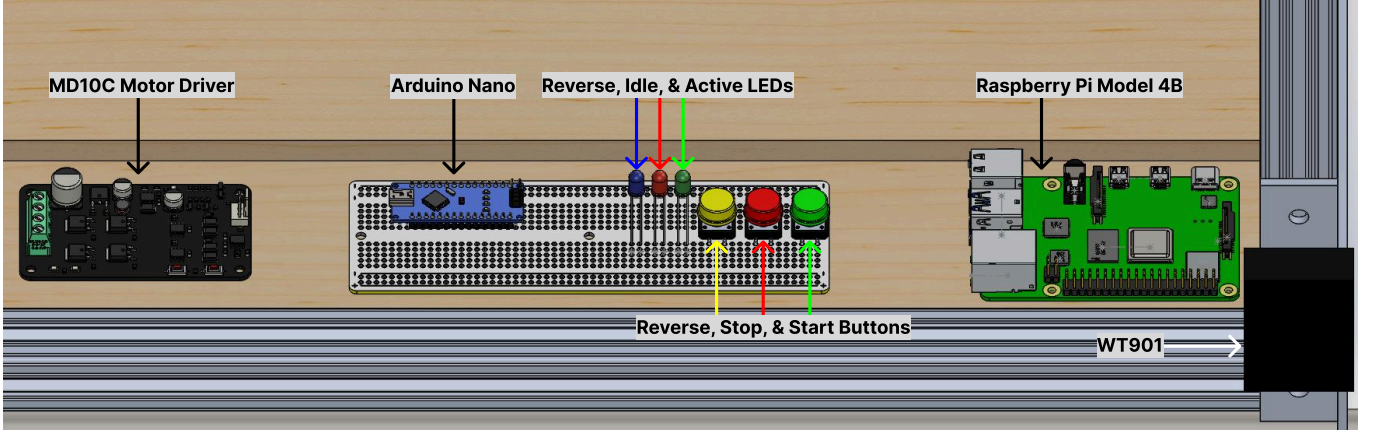


FIG. 2. All electrical components used to control and monitor tilting of the lab-slide generator.

ously increases as well³¹. The rate at which the tracking error grows can be minimized by implementing feedforward terms that approximate the voltage required to produce the desired motion, minimizing reliance on the P-controller alone³⁸. The feedforward terms that we use are,

$$W_v = K_W \theta_m + W_{v_0}, \quad (12)$$

$$\omega_v = K_\omega \omega_r \quad (13)$$

where, the weight term W_v represents the voltage required to tilt the device. W_v decreases as θ_m increases due to the geometry of the system. The angular velocity term ω_v represents the voltage required to tilt the device at a certain angular velocity. K_W and K_ω are the weight and angular velocity gains, respectively, and the initial weight term W_{v_0} represents the voltage required to start tilting the device when resting on the table.

We determine the gains K_W and K_ω by first setting both to 0. We then increase the initial weight term W_{v_0} to the point where, if increased any further, the device would begin to move from its starting angle. Next, we increase K_ω until the measured angle curve remains just below the reference angle curve except at larger angles, where the measured angle curve overshoots the reference angle curve. Then, we increase K_W until the measured angle curve no longer overshoots the reference angle curve at larger angles. Finally, we increase K_p until the desired reduction in tracking error throughout the motion is achieved. Through this tuning, we determined that

$W_{v_0} = 10$, $K_\omega = 200$, $K_W = 0.4$, and $K_p = 50$ provide satisfactory performance for constant angular acceleration profiles from 0.005 to $0.03^\circ/s^2$. Summing all feedforward terms allows the device to more closely track the reference angle. However, because these terms are linear, nonlinear uncertainties still exist that the controller cannot account for, producing a small and tolerable residual tracking error.

B. Sample Containers and Preparation

We present three sample container designs (Fig. 1T–V) that can be used with the lab-slide generator, and later present results from two of the designs. The simplest sample container enables investigations of the influence of tilt profiles, grain properties, and volume fraction on the initiation, cessation, and dynamics of granular flow. We modify the simple container to enable (1) collection of the data required to estimate τ_s before, during, and after plastic avalanches within the granular material and (2) efficient transmission and recording of acoustic emissions within the granular materials. We control volume fraction in all containers using an air-fluidization system described below.

The simple container is an acrylic cuboid with dimensions $l = 120$ mm, $w = 30$ mm, and $h = 83$ mm, sealed at the edges with acrylic cement and epoxy (Fig. 1T). We attach horizontal flaps to the four top edges of the sample containers; each acrylic flap contains two screw holes that allow us to secure

the sample container to wooden platforms on the lab-slide generator. We choose this geometry as a balance between minimizing container boundary effects on granular flow, selecting a container width-to-length ratio that promotes flow during our reference tilt profiles, and obtaining manageable file sizes when imaging particle displacement fields at our desired frame rates. The top of the simple container is open, while the bottom houses the air-fluidization system. This system includes a polyurethane fluidization plate (average pore size = $50\ \mu\text{m}$) that we epoxy to the sides of the acrylic container and a 3D-printed funnel that we epoxy to the bottom of the acrylic container. We connect the funnel to a tube that transports air from the compressor, with a solenoid valve near the tube-funnel junction allows us to control the airflow.

Our second container (Fig. 1U) enables estimation of shear stress τ_s , which is thought to change on approach to and after failure^{39,40}. We can estimate τ_s from the displacement fields of a linearly elastic polymer that is in contact with the granular material⁴¹. We fabricate and place a 2-mm-thick slab of polydimethylsiloxane (PDMS) polymer along all four vertical walls to maintain consistent boundary conditions. We only embed tracer particles within the PDMS slab adhered to the sample-container wall that we image through the 45° mirror. Anticipated strains from particle motion remain within the linear elastic regime of PDMS at this E , enabling us to use Hooke's law to estimate shear stresses from the tracer particle displacement fields⁴¹.

We use a 3D-printed casting mold to adhere PDMS to the walls of the container. We first prepare PDMS in its liquid state by mixing Dow Sylgard 184's base and cross-linker at a ratio of 15:1 in a beaker. We pour the viscous PDMS into the casting mold, with the acrylic piece at the base of the mold. We then remove trapped air bubbles by placing the mold under vacuum for a total of 60 minutes, applied in three 20-minute periods, with the vacuum released between each period. We first partially cure the degassed PDMS in a Memmert oven at $50\ ^\circ\text{C}$ for 45 minutes. Next, we deposit 75-125 μm -diameter polyethylene microspheres onto the partially cured PDMS slabs that we will image using the 45° mirror, light, and camera. We achieve near-uniform particle positions by depositing them through a mesh with uniform square openings of 125 μm length while vibrating the entire assembly. We then return all molds to the oven at $50\ ^\circ\text{C}$ for 60 minutes to complete curing. These steps secure any tracer particles at or near the top of the PDMS while also producing a PDMS slab with Young's modulus $E \approx 900\text{--}1300\ \text{kPa}$. Finally, we use acrylic cement and epoxy to connect all acrylic walls and adhere the fluidization system as described above.

Our third container, which we make to demonstrate the flexibility of the design, enables transmission and recording of acoustic waves within the granular material (Fig. 1V). These waves can provide non-invasive insights into the internal dynamics of granular flow⁴², including transitions from creep to mass failure²². We create this container by laser-cutting three openings in the long walls of the simple container and inserting three piezoelectric disc-shaped crystals; two crystals for receiving emissions are on the opposite side of a single crystal for transmission. We laser-cut these holes to place the

crystals in direct contact with the granular materials, making it more likely that emissions from the granular material are efficiently transmitted to the crystals while reducing noise from the sample container. The crystals have a central frequency of 1 MHz, a diameter of 12.7 mm, and a thickness of 4.6 mm. We use hard epoxy to attach grounding and live wires to the two faces of each crystal. The voltages produced by the crystals can be digitized using an oscilloscope. We place a 3D-printed ring-shaped spacer between the crystals and the container to reduce vibration transfer from the rest of the apparatus to the crystals. We also apply tape to isolate the crystals and spacers from direct grain contact and to contain grains within the sample container.

C. Build and Manufacturing Safety Details

We anticipate that the lab-slide generator and sample containers will be relatively straightforward to build for users with only basic mechanical skills. Most of the build time is associated with adhesive curing (e.g., acrylic cement for the acrylic container, wood glue for the wooden components, and adhesive sealant for the mesh), since we pre-source many components of the lab-slide generator. Therefore, the project can be completed in a little over three weeks once all components are purchased or fabricated.

We purchase the main structural elements of the lab-slide generator (e.g., rails, corner brackets, rods, nuts, and screws) from commercial vendors. We fabricate the custom components (e.g., the hinges, steel brackets, and top and bottom wooden panels) through 3D printing, laser cutting, and/or band sawing. We provide all required SOLIDWORKS .SLDPRT files in the project repository. We provide all code required to run the hardware in⁴³.

Chemical, fabrication, and electrical safety protocols should be followed when building the apparatus. For example, the use of acrylic adhesives and epoxy requires appropriate laboratory personal protective equipment (PPE), including masks, safety glasses, and lab coats, to avoid exposure to chemical fumes and uncured residues. The glass beads used in the experiments described below are small (100–200 μm in diameter) and may pose health hazards if inhaled or if they come into contact with the eyes. Processes such as laser cutting, 3D printing, drilling, and band sawing require adherence to proper operating procedures. These procedures are machine-dependent and are typically listed on the equipment or in user manuals. As with any electrical system, there is also a risk of electrical shock, and appropriate precautions should therefore be taken while working with the electrical setup.

III. EQUIPMENT TESTING

We assess the ability of the lab-slide generator to achieve a reference stationary angle (static angle reliability) and to follow a specified tilting profile (dynamic angle reliability). Unwanted vibrations of the sample container can induce motion within the granular material⁴⁴, complicating efforts to iso-

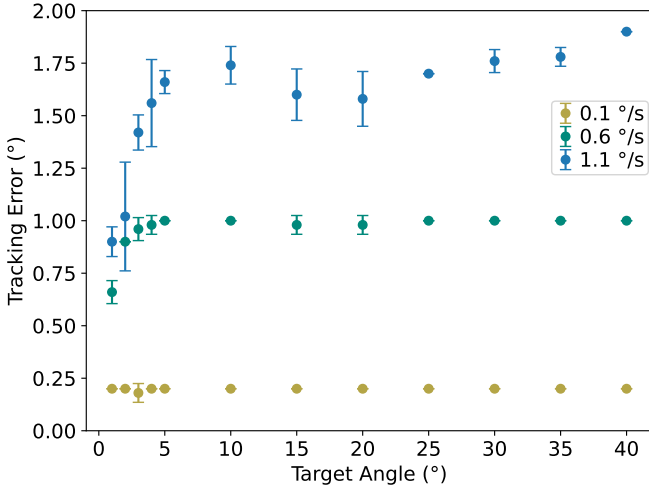


FIG. 3. The difference between the target static and achieve static angle (tracking error) measured as a function of the target angle. The angles are measured by the WT901 inclinometer.

late the effects of the reference tilt profiles on slide initiation. We therefore use a transducer–oscilloscope system to record the waveforms of these unwanted vibrations (“noise”) experienced by the sample container during tilting. This analysis provides a direct measure of the extent to which mechanical noise from the lab-slide generator may influence experimental observations.

A. Static Angle Reliability

We assess static angle reliability by tilting the device at three reference constant angular velocities, $\omega_r = 0.1, 0.6$, and $1.1^\circ/\text{s}$, and halting motion once the WT901 reports the reference target angle (Fig. 3). We perform five trials for each angular velocity and target angle pair, and compute the mean and standard deviation of the tracking error, defined as the difference between the target angle and the angle reported by the WT901. The results show that the device is capable of halting motion within 0.2 to 1.9° of a target angle (Fig. 3), with the error increasing with increasing angular velocity. Our experimental observations indicate that error exists because the device tilts slightly more forward after the target angle is reached and the power is cut. Therefore, the error and its distribution are likely due to inertial effects. Future updates to the device might therefore use similar PWM mechanisms (i.e., feedforward compensation at the boundaries) to reduce these effects.

B. Dynamic Angle Reliability

We assess the dynamic angle reliability by quantifying how well the device follows reference constant angular velocity and acceleration profiles. We perform five trials per reference tilt profile.

For all constant angular velocity profiles, the magnitude

of the tracking error remains within 5.1° across the device’s entire motion, as shown in Fig. 4E. The measured angular velocity exhibits an overshoot within the first $1\text{--}10^\circ$ of tilt (Fig. 4C), largely due to the torque required to lift the device and the settling time required for the controller to stabilize the motion³¹. The overshoot increases with reference angular velocity because higher angular velocities require greater actuator torque, producing a larger transient response. After the overshoot, the tracking error decreases as the reference angle increases (Fig. 4E). This occurs because the torque, and therefore the voltage, required to continue tilting the device decreases as the angle increases due to the changing leverage. Consequently, the tracking error decreases nonlinearly with angle, meaning the measured angular velocity increases over time (Fig. 4C). The tracking error also increases with increasing reference angular velocity (Fig. 4E). This occurs because the P-controller requires larger tracking errors to command the greater actuator voltage needed to achieve higher angular velocities³¹.

For all constant angular acceleration profiles, the magnitude of the tracking error remains within 0.7° across the device’s entire motion, as shown in Fig. 4F. This is much less than the maximum tracking error for the constant angular velocity profiles, likely because the feedforward terms in the controller allow it to depend less on the proportional term to command voltage to the actuator³⁸. The tracking error nevertheless increases with increasing reference angular acceleration (Fig. 4F) because the controller still contains a proportional term, requiring more error to achieve the larger angular velocities reached by the higher acceleration profiles³¹. As the reference angle increases, the device increasingly leads the reference angle (Fig. 4F) because the weight gain, K_W , is not large enough to compensate for the decreasing torque required to tilt the device. Increasing K_W causes the measured angle to lag the reference angle at smaller angles because the required compensation decreases nonlinearly with angle. Since the tracking error is already small, K_W does not need to be adjusted. However, regardless of the value of K_W , the device always initially lags the reference angle due to its inertia. Taking the slope of the measured angular velocity in Fig. 4D indicates that constant angular acceleration is achievable with a resolution of 1° . For smaller intervals, quantization error in the angle measurements and time jitter greatly increase the variance of the measured angular velocity estimate⁴⁵.

C. Noise Analysis

We record unwanted vibrations from the apparatus by placing piezo transducers on three faces of the empty simple sample container to capture motion in the vertical and two horizontal directions. We conduct five experimental runs per angular velocity and five runs where we record noise while the apparatus is not operational. We analyze the recorded time series using Fourier and signal-to-noise-ratio analyses.

The waveforms recorded when the apparatus is not operational (Fig. 5) exhibit a small and relatively constant noise level. The spectrograms show constant bands at higher fre-

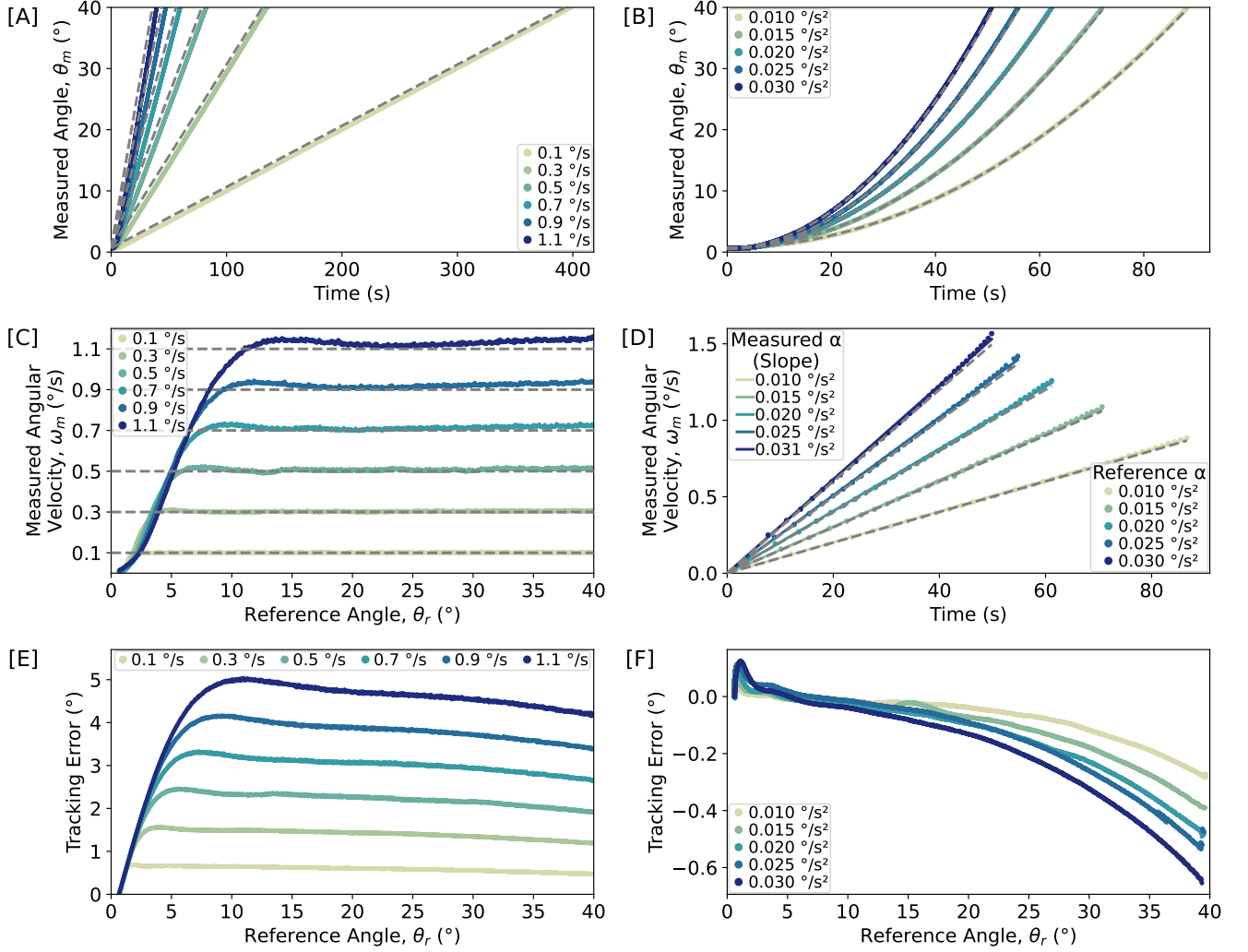


FIG. 4. The figure shows the dynamics of the device vs. time and reference angle θ_r . Data represents measured tilt profiles averaged across five trials. Each legend maps colors to their corresponding reference constant angular velocity ω_r and acceleration profiles α_r . [A], [C], and [E] are ω_r profiles. [B], [D], and [F] are for α_r profiles. [A] and [B] plot θ_m vs. time, [C] plots the measured angular velocity ω_m vs. θ_r , [D] plots ω_m vs. time, and [E] and [F] plot the tracking error vs. θ_r . ω_m data in [C] is a moving average with a window of 100 data points. ω_m data in [D] is calculated as the slope of sequential, non-overlapping 1 degree intervals starting from the initial angle and is plotted at the interval's time midpoint. Lines in [D] are zero-intercept trends of the ω_m data with their slopes tabulated as average measured angular accelerations.

quencies around 2400 Hz for all angular velocities and another band at lower frequencies around 60 Hz (Fig. 6). The latter is expected because of the electrical noise associated with powering the device.

The waveforms recorded during the tilting of the sample container (Fig. 5) exhibit higher amplitudes and more inconsistent noise than the stationary waveforms. We observe similar results on all sides of the sample container (Fig. 6). For the lower angular velocities, 0.1 $^\circ/s$ appears slightly noisier than 0.3 $^\circ/s$ on both the short and long sides of the container (Fig. 6G-L, 6M-R). For angular velocities exceeding 0.1 $^\circ/s$, the number of spikes generally increases in both amplitude and frequency as angular velocity increases. Like the stationary spectrograms, the tilting spectrograms show a band of ele-

vated power near 2400 Hz. The tilting spectrograms also show a gradual increase in broadband noise as tilting progresses, with higher levels during the later stages.

The signal-to-noise ratios (tilting-to-stationary) (Fig. 7) exhibit similar ratios on each side of the container for each angular velocity, where ratios are between 1 and 2. For the lower angular velocity, 0.1 $^\circ/s$, the ratio is higher on the long face of the container.

IV. EXAMPLE USE CASES

We collect data required to determine [1] how the lab-slide initiation angle changes as a function of $\phi = 0.63, 0.60, 0.57$

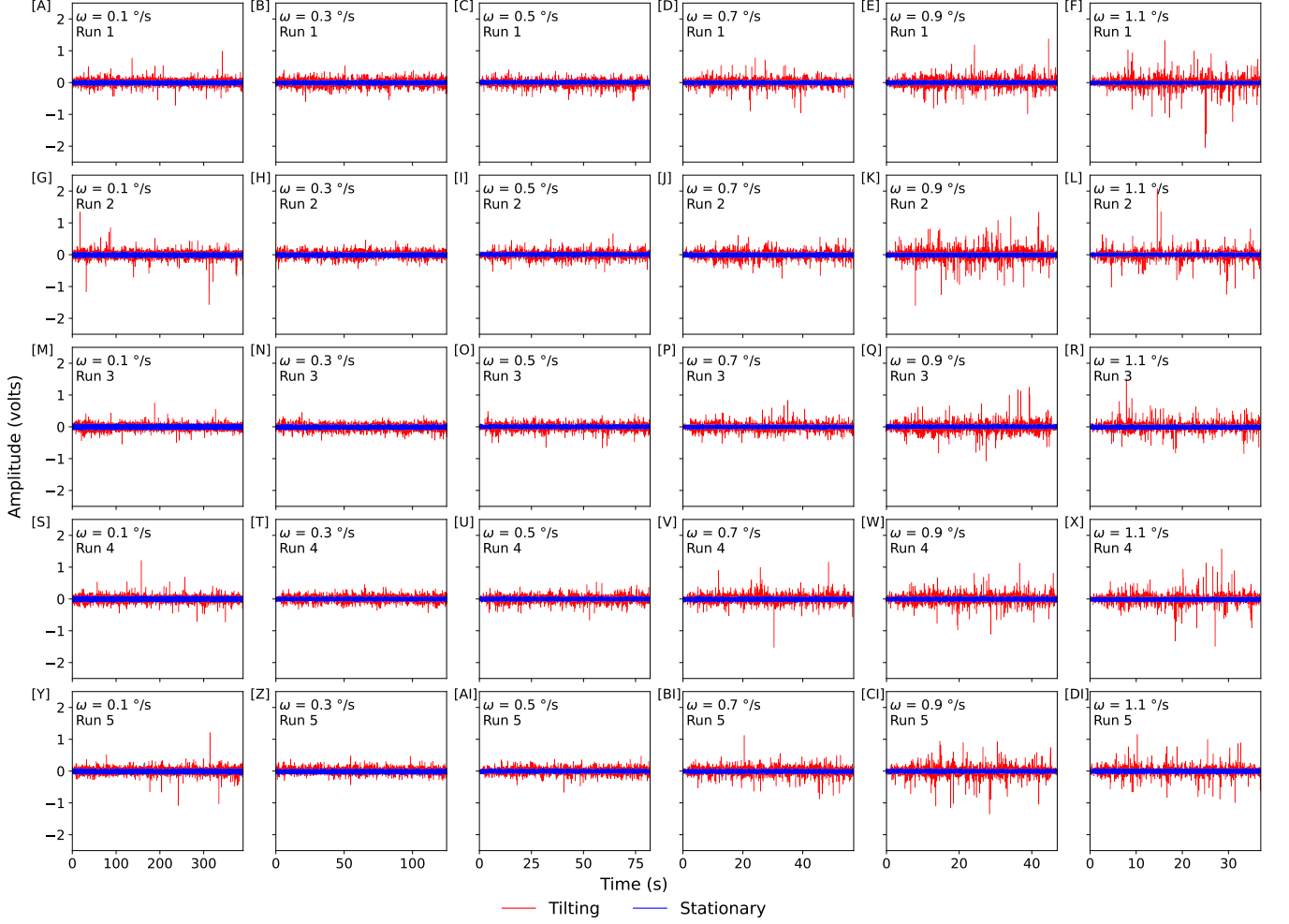


FIG. 5. We conducted five experimental runs where we collected waveforms on the short side of the container for each angular velocity. [A]–[F] are the first experiment for each angular velocity. [G]–[L] are the second run experiment for each angular velocity. [M]–[R] are the third experiment for each angular velocity. [S]–[X] are the fourth experiment for each angular velocity. [Y]–[DI] are the fifth experiment for each angular velocity.

and 5–6 different reference ω and α tilt profiles. We also collect data to determine [2] how τ changes before, during, and after a lab-slide that occurs within packings with $\phi = 0.57$ subjected to a $\omega = 1.1^\circ/\text{s}$ tilt profile. We conduct five tests for each ϕ - ω and ϕ - α combination. We control ϕ in all experiments using the air fluidization system and mechanical agitation. We obtain our lowest ϕ , 0.57, by fluidizing the sample with compressed air at 25 psi for 30 seconds, then gradually shutting off the air using a solenoid valve located within a few centimeters of the funnel. To obtain higher ϕ s, we use a combination of gradually decreasing the airflow, and tapping on the sides of the container with a rubber-ended mallet⁴⁶. These studies are meant to demonstrate proof-of-concepts, and are thus considered preliminary.

A. Slide Initiation Angle

To detect slide initiation angles, we prepare the granular material in the simple container and tilt the apparatus while using the camera-mirror-light setup to collect images of the grains along the long side of the container. We collect images at 100 Hz and use algorithms in particle image velocimetry laboratory (PIVLab)⁴⁷ to calculate grain displacement fields from the recorded images. We begin by converting displacement to velocity and stacking the resulting velocity fields along the temporal axis. We then crop the displacement fields and downsample the data using 2×2 median metapixels to reduce noise and minimize boundary-condition effects. The resulting datasets contain the in-plane displacement components, denoted u and v in the horizontal and vertical directions, respectively.

We determine that a slide has initiated when the maximum value of $\frac{\partial u}{\partial y}$ exceeds 0.08 for at least 0.5 s, chosen empirically.

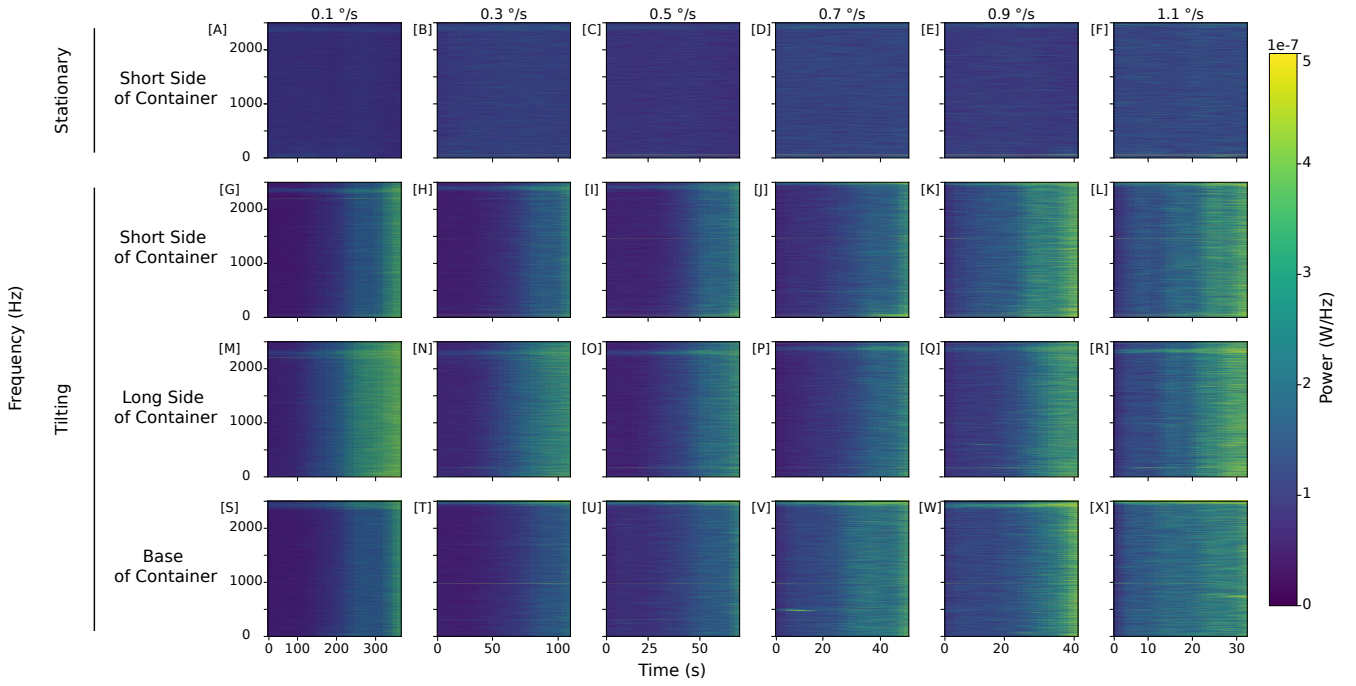


FIG. 6. Average spectrograms of experimental runs for each angular velocity on the three faces of the sample container. [A]–[F] are data from the short side of the sample container while the device was stationary, whereas all other spectrograms are from data while the device was in motion. For [G]–[L], the piezo is on the short side of the sample container, and for [M]–[R], the piezo is placed on the long side of the sample container. For [S]–[X], the piezo is placed on the base of the sample container.

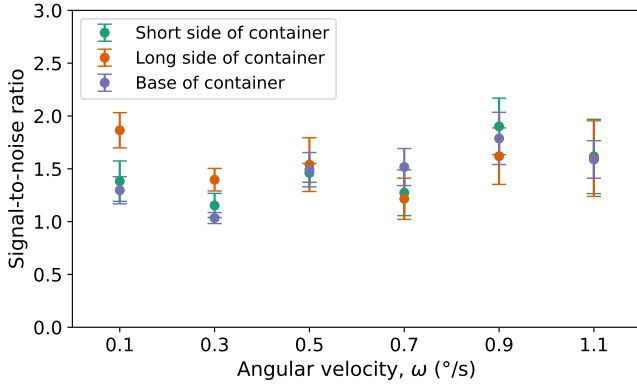


FIG. 7. Signal-to-noise ratio (tilting-to-stationary) for each side of the sample container derived from the timeseries data in Fig. 5

cally from visual observations and sensitivity testing. If there is no instance that satisfies this empirical criterion, we reduce the required number of consecutive frames by one until the slide-detection condition is met. We associate detected events with tilt-angle measurements by synchronizing the timestamps from the WT901 and the camera images. For each detected event frame, we match the corresponding timestamp to the closest WT901 measurement in time, giving the tilt angle at which failure initiates.

The results show slide initiation angle decreases with increasing constant angular velocity (Fig. 8A). The slide ini-

ation angle is also controlled by volume fraction, with denser packings generally initiating sliding at higher angles than looser ones. This dependence on volume fraction exists across all angular velocities that we investigate. The decrease in slide initiation angle with increasing angular velocity is strongest for the loosest packing ($\phi = 0.57$), intermediate for $\phi = 0.60$, and weakest for the densest packing ($\phi = 0.63$).

Like with angular velocity, the slide initiation angle generally decreases with increasing angular acceleration (Fig. 8B). The loosest packing is most affected by increasing angular acceleration, as the slide initiation angle decreases at a faster rate than for the intermediate and densely packed beds. The intermediate packing likewise exhibits a greater decrease in slide initiation angle than the densest packing. Consequently, differences in slide initiation angle between dense and loose packings become more pronounced at higher angular accelerations.

Comparing the results from both sets of experiments reveals that increasing angular velocity produces a larger decrease in slide initiation angle than increasing angular acceleration over the ranges we investigate. The response to angular velocity is, therefore, more systematic across all volume fractions. However, because angular velocity increases continuously during the constant-acceleration experiments, the effects of velocity and acceleration cannot be completely separated. Additional experiments would be required to determine the relative contributions of each parameter to slide initiation.

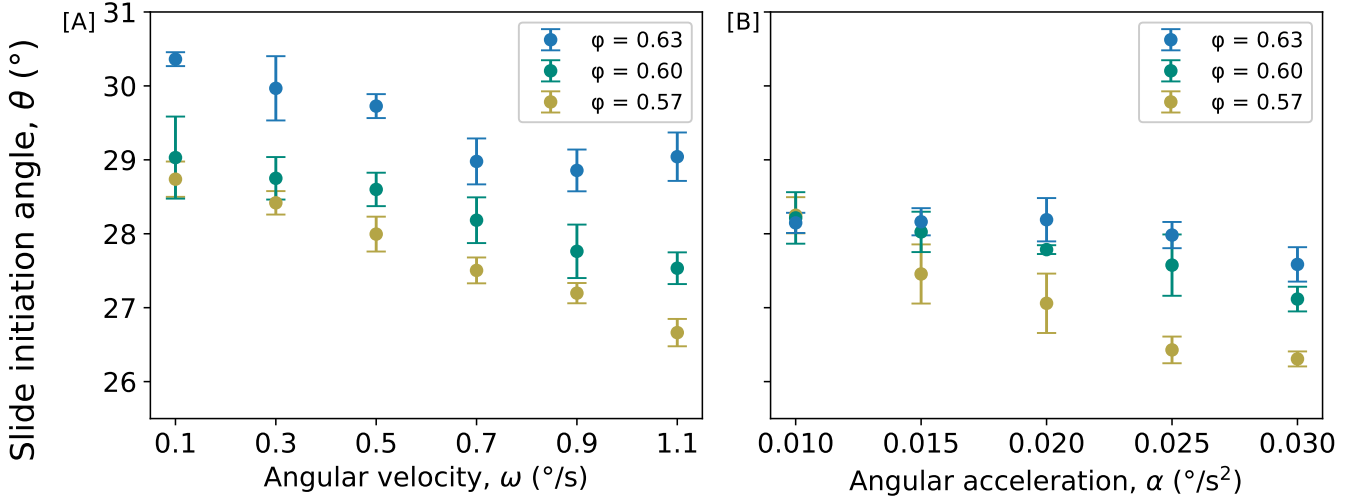


FIG. 8. Graph show the slide initiation angles for the volume fractions and [A] angular velocities or [B] angular accelerations tested.

B. Traction Shear Stress

Deriving τ using Hooke's law requires knowledge of the Young's modulus E of PDMS and full-field displacement gradients along the boundary being considered (see⁴¹ for details). We demonstrate the ability to estimate τ by tilting the device at $\omega = 1.1^\circ/\text{s}$ while acquiring images of tracer particles embedded within the PDMS sample container. We use PIVLab⁴⁷ to compute displacement fields from the tracer particle motion. While doing so, we reduce edge effects while retaining near-boundary displacement data by applying a modified Hann window with a minimum taper value of 0.5,

$$w_m = 1 - 0.5(1 - w_H), \quad (14)$$

where w_m is the modified window function and w_H is the standard Hann window. This parameterization preserves 50% weighting at the boundaries while maintaining smooth tapering toward the interior. Post windowing, we apply boundary clipping to remove edge artifacts outside the region of reliable PIV correlation. We quantify noise by performing five experiments with the same parameters but no grains in the container, and then compute the shear stress distribution for this scenario. We use the results from these experiments to define a noise threshold as $\mu_{\text{stress}} + 2\sigma$, and set all values below this threshold to zero when evaluating τ during tilt angles between 15° and 38° for experiments with grains inside the container.

We identify two distinct sliding events of different magnitudes, which motivated us to separate the analysis into five distinct phases that capture the evolution of shear stress before, during, and after granular failure (Fig. 9). The pre-slip phase ($\theta = 14.3 - 15.9^\circ$) shows no visible grain motion. The minor slip phase ($\theta = 22.6 - 24.4^\circ$) exhibits only small, localized surface displacements. The pre-failure phase ($\theta = 24.4 - 26.0^\circ$) captures the interval immediately preceding the major failure event. The failure phase ($\theta = 26.1 - 27.8^\circ$) corresponds to the largest lab-slide event, during which a signifi-

cant portion of the granular bed is displaced. Finally, the post-failure phase ($\theta = 27.8 - 29.5^\circ$) shows continued small-scale sliding as the system relaxes while tilting continues (Fig. 9). Across all phases, stress magnitudes increase progressively toward failure, consistent with the accumulation of shear deformation and progressive weakening of the granular structure.

V. CONCLUSION

We present a novel equipment to study the distribution of shear stresses as well as the initiation and cessation of granular flow as a function of angular velocity, angular acceleration, and volume fraction. The device is capable of achieving the desired constant angular velocities and constant angular acceleration with sufficient precision for robust granular physics studies. This is our first version of this device, and so we readily admit that several changes can be implemented to improve different aspects of the design. To reduce tracking error in the constant angular velocity runs, we anticipate that we would be able to reduce the measure and control loop period to 5 ms instead of 30 ms and introduce the same feedforward terms to the controller as we did in the constant angular acceleration runs. To achieve a wider range of angular velocities, we can use a linear actuator capable of faster shaft speeds. There was also a great amount of variance present when measuring the device's angular velocity partially due to quantization error in the angle measurements. To reduce this noise, we can use an inclinometer with a higher resolution³¹. To reduce initial overshoot without increasing the time it takes to achieve the reference angle, we can install a dampening mechanism, such as a dashpot or an Eddy current brake, while increasing K_p ³¹.

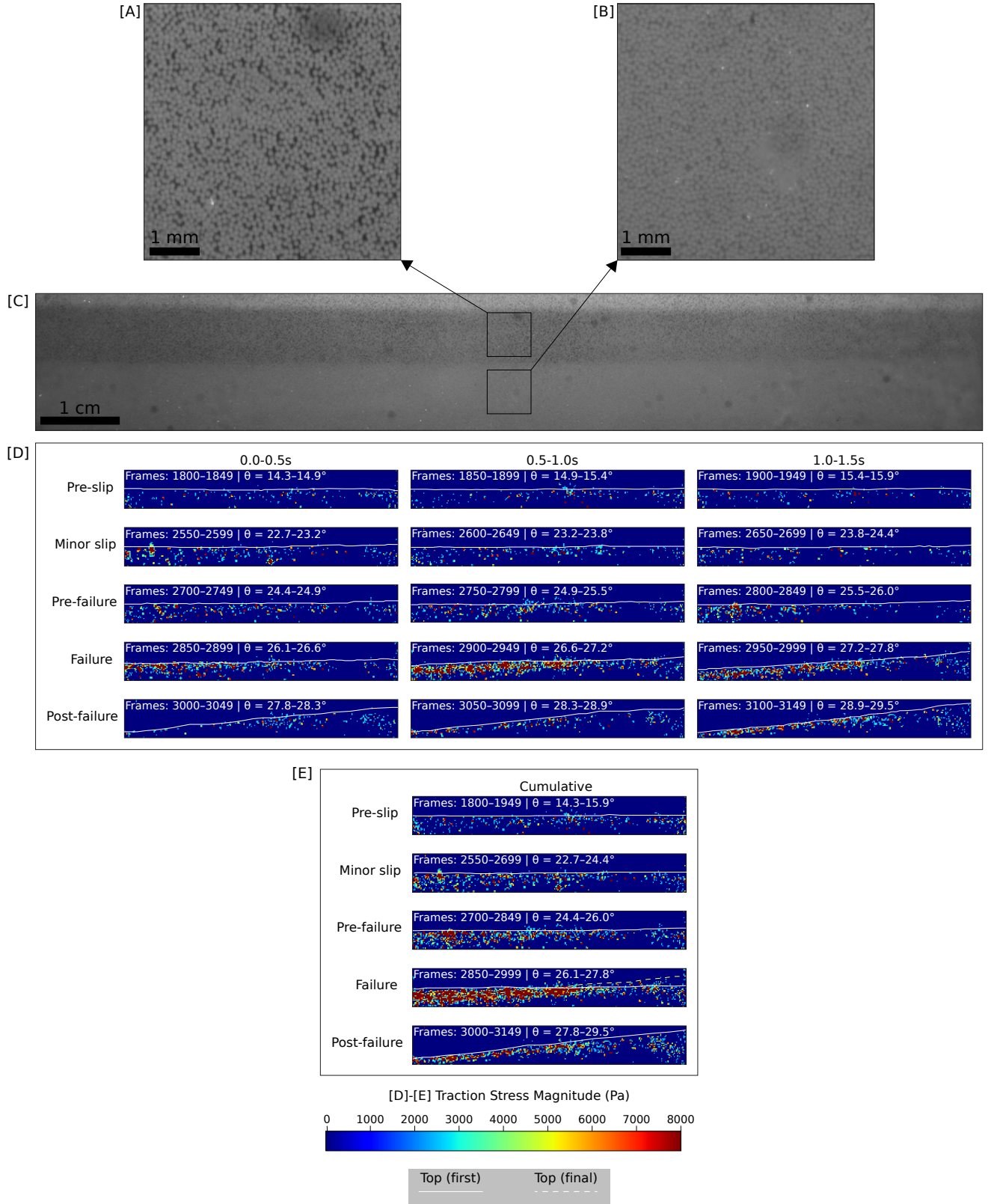


FIG. 9. Figures show images of the tracer particles embedded in PDMS; we track these particles with the camera on the lab-slide generator and use the resulting displacement field to calculate traction shear stress. [A] Magnified image of a select region of tracer particles that is above the granular materials; the darker pixels reflect areas without grains, while the gray pixels are the tracer particles. [B] Magnified image of a select region showing tracer particles adjacent to a section of the sample container that has granular materials; the lighter areas are tracer particles, and the darker areas are without tracer particles. [C] Full extent of the long-side of the container that hosts the PDMS with embedded grains. The difference between where there are grains versus no grains is evident via the shift from the darker to the lighter part of the image near the center. [D] Sum of traction stress over 0.5s windows during each distinct slip and no-slip phase during the tilting of the device. Panel [E] is the cumulative traction stress over each phase.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors declare that they have no competing interests.

Author Contributions

M. Pratt: design, assembly, validation, formal analysis, visualization, writing; **K. Booth:** design, assembly, software, visualization, writing; **V. Mallela:** design, assembly, documentation, software, validation, writing; **V. Wright:** supervision, funding acquisition, conceptualization, writing - review and editing

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Zenodo at <https://doi.org/10.5281/zenodo.15785297>, reference number 15785297.

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