

Flow-following behavior of centimeter-sized air-filled soap bubbles as assessed in a cylinder wake

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ABSTRACT

In this study, the flow-following behavior of centimeter-sized air-filled soap bubbles is explored in the wake of a circular cylinder in order to assess when these soap bubbles no longer faithfully follow the flow. Air-filled soap bubble motion is captured by tracking the two largest glare points, with depth retrieval based on the glare-point particle tracking technique. The experiments are conducted in the wake of a circular cylinder at a freestream velocity of $U_\infty \approx 6 \text{ m s}^{-1}$. Based on the cylinder diameter, this corresponds to a Reynolds number of $Re_D \approx 65000$. To assess the flow-following behavior, a dimensionless time-scale ratio $\eta = \tau_p / \tau_f$ is introduced. The distribution of η shows that, for 10.4% of all wake sample points, the particle time scale is smaller than or comparable to the selected wake-flow time scale. When only sample points corresponding to vortical wake tracks are considered, this fraction increases to 28.7%.

1. Introduction

Tracer-based optical measurement techniques provide a valuable approach for investigating large-scale airflows in both engineering applications (Hong et al., 2014) and geophysical studies (Rosi et al., 2014; Bou-Zeid et al., 2020). Efforts to increase the measurement volume have been constrained by the light-scattering properties of tracer particles. This limitation has been partially addressed by employing larger tracers with higher light-scattering efficiency (Bosbach et al., 2009; Rosi et al., 2014; Toloui et al., 2014). However, the higher light-scattering efficiency and experimental simplicity of larger particles comes at the cost of a reduced tracer response and an increased theoretical complexity (Melling, 1997; Barros et al., 2021; Calzavarini et al., 2009).

In conventional lab-scale flow-tracer applications, tracer behavior is typically described under the assumption of Stokes flow (J. N. Galler & Rival, 2021). However, for larger particles with substantial density relative to air, such as centimeter-sized air-filled soap bubbles (AFSBs), the Stokes drag

assumption is no longer valid (J. Galler & Rival, 2023). Therefore, the current study assesses the flow-following behavior of the centimeter-sized AFSBs in a cylinder wake using a dimensionless number η . AFSB motion is captured by tracking the two dominant glare points, and depth information is retrieved using the glare-point particle tracking (GPPT) technique. Further details on the method can be found in Hou et al. (2021); Kaiser & Rival (2023); Leister & Rival (2025).

This paper is organized as follows. In Sect. 2 the derivation of the dimensionless number η , the measurement setup, the fundamentals of the GPPT technique and the post-processing procedure are described. In Sect. 3 the autocorrelation functions of the velocity components v_x and v_y as well as the distribution of the dimensionless number η are shown and discussed. In Sect. 4 conclusions are presented, with particular emphasis on the interpretation of the η -distributions.

2. Experimental methods

This section outlines the methods employed for assessing the flow-following behavior of centimeter-sized AFSBs, including the introduction of a dimensionless number in Sect. 2.1, the experimental setup in Sect. 2.2, the GPPT fundamentals in Sect. 2.3, and the post-processing procedure in Sect. 2.4.

2.1. Derivation of a dimensionless number

Following the concept of the Stokes number, a dimensionless number η is defined to assess whether a centimeter-sized AFSB can follow vortical structures in the wake of a cylinder:

$$\eta = \frac{\tau_p}{\tau_f}, \quad (1)$$

where τ_f and τ_p are the fluid timescale and the particle timescale, respectively. In the following, acceleration refers to the component perpendicular to the instantaneous velocity. For curvilinear motion, this acceleration increases quadratically with the local velocity U and inversely with the local radius of curvature R (Demtröder, 2006):

$$a = \frac{U^2}{R}. \quad (2)$$

Using $U = U_\infty$ and $R = D/2$, the fluid acceleration can be written as follows:

$$a_f = \frac{2U_\infty^2}{D}. \quad (3)$$

The acceleration is divided by the freestream velocity U_∞ , yielding a quantity with the dimension of inverse time. Taking the reciprocal gives the timescale of the fluid in the cylinder wake:

$$\tau_f = \frac{D}{2U_\infty}. \quad (4)$$

The particle timescale τ_p was computed from the obtained particle tracks. Analogously to the fluid timescale, the particle acceleration was divided by the particle speed, yielding a quantity with the dimension of inverse time. Taking the reciprocal of this ratio gives the particle timescale:

$$\tau_p = \frac{U_p}{a_p}, \quad (5)$$

where $U_p = \|\mathbf{U}_p\|$ is the particle speed and R_p is the local particle radius of curvature. The particle acceleration was computed as

$$a_p = \frac{U_p^2}{R_p}, \quad (6)$$

with the radius of curvature

$$R_p = \frac{U_p^3}{\|\mathbf{U}_p \times \mathbf{a}_p\|}. \quad (7)$$

Here, $\mathbf{U}_p$ and $\mathbf{a}_p$ are the measured particle velocity and acceleration vectors, respectively.

2.2. Setup

A cylinder wake study is conducted using a circular cylinder with an outer diameter of $D = 160$ mm and a length of $L = 2800$ mm, oriented parallel to the ground plane, as shown in Fig. 1. A non-uniform flow is generated by a custom flow simulator with a cross-section of 2×2 m, consisting of 36 fans arranged in a 6×6 grid and operated at identical speeds. This configuration produces a freestream velocity of $U_\infty \approx 6 \text{ m s}^{-1}$, corresponding to a Reynolds number of $Re_D = \frac{U_\infty D}{\nu} \sim 65\,000$, with the kinematic viscosity of air $\nu = 1.47 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$. The flow is seeded with centimeter-sized AFSBs of diameter $D_B \approx 30$ mm produced at a rate of ~ 25 AFSBs/s, with the AFSB generator aligned vertically with the camera and the LED. The test section is illuminated laterally by an LED operated in steady mode. Imaging is performed using a high-speed camera (Phantom V711, Vision Research) with a 35 mm focal-length lens (Nikon), set to an aperture of $f/8$, and a CMOS sensor with a pixel size of $20 \mu\text{m}$, positioned 5 m downstream of the propeller plane and facing upstream. The camera is operated at an image size of 1280×720 pixels, and images are acquired at 400 Hz. The exposure time is set to $1/5000$ s. The image acquisition is performed in consecutive 30.7 s intervals, yielding 12 281 frames per segment, and a total of 60 segments is recorded, resulting in a measurement time of 30.7 min.

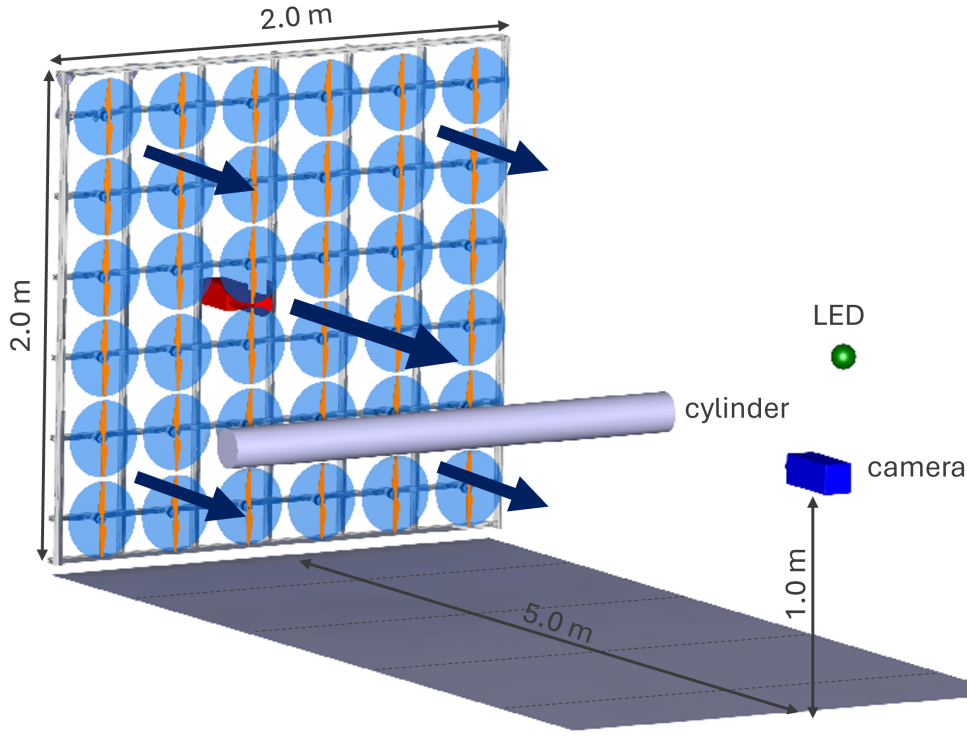


Figure 1. The experimental setup consists of the flow simulator, the AFSB generator, the circular cylinder, the camera and the LED. The AFSB generator, positioned upstream of the flow simulator, is vertically aligned with the LED (positioned laterally of the test section) and the camera (positioned downstream of the measurement region). The non-uniform flow is seeded with AFSBs and has a freestream velocity of $U_\infty \approx 6 \text{ m s}^{-1}$.

2.3. Basics of glare-point particle tracking

Using a single camera, the GPPT technique enables volumetric flow measurements by capturing the glare points of illuminated soap bubbles of known diameter D_B . The flow is seeded with soap bubbles, which are recorded with a camera capturing the light reflected from the soap bubble surface. For the two brightest glare points, the glare-point distance D_G depends on the soap bubble diameter D_B and the angle θ between camera and light source, and is expressed as:

$$D_G = D_B \sin\left(\frac{\theta}{2}\right), \quad 0^\circ \leq \theta \leq 90^\circ \quad (8)$$

(Kaiser & Rival, 2023; Leister & Rival, 2025). Under the assumption of a known and consistent diameter D_B , the distance between the soap bubble and the camera (depth) can be assessed using the depth-dependent image glare point distance of the soap bubble's two brightest glare points.

2.4. Post-processing procedure

The post-processing procedure is carried out using Python. The frame-based camera images are monochromatic and recorded with a 12-bit depth. For reduction of background information, a pixel-wise 10th intensity percentile is computed over a subset of frames and subtracted from each frame. The resulting images are thresholded using a value of 200 intensity counts to obtain binary images with a resolution of 1280×720 pixels. Following Kaiser & Rival (2023), the particle detection intensity threshold is selected to ensure that only the two brightest glare points are detected. Glare-point candidates are detected as local intensity maxima in the thresholded, background-subtracted images. Their sub-pixel positions are subsequently refined using a two-dimensional Gaussian fit, and a tracking algorithm is applied. Tracks corresponding to a single AFSB are paired and depth information is extracted using the GPPT technique. The glare-point distance in pixels d_G is obtained by calculating the Euclidean distance between the two brightest glare points corresponding to each AFSB:

$$d_G = \sqrt{(A_x - B_x)^2 + (A_y - B_y)^2}. \quad (9)$$

Subsequently, for each velocity component, the mean velocity is subtracted prior to computing the autocorrelations. The autocorrelations of all valid tracks are then averaged. The integral time scale is obtained by integrating the averaged autocorrelation up to its first zero crossing. Furthermore, a time-scale ratio η is evaluated to assess the flow-following behaviour of the AFSBs. For each valid sample point, the particle response time scale is estimated as:

$$\tau_p = \frac{v}{a_p}. \quad (10)$$

The time-scale ratio is then given by:

$$\eta = \frac{\tau_p}{\tau_f} = \frac{2U_\infty v}{Da_p}. \quad (11)$$

Values of $\eta \leq 1$ indicate that the particle response time is smaller than or comparable to the characteristic flow time scale, whereas larger values indicate reduced flow-following capability.

3. Results and discussion

In this section, results are presented and discussed. Fig. 2 shows the AFSB tracks located inside the prescribed cylinder wake region, defined as $0 \leq (x - x_{\text{cyl}})/D \leq 10$, $|(z - z_{\text{cyl}})/D| \leq 1$, $|(y - y_{\text{cyl}})/D| \leq 2.5$, where $D = 0.16$ m is the cylinder diameter. $N_{\text{tracks}} = 653$ and $N_{\text{samples}} = 18\,659$ are shown. Although the tracks exhibit lateral and vertical displacements, a clear downstream motion along the main flow direction remains visible.

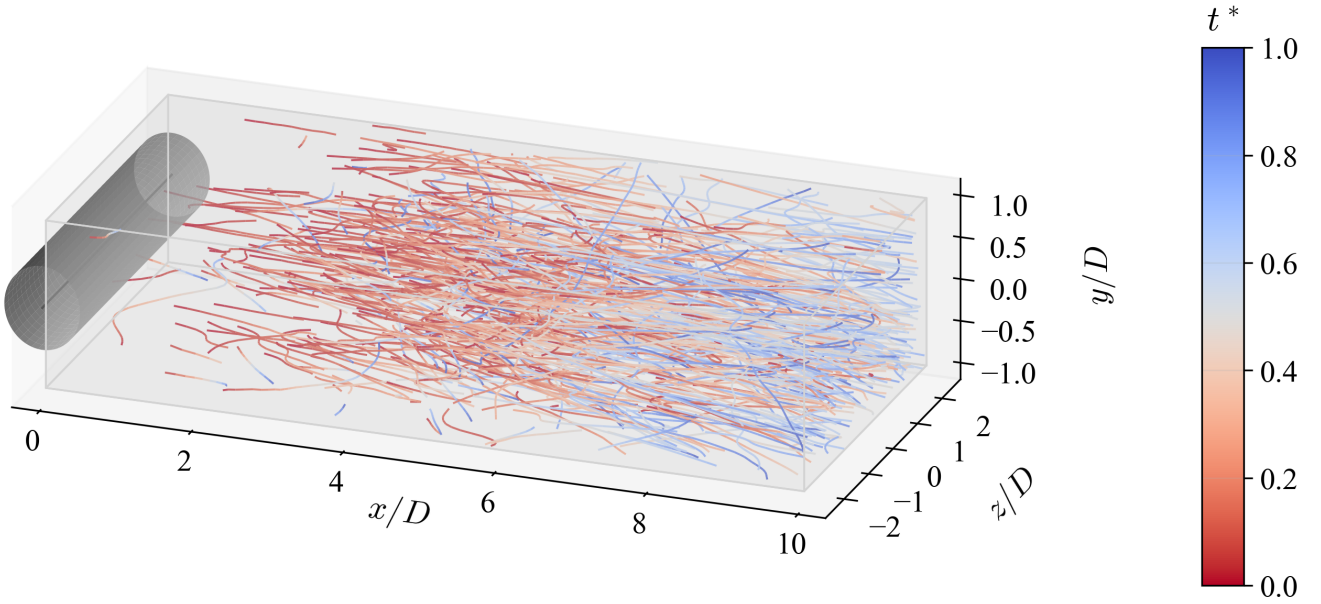


Figure 2. $N_{\text{tracks}} = 653$ and $N_{\text{samples}} = 18\,659$ are visualized in the cylinder wake. The wake region is defined as $0 \leq (x - x_{\text{cyl}})/D \leq 10$, $|(z - z_{\text{cyl}})/D| \leq 1$, $|(y - y_{\text{cyl}})/D| \leq 2.5$, where $D = 0.16$ m is the cylinder diameter. The color represents the normalized time within each individual track, with $t^* = 0$ shown in red and $t^* = 1$ shown in blue.

Fig. 3 shows the normalized autocorrelation functions of the velocity components v_y and v_z , evaluated for $N_{\text{tracks}} = 622$ and $N_{\text{samples}} = 47\,353$ located inside the wake region. The autocorrelation track and sample counts differ from the wake-plot track and sample counts because the wake region visualization includes track segments or sample points located inside the prescribed wake volume, whereas the autocorrelation analysis uses complete time series of tracks for which a sufficient fraction of samples lies inside the prescribed wake region. The autocorrelation decays within the first few tens of milliseconds. Inside the wake region, the integral autocorrelation times are $\tau_{\text{int},y} = 16.8$ ms and $\tau_{\text{int},z} = 14.5$ ms, respectively.

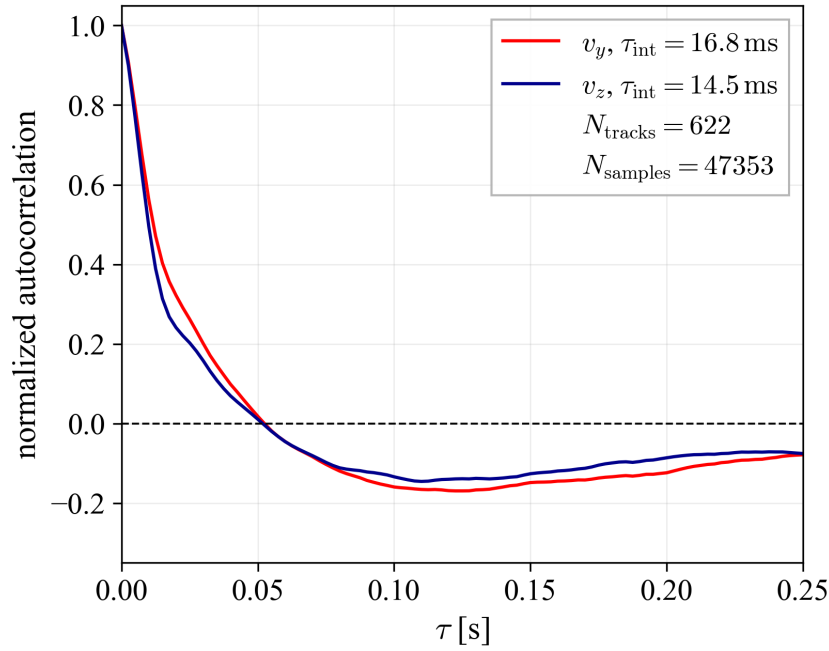


Figure 3. Normalized autocorrelation functions of the velocity components v_y and v_z for $N_{\text{tracks}} = 622$ and $N_{\text{samples}} = 47\,353$ inside the wake region. τ_{int} denotes the integral timescale. The integral autocorrelation times are $\tau_{\text{int},y} = 16.8$ ms and $\tau_{\text{int},z} = 14.5$ ms.

Fig. 4 shows the normalized probability-density distributions of the dimensionless number η , as defined in Sect. 2.1, for AFSB sample points inside the prescribed wake region. Panel (a) includes all wake sample points, corresponding to $N_{\text{tracks}} = 653$ and $N_{\text{samples}} = 18\,659$. Panel (b) shows the subset with vortical wake tracks, which were identified by requiring at least 25 % of the in-wake samples of a track to satisfy $a_p/a_{\text{ref}} \geq 0.5$, with $a_{\text{ref}} = U^2/(D/2)$. This subset contains $N_{\text{tracks}} = 140$ and $N_{\text{samples}} = 2777$. The vertical dashed line indicates $\eta = 1$, where the particle response timescale equals the wake-flow timescale. For all wake samples, 10.4 % satisfy $\eta \leq 1$, whereas the vortical-track subset shows a larger fraction of 28.7 %. In the present study, $\eta = 1$ is used as a reference limit: sample points with $\eta \leq 1$ exhibit a particle time scale that is smaller than or comparable to the estimated fluid time scale and are therefore considered compatible with flow-following on the resolved scale. For the full wake region data set, only 10.4 % of the sample points satisfy this criterion. This indicates that flow-following behavior cannot be assumed throughout the wake region. When the analysis is restricted to sample points from vortical wake tracks, the fraction of samples with $\eta \leq 1$ increases to 28.7 %. This subset is more directly related to the question of vortex-following behaviour, because it excludes a large number of comparatively straight wake tracks that exhibit small accelerations. Such tracks yield large values of $\tau_p = U_p/a_p$ and consequently large values of η .

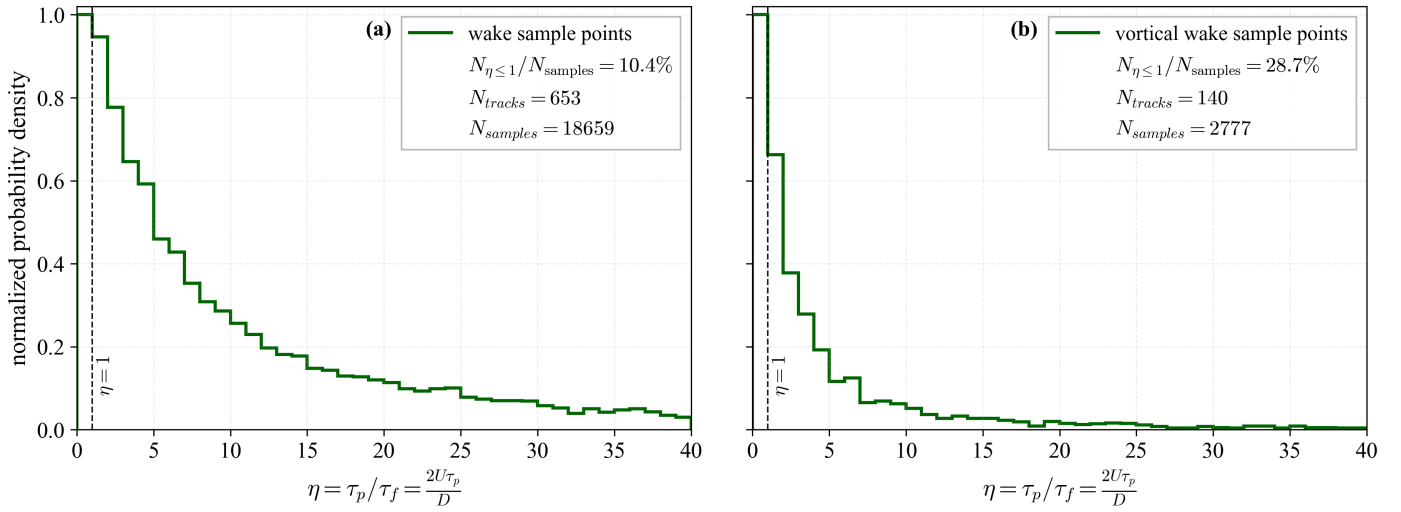


Figure 4. Normalized probability-density distributions of the timescale ratio $\eta = \tau_p/\tau_f = 2U\tau_p/D$ for AFSB sample points located inside the cylinder wake region. The bin width is set to 1. Panel (a) shows $N_{tracks} = 653$ and $N_{samples} = 18659$, while panel (b) shows sample points from vortical tracks. The vertical dashed line marks $\eta = 1$, where the particle timescale equals the flow timescale. Values below this threshold indicate samples for which the AFSBs respond on a timescale shorter than or comparable to the wake motion. In panel (a), 10.4% of the wake samples satisfy this condition, while the vortical-track subset in panel (b) shows a fraction of 28.7%, suggesting that the the high- η values can partly arise from nearly straight track segments with small acceleration.

4. Conclusions

In this study, the flow-following behaviour of centimeter-sized air-filled soap bubbles was assessed in the wake of a circular cylinder using a dimensionless ratio $\eta = \tau_p/\tau_f$. This ratio compares the particle time scale, obtained from the AFSB tracks, with a characteristic wake-flow time scale.

The analysis shows that, for 10.4% of all wake sample points, the particle time scale is smaller than or comparable to the selected wake-flow time scale. When only sample points from tracks classified as vortical are considered, this fraction increases to 28.7%. Thus, the selected time-scale criterion is more frequently satisfied when vortical motion is present in the AFSB particle tracks.

These results show that the interpretation of AFSB flow-following behaviour depends on the sampled track dynamics. Large values of η do not necessarily indicate insufficient particle response alone, but may also occur for weakly curved tracks. Overall, the results indicate that centimeter-sized AFSBs can provide useful information in large-scale airflow measurements. However, the η -method should be interpreted with respect to the sampled track curvature: tracks that remain nearly straight yield large η values and do not provide a direct test of vortex-following behaviour.

Nomenclature

D	cylinder diameter [mm]
D_B	AFSB diameter [mm]
D_G	physical glare-point distance [mm]
d_G	image glare-point distance [px]
L	cylinder length [m]
Re_D	Reynolds number based on cylinder diameter [-]
t	time [s]
U	velocity [m s^{-1}]
U_∞	freestream velocity [m s^{-1}]
v_y, v_z	velocity components [m s^{-1}]
θ	angle between camera and light source [$^\circ$]
ν	kinematic viscosity of air [$\text{m}^2 \text{s}^{-1}$]
τ	time lag [s]
τ_{int}	integral autocorrelation time [s]
AFSB	air-filled soap bubble
GPPT	glare-point particle tracking

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