International Journal of Civil and Structural Engineering Research ISSN 2348-7607 (Online)
Vol. 5, Issue 2, pp: (72-80), Month: October 2017 - March 2018, Available at: www.researchpublish.com

EXPERIMENTAL STUDY ON INCOMPRESSIBLE FLOW WITH MOVING PARTICLES USING HIGH-SPEED PHOTOGRAPHY

[1]Muhammad Sada Sani, [2]Wu Yu Ching

[1,2] Department of Structural Engineering, College of Civil Engineering, Tongji University, 1239 siping road,
Shanghai 200092, China.

Abstract: **The importance of incompressible viscous flow with moving particles cannot be overemphasized in the analysis and description of several physical phenomena in different fields, such as: Engineering, Oceanography, Meteorology and Geodynamics among others. Several numerical methods have been applied during the past decade to predict the behaviour and interactions between fluid and solid phases. However, these methods do not allow the detail visualization of the information of the problem under consideration. In this study an experiment of incompressible viscous flow phenomenon is carried out using high-speed photography. The experimental set-up includes: an incompressible viscous fluid (transparent shampoo solution), Glass container and spherical particles. The Stokes law is employed to calculate the settling velocities of the particles (spherical). This paper is divided into the following sections, Section 2 Combined high-speed photography methods, Section 3 Experimental procedures, Section 4 Results and discussion and Section 5 Conclusion.**

Keywords: **high-speed photography, incompressible viscous flow, and Stokes law.**

---

1. INTRODUCTION

The demand for comprehensive understanding of the behaviour of incompressible viscous flow with moving particles is very important in many engineering applications. The emergence of high-speed photography can be traced to the work of William Henry Fox Talbot (1851), an experimentation that produced a square inch (1/2000th of a second) readable image of a London time’s newspaper attached to a rotating wheel in front of a wet plate (amphytypes) camera in a darkened room.

Additional works by Foucault (1856) and Toepler (1864) were done and on July 15, 1878 series of photographs of a galloping horse were taken by Muybridge using 24 cameras with stripe thread attached to their shutters to settle a debate: “if there is a moment in a horse’s gait when all four hooves are off the ground at once?” However the invention of a small hand-held camera that uses a focal plane shutter that provides very short exposures of 1/1000th s by Ottomar Anshutz (1884) became the corner stone for other developments. See [1, 2].

High-speed photography have been applied in the visualization of several physical phenomena for over a century, most especially in the field of ballistics and explosives, fluid dynamics, medicine and biomechanics to mention but a few. Recent research developments using high-speed photography includes the work of [3] in which the supercavitating underwater projectiles travelling to a speed exceeding the speed of sound in water were captured and the results were used in verification of computer models, aiding failure analysis and understanding the physics of supercavitating bodies among others.

While bubbles created using high voltage pulse electric sparkle system (with and without a wall) where studied by [4] using high-speed photography and it was discovered that the wall has no impact on cavitation bubbles in the expansioncontraction phases thus the two bubbles used in the experiment collapsed in opposite directions as opposed to the case without a wall among others. However more recently, other shortcomings such as empty cavitation bubbles, which are known as causative agents for the destruction of ship propellers motivated [5] to study bubble dynamics using high-speed photography hence, proposed numerical ideas for the extension of camera speed limits and [6] investigated the dynamic characteristics of femtosecond laser ablation process using high-speed photography. [7] Verified the numerical calculation of the movement of particles in sound wave field using high-speed photography and the amplitude and vibration speed obtain were reported to be in consistency with experimental records. Further more [8] calculated the temperature field of a pendent droplet of a nickel wire-end exposed to a collimated laser beam and also was able to capture the melting process and [9] investigated the propagation, attenuation and localization of non-linear elastic waves in a one-dimensional granular crystal using high-speed photography, resulting in the successful measurement of the dynamics of hard chrome particles among others.

In the context of solid mechanics, an investigation of the propagation of fast cracks in zone-tempered glasses was carried out by [10].

Soft materials behaviour under dynamic loading was studied by [11] using combined viscoelastic split Hopkinson pressure bar (SHPB) and high-speed photography. A less than 2% difference between axial strains measured using SHPB and the high-speed camera was obtain and the measured diameters using the camera matched very well with theoretical predictions among others thus the feasibility of using high-speed photography for measuring dynamic axial and transverse strains was validated.

However, the dynamic strength behaviour of a windshield subjected to bird impact was carried out by [12] using combined finite element method and high-speed photography and the results of the finite element method was found to be in agreement with the results obtained using high-speed photography of the bird impact test. Using high-speed photography to better understand the failure initiation and release process of a slab avalanche, observation of fracture in weak snowpack layers was carried out by [13] and [14] determined the constitutive parameters in high strain-rate materials model using combined high-speed photography and numerical method. With the former used to investigate the deformation and fracture processes during the impact loading experiment and the evaluated data applied in the inverse modelling, which was in-turn used to estimate material properties in a Perzyna’s viscoplastic model.

Also [15] utilized high-speed photography to overcome the drawbacks of standard mechanical test and functional imaging used in the diagnoses of trabecular and cortical bone disease. This allows the uncovering of failure dynamics of bone samples subjected to mechanical testing in a 2D fashion in real time.

The true stress and strain of materials such as honeycomb structures, metallic and polymeric foams as well as porous compacts cannot be extracted as a result of volume change during loading. To resolve the drawback of the inability of previous methods to extract the true stress and strain of such materials, [16] proposed viscoplastic parameter estimation based on high-strain rate, inverse modelling and high-speed photography.

A new method was proposed for the assessment of cutting variable (e.g. shear angles, chip thickness, strain rate, strain etc.) and chip topology studies using high-speed photography combined with laser printed square grid patterns on the work-piece at industrial cutting speeds and feeds [17] and [18] used online high-speed photography to investigate increased drilling speed of holes in stainless steel with temporal and spatial superpose laser radiation performed for oxygen, argon and helium and constant laser parameters.

Motivated by the importance of droplets impingements such as ink-jet printing, rapid spray cooling of hot surfaces and the recent use of raindrops to harvest electric energy for micro-electro mechanical system (MEMS) from piezoelectric systems among others. [19] Studied the head-on collision of binary liquid droplets using high-speed photography and estimating the contact time using a Hertz contact theory.

The analytical results were reported to be in agreement with the experimental data. Motivated by the requirement to improve the fracture toughness of materials by adding stiff or compliant filler particles relative to the matrix [20] successfully investigated the interaction between a dynamically growing matrix crack and a stationary inclusion using combined high-speed photography and 2D digital image correlation (DIC) technique, to ascertain the failure behaviour of such materials.

[21] Presented recent developments of high-speed digital image correlation method for vibrational mode shape analysis, hence improvements in the calibration process decreases the calibration time and enhances the reliability and quality of the results thus making the method easier to use and Shortcomings in gas dynamics processes such as: Invisibility due to

occurrence in transparent medium, transient behaviour as well as characteristic time that are below the threshold of human perception motivated [22] to develop a combined high-speed photography and visualization method, to determine the inaccessible thermodynamic properties of a compressible flow While Morphological changes with decreasing relative humidity were investigated by [23] using high-speed photography to observe the droplets of sea-salt aerosols on a quartz substrate. However, the non-existence of research work in the context of incompressible viscous flow using high-speed photography motivated the authors to carry out this research study.

2. COMBINED HIGH-SPEED IMAGING TECHNIQUES

In the context of flow visualization high-speed imaging is aimed at acquiring precise information about the position and dimensions of fluid flows at series of time instants (i.e. solving the best possible extent of the spatial and temporal scales).

2.1 stroboscopic photography:

As an abstract branch of photography, stroboscopic photography involves taking still images of moving objects at a time instant in the darkness using a flashing strobe light and a camera with an open shutter. Hence it involves the delaying of all successive recordings by fixed time spacing δt, where δt is a fraction of period T of the event. Moreover δt is made in such a way that it spans the inter frame time of a camera [24].

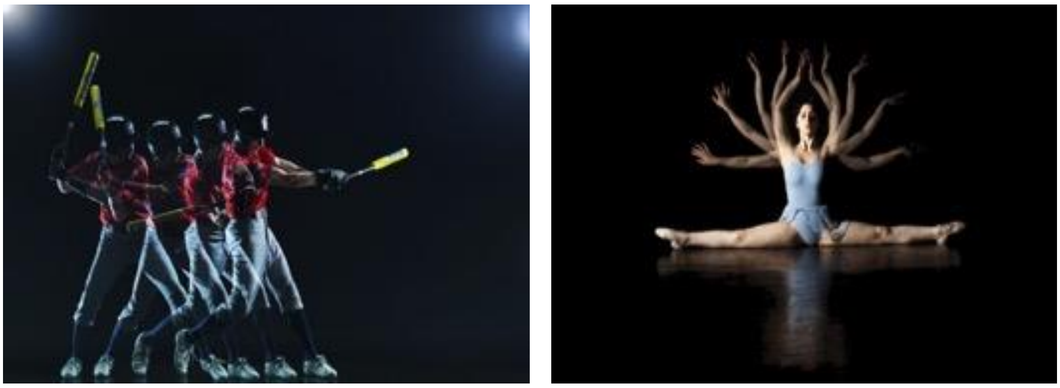


Figure 1: Stroboscopic images

2.2 High-speed shadowgraphy and Schlieren imaging

Schlieren and shadowgraphy are techniques used in compressible flow visualization, changes in density or temperature may cause the spatial derivative of the refraction index to vary, the Schlieren technique is used to visualize the spatial derivative of refraction index while shadowgraphy is simpler to setup, it depends on the second derivative of the refraction index thus making it difficult to quantify and basically serves as a powerful visualization tool. Light traveling through a medium will have different refraction depending on the local density gradient of the medium. Moreover

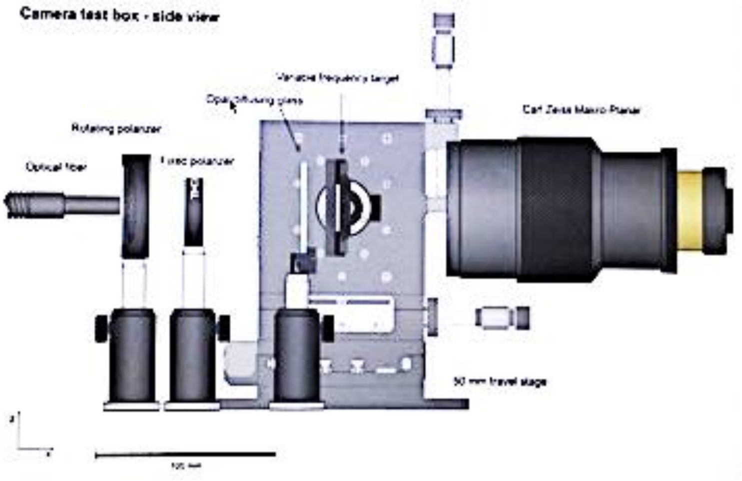
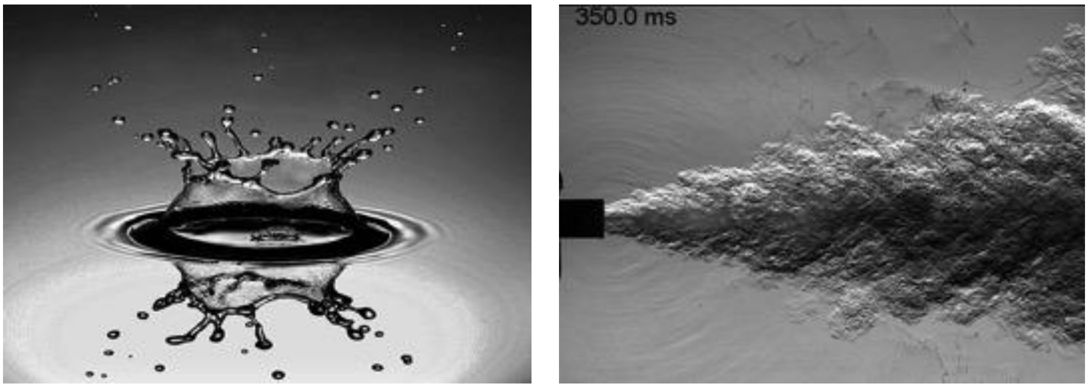


Figure 2: Shadowgraphy is a relatively straightforward technique for the visualization of shock waves in fluids. It is being used for the display of shock waves in aerodynamics and in wind tunnel supersonic flows [24, 25].



(a) **(b)**

Figure 3: (a) Splash image (Shadowgraphy) (b) Flow visualization (Schlieren),

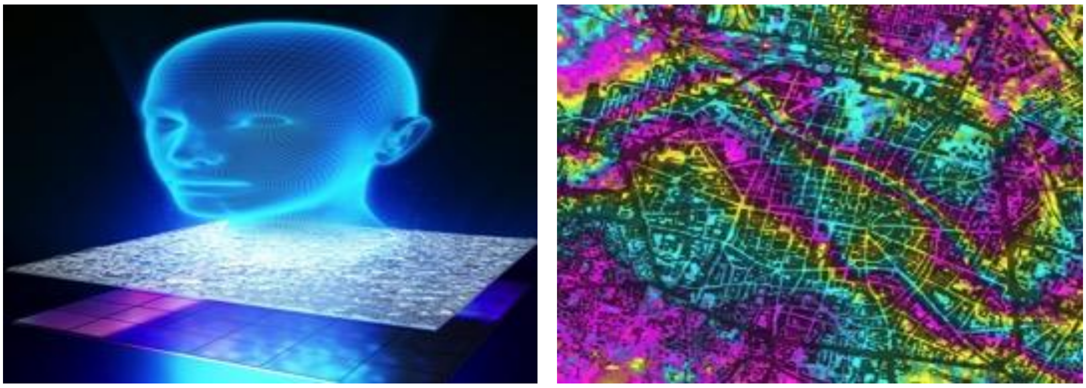
Source: www.bing.com

2.3 High-speed holography and interferometry:

Although Schlieren and shadowgraphy are famous techniques, they suffer some limitations such as lack of accuracy due to the dependence on first-order and second-order of the refractive index, the methods do not offer enough resolution to measure the quantitative details of shock waves and other simple geometries and it cannot deal with intrinsic difficulty of measuring with limited field depth dictated by geometrical optics. To overcome such shortcomings digital holographic imaging techniques are used, in this technique the recorded phase image serves as an interface pattern from the superposition of a spherical scattering wave and a reference plane wave. Information about the objects in the field of view is contained in the image, also with having a nearly indefinite depth of field [24].

This method has been used in a variety of fluids applications such as compressible flows and re-entry problems, characterization of micro droplets and micro particle flow velocimetry among others.

On the other hand interferometry has been used for over century, beginning from (1891 and 1892) when the first interferometer was built by Zehnder and Luwdig respectively. Interferometry techniques such as speckle interferometry and differential interferometry have been used for compressible high-speed flows visualization and in the measurement of air layer thickness during drop impact on a solid surface at frames of up to 100kfps among others [24].



(a) **(b)**

Figure 4: (a) 3D holography (b) Subsidence map of Bologna Differential interferometry,

Source: www.bing.com

2.4 High-speed particle tracking velocimetry:

This is defined as a technique used to measure the velocity of particles resident in a fluid. In contract to the particle image velocimetry (PIV), which is a Eulerian approach and measures the velocity field at a (rectangular) grid, particle-tracking method (PTV) is a Lagrangian approach [1].

There are two very different experimental methods:

1. Two-dimensional (2D) PTV: The flow field is measured in 2D slice of the flow illuminated by a laser sheet, low density of seeded particles allows tracking of each of them individually for several frames.
2. Three-dimensional (3D) PTV: This is a distinctive experimental technique, which is based on multiple camera system, 3D volume illumination and tracking of flow tracer (particles) in tree-dimensional space using photogrammetric principles.

Recent developments in high-speed imaging paved the way for the use of particle tracking velocimetry (PTV) method. More recently 3D-particle tracking velocimetry have become a powerful measurement technique in fluid mechanics. It has been successfully implemented in studies such as, turbulent motion of particles [26] and bubbly flows [27] among others. However, the particle tracking velocimetry also suffer some setbacks, see [28].

2.5 *High-speed particle imaging velocimetry (PIV):*

This is an optical method of flow visualization used to obtain instantaneous velocity measurements and related properties in fluids. This involves the seeding of the fluid with tracer particles which are assumed to follow the flow dynamics due their small sizes, with the degree to which the particles follow the flow dynamics represented by stokes number. The fluid is illuminated to make the particles visible and using the motion of the seeding particles, the speed and direction (velocity) of the flow [1].

The typical instrumentations used consists of a camera (digital with CCD chip), strobe or laser with an optical arrangement to limit the physical region illuminated (normally a cylindrical lens to convert light beam to a line), synchronizer which acts as an external trigger for controlling the camera and laser, seeding particles and fluid. A fibre optic cable or liquid light guide may be used to connect the laser to the lens setup and PIV software is used for post-processing of the optical images. Some advantages and disadvantages of the high-speed particle imaging velocimetry are highlighted below:

Advantages:

1. Nonintrusive and the tracer (if properly chosen) generally cause negligible distortions of the fluid flow.
2. No need for pitot tubes, hotwire anemometers or intrusive flow measurement probes.
3. Simultaneous measurement of the whole two-dimensional cross-section (geometry) of the flow field is possible.
4. High-speed data processing allows the generation of large numbers of image pairs, which may be analysed, in real time or at a later time on a personal computer and high quantity of near-continuous information may be gained.
5. Sub pixel displacement values allow high degree of accuracy and displacement may typically be accurate down to 10% of one pixel on the image plane.

Disadvantage:

1. Particles may not perfectly follow the motion of the fluid (gas or liquid) due to higher densities.
2. Generally components along the z-axis cannot be measured (towards or away from the camera) thus leading to the components being missed or introduce interference in the data for the x and y components caused by parallax. However, such problems do not exist in stereoscopic PIV, which uses two cameras to measure all three-velocity components.
3. The velocity field is a spatial averaged representation of the actual velocity field due to the fact that the resulting velocities vectors are based on cross correlating of the intensity distributions over small areas of the flow. Hence having consequences on the accuracy of the spatial derivatives of the velocity field, vorticity and spatial correlation functions that are often derived from PIV velocity fields.
4. High cost due to the use of class IV lasers and high-resolution, high-speed cameras.

There are different types of PIV setups, which include: Stereoscopic PIV, Dual plane stereoscopic PIV, Multi-plane stereoscopic PIV, Micro PIV, Holographic PIV, Scanning PIV, Tomographic PIV and Thermo-graphic PIV.

3. EXPERIMENT PROCEDURE

Equipment used: Nikon D3200 camera, Tripod stand, White backdrop (Cardboard), subject (glass container filled transparent viscous liquid) and different colours of spherical balls (particles).

3.1 Setting up the composition:

1. The white backdrop was set on a table both; white backdrop was used to enhance the visible of the coloured particles and the set up was place on a white cardboard as well.
2. There is no need for an external flash, thus eliminating the need to synchronize the camera with the external flash.
3. The camera was placed in position using the tripod stand.

***3.2 Camera settings*:**

1. The shutter speed was set to be around 2-3 second, which provides enough time for the shutter to open and the set up inverted for the particles to settle and the results captured.
2. The aperture was set around f/8 and test shots were taking and adjustments made before beginning the actual experiment shots.
3. And finally the experimental shots were taken.

4. EXPERIMENTAL RESULTS AND DISCUSSION

(a)

(b)

(c)

(d)

(e)

(f)

(g)

The Stoke’s law best characterizes the behavior of spherical particles in liquid and at a specified environment. This is a mathematical equation developed by Sir George G. Stokes (British scientist) used for calculating the settling velocities of small spherical particles in a fluid medium, taking into consideration the forces acting on a particular particle as it settles in a liquid under the influence of gravity. The basic assumptions using the Stoke’s law includes:

1. The motion of the particle is constant
2. The particle is spherical and rigid
3. The air velocity at the particle surface is zero
4. The fluid is incompressible
5. There is no other particle affecting the flow pattern

The settling velocity is given as:

$$V_t = \frac{gd^2(\rho_p - \rho_m)}{18\mu} \dots (1)$$

Where,
g = acceleration due to gravity, given as:

$$g = \frac{18\mu V_t}{d^2(\rho_p - \rho_m)} \dots (2)$$

Or 9.81 m/s^{-1}

d = particle diameter, given as:

$$d = v18\mu \frac{V_t}{g(\rho_p - \rho_m)} \dots (3)$$

ρ_m = Density of the medium, given as:

$$\rho_m = \rho_p - 18\mu\frac{V_t}{d^2} \dots (4)$$

ρ_p = Particle density, given as:

$$\rho_p = 18\mu\frac{V_t}{d^2} + \rho_m \dots (5)$$

μ = Viscosity of the fluid, given as:

$$\mu = \frac{gd^2(\rho_p - \rho_m)}{18V_t} \dots (6)$$

From the above equation it can be clearly seen that, the settling time and settling velocity are proportional to the diameter of the particle (i.e. the larger the particle the faster it will settle), this can be observed from (a) and (b) above, also the settling time and velocity are proportional to the difference between the densities of the particle and fluid (density mismatch) thus indicating that by matching the densities between the particle and fluid minimizes the settling time thereby maximizing the time a particle spends in suspension. This can also be observed from the experiment above, the particles. The settling velocity is inversely proportional to the viscosity of the fluid (i.e. the more viscous the fluid the longer the settling time) and vice-versa. Moreover, the general formula developed by [29] can also be used to obtain the velocity of the particles, see [29] and the references therein for more details.

5. CONCLUSION

An experiment of incompressible viscous flow with moving particles using high-speed photography has been carried out in this research study and it was shown that high-speed photography can be utilized as a method for the verification of numerical models used for predicting the parameters and behaviors of incompressible viscous flows with moving particle and this will serve as a new insight for future wider and deeper research works in analyzing incompressible viscous flow with moving particle using high-speed photography.

ACKNOWLEDGEMENT

The author wish to acknowledge the support of Professor Yu Ching Wu and the Department of structural engineering, College of Civil Engineering, Tongji University

REFERENCES

[1] Wikipedia, The free Encyclopedia. www.wikipedia.com

[2] Endelman. L. L, A brief history of high-speed photography 1851-1930, SPIEs 32nd Annual Int'l. Technical symposium 16-18(1988)

[3] Hrubes. J. D, High speed imaging of super cavitating under water projectiles, Experiments in fluids 30(2001) 57-64

[4] Luo. J, Xu. W, Li. R, High-speed photographic observation of collapse of two cavitation bubbles. Technological Science, vol. 59 No. 11: 1707-1716

[5] Lauterborn. W, Kurz. T, The bubble challenge for high-speed photography, DrittesPhysikalisches Institut, Georg-August-Universitat Gottingen,Friedrich-Hund-Platz 1, 37077 Gottingen, Germany

[6] Zhong. D, Li.Z, The high-speed photography research of femtosecond laser ablation process, Procedia Computer Science 107(2017) 891-896

[7] Zhou. D, Luo. Z, Fang. M, Lu. M, Jiang. J, Chen. H, He. M, Numerical calculation of particle movement in sound wave fields and experimental verification through high-speed photography, Applied energy 185(2017) 2245-2250

[8] Bizjan. B, Kuznetsov. A, Jeromen. A, Govekar. E, Sirok. B, High speed camera thermometry of laser droplet generation, Applied thermal engineering 110(2017) 298-305

[9] Yang. J. Gonzalez. M, Kim. E, Abasi. C, Sutton. M, Attenuation of solitary waves and localization of the Breathers in 1D granular crystal visualization via high speed photography, Experimental Mechanics (2014) 54: 1043-1057

[10] Takahashi. K, Aratani. S. I, Yamauchi. Y, Dynamic fracture in zone-tempered glasses observed by high speed photoelastic colour photography, Journal of materials science letters 11(1992) 15-17

[11] Sharma. A, Shukla. A, Prosser. R. A, Mechanical characterization of soft materials using high speed photography and split Hopkinson pressure bar technique, Journal of materials science 37(2002) 1005-1017

[12] Jialing. Y, Xujie. C, Cunhao. W, Experimental and Finite element method study of windshield subjected to high speed bird impact, Acta mechanica sinica, 19(2003) 6

[13] Herwijnen. V. A, Jamieson. B, High speed photography of fractures in weak snowpack layers, Cold region science and Technology 43(2005) 71-82

[14] Kajberg. J, Sundin. K. G, Melin. L. G, Stahle. P, High strain-rate tensile testing and viscoplastic parameter identification using microscopic high-speed photography, International journal of plasticity, 20(2014) 561- 575

[15] Thurner. P. J, Erickson. B, Jungmann. R, Schriock. Z, Weaver. J. C, Fantner. G. E, Schitter. G, Morse. D. E, Hansma. P. K, high speed photography of compressed human trabecular bone correlates whitening to microscopic damage, Engineering Fracture Mechanics 74(2007) 1928-1941

[16] Kajberj. J, Wikman. B, Viscoplastic parameter estimation by high strain-rate experiments and inverse modelling-speckle measurements and high speed photography, International journal of solids and structures 44(2007) 145-164

[17] Pujana. J, Anazola. P. J, Villar. J. A, In-process high speed photography applied to orthogonal turning, Journal of materials processing technology 202(2008) 475-485

[18] Dietrich. J, Brojdic. M, Walther. K, Horn. A, Kelbassa. I, Poprawe. R, Investigation of increased drilling speed by online high speed photography, Optics and lasers in Engineering 46(2008) 705-710

[19] Wang. F. C, Feng. J. T, Zhao. Y. P, The head-on colliding process of binary liquid droplets at low velocity: High speed photography experiments and modelling, Journal of colloid and interface science 326(2008) 196-200

[20] Jajam. K, Tippur. H, Interaction between a dynamically growing crack with stiff and complaint inclusions using DIC and high speed photography, SEM annual conference Indianapolis 2010

[21] Siebert. T, Crompton. M. J, Application of high speed digital image correlation for vibration mode shape analysis, SEM annual conference Indianapolis 2010

[22] Kleine. H, Filming the invisible-time-resolved visualization of compressible flows, Eur. Ohys. J. Special Topics 182, 3-34 (2010)

[23] Qian. Z, Wang. F, Zheng. Y, Yu. J, Zhang. Y, Crystallization kinetics of sea-salt aerosols studied by high-speed photography, Physical Chemistry 57(2012) 6:591-594

[24] Versluis. M, High speed imaging in fluids, Exp. Fluids (2013) 54:1458

[25] Versluis. M, Blom. C, Van der Meer. D, Van der weele. K, Lohse. D, Leaping shampoo and the stable kaye effect, Journal of stat. Mech. Theory and experiment 2006(2006) P07007s

[26] Porta. A. L, Voth. G. A, Crowford. A.M, Alexander. J, Bodenschatz. E, Fluid particle accelerating in fully developed turbulence. Nature 409: 1017-1019 (2001)

[27] Rensen. J, Luther. S, Lohse. D, The effects of bubbles on developed turbulence, J. Fluid Mech. 538(2005) 153-187

[28] Feng. Y, Goree. J, Liu. B, Errors in particle tracking velocimetry with high-speed cameras, Review of scientic instruments 82, 053707 (2011)