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# Highly Efficient PIV Measurement of Complex Flows Using Refractive Index Matching Technique

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*Abstract:* A new approach for PIV measurements of complex flows encountered in various applications is presented. It is based on rapid-prototyping of transparent model for flow visualization and on the use of refractive index matching that enables efficient and clear visualization of the flow inside the model. The model is immersed in the index-matching fluid in a glass tank so that any displacement and rotation of the model in the tank have no influence on the optical setup for image acquisition to be made through a glass wall. This can facilitate greatly the camera calibration for stereo PIV and 3-D PTV. As the flow model is generated directly from 3-D surface data, no laborious preparation of the flow model is needed. This approach for seamless linking of model generation and PIV measurement is applicable to various flow measurements in automobile, ship building, fluid machinery, turbine, electrical appliances, heat exchanger, electronic cooling, bio-engineering and so on.

***Keywords:*** PIV, Rapid Prototyping, Refractive Index Matching, Complex Flows

## 1. Introduction

In many applications of PIV technique, the complexity of flow geometry involved often limits the exploitation of the power of the technique. This is particularly so when sophisticated PIV techniques, such as stereo PIV and 3-D PTV, are to be applied because of the fact that those techniques need accurate camera calibration.

A good example is the measurement of turbulent flow near the intake and exhaust ports of internal combustion engine, where the flow going through highly three-dimensional, curved pipes must be considered. Figure 1 shows a typical model of intake and exhaust pipes near the cylinder head to be considered in the design of internal combustion engine. The aim of flow measurement is to reveal instantaneous flow patterns inside these pipes with a view to determining their best shape that can reduce pressure loss, which is directly related to the increase of net power achieved by the engine. In practice, the compressibility of the fluid may often be ignored as a compromise and a water model can therefore be used to make accurate, reliable flow measurements.

A usual approach for PIV measurement of such complex flow geometry is to fabricate a transparent model that permits optical access both for illumination and image acquisition and to setup the measurement by making considerable case-by-case effort for overcoming experimental difficulties due to the presence of curved wall surfaces. The sections to be measured are often limited only to some representative planes, such as symmetry plane, and consequently the flow

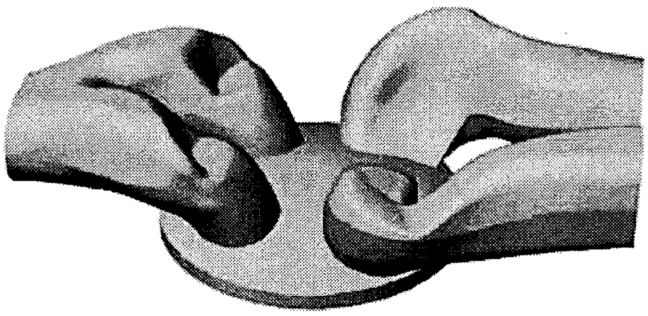

Fig. 1 Surface model of intake and exhaust pipes near the cylinder head.

patterns in the entire region of interest are not resolved. Such limitations can be found in many applications, such as automobile, ship building, fluid machinery, turbine, electrical appliances, heat exchanger, electronic cooling, bio-engineering and so on. The resolution of this limitation can lead to a full exploitation of the power of PIV technique.

The present study and proposal stems from such practical limitation in the application of PIV technique. The key technology proposed here is the combined use of rapid prototyping (RP) and refractive index matching (RIM). As shown later, the present approach permits clear and undistorted visualization of flow fields in complex, three-dimensional geometries, thus leading to quite an efficient PIV measurement of practical flows in many applications. In this paper, PIV measurement of a simulated blood flow (steady flow) in a cerebral aneurysm is described with a view to demonstrating the usefulness of the proposed approach.

# 2. Method

## *2.1 Rapid prototyping (PR)*

RP is widely utilized for the efficient fabrication of test products in many industrial fields. It needs a surface model of the test product to be fabricated. Usually, 3-D CAD data are available, from which a surface model is readily generated (cf. Fig. 1). There are several techniques for RP, such as photo fabrication, paper lamination, selective laser sintering, 3-D printing and so on, each having its own merits and demerits. The one chosen here is 3-D printing, in which powder layers are

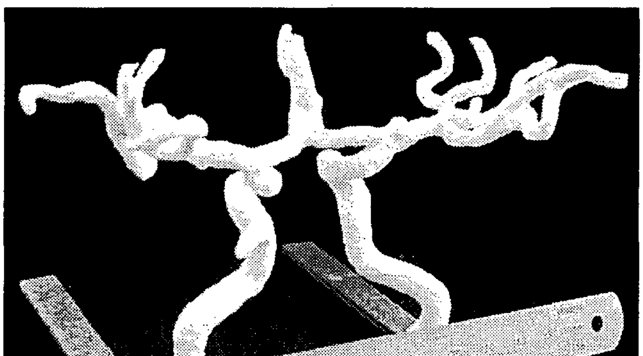

Fig. 2 3-D model of cerebral artery fabricated by 3-D printing technique.

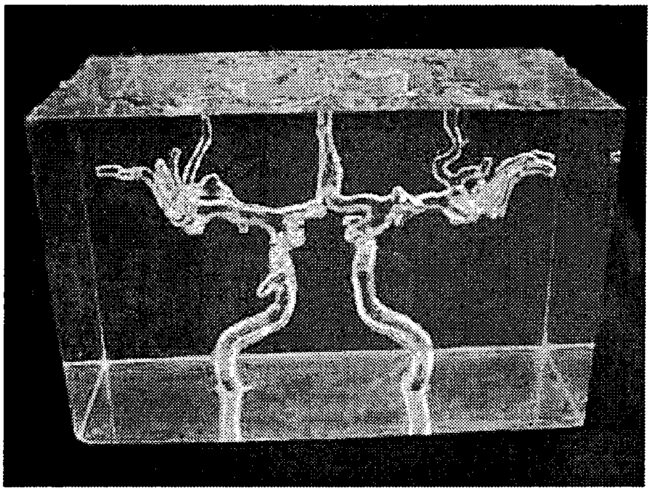

Fig. 3 Transparent model for flow visualization casted from 3-D powder model.

successively piled up with binder being printed on each powder layer. The printed patterns depict cross-sections of the model to be fabricated. Since the fabricated model is buried in unbound powder, any complex shape having even overhanging portions can faithfully be embodied. Another merit of 3-D printing lies in the use of powder, which allows casting of a large variety of materials including rubber, plastic, metal and so on. After casting, the powder model can be removed by using an appropriate washing technique. On the other hand, most of other RP techniques should use their specified material that are either inadequate for casting or difficult to remove after casting.

An example of 3-D model of cerebral artery fabricated by the 3-D printing technique is shown in Fig. 2. The original 3-D shape data for fabrication are taken from a real human brain by using the magnetic resonance angiography (MRA) at Hamamatsu University School of Medicine, Japan. The surface of the fabricated model is coated smoothly with a sort of wax in order to reduce the surface roughness of the model and to facilitate the removal of the powder model after casting. The accuracy in shape of the fabricated model is within ±0.2mm and arbitrary magnification or reduction in size is possible. Figure 3 shows an example of a transparent model suitable for flow visualization casted from the 3-D powder model shown in Fig. 2. The material is silicone rubber whose index of refraction is 1.40-1.43. As recognized in Fig. 2, a very complex flow passage is faithfully embodied in the silicone rubber block.

Note that 3-D CAD data are usually available for the models in industrial fields. In that case, no time-taking process for 3-D data acquisition is needed and therefore the fabrication of 3-D model and corresponding transparent model can be done more quickly.

## *2.2 Refractive index matching (RIM)*

The use of RIM for visualization and measurement of flow field is not new idea and has been proposed by several researcher so far. Budwig (1994) summarized candidates for working fluids and model materials for refractive index matching. Some typical combinations are listed in Table 1. The refractive index of model material ranges from 1.4 to 1.57. All the working fluids listed here are aqueous solutions whose refractive index can be adjusted by the concentration and the

Table 1 Typical combinations of model material and working fluid for refractive index matching.

| Model material | Refractive index | Working fluid |
|---|---|---|
| Silicone rubber | 1.40-1.43 | Glycerol solution |
| Acrylic | 1.49-1.53 | Sodium iodine solution |
| Urethane | 1.49-1.52 | Zinc iodine solution |
| Epoxy | 1.55-1.57 | Zinc iodine solution |

* all working fluids are aqueous solutions

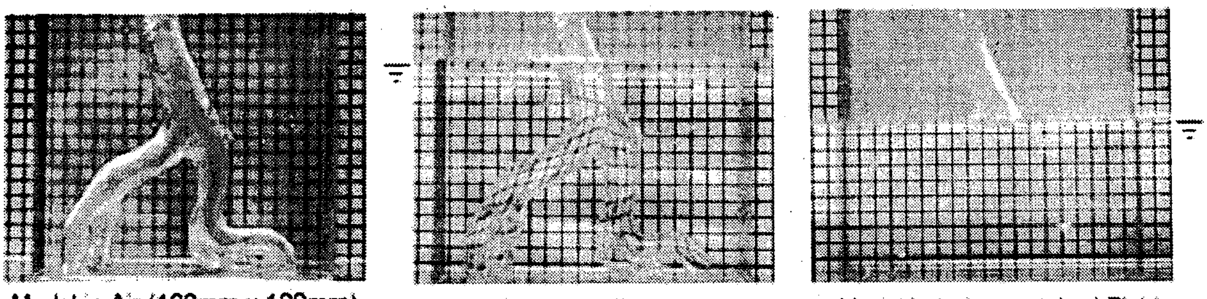


Fig. 4 Effect of refractive index matching between silicone rubber and glycerol solution.

temperature of the solution.

The combination of silicone rubber and glycerol solution has some advantages in their safety, price and transparency at a sacrifice of high viscosity of glycerol. The glycerol solution used in the present study has a weight density of about 53%, giving the refractive index of 1.40-1.42, depending on the temperature. Its dynamic viscosity and density are respectively 18.6 Pa·s and 1,151kg/m$^3$ at 20°C. Since the viscosity of glycerol solution is strongly dependent on the fluid temperature, it may be preferable to heating up the fluid (say, to 40°C) in some applications in order to lower the viscosity and thus to raise the Reynolds number. On the other hand, sodium iodine and zinc iodine solutions have much lower viscosity than glycerol solution, roughly 2-3 times that of water. However, those solutions change their color from light brown to dark brown with elapse of time. In addition, they are expensive and needs care in disposal.

The effect of index matching is demonstrated in Fig. 4, where an artery model made of silicone rubber is placed in the air, in the water or in the glycerol solution. When the model is in the air, the inside of the artery is invisible owing to the effect of light refraction at the curved wall surface. The effect is somewhat relaxed when the model is in the water, but there is still a large image distortion. When the model is immersed in the glycerol solution, there is no discernible image distortion as expected.

# 3. PIV Measurement

## *3.1 Cerebral aneurysm model and flow facility*

The flow model considered here is a cerebral aneurysm model shown in Fig. 5. The 3-D surface data are taken from a real patient at Hamamatsu University School of Medicine. This model is called ruptured model in that this aneurysm actually ruptured after its surface data were taken. The size of the silicone rubber block is about 250mm, in which an enlarged model of the cerebral aneurysm (magnification ratio is three) is embodied together with one inlet and three outlets of arteries. As a preliminary measurement of simulated blood flow in cerebral aneurysms, a steady flow of glycerin solution driven by a small centrifugal pump is measured.

The present experimental setup is illustrated in Fig. 6. The model is immersed in a glass tank filled with the glycerin solution. The temperature of the fluid is controlled within ±1°C to achieve satisfactory RIM between the fluid and the model. The model is mounted on an x-stage so that it can be translated precisely. Flexible vinyl tubes are connected to one inlet and three outlets to realize smooth translation of the model. Note that any translation does not change optical configuration for PIV measurement because of the perfect RIM in the glass tank. This has greatly facilitated the present PIV measurement aiming at multiple cross-sections of the model. The working fluid, glycerin solution, is recirculated by the centrifugal pump. The temperature of the working fluid is controlled in an isothermal fluid container. The flow rate during experiment is monitored with an electromegnetic flowmeter. The flow is seeded with spherical, metal-coated tracer particles made of plastic 19.6μm in average diameter and 1.63kg/m$^3$ in density. Care is paid not to contaminate the surrounding fluid in the glass tank with tracer particles.

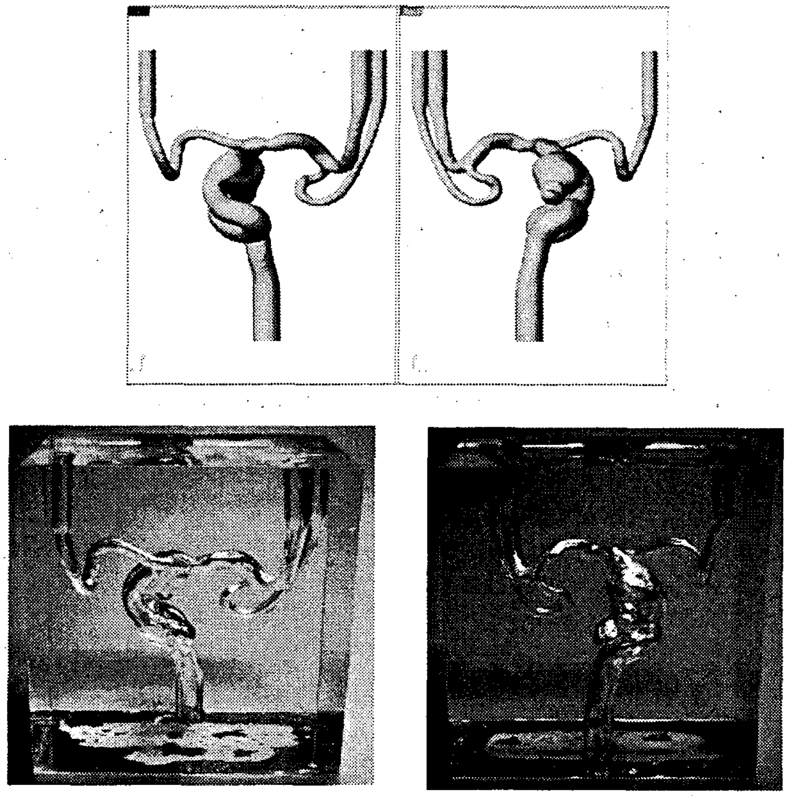

Fig. 5 A cerebral aneurysm model and original surface data viewed from two directions.

### *3.2 PIV system and flow conditions*

The present PIV system is a conventional one consisting of a digital CCD camera (1,300×1,300 cells), a double-pulsed Nd:YAG laser (25mJ/pulse at 30Hz) and a timing controller. The thickness and width of the laser light sheet are respectively 0.3mm and 70mm at the measuring section. A total of seven cross-sections are measured. As mentioned above, the model is translated in the fluid while the laser light sheet and the camera are fixed in position. Those measuring locations with

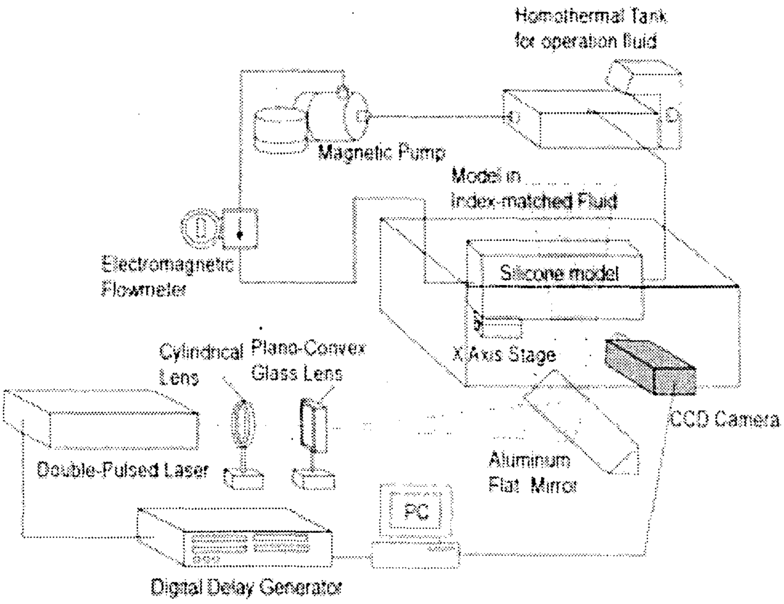


Fig. 6 Present PIV setup.

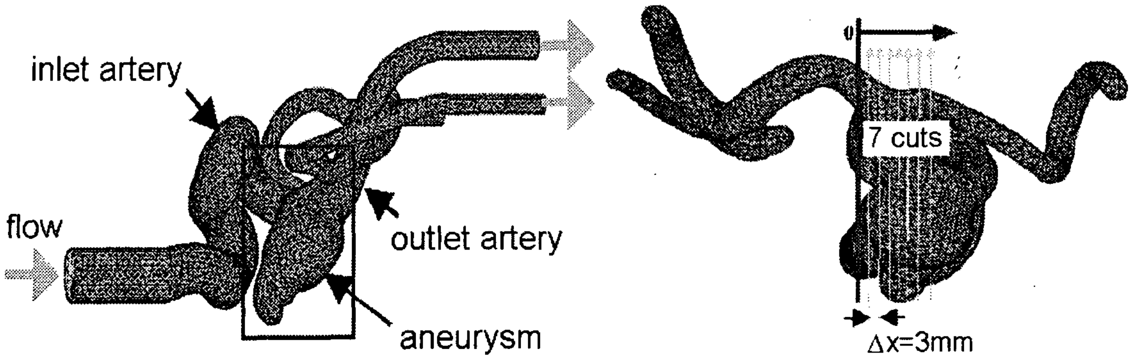


Fig. 7 Measuring locations with respect to the aneurysm model.

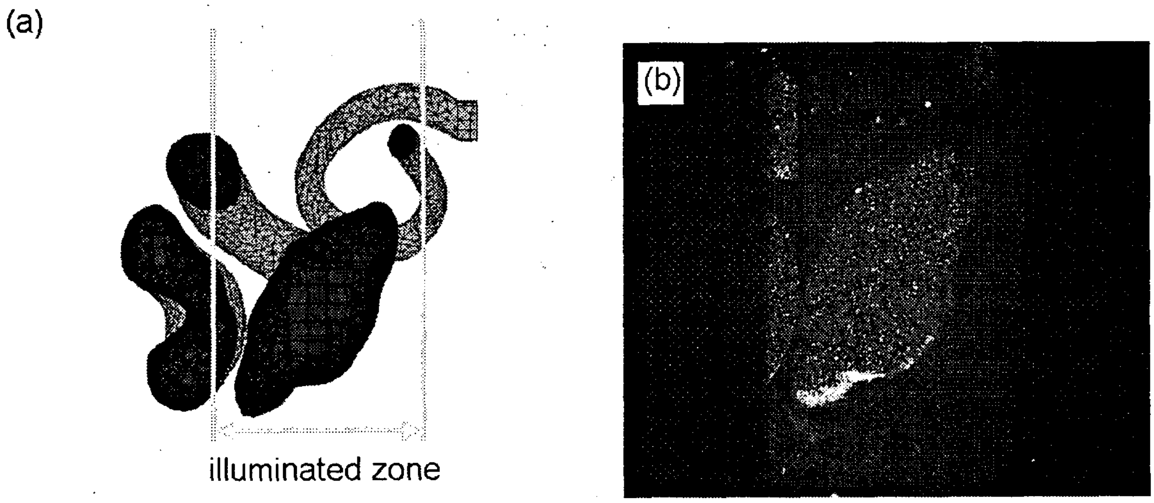


Fig. 8 Particle images taken at one of the measuring cross-sections.

respect to the aneurysm are illustrated in Fig. 7. Figure 8 shows particle images acquired at one of the measuring cross-sections, demonstrating clear flow visualization in the aneurysm.

The Reynolds number based on the inlet tube diameter (15mm) and the mean velocity (20mm/s) is about 20. Such a low Reynolds number is chosen as a preliminary measurement, while actual blood flows in cerebral arteries are pulsatile flows whose Reynolds numbers can range from nearly zero up to 1,000.

# 4. Results and Summary

An instantaneous velocity field taken at $x$=15mm (cf. Fig. 7) is presented in Fig. 9. It is seen that the most of the fluid entering into the aneurysm flows out of the region without reaching the tip region called bleb where the rupture often takes place. A part of the fluid forms a recirculating flow pattern in the aneurysm but the flow in the bleb is mostly stagnant. Although preliminary yet, such feature inside the aneurysm revealed by the present detailed flow measurement is expected to contribute to clarifying the flow mechanisms responsible for the rupture of cerebral aneurysm.

In this work, a new approach for PIV measurements of complex flows encountered in various applications is tested. It is based on rapid-prototyping of transparent model for flow visualization and on the use of refractive index matching that enables efficient and clear visualization of the flow inside the model. The model is immersed in the index-matching fluid in a glass tank so that any


Fig. 9 PIV result taken at $x$=15mm and illustration of flow pattern.

displacement and rotation of the model in the tank have no influence on the optical setup for image acquisition to be made through a glass wall. This can facilitate greatly the camera calibration for stereo PIV and 3-D PTV. As the flow model is generated directly from 3-D surface data, no laborious preparation of the flow model is needed. This integrated approach for seamless linking of model generation and PIV measurement is expected to be applicable to various flow measurements in automobile, ship building, fluid machinery, turbine, electrical appliances, heat exchanger, electronic cooling, bio-engineering and so on, where complex flow geometries are involved.

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