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OSCILLATORY DYNAMICS OF A SPHERICAL BODY IN A CYLINDRICAL LIQUID-FILLED CAVITY ROTATING ABOUT AN INCLINED AXIS

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Abstract: This work presents findings from an experimental study of the dynamics of a light sphere moving in a liquid-filled cylindrical cavity that rotates around an inclined axis. In the experiments, the rotation rate of the cavity and the tilt angle of the axis are varied. It is demonstrated that the sphere undergoes radial oscillations during its axial motion. This phenomenon occurs due to the gravitational force acting on the sphere, with the axis of rotation tilted away from the vertical. It is observed that the sphere accelerates and decelerates during its ascent. It is demonstrated that the rotational velocity of the sphere varies in phase with its ascent velocity. The intensity of the sphere's oscillatory motion increases as the cavity's rotation rate decreases and the tilt angle of the rotation axis increases. The system under consideration is found to have feedback: gravity-induced radial oscillations of the sphere generate inertial waves, which, when focused at a certain axial position of the sphere, affect its oscillatory dynamics.

Key words: spherical body; rotation; Taylor-Proudman column; inertial waves.

Introduction

The dynamics of a light spherical body in a rotating fluid has long been a subject of interest to the research community. This field of research is of fundamental interest and has extensive practical potential (Annamalai et al., 1982; Sherwood, 1986; Roberts et al., 1991; Bush et al, 1994; Sarkar et al, 2021). The axial motion of a light sphere, or its differential rotation within a rotating fluid, leads to the formation of a Taylor–Proudman column around it, which affects the sphere's motion (Proudman 1916, Taylor 1922). In the geostrophic limit of low Rossby and Ekman numbers, the column is two-dimensional, with viscosity manifesting only in thin boundary layers at the edges of the cavity and on the surface of the sphere. When the cavity rotates about a vertical axis, the Taylor–Proudman column significantly decreases the rate of axial motion of the light sphere, as fluid circulation within the cavity occurs solely through the viscous boundary layers (Moore and Saffman 1968, Maxworthy 1968). Recent experimental studies (Kozlov et al 2023, Vlasova 2025) have confirmed the theoretical predictions: the axial velocity of the sphere in a cylinder of finite length decreases as the cavity's rate of rotation increases and as fluid viscosity decreases. The sphere rises almost uniformly (Vlasova 2025). Another consequence of the interaction between the sphere and the Taylor–Proudman column is the development of differential rotation.

The direction and velocity of the sphere's rotation are determined by its axial position: the body rotates progradely in the lower part of the cavity, while in the upper part, it rotates retrogradely. Also, there is no differential rotation in the central part of the cavity. According to (Kozlov et al 2023), the rate of the sphere's differential rotation varies linearly with the sphere's axial coordinate and decreases as the cavity rotation rate and fluid viscosity increase.

When the cavity rotates about a horizontal axis, the gravitational force rotates in the cavity frame and induces forced circular oscillations of the sphere about the rotation axis at a frequency equal to the frequency of rotation. Ivanova and co-authors (2012) found that the sphere undergoes retrograde rotation, which leads to the formation of a Taylor–Proudman column. The differential rotation of the light sphere is due to the mass force in the viscous boundary layers near the surfaces of the body and the cavity (Kozlov and Kozlov 2007). As the cavity rotation rate decreases, the velocity of the sphere's differential rotation increases, and an instability develops at the boundary of the Taylor-Proudman column in the form of a wave propagating in the azimuthal direction. It should be noted that the sphere oscillations are the source of inertial waves which contribute to the emergence of steady flows capable of influencing the dynamics of the free sphere (Kerswell 1995). Kozlov and Subbotin (2017) found that the sphere's differential rotational velocity varies periodically under low-frequency cavity oscillations.

This motion is accompanied by periodic changes in the sphere's position within the rotating cavity. It is determined that the sphere's relaxation oscillations are triggered at their natural frequency during a specific part of the cavity oscillation cycle. The initial data on the dynamics of a free light sphere in a cavity rotating about an inclined axis are given in (Zvyagintseva et al, 2022). The authors found that the time-averaged velocity of a sphere decreases as the angle of inclination of the rotation axis increases. This effect is due to a decrease in the buoyancy force projected onto the direction of the sphere's motion. It is demonstrated that the motion of a light spherical body along the axis of an inclined rotating cylinder containing a low-viscosity fluid is analogous to the motion of a sphere in a vertical rotating cavity in

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a reduced gravitational field. The paper gave a qualitative description of the differential rotation of the sphere during its ascent. It was determined that the prograde differential rotation of the sphere in the lower part of the cavity diminished as the inclination of the rotation axis increased.

The present paper continues the research initiated in (Zvyagintseva et al 2022). The focus of the study is a detailed examination of the sphere's axial motion, its axial velocity, and differential rotational velocity. The motion of the sphere is investigated by varying the inclination of the cavity axis and the cavity rotation rate.

Experimental setup

The study examines the dynamics of the spherical body *1* in a liquid-filled cylinder *2* rotating about an inclined (including vertical) axis (Fig. 1). The experiments use a spherical body with a diameter of $d = 2r = 2.5$ cm and a density of $\rho_b = 0.869$ g/cm^3. The sphere is marked with equatorial lines to track its rotation about its axis. The working fluid is water with a density of $\rho_l = 0.997$ g/cm^3 and a viscosity of $\nu = 0.95$ cSt. The relative density of the body is $\rho = \rho_b/\rho_l = 0.872$. The cavity has a radius of $R = 2.65$ cm and a height of $H = 18$ cm. Uniform rotation of the cavity is provided by a stepper motor connected via a coupling to the removable cap of the cylinder. The rotation rate varies in the range $f = \Omega/2\pi = 10 – 20$ rps with a measurement accuracy of 10^{-3} rps. Here, Ω is the angular velocity of the cylinder. The lower transparent end face of the cavity is mounted in a large-diameter bearing, allowing observation of the body's dynamics in the *xy*-plane. The cavity is mounted on a vertical rotating platform, allowing its orientation to be varied in the gravitational field. The launch of the light sphere from the lower end face of the cavity is initiated using a technique first described in (Kozlov et al 2023). At the start of the experiment, the cavity rotates about a horizontal axis passing through the point $H/2$. As it does so, the sphere moves to the lower end face of the cavity. In this position, the cavity is accelerated to a selected value of *f*. After the sphere has been centrifuged, the cavity is rotated in the opposite direction to a selected angle α. For a detailed description of the experimental methodology, refer to (Vlasova 2025). In the experiments, the angle of inclination of the cavity's axis of rotation relative to the vertical varies within the range $\alpha = 0 – 75°$.

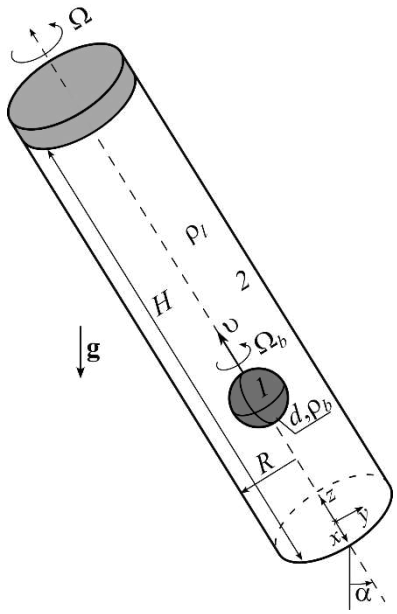


Fig. 1. Scheme of the experimental setup

The motion of the rising sphere is recorded by a camera positioned in front of the cavity or opposite the lower end face of the cavity. Video recording is made at a frame rate equal to the rotation frequency *f*, enabling the sphere's motion to be tracked in the cavity's reference frame. The resulting video recording is processed using software that accurately tracks the position of the sphere for each frame. The result of this processing is a dataset comprising the frame number and the coordinates of the sphere's centre (x, y) or (y, z). The number of frames processed from the video varies between 100 and 2000. The origin of the coordinate system is located at the centre of the lower end face of the cavity. The data obtained are used to calculate two variables: the sphere's buoyancy velocity υ and the position of the sphere's centre z relative to the bottom of the cavity. To measure the differential rotation rate of the sphere $\Omega_s \equiv \Omega_b – \Omega$, the recorded video is analysed frame-by-frame using advanced software that tracks the position of equatorial markers on the sphere.

Experimental Results

A consequence of the Taylor–Proudman column formation is a significant decrease in the sphere's buoyancy velocity in comparison to the scenario where rotation is absent. This is due to the configuration of the Taylor–Proudman column, which restricts the radial motion of the fluid. The diameter of the column is determined by the diameter of the sphere;

the height of the column is equal to the height of the cavity. As it moves, the sphere pushes the fluid ahead of it; the fluid flow from the column above the sphere to the column below it only takes place through the Ekman shear layers and the shear layer at the boundary of the Taylor–Proudman column. Consequently, additional hydrodynamic drag is generated, which decreases the sphere velocity (Moore and Saffman 1968, Maxworthy 1968). Previous experimental studies focused solely on the buoyancy velocity of the sphere and its differential rotational velocity (Maxworthy 1968, Kozlov et al 2023, Vlasova 2025). When the axis of rotation deviates from the vertical, the trajectory of the sphere requires careful analysis, as the gravitational force acting on the sphere results in a radial displacement of the sphere. Experimental studies (Ivanova et al 2012, Kozlov et al 2015) demonstrated that, when the cavity rotates about a horizontal axis, the sphere undergoes circular oscillations with a frequency equal to the cavity's rate of rotation.

The experiments demonstrate that the sphere does not move strictly along the axis of rotation (Fig. 2a). In the lower part of the cavity ($z < 9$ cm), the sphere moves irregularly; for $z > 9$ cm, radial oscillations occur with a frequency that increases as the sphere approaches the upper end face of the cavity. When the axis of rotation is tilted away from the vertical, it is found that the sphere undergoes radial oscillations of small amplitude (Fig. 2b). In Fig. 2, the coordinate $y = 0$ does not coincide with the axis of rotation of the cavity. Instead, it is an average value calculated from the amplitude of the sphere's radial oscillations. The experimental technique used to measure the centre of the sphere and the cavity does not allow the radial displacement of the sphere from the axis of rotation to be determined with sufficient accuracy. According to theoretical estimates (Karpunin et al., 2018), the sphere is predicted to move at a distance $b \sim 0.08$ mm at an angle of $\alpha = 45°$. The frequency spectrum of the detected radial oscillations will be discussed below. As the angle of inclination of the rotation axis increases, or as the rotation rate decreases, the amplitude of the sphere oscillations increases, while the frequencies remain similar. It should also be noted that the mean position of the sphere changes as it moves axially. The significant increase in the amplitude of the sphere's oscillations at $z > 15$ cm is due to the sphere approaching the upper end face of the cavity.

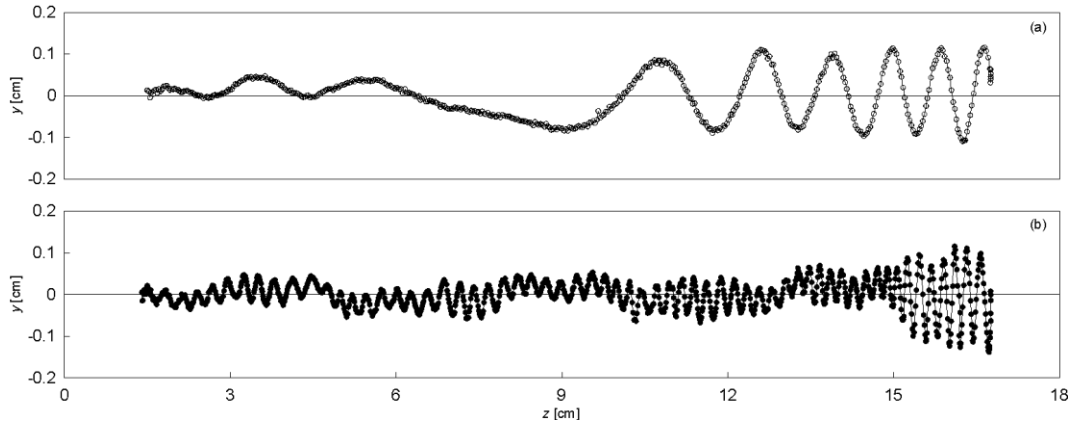


Fig. 2. Radial oscillations of a sphere during its axial motion at $\alpha = 0°$ (a) and 45° (b); $f = 10$ rps

Radial oscillations of the sphere occur along the x and y directions. Figure 3 shows the trajectory of the centre of the sphere in the cavity reference frame. These data refer to the sphere's axial coordinate $z \approx 7$ cm at a rotation rate of $f = 10$ rps and an angle $\alpha = 45°$ (Fig. 2, *b*). The direction of motion along the trajectory is indicated by the arrow. In the laboratory frame, the cavity rotates clockwise. The centre of the coordinate system is also the average value of the coordinates x and y, calculated from the amplitude of the sphere oscillations. One can find that the sphere undergoes circular oscillations relative to the centre of the coordinate system in the direction opposite to the direction of rotation. This is consistent with the results of experiments with a cavity rotating about a horizontal axis (Kozlov and Subbotin 2017). Observations reveal circular oscillations of the sphere across the entire range of cavity rotation rates at $\alpha \geq 30°$.

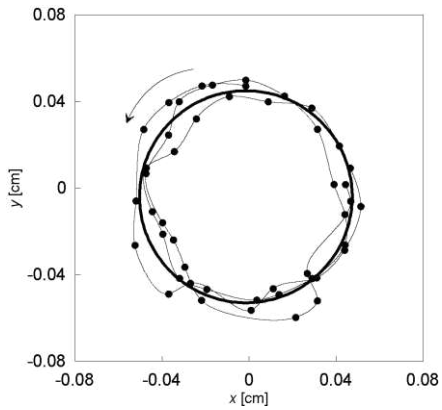


Fig. 3. The oscillatory motion of a sphere relative to the cavity reference frame at $z \approx 7$ cm; $\alpha = 45$, $f = 10$ rps

Earlier research on the dynamics of a rising sphere in a cavity rotating about a vertical axis ($\alpha = 0^o$) demonstrated that a light spherical body rises almost uniformly along the axis of rotation (Vlasova 2025). In the present study, a similar correlation is observed between the sphere velocity υ and its axial coordinate z for $\alpha = 0^o$ (Fig. 4a). Here, filled symbols represent the axial velocity, while the empty symbols indicate the angular velocity of rotation. When the axis of the cavity rotation is tilted from the vertical by an angle of $\alpha \geq 15^o$, the sphere's motion becomes non-uniform: upward motion is periodically accelerated and decelerated (Fig. 4b). It should be noted that the buoyancy velocity of the sphere is lower than that at $\alpha = 0^o$ due to a reduction in the projection of the buoyancy force on the y-axis (Zvyagintseva et al 2022). As the angle of inclination increases (and so does the effect of gravitational force), the amplitude of the oscillations increases at a fixed cavity rotation rate (Fig. 4c). It should be noted that the oscillation frequency remains constant across the entire range of rotation rates and angles of inclination studied.

During its axial motion, the sphere undergoes differential rotation at an angular velocity Ω_s, the magnitude and direction of which are determined by the sphere's position relative to the end faces of the cavity. The differential rotation of a free sphere within a cavity rotating about an inclined axis arises for two reasons: the interaction of the sphere with the lower and upper Taylor–Proudman columns (Kozlov et al. 2023, Vlasova 2025) and the action of the force of gravity on the sphere, which causes its retrograde differential rotation (Ivanova et al. 2012, Kozlov and Kozlov 2007). When $\alpha = 0$, the angular velocity Ω_s is determined solely by the interaction with the Taylor–Proudman column: in the lower part of the cavity, the sphere undergoes prograde rotation, while in the upper part it undergoes retrograde rotation (empty symbols in Fig. 4a). The relationship between the angular velocity Ω_s and the axial coordinate z is linear regardless of the cavity rotation rate and the viscosity of the fluid (Kozlov et al. 2023, Vlasova 2025). When the rotation axis tilts from the vertical, the projection of the gravitational force on the direction of the sphere motion contributes to the rotation of the sphere, thereby decreasing the velocity of the prograde rotation and increasing that of the retrograde rotation. Figure 4b and c illustrates that the body undergoes retrograde differential rotation at $\alpha \geq 30^o$. It should be noted that the differential rotational velocity oscillates at the same frequency as the sphere's buoyancy velocity. The amplitude of Ω_s increases as α increases. The buoyancy velocity and the differential rotational velocity vary almost in phase: when the buoyancy velocity increases, so does the velocity of the retrograde rotation. As the cavity rotation rate decreases, or the inclination angle α increases, the deviation from the mean values of υ and Ω_s increases.

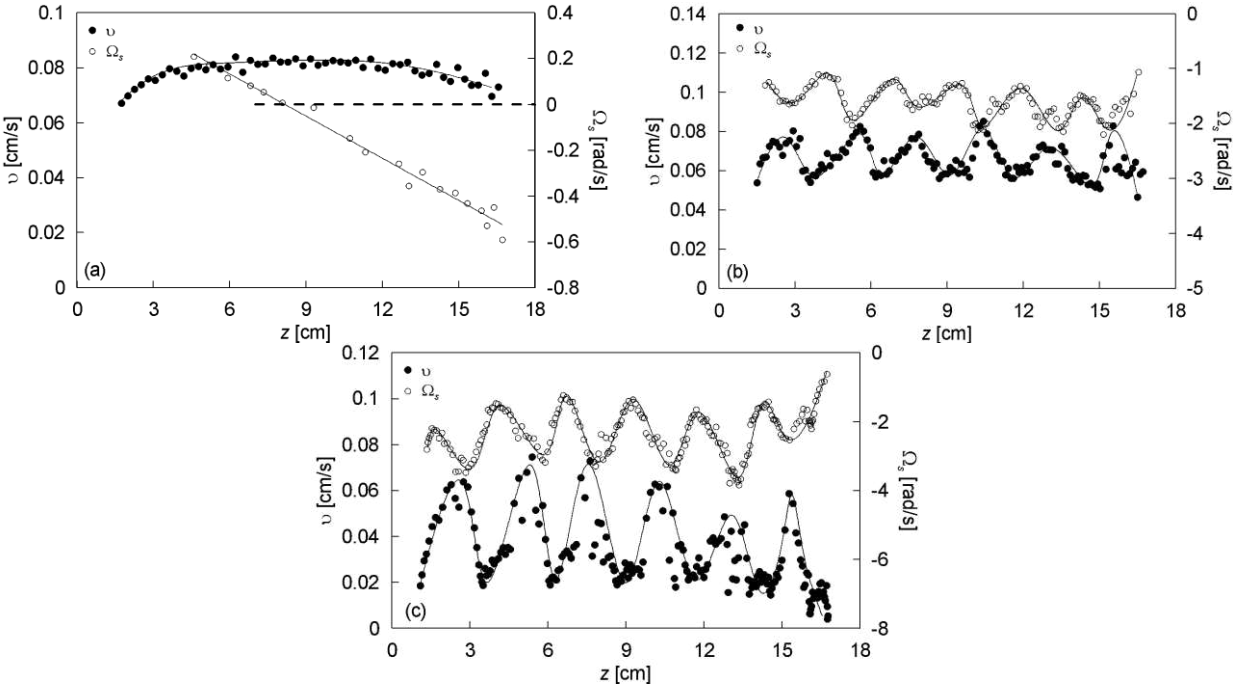


Fig. 4. Dependence of buoyancy velocity υ and velocity of differential rotation Ω_s on axial coordinate z at various inclination angles: $\alpha = 0$ (a), 45° (b), and 75° (c), $f = 10$ rps

The radial oscillations of the sphere at $\alpha > 0$ are caused by the projection of the gravitational force on the direction of its axial motion. In the absence of axial motion of the sphere (for example, when the cavity rotates about a horizontal axis), the sphere undergoes radial oscillations with a frequency equal to the frequency of the cavity rotation (Kozlov and Kozlov 2007, Kozlov and Subbotin 2017). Axial motion significantly complicates the sphere's dynamics: the oscillations with a frequency equal to the frequency of the cavity rotation that are not observed. Figure 5 illustrates the findings of a Fourier analysis of the radial oscillations of a sphere and the oscillations in its buoyancy velocity. The empty symbols illustrate the spectrum for the sphere's radial oscillations, while the filled symbols indicate the spectrum for the buoyancy velocity. A detailed analysis of radial oscillations reveals three resonant frequencies: $f_{osc1} = 0.21$ 1/s, $f_{osc2} = 0.29$ 1/s, and $f_{osc3} = 0.02$ 1/s. The analysis of the buoyancy velocity oscillations reveals a single resonant frequency f_{osc3}. It can be concluded that the sphere is involved in several oscillatory motions, one of which has a significant impact on the buoyancy velocity and the frequency of differential rotation.

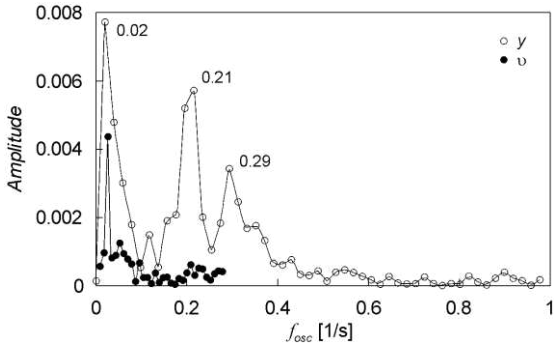


Fig. 5: The frequency spectrum extracted from Fig. 2b (empty symbols) and Fig. 4b (filled symbols); $\alpha = 45°$, $f = 10$ rps

It is reasonable to assume that one of the resonant frequencies corresponds to the natural frequency of the body oscillations. To verify this assumption, further experiments were carried out to determine these frequencies. The experimental protocol is as follows. The horizontal cavity is mounted on the head of an electrodynamic shaker, which oscillates at a frequency of 12.5 Hz and an amplitude of 0.3 cm. By varying the rotation rate of the cavity, a velocity of differential rotation can be measured using a stroboscope. When the rotational frequency of the gravitational force equals one of the sphere's natural frequencies, the amplitude of its oscillations increases resonantly, thereby exciting its intense differential rotation. Figure 6 shows the dependence of the dimensionless differential velocity of the sphere on the dimensionless frequency of its oscillations relative to a rotating reference frame. The empty symbols illustrate the data obtained as the rotation rate increases, while the filled symbols illustrate the data as the rotation rate decreases. Two resonance regions could be identified. When dimensionless frequency $|(\Omega_{osc} - \Omega)/\Omega| = 0.04$, an intense retrograde rotation of the sphere is initiated, such that this frequency corresponds to the natural frequency of the sphere's circular oscillations in the direction opposite to the cavity rotation. When $(\Omega_{osc} - \Omega)/\Omega = 0.13$, the prograde rotation of the sphere is observed. Here, the frequency corresponds to the natural frequency of the sphere's circular oscillations in the direction of the cavity rotation. According to the spectral analysis, the resonant frequencies of the sphere oscillations have the dimensionless values $f_{osc1}/f = 0.021$, $f_{osc2}/f = 0.029$, and $f_{osc3}/f = 0.002$. One can find that the frequency f_{osc2} is close to the natural frequency of the sphere's oscillations in the direction opposite to the cavity rotation, thus confirming the assumption made above.

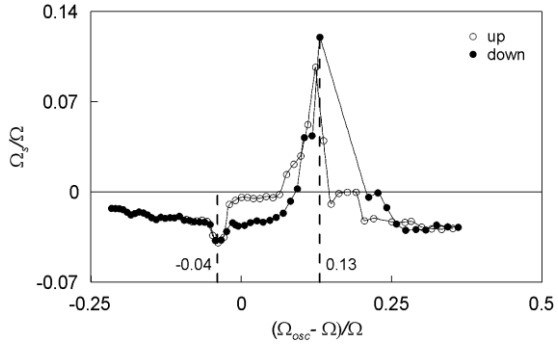
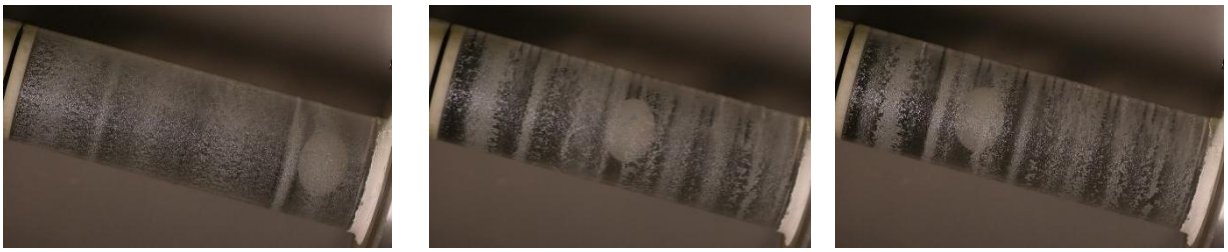


Fig. 6: Dependence of the dimensionless velocity of differential rotation of the sphere on the dimensionless oscillation frequency

It is known that the radial oscillations of a sphere can generate inertial waves. The direction of wave propagation can be determined as follows: $\varphi = \arcsin(f_{osc}/(2f))$ (Greenspan 1968). Inertial waves are visualized using tracer particles whose density exceeds that of the liquid. In a rotating cavity, these particles are distributed along the cylindrical wall. Inertial waves propagating from a radially oscillating sphere form band patterns of tracer particles near the points where inertial waves are reflected from the cylindrical wall (Fig. 7). However, these bands are not stationary: they collapse and reassemble during the experiment, indicating a changing pattern of inertial wave reflections within the cavity.

Now, we will examine in more detail the dynamics of the band pattern in front of the rising sphere (Fig. 7a). The band formation/collapse in front of the sphere is accompanied by a deceleration/acceleration of the axial motion. It should be noted that the axial coordinate corresponding to the maximum or minimum axial velocity of the body does not depend on the cavity rotation rate and the inclination angle (Fig. 4). The frequency of the oscillations in the rise velocity and the differential rotational velocity depends solely on the sphere's axial coordinate. Consequently, in specific axial positions of the sphere, the focusing of inertial waves is possible. This results in the sphere decelerating and the band formation in front of it (Fig. 7a and 7c). Once the sphere changes position, the pattern of reflections of the inertial waves changes, and their energy dissipates, which is accompanied by the collapse of the band (Fig. 7b). This results in the acceleration of the sphere. It can be concluded that a coupling exists between the sphere and the inertial waves: the radial oscillations of the free sphere generate inertial waves, which, in turn, affect the motion of the sphere. The

frequency of radial oscillations f_{osc1}, which has no clear explanation yet, is likely to be a modification of the natural frequency of the sphere's circular oscillations in the direction opposite to the cavity rotation under inertial waves.



(a) (b) (c)

Fig. 7: Photographs of band patterns formed by tracer particles near the cylindrical wall of the cavity at t = 18 (a), 118 (b), and 189 s (c); α = 45°, f = 8 rps

Conclusion

An experimental study of the dynamics of a light spherical body in a liquid-filled cylindrical cavity is examined. The body is rotated about an inclined axis, with the rotation rate and the inclination of the axis of rotation varying. The focus of the study is the trajectory of the sphere, its buoyancy and rotation velocities. It is observed that, for inclination angles greater than 15°, the sphere undergoes radial oscillations of small amplitude. Additionally, axial and azimuthal oscillations are detected, with the sphere's buoyancy velocity and rotational velocity varying in phase during its axial motion. The intensity of the oscillations increases with an increase in the inclination of the cavity's rotation axis and with a decrease in the rotation rate. Fourier analysis of the oscillatory motion shows that there are several primary oscillation frequencies, which remain constant within the given geometry of the cavity. It is determined that one of the frequencies is close to the natural frequency of the sphere's circular oscillations in the direction opposite to the cavity rotation, while another is caused by the interaction between the sphere and inertial waves, with the source of these waves being the sphere itself. The analysis of experimental data indicates that the oscillations in the buoyancy velocity and differential rotational velocity are caused by the repeated focusing and scattering of inertial waves within the cavity. These oscillations, in turn, are affected by the sphere's axial position. Therefore, the motion of a free sphere in a liquid-filled cavity rotating about an inclined axis is a complex system with feedback. The interplay between rotation and gravity enables the control of the dynamics of a light sphere, a finding that may be of interest to those developing methods for non-contact control of sediments in industrial processes.

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Declarations
Conflicts of interest: The author declares no conflicts of interest to report regarding the present study.
Authors' contributions: All the work is done by the corresponding author.
Ethics approval: Not applicable.
Consent to participate: Not applicable.

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