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Fundamental Study of Superimposed Image Flow Visualization using UVP

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The Fukushima Daiichi Nuclear Power Plant accident at TEPCO Holdings, Inc. caused by the earthquake and tsunami has had a major impact on nuclear energy policy. However, Japan needs nuclear power generation in the future because of its fragile energy supply structure, and further safety improvement of power plants is required to restart operations. In existing power plants, fluid flow monitoring in pipes is indispensable because of the erosion and corrosion caused by fluid flow, which leads to defects and wall thinning in the pipes, and early detection of abnormalities in the piping system before pipe rupture. Therefore, the purpose of this study is to develop a flow visualization system to improve safety. The system visualizes the flow field by superimposing images of the flow field measured by the ultrasonic velocity profiler method (UVP) and images of the measurement location taken by a camera. Visualization and measurement of the flow in a circular pipe flow were conducted using this system. The results showed that the relative error between the distance from the starting point of the measurement to each measurement point in the image and the distance of the velocity distribution measured by UVP was about 5%. It indicates the effectiveness of the system.

Keywords: UVP, Pipe flow, Smartification.

1. Introduction

The Fukushima Daiichi Nuclear Power Plant accident at TEPCO Holdings, Inc. caused by the earthquake and tsunami has had a major impact on nuclear energy policy, including the decommissioning and shutdown of nuclear power plants. However, Japan's energy supply structure is fragile, and nuclear power generation, which can be utilized as a base power source, is necessary in the future. To restart nuclear power plants, further safety improvement of nuclear power plants is required. In addition, it is necessary to promote energy policies that consider global environmental issues to realize a sustainable society. Therefore, maintaining the integrity of existing power plants using renewable energy and nuclear power plants and ensuring the safety of future power plants are the most important issues. In power plants, fluid flow monitoring in pipes is essential for nondestructive and early detection of abnormalities in the piping system before pipe rupture, because fluid flow in pipes causes erosion and corrosion, which leads to defects and wall thinning in pipes. Shoji et al. have been conducting research on the development of a measurement system using the ultrasonic velocity profiler method (UVP method) [1], which enables non-destructive and non-invasive measurement of the flow field in piping and have developed a portable UVP device that integrates the necessary hardware elements [2]. This technology is highly compatible with small display devices due to its portability and simplicity and can be easily combined with devices such as smart glasses to realize hands-free inspections, thus contributing to more efficient piping inspections. Therefore, in this study, we constructed a system in which a superimposed image of the flow velocity distribution measured by UVP, and an image of the measurement target taken by a camera are superimposed and then projected onto smart glasses and verified the operation by measuring the flow velocity distribution in pipes to examine the feasibility of the system.

2. Development of an automatic superimposition system for flow velocity distribution

In realizing this system, the accuracy of the sensor position and angle, the thickness of the piping, and the sound velocity are important parameters to consider. Sensor position and angle are factors that have a direct impact on position and velocity accuracy, and piping conditions are of high importance because sound refraction can change the measurement position and the system must automatically determine whether to use longitudinal or transverse propagation mode conversion accordingly. This study focused specifically on methods for automatic detection with respect to the sensor's position. It is assumed that the camera is attached to the head of the measurement person, and it is expected that the image superimposed position will be shifted frequently due to shaking, so the development of a system to improve this is required. Therefore, to improve the misalignment of the image superimposition position, we develop an automatic flow velocity distribution superimposition system.

2.1 System configuration

A flow visualization system was constructed to visualize the flow in a pipe. Figure 1 shows a schematic of the system and Figure 2 shows the system configuration. Table 1 shows the specifications of the equipment used in this system. The person taking measurements in this system wears a device with a USB camera attached to smart glasses on his or her head and carries a device for UVP measurement and a PC for image processing in his or her hand. At the same time, the UVP device in the hand acquires the flow velocity distribution information of the measurement target and sends it to the PC, which creates a superimposed image of the measurement target and the flow velocity distribution information and projects it on the small display of the smart glasses. This allows the user to visualize the velocity distribution information obtained by the UVP device on the measurement target via the Smart Glasses display. The UVP device is a portable device (150 mm long, 120 mm wide, and 60 mm high) [2] developed by Shoji et al. A sensor holder (Figure 3) is attached to the tip of the ultrasonic transducer to enable measurement of the flow velocity distribution at any position.

2.2 Acquisition of flow velocity distribution information

Experiments were conducted to measure circular tube flow. Figure 4 shows a schematic of the experimental apparatus used in this experiment. A transparent vertical circular tube (inner diameter 30 mm, made of acrylic) was used for the basic study of the system to enable future comparison with optical visualization and measurement methods. Nylon particles with an average diameter of 80 μm and a specific gravity of 1.02 (made of nylon 12, nylon powder WS200P, Nippon Laser Co., Ltd.) were dispersed in water stored in a tank as a reflector of ultrasonic waves, and a pump was used to generate an upward flow circulating through the acrylic pipe. An ultrasonic transducer (8 mm in diameter, 4 MHz center frequency) was placed acrylic pipe to measure the velocity distribution in the pipe from ultrasonic pulses reflected by reflectors. A liquid gel was inserted between the acrylic pipe and the ultrasonic transducer to prevent reflection of ultrasonic waves on the pipe surface. The flow rate in the piping, the incident angle of the ultrasonic beam, the setting conditions of the UVP device, and the Reynolds number of the flow field are shown in Table 2. Note that in this study, the frame rate on the UVP side is lower than that of the camera, so the images are updated according to the UVP time. However, there may be cases where the UVP frame rate is higher depending on the settings. In such a case, adjust the image update to match the frame rate of the camera side.

2.3 Detecting the measurement position

This section describes the development of an automatic superimposition system for flow velocity profiles. To determine the position of the superimposed image of the flow velocity distribution, it is important to detect the position of the ultrasonic transducer in the captured image. Color tracking is one of the methods to detect the position of an object in an image [3]. In this system, the sensor holder is colored in an arbitrary color, and the measurement position is obtained by detecting the color of the sensor holder in the captured image.

The sensor holder used in this system is colored red at the tip, and the measurement position is obtained by generating a mask image in which only the sensor holder is extracted from the captured image by color detection, as shown in Figure 5. To detect the sensor holder in the mask image, the image of the measurement target is converted to HSV color space (Hue, Saturation, and Value), and only color components in the HSV range are extracted. The position of the sensor holder was then estimated by extracting the area with the largest area within the extracted color range.

2.4 Automatic superimposition method of flow velocity distribution

Figure 2 shows the configuration of the automatic superimposition system for flow velocity distribution. In this system, a PC processes the captured images and measured flow velocity distribution to create an image of the superimposed flow velocity distribution on the measurement target. The image is then projected onto the display of the smart glasses to visualize the flow information of the measurement target. At this time, a portion of the screen of the application used for UVP measurement is captured to be used as the flow velocity distribution measurement image. First, a mask image is created by extracting the sensor holder from the image of the measurement target. Then, taking advantage of the fact that the dimensions of the sensor holder are known, the relationship between the dimensions of the sensor holder in the image (number of pixels) and the actual dimensions of the image captured by the camera (mm) is obtained from the size of the sensor holder in the mask image. Let y_{pv} be the number of pixels of the vertical width of the sensor holder position obtained from the mask image, x_{ph} be the number of pixels of the horizontal width, y_v be the vertical dimension of the sensor holder, and x_h be the horizontal dimension, and let y_{ts} and x_{ts} be the conversion factors for the vertical and horizontal dimensions, respectively.

$$y_{ts} = \frac{y_{pv}}{y_v}, x_{ts} = \frac{x_{ph}}{x_h} \tag{1}$$

The conversion coefficients were averaged. These were averaged to obtain the Conversion Factor (CF) between pixels and actual size.

$$CF = \frac{y_{ts} + x_{ts}}{2} \tag{2}$$

In this study, CF was determined based on the dimensions of the holder, but in principle it is sufficient if an object with known dimensions exists in the image. Therefore, whether the holder is square or trapezoidal, it can be mapped to the holder by attaching a sticker or marker to it. Next, based on the relationship between pixels and actual dimensions, the flow velocity distribution measurement results are scaled to the appropriate dimensions. The appropriate distance where the velocity distribution exists from the sensor holder is calculated considering the previously obtained dimensions of the wall surface to be measured. Finally, the velocity distribution measurement results obtained by the UVP device are scaled and positioned to the appropriate dimensions in the image taken of the measurement target, and a superimposed image of the velocity distribution is created.

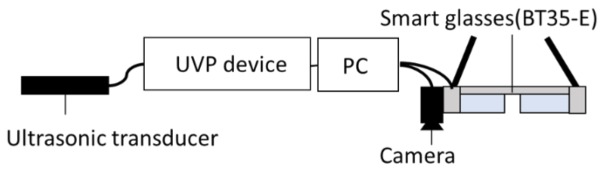

Figure 1: Flow visualization system overview

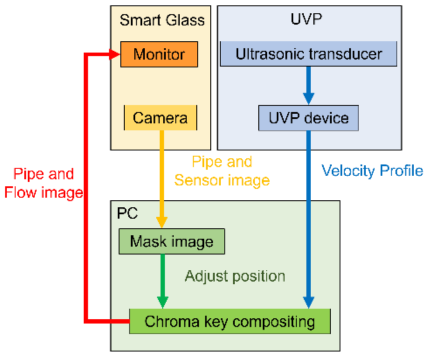

Figure 2: Configuration of automatic superimposition system of flow velocity distribution

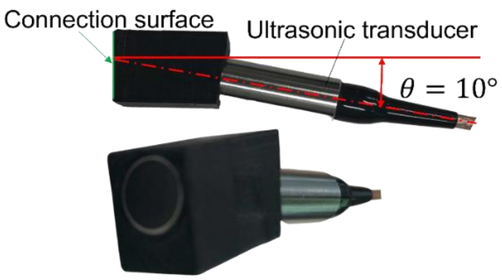

Figure 3: Sensor holder for ultrasonic transducers

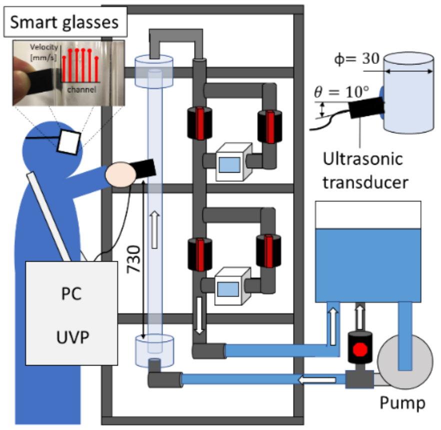

Figure 4: Schematic of flow measurement of circular tube flow

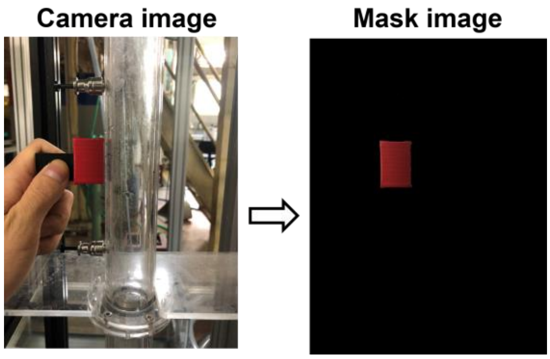

Figure 5: Mask image of sensor holder detected from camera image.

Table 1: List of equipment used in flow visualization systems.

Equipment	Model number, Maker	Specification
Smart glasses	BT35-E, EPSON	Resolution: 1280 × 720
USB camera	CM02, SROSS	Resolution: 1920 × 1080 Flame rate: 30 fps

Table 2: Measurement conditions for flow visualization system operation experiments

Flow rate	20 L/min
Ultrasonic center frequency	4 MHz
Angularity of incidence of ultrasonic waves	10 °
Pulse repetition frequency	2 kHz
Number of pulse repetitions	128
Sound velocity(25°C)	1497 m/s
Spatial resolution	0.75 mm
Time resolution	64 ms
Reynolds number	3900

3. Basic study test on system feasibility

Experiments were conducted to verify the operation of this system. Figure 6 shows the experimental system. PC acquires the image of the sensor holder captured by the USB camera and displays a sample image of the flow velocity distribution measured by the UVP device on the PC display. PC acquires the flow velocity distribution measurement result by searching for the result image from the window name. The PC calculates the relationship between the actual dimensions and the number of pixels in the image and the appropriate display position of the flow velocity distribution by creating a mask image from the sensor holder image using color detection. After that, the measured velocity distribution is scaled down and a superimposed image with the sensor holder is created. Table 3 shows the dimensions of the colored part of the sensor holder, the thickness of the pipe to be measured, and the threshold values for color detection, which were given when positioning the superimposed image in this operation verification experiment.

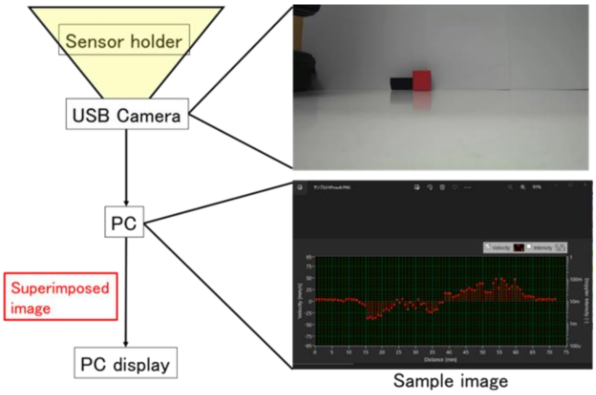

Figure 6: Schematic of the operation verification experiment of the automatic superimposition system

Table 3: Experimental conditions for verifying the operation of the automatic superposition system.

Dimensions of the colored part of the sensor holder	20 mm×30 mm
Thickness of piping	3 mm
Color detection threshold (HSV color space)	H:0～10, S:80～255, V:0～255

4. Experimental results and discussion

Figure 7 shows the results of an experiment to verify the operation of this system. Based on these results, we succeeded in developing a system that automatically determines the position of the sensor holder by color detection, scales the flow velocity distribution measurement results based on the dimensions of the sensor holder, and automatically superimposes them on the image taken of the sensor holder. The system automatically superimposed the measured velocity distribution on the image taken by the sensor holder after scaling it based on the dimensions of the sensor holder. The results of 150 superimposed images (5 seconds at 30 fps) measured with a scale in the background of the superimposed images showed that the relative error between the measured distance (mm) on the horizontal axis and the measured velocity distribution was within 5%. This system scales the flow velocity distribution based on the number of pixels in the captured image and the dimensions of the sensor holder, so when the resolution is low or the occupancy rate of the sensor holder in the captured image is low, the accuracy of the conversion coefficient between image pixels and actual dimensions: CF is reduced. To solve this problem, it is possible to increase the occupancy ratio of the sensor holder in the captured image by using a high-resolution camera or by increasing the size of the sensor holder. And regarding the time lag between measurement and display, currently a relatively simple algorithm is used to detect the sensor position, and thus the delay is on the order of a few milliseconds. However, in the future, it is expected that algorithms will become more sophisticated and that more parameters will be considered in the correction process, which may result in an increase in processing volume. Thus, optimization will be required.

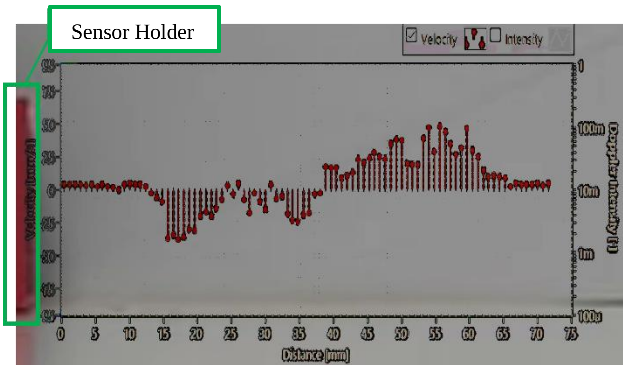

Figure7: Result of operation verification experiment of automatic superposition system

5. Summary

We developed a flow visualization system that utilizes a flow velocity distribution measurement method by UVP and AR technology using small display devices such as smart glasses. An automatic superimposition system of the flow velocity distribution was developed to improve the effect of camera shaking, and experiments were conducted to verify the operation of the system. As a result, we succeeded in automatically superimposing the flow velocity distribution and the camera image of the measurement target by scaling and positioning the flow velocity distribution based on the dimensions of the sensor holder. The relative error between the flow velocity distribution and the actual dimensions was within 5%, and the superimposition of the flow velocity distribution followed the sensor holder's position, thus reducing the influence of camera shaking. In conclusion, the development of the flow visualization system has shown the possibility of solving the problem of requiring expert knowledge to determine the measurement position of the flow velocity distribution in flow velocity distribution measurement by UVP, and of improving piping inspection in narrow spaces in power plants and plants by making it hands-free.

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