

Imaging Transient Stress Fields in Soft Materials during Droplet Impact by Photoelastic Tomography

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ABSTRACT

Droplet impact on soft materials is a fundamental fluid–structure interaction problem relevant to erosion, coating, inkjet printing, and biomedical applications. Although droplet kinematics such as spreading, splashing, and rebound have been extensively investigated, direct experimental access to the internal stress fields generated inside soft substrates during impact remains limited. Most existing approaches infer impact stresses indirectly from surface deformation or kinematic measurements, which becomes particularly challenging for highly transient and localized events. In this study, we present a polarization-based optical approach for measuring transient stress fields induced by droplet impact on soft substrates. Building on our previous developments of integrated photoelasticity and high-speed photoelastic tomography for soft materials, we extend these techniques to liquid droplet impacts involving strong fluid–structure coupling. A high-speed polarization camera records the phase retardation and orientation of polarized light transmitted through the stressed substrate in a single shot. The measured photoelastic parameters are then used to reconstruct time-resolved, axisymmetric stress fields inside the substrate. The reconstructed stress fields reveal the spatio-temporal evolution of compressive stresses beneath the impact zone and allow the normal impact force to be evaluated by integrating the axial stress distribution. By comparing sphere and droplet impacts, we show that fluid and solid impactors generate distinct internal stress structures even under comparable impact velocities. The stress-based force measurements further reveal a crossover from inertia-dominated impact behavior to Hertzian-like elastic response as the relative importance of droplet inertia and substrate elasticity is varied. These results demonstrate that high-speed photoelastic tomography provides direct access to internal stress dynamics that cannot be obtained from surface observations alone. The present approach establishes polarization-based stress imaging as a powerful laser diagnostic for probing transient stress fields in soft matter and impact-driven fluid–structure interactions.

1. Introduction

Droplet impact on solid and soft substrates is a canonical problem in fluid mechanics and has been investigated for more than a century. It plays a central role in a wide range of natural and

industrial processes, including rain-induced erosion, spray cooling, inkjet printing, and emerging bioprinting technologies (Josserand & Thoroddsen, 2016; Yarin, 2006). Most previous studies have focused on droplet kinematics, such as spreading, splashing, rebound, and contact time, leading to a well-established phenomenological understanding of impact dynamics.

In contrast, the stresses generated during droplet impact—both within the droplet and inside the substrate—have received comparatively less experimental attention. Recent reviews have emphasized that impact force and stress distributions are key quantities governing material response and damage, yet remain difficult to access experimentally (Cheng, Sun, & Gordillo, 2022). Existing approaches typically infer stresses indirectly from velocity gradients measured by particle image velocimetry or from surface deformation combined with constitutive models (Gordillo, Sun, & Cheng, 2018; Mitchell, Klewicki, Korkolis, & Kinsey, 2019). Such methods face intrinsic limitations in spatial resolution and temporal fidelity, particularly for highly transient and localized impact events.

Photoelasticity provides a unique, non-contact optical method for stress measurement by exploiting stress-induced birefringence (Aben & Guillemet, 1993; Ramesh, 2021). The technique relates the modulation of polarization—characterized by the phase retardation and orientation of transmitted light—to the internal stress state of a material through the stress-optic law. While photoelasticity has been widely used for hard materials such as glass, its application to soft materials undergoing large deformation was long considered challenging.

Recently, integrated photoelasticity was shown to be quantitatively applicable to soft materials, including gels with elastic moduli several orders of magnitude lower than glass (Yokoyama et al., 2023). Furthermore, the advent of high-speed polarization cameras has enabled time-resolved measurement of photoelastic parameters in a single shot, eliminating the need for conventional phase-stepping procedures (Onuma & Otani, 2014). By combining these advances with photoelastic tomography, it became possible to reconstruct all stress tensor components in dynamic, axisymmetric problems, such as static and dynamic Hertzian contact in soft materials (Mitchell et al., 2023; Yokoyama, Ichihara, & Tagawa, 2024).

In addition to stress measurements in soft solids, polarization-based diagnostics have recently been extended in our group to fluid stress measurements using flow birefringence. For example, cellulose-nanocrystal suspensions have been used to examine the validity of the stress-optic law in three-dimensional flow fields (Nakamine, Yokoyama, Worby, Muto, & Tagawa, 2024; Worby, Nakamine, Yokoyama, Muto, & Tagawa, 2024), and related approaches have been applied to shear-thinning flows, combined extensional-shear flows, and stress fields around moving bubbles or spheres (Kawaguchi et al., 2026; Kobayashi et al., 2026; Kusuno & Tagawa, 2025). Recent developments have further aimed at reconstructing full three-dimensional fluid stress tensors from polarization measurements (Igarashi et al., 2025; Kumagai et al., 2026). These studies, together with high-speed photoelastic tomography in soft materials (Yokoyama et al., 2024, 2023), form the

methodological background of the present work.

In parallel, recent droplet impact experiments on elastic substrates revealed a crossover in impact force scaling from inertia-dominated behavior to Hertzian-like elastic response, inferred from stress measurements within the substrate (Yokoyama, Maruoka, Matsunuma, & Tagawa, 2026). These findings highlight the importance of direct, volumetric stress measurements for fully understanding fluid–structure interactions during impact.

In the present study, we extend high-speed polarization-based stress imaging to droplet impact on soft substrates. By applying integrated photoelasticity and high-speed photoelastic tomography, we directly visualize and quantify the transient stress fields generated inside soft materials during droplet impact. This approach provides new insight into stress localization, force transmission, and scaling behavior that cannot be obtained from kinematic measurements alone, and establishes polarization-based laser diagnostics as a powerful tool for probing transient stress fields in soft matter and impact-driven phenomena.

2. Measurement Principle

2.1. Integrated Photoelasticity

Photoelasticity is an optical technique that exploits stress-induced birefringence to measure internal stress fields in transparent materials. When circularly polarized light passes through a stressed medium, it emerges as elliptically polarized light characterized by two photoelastic parameters: the phase retardation Δ and the orientation angle ϕ of the polarization ellipse. These parameters are related to the stress field through the stress–optic law (Aben & Guillemet, 1993; Ramesh, 2021).

For a material subjected to a three-dimensional stress state, the measured photoelastic parameters correspond to line-of-sight integrals of stress components along the camera optical axis. When the y -axis is chosen as the optical axis, the relationship can be written as

$$\Delta \cos 2\phi = C \int_{-\infty}^{\infty} (\sigma_{xx} - \sigma_{zz}) dy, \quad \Delta \sin 2\phi = 2C \int_{-\infty}^{\infty} \sigma_{xz} dy. \quad (1)$$

where C is the stress–optic coefficient of the material, and σ_{ij} are the stress tensor components. Because the measured quantities are integrated values, this approach is referred to as integrated photoelasticity.

Integrated photoelasticity has been extensively used for residual stress measurements in hard materials such as glass (Aben & Guillemet, 1993). However, its application to soft materials was long considered challenging due to large deformation, low stress levels, and uncertainty in the stress–optic coefficient. Recently, it was demonstrated that integrated photoelasticity remains quantitatively valid for soft materials, including gels with elastic moduli several orders of magnitude lower

than glass, provided that the stress-optic coefficient is properly calibrated (Yokoyama et al., 2023).

2.2. High-Speed Polarization Imaging

Conventional photoelastic measurements often rely on phase-stepping techniques, which require multiple images acquired under different polarization states. Such approaches are unsuitable for highly transient phenomena such as droplet impact. The development of polarization cameras with pixelated micro-polarizer arrays has enabled single-shot measurement of photoelastic parameters (Onuma & Otani, 2014).

In a polarization camera, four linear polarizers with different orientations are integrated directly onto the image sensor. From the simultaneously recorded intensity values, both the retardation Δ and the orientation ϕ can be reconstructed at each pixel in a single exposure. When combined with high-speed imaging, this enables time-resolved measurement of photoelastic parameters at frame rates exceeding $\mathcal{O}(10^4)$ fps, making it possible to capture rapidly evolving stress fields without temporal aliasing.

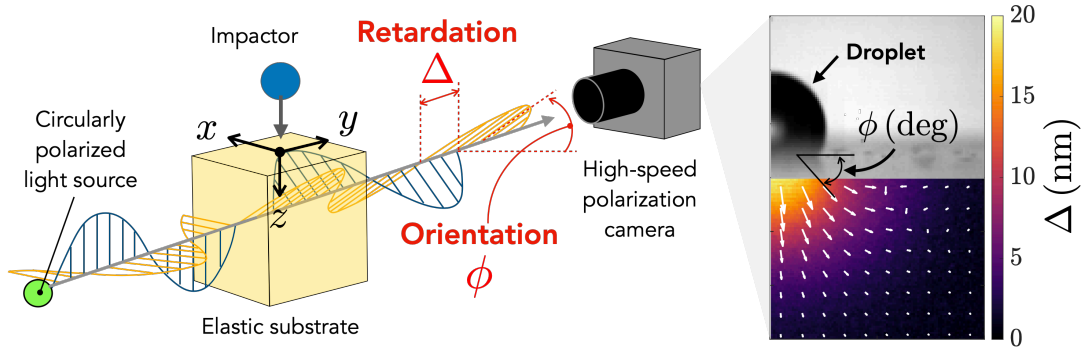


Figure 1. Schematic of the experimental setup for polarization-based stress measurement in an elastic substrate during sphere or droplet impact. The right panel shows a typical snapshot of the photoelastic parameters, phase retardation Δ and orientation ϕ , measured during droplet impact. The colour indicates Δ , and the white arrows indicate the orientation ϕ of the polarization ellipse.

Figure 1 illustrates the experimental and optical configuration used in the present study. Circularly polarized light is transmitted through the soft substrate, and stress-induced birefringence modulates the polarization state of the light, which is captured by the high-speed polarization camera. The right panel of Fig. 1 shows a representative snapshot of the measured photoelastic parameters during droplet impact, highlighting the spatial distributions of Δ and ϕ .

2.3. Photoelastic Tomography for Axisymmetric Stress Fields

The photoelastic parameters given by Eq. (1) provide integrated information about the internal stress field. To recover local stress components, a tomographic reconstruction is required. In gen-

eral, stress is a tensor quantity, and its reconstruction from two integrated measurements is an ill-posed problem. However, when the stress field is axisymmetric, the number of independent stress components is reduced, and photoelastic tomography becomes tractable (Aben & Guillemet, 1993).

For axisymmetric problems such as normal impact of a droplet onto a flat substrate, the stress tensor in cylindrical coordinates (r, θ, z) reduces to four components: radial stress σ_{rr} , hoop stress $\sigma_{\theta\theta}$, axial stress σ_{zz} , and shear stress σ_{rz} . Using the measured photoelastic parameters, the shear and axial stresses can be reconstructed from the integrated relations, and the remaining components can be obtained from equilibrium and compatibility conditions of linear elasticity.

This framework was recently implemented as photoelastic tomography and validated for both static and dynamic Hertzian contact problems in soft materials (Mitchell et al., 2023; Yokoyama et al., 2024). By extending this approach to high-speed polarization imaging, it becomes possible to reconstruct the full, time-resolved stress tensor field in dynamically deforming soft substrates.

2.4. Application to Droplet Impact

In the present study, the above framework is applied to droplet impact on soft substrates. Droplet impact generates a transient, localized stress field that evolves on sub-millisecond timescales and exhibits approximate axial symmetry during the early stage of impact. Under these conditions, high-speed photoelastic tomography provides direct experimental access to the internal stress field generated beneath the impact zone.

By reconstructing the axial stress distribution at the substrate surface, the normal impact force can be evaluated as

$$F(t) = 2\pi \int_0^\infty \sigma_{zz}(r, z = 0, t) r dr. \quad (2)$$

allowing a direct link between internal stress fields and macroscopic force measurements. This stress-based approach provides a physically transparent interpretation of impact-force scaling and enables investigation of the transition from inertia-dominated to elasticity-dominated response observed in recent droplet impact studies (Yokoyama et al., 2026).

3. Experimental Setup

3.1. Overview

The experimental setup is designed to measure transient stress fields generated inside soft substrates during droplet impact using high-speed polarization-based photoelastic tomography. The system consists of a droplet generation and impact unit, a transparent soft substrate, and an optical

measurement system composed of a circularly polarized light source and a high-speed polarization camera.

Droplets impact the substrate vertically under gravity, producing a localized and rapidly evolving stress field beneath the contact region. The optical system records the spatio-temporal evolution of photoelastic parameters within the substrate, which are subsequently used to reconstruct the internal stress tensor field as described in Section 2.

3.2. Soft Substrates

Transparent elastic substrates were used to enable photoelastic measurements during impact. The substrates were selected to exhibit sufficient photoelastic sensitivity while maintaining mechanical stability under repeated impacts. Their Young's moduli were independently characterized using quasi-static indentation tests based on Hertzian contact theory, following established procedures (Mitchell et al., 2023; Yokoyama et al., 2023).

The substrates were cast into blocks with lateral dimensions much larger than the droplet radius. This ensured that boundary effects and stress reflections from the edges were negligible during the time window of interest. The substrate thickness along the optical axis was chosen to satisfy the assumptions of integrated photoelasticity while providing adequate signal-to-noise ratio for polarization measurements.

3.3. Droplet Generation and Impact Conditions

Liquid droplets of controlled radius R were generated and released from rest above the substrate. The impact velocity V was varied by adjusting the release height, covering a range relevant to inertial-capillary and inertial-elastic regimes. The droplet radius and impact velocity were measured independently from high-speed imaging of the droplet trajectory prior to impact.

The working liquids were chosen to minimize optical absorption and to ensure reproducible droplet formation. Within the parameter range investigated, droplet deformation prior to contact was negligible, and the initial impact conditions were well defined. The impact was approximately axisymmetric during the early stage, which is the primary focus of the present stress analysis.

3.4. Optical Measurement System

The optical measurement system consists of a continuous light source, a polarizer, a quarter-wave plate, and a high-speed polarization camera. The incident light is converted into circularly polarized light before passing through the stressed substrate. Stress-induced birefringence within

the substrate modulates the polarization state of the transmitted light, which is captured by the polarization camera.

The polarization camera incorporates a micro-polarizer array directly on the image sensor, enabling simultaneous acquisition of intensity images corresponding to different polarization orientations. From these intensity values, the phase retardation Δ and orientation ϕ are reconstructed at each pixel in a single exposure (Onuma & Otani, 2014). This single-shot capability is essential for capturing rapidly evolving stress fields during droplet impact.

High-speed acquisition is performed at frame rates of order $\mathcal{O}(10^4)$ – $\mathcal{O}(10^5)$ fps, allowing the stress evolution to be resolved on sub-millisecond time scales. The spatial resolution is selected to balance optical sensitivity and tomographic reconstruction accuracy.

3.5. Data Processing and Stress Reconstruction

The measured retardation and orientation fields are first corrected for background birefringence and optical non-uniformity. Subsequently, the photoelastic parameters are converted into integrated stress quantities using the stress–optic law described in Section 2.

Assuming axisymmetry, photoelastic tomography is applied to reconstruct the shear and axial stress components within the substrate. The remaining radial and hoop stresses are obtained from equilibrium and compatibility relations of linear elasticity (Yokoyama et al., 2024). The full stress tensor field is reconstructed for each time frame, providing a time-resolved, volumetric view of stress generation and propagation during impact.

The normal impact force acting on the substrate is evaluated by integrating the reconstructed axial stress distribution over the contact region. This stress-based force measurement enables direct comparison with existing impact-force scaling laws and provides a physically transparent interpretation of droplet–substrate interactions (Yokoyama et al., 2026).

4. Results

4.1. Visualization of Transient Stress Fields

Representative snapshots of the measured photoelastic parameters and reconstructed stress fields during droplet and sphere impact are shown in Fig. 2. The bottom-left panels show the experimentally measured photoelastic parameters, phase retardation Δ (colour) and orientation ϕ (white arrows), while the bottom-right panels show the reconstructed axial stress σ_{zz} inside the elastic substrate.

Immediately after impact, a localized region of high stress appears beneath the impact point. The

reconstructed axial stress exhibits a pronounced compressive region near the centreline, while stress gradients develop radially away from the impact axis. These features are consistent with axisymmetric impact mechanics and demonstrate the ability of high-speed polarization imaging to resolve internal stress fields that cannot be inferred from surface observations alone.

A clear qualitative difference is observed between sphere and droplet impacts under comparable impact velocities. While both cases generate strong compressive stress beneath the contact region, the spatial extent and temporal evolution of the stress field differ, reflecting differences in the force transmission mechanism between solid and fluid impactors.

4.2. Temporal Evolution and Impact Force

The temporal evolution of the reconstructed stress components is examined by tracking the axial stress distribution at the substrate surface and within the bulk. Figure 3(a) shows the time evolution of the axial stress distribution acting on the substrate surface for a representative case with Cauchy number $Ca = \rho V^2 / E \approx 0.02$.

Following impact, the axial stress rises sharply and reaches a maximum within sub-millisecond time scales, reflecting the inertial deceleration of the impactor. Subsequently, the stress distribution broadens and decays as elastic relaxation proceeds within the substrate. Notably, the maximum stress is not located exactly at the surface but slightly beneath it, further emphasizing the importance of volumetric stress measurements.

The normal impact force acting on the substrate is evaluated by integrating the reconstructed axial stress at the substrate surface according to Eq. (2). Figure 3(b) shows the resulting force–time histories for different impact velocities during sphere and droplet impact. The impact force rises rapidly after contact, reaches a clear maximum, and subsequently decays as the substrate elastically recovers. The shaded regions indicate one standard deviation over three independent experiments.

4.3. Force Scaling and Crossover Behaviour

The peak impact force extracted from the force histories is analysed in terms of scaling behaviour. Figure 4(a) shows the dimensionless peak force $\Pi = F_{\max} / (ER^2)$ as a function of the Cauchy number $Ca = \rho V^2 / E$. The grey square markers represent the sphere impact data, while droplet impact data follow a continuous transition across the explored parameter range.

At low values of Ca , the peak force follows inertia-dominated scaling, consistent with impacts on rigid or weakly deformable substrates. As Ca increases, the force response gradually transitions toward Hertzian-like elastic scaling. This transition reflects a change in the relative importance of droplet inertia and substrate elasticity.

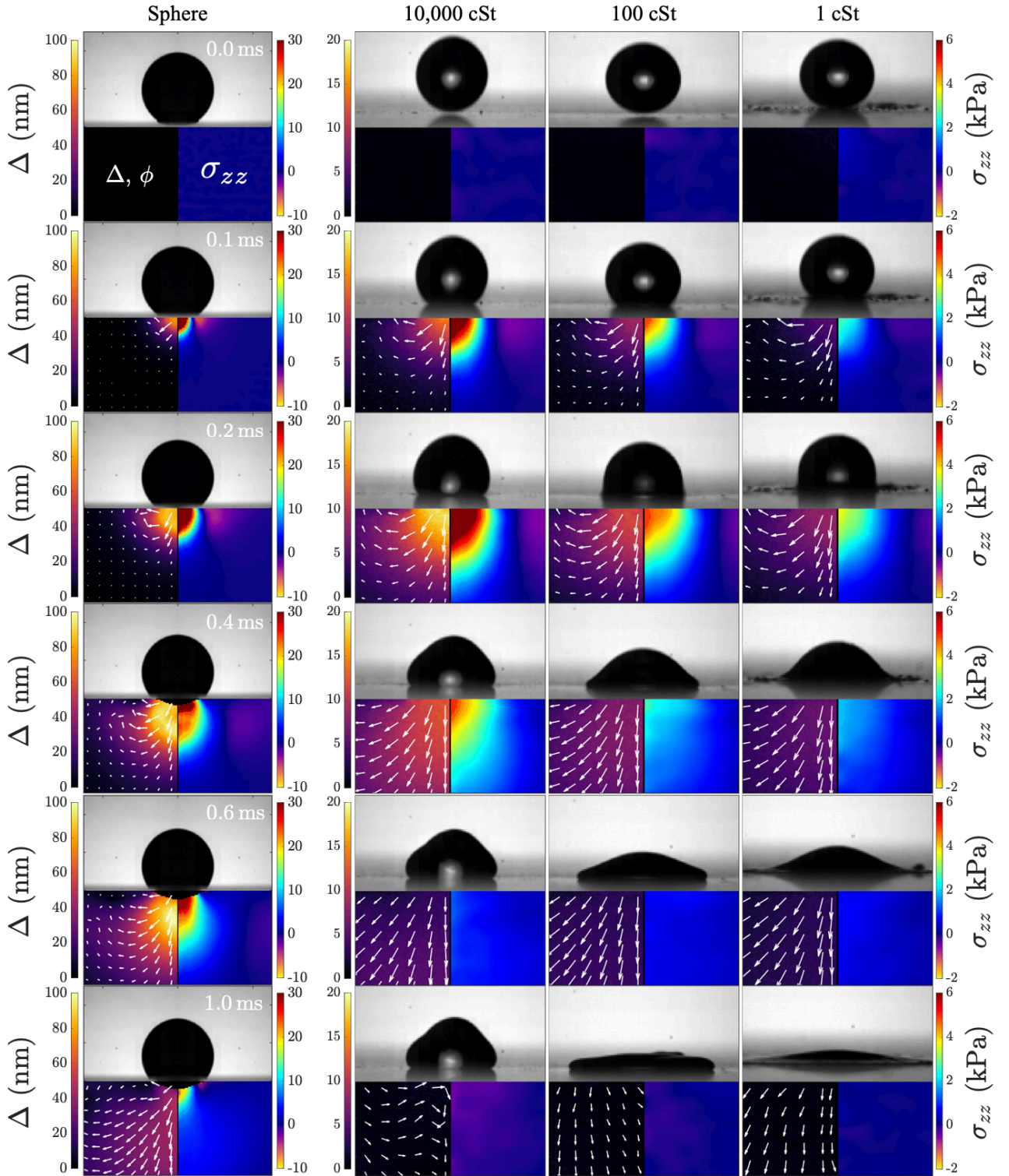


Figure 2. Spatio-temporal distribution of photoelastic parameters and reconstructed stress fields during sphere and droplet impact on an elastic substrate with $V \simeq 2.8 \pm 0.1$ m/s. Bottom-left panels show the measured photoelastic parameters, retardation Δ (colour) and orientation ϕ (white arrows), while bottom-right panels show the reconstructed axial stress σ_{zz} . The measurements reveal distinct internal stress field structures for sphere and droplet impacts that cannot be inferred from surface observations alone.

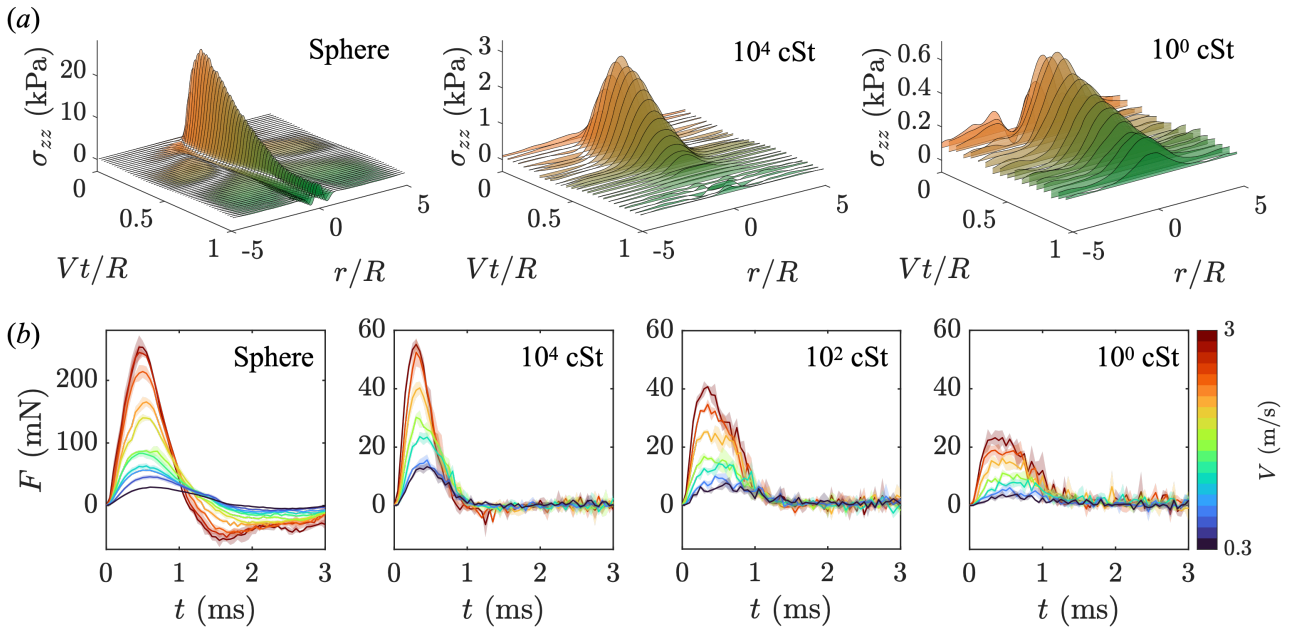


Figure 3. (a) Temporal evolution of the axial stress distribution acting on the substrate surface for a representative case with Cauchy number $Ca = \rho V^2 / E \approx 0.02$. (b) Temporal evolution of the impact force obtained by integrating the reconstructed axial stress, shown for different impact velocities during sphere and droplet impact. The shaded regions represent one standard deviation over three independent experiments.

This crossover is further clarified by introducing the similarity variable $Z = \theta^\alpha Ca$ with $\alpha = 0.28$, where $\theta = \eta / \sqrt{\rho E R^2}$. As shown in Fig. 4(b), the data collapse onto two asymptotic regimes corresponding to inertial and Hertzian impact scaling, respectively. The inset shows the optimisation metric used to determine the exponent α .

5. Discussion and Conclusions

5.1. Stress-Based Perspective on Droplet Impact

The present results demonstrate that polarization-based photoelastic tomography provides direct experimental access to internal stress fields generated during droplet impact on soft substrates. Unlike conventional approaches that infer stresses indirectly from kinematic measurements or surface deformation, the present method visualizes how stresses are generated, transmitted, and redistributed inside the material.

The reconstructed stress fields reveal that the maximum stress does not necessarily occur at the substrate surface but often appears at a finite depth beneath the contact region. This feature, which is difficult to capture using surface force sensors or optical tracking of droplet motion alone, highlights the importance of volumetric stress measurements for understanding fluid–structure

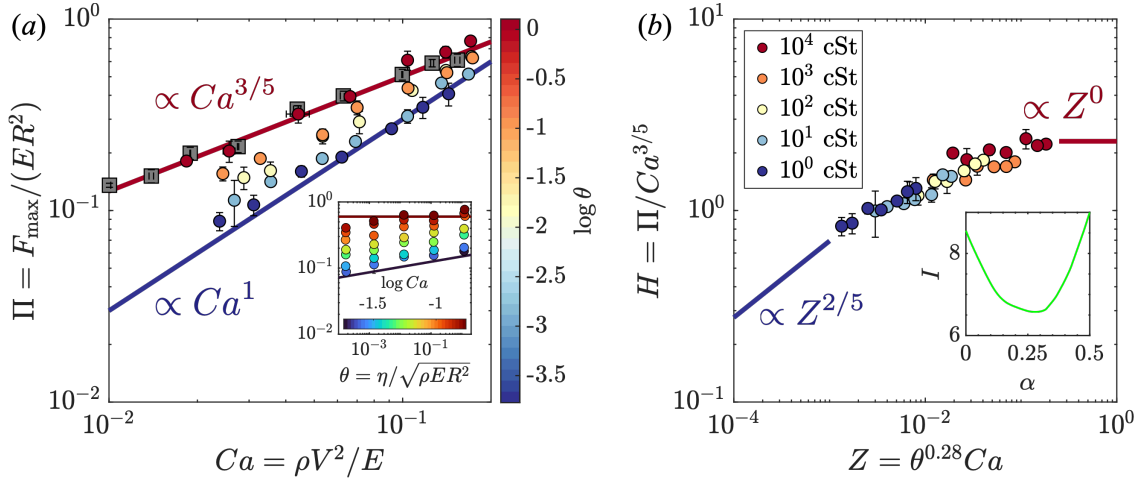


Figure 4. (a) Dimensionless peak force Π as a function of the Cauchy number Ca . Grey square markers indicate the rigid-sphere impact data. The inset shows Π plotted against the viscosity-related parameter θ . (b) Collapsed representation using the similarity variable $Z = \theta^\alpha Ca$ with $\alpha = 0.28$, showing a crossover from inertial force scaling (blue line) to Hertzian impact scaling (red line). The inset shows the optimisation metric as a function of α . Error bars represent one standard deviation over three impacts.

interactions.

5.2. Interpretation of Force Scaling Crossover

The stress-resolved measurements provide a physically transparent interpretation of the scaling crossover in droplet impact force. At low values of $\rho V^2/E$, the stress field spreads broadly within the substrate, resulting in a force response dominated by droplet inertia. As $\rho V^2/E$ increases, stress localization intensifies and penetrates deeper into the substrate, leading to a transition toward Hertzian-like elastic behavior.

This interpretation is consistent with recent experimental observations of scaling crossover in droplet impact force on elastic substrates (Yokoyama et al., 2026), but goes beyond force-based analysis by directly linking macroscopic scaling behavior to the internal stress field structure. The present results show that the crossover is governed not only by global force balance but also by the spatial organization and temporal evolution of stresses within the substrate.

5.3. Implications for Laser-Based Stress Diagnostics

From the perspective of laser and optical diagnostics, this study demonstrates the capability of high-speed polarization imaging combined with photoelastic tomography to resolve rapidly evolving stress tensor fields in soft matter. The method requires only circularly polarized illumination and a polarization camera, without markers, laser sheets, or mechanical contact with the specimen.

The single-shot nature of polarization measurement is particularly advantageous for highly transient phenomena such as droplet impact, cavitation, and jet penetration, where traditional phase-stepping techniques are not applicable. By extending integrated photoelasticity to dynamic fluid–structure interaction problems, the present approach bridges classical photoelastic methods and modern high-speed optical measurement techniques.

5.4. Outlook

The methodology presented here is not limited to droplet impact but is broadly applicable to a variety of problems involving transient stress generation in soft materials. Potential applications include impact and penetration of liquid jets, cavitation-induced stress waves, and mechanically induced stresses in biological tissues.

Future developments may include extension to materials with different stress–optic sensitivities, use of color polarization imaging to expand the measurable stress range, and coupling with other laser-based diagnostics to simultaneously capture flow and stress fields. Such developments will further enhance the role of polarization-based stress imaging as a versatile tool for investigating complex, transient phenomena in fluid mechanics and soft matter.

Concluding Remarks

In summary, we have demonstrated that high-speed photoelastic tomography enables direct, time-resolved measurement of internal stress fields generated by droplet impact on soft substrates. The stress-based measurements provide new insight into impact-force scaling and the transition between inertia-dominated and elasticity-dominated response. This work establishes polarization-based laser diagnostics as a powerful approach for probing transient stress fields in soft materials and fluid–structure interaction problems.

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