Non-contact inspection for inner surface of small-diameter pipes based on laser-PSD*

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A new non-contact inspection technique based on laser-PSD (position sensitive detector) to inspect the inner surface of small-diameter pipe is proposed, and the corresponding sensor has been developed. After being reflected by two mirrors in series, a laser beam is projected onto the inner wall of a pipe as a small light spot and is read by a two-dimensional PSD. Based on the signals from the PSD and the structure parameters of the sensor, the spot position on the wall can be calculated in a local 3D coordinate system. The spot controlled by the micro-motor driven mirrors will scan a closed section ring on the inner wall of the pipe to obtain the relative coordinates of all the sampled points. The data will be then processed through data segmentation and least square fitting, to reconstruct the section curve used for obtaining the radius and the defect description of the section. Driven by a micro-pipe robot, the sensor can inspect a long curved pipe and obtain its 3-D reconstruction. An inspection system based on this technique can detect the mini-diameter pipe with an inner diameter of 9.5 mm~10.5 mm and a curvature radius larger than 100 mm at a measurement accuracy of the inner surface defect of ±0.1 mm.

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Small-diameter pipes are used widely in many fields, such as energy industry, chemical industry, aviation, weapon manufacturing and so on. The inspection of these pipes is very important because of the bad working conditions. There are many methods to inspect the pipes with inner diameters larger than 20mm, such as the whole circle image method[1], the ring optical cutting image method[2], the laser-beam scanning displacement measuring technique[3], the CCTV camera method[4], Omni-directional method[5] etc. But few methods can detect the pipes with an inner diameter less than 20 mm. With the development of photoelectronics, the diameter of electronic endoscope is diminished to 4 mm and even small. Therefore the endoscopes can even adapt to inspect pipes with a diameter as small as 10mm. However, the endoscopes can only tell us, whether there is or not some defect in the inner surface, rather than the right position or the accurate size of the defect. Tsuruta k[6] has developed a micro pipe robot to inspect the pipe with 10mm inner diameter, based on the picture of the defect captured by CCD camera, which cannot, however, overcome the problem of endoscopes at all. With a smaller CCD camera, the sensor in[1] can be miniaturized to inspect small pipes, where the processing circuit is, however, very complicated, and the signal cable should be shielded carefully, therefore the considerable weight and friction of the micro-pipe robot make it difficult for the sensor to inspect a long pipe.

A new non-contact laser inspection technique based on Laser-PSD for inspecting small-diameter pipe is proposed in this article, and the corresponding profile sensor has been developed. Compared with the CCD based methods, the sensor is smaller in size, lighter in weight, simpler in processing circuit, and without any complicated image processing. Compared with the system in[3], the rotating mechanism is simpler and the whole structure is easier to be miniaturized. The sensor is suitable for inspecting the long curved pipe with an inner diameter of 9.5 mm~10.5 mm, or the curvature radius larger than 100 mm. The measurement accuracy of inner surface defect is as small as ±0.1 mm.

PSD is an optoelectronic position sensor utilizing photodiode surface resistance, which has the advantage of high position resolution, high response speed, simple periphery circuit, low demand for optical system, and so on. The two-dimensional PSD will provide four channels of current signals, I_1, I_2, I_3, and I_4, when its sensitive surface is illuminated by a beam of light. Taking the center of photosensitive surface of the PSD as the origin, a plane coordinate system can be set up. The position of light spot in the surface can be calculated by

$$u = \frac{s(I_1 - I_3)}{2(I_1 + I_3)}, v = \frac{s(I_2 - I_4)}{2(I_2 + I_4)} \tag{1}$$

where s is the length of the photosensitive surface, and the distance between the light spot and the PSD center is

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$$r = \sqrt{u^2 + v^2} \tag{2}$$

Based on the characteristics mentioned above, a profile sensor for inspecting the inner surface of pipes with small diameter has been developed. The sensor mainly consists of a laser diode, a mirror with a small hole, a scanning mirror, a glass window, a micro motor, an imaging lens and a two-dimensional PSD. The prototype of the profile sensor is showed in Fig. 1. Its length is 37. 5 mm, and its weight is about 4 g. The measurement principle of the sensor is illustrated in Fig. 2. Where a pipe's inner surface at point D is illuminated by a laser beam from point A and reflected by two mirrors, and

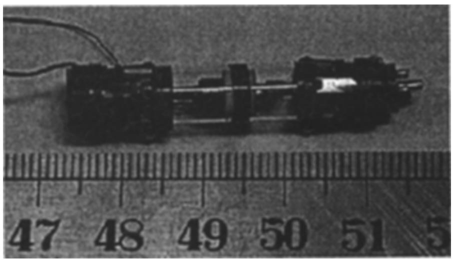

Fig. 1 Prototype of the profile sensor

point D is imaged onto point N of the sensitive surface of a PSD. Based on the current signal from the PSD, the position of N can be calculated by formula (1). R is the distance between point D and the central axis OA of the sensor, θ is deflection angle of the scanning mirror, d is the distance between the two major faces of the imaging lens, L is distance between point B' and the PSD surface, f is the distance between the center O of imaging lens and the PSD surface. Then R can be calculated by the theory of optical triangulation.

For small-diameter pipes, the reflection of the window should be taken into account during the above calculation, otherwise the results will be inaccurate. As shown in figure 2, the influence of the reflection can be regarded as that by moving point B' and point E (the right main point of the lens) into point B'' and point E', respectively. Setting the two move offsets are a and b, respectively, then we get the result:

$$R = \frac{r(L - f - d + a + b)}{f + r/\tan 2\theta} \tag{3}$$

where a and b can be calculated from the reflection of glass window.

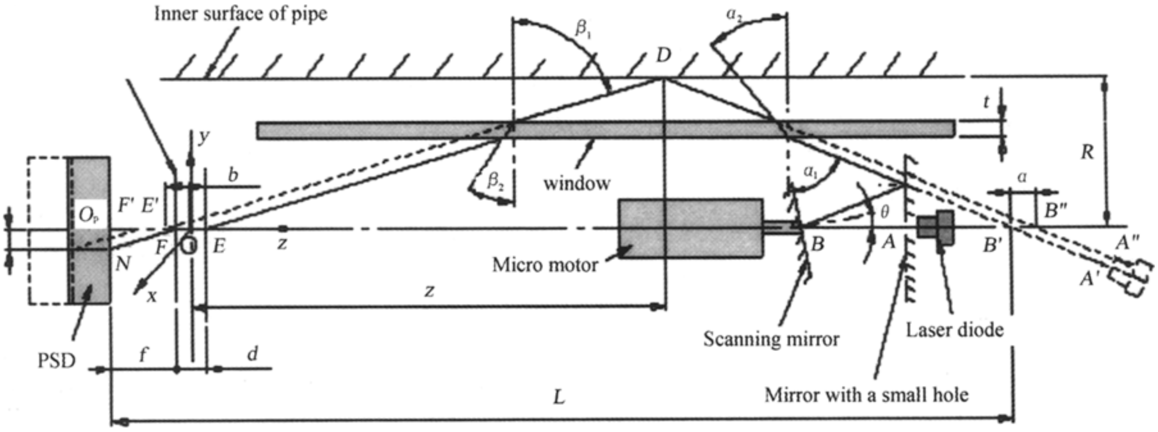

Fig. 2 Measuring principle of the profile sensor

Taking the imaging lens center O as the origin, and the axis OC as 2 axis, a local 3D coordinate system is built as shown in figure 2. The position of point D on the pipe inner surface can de described by:

$$\begin{cases} x = R\cos\omega \\ y = R\sin\omega \\ z = L + 1 - f - R/\tan 2\theta - d/2 \end{cases} \tag{4}$$

where ω is the rotating angle of the scanning mirror.

Correspondent with each sampling of the PSD, the local coordinate of the measurement point on the inner surface can be obtained by formula (4). Discrete points of the inner wall section of the pipe will be inspected, during the 360 degrees' rotation of the scanning mirror. If the pipe is straight, the center axis of the sensor and the center axis of the pipe are collinear, and the value of R obtained from formula (3) is right the radius of the pipe. For a curved pipe, the two axes are not collinear, and the calculation of R is difficult, because it need several sections' data and the curvature radius of the inspection position. There will be crack, pit or other defect on the inner surface, if the value of R changes abruptly.

The inspection system mainly consists of a profile sensor, a control circuit module, a post processing circuit module, and a data processing module, as shown in figure 3. The sensor can be driven by a mini-pipe robot to inspect the inner surface of a pipe, and for a bended pipe, another curvature sensor is needed to reconstruct the inner surface.

We measured that the highest frequency for the system to process is 10 KHz. Assumed that the theoretical resolution is Δ and the measurement accuracy is not affected by the size of the light spot, then the number of sampling points in each section is $N_1 \geq 2\pi R/\Delta$. The highest rotating speed is $n = 10\,000/N_1$.

For pipe of 10 mm, the needed rotating speed is $n \leqslant 15$ r/s, if $\Delta \geqslant 0.05$ mm. But the rated speed of the motor is about 500 r/s, so it needs to be decreased. Therefore, the impulse-driving signal is applied. We can adjust the duty ratio of the signal to match the speed and the sampling frequency. With the digital filter, some sampling data will be lost. Additionally, due to the possible change of the rotating speed, the sampling data may not able to describe a whole section of the pipe, if the number of sampling points is right equal to N_1. Therefore the needed numbers of sampling points in every inspection position of pipe should be more than N_1. It is assumed according to corresponding experiment results that $2N_1$ would be suitable.

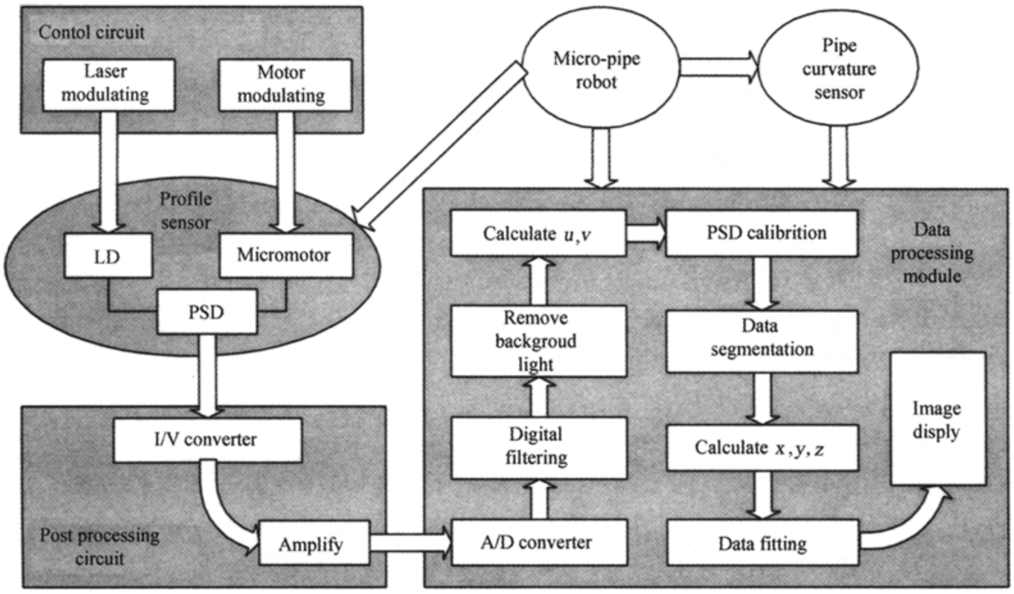

Fig. 3 The composition of the sensor and its working process

Even when the laser diode is powered off, the electric current signals will still be produced in PSD because of the background light and dark current. To eliminate this kind of noise current for a higher measurement accuracy, rectangular wave current is used to modulate the laser diode. Two period signals are sampled in every inspection position. One period signal is sampled when LD is turned off, and the average value ($I_{b1}, I_{b2}, I_{b3}, I_{b4}$) of each channel is taken as noise signal. Another period signal is sampled when LD is powered on. The four channels' signals ($I_{d1}, I_{d2}, I_{d3}, I_{d4}$) are subtracted the noise signal of corresponding channel, the practical signals (I_1, I_2, I_3, I_4) of every sampling point can be obtained. The image position (I_1, I_2, I_3, I_4) of every point can be calculated by formula (1).

But the calculated points can not form a smooth circle because of the noise of circuit. Figure 4 shows the initial

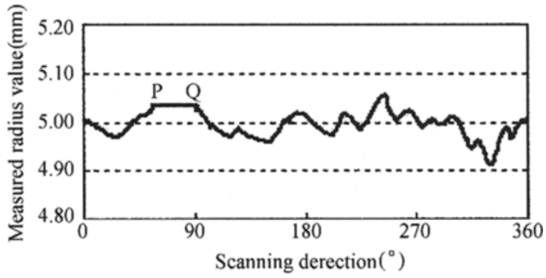

Fig. 4 Initial relationship between R and W

relationship between R and ω. PQ section is the place where the signal cable passes, which hasn't been measured.

It is considered that the measurement is ±0.1 mm, because the measured radii with the range varied only within ±0.1 mm. Data segmentation and data fitting are applied, and the final relationship between R and ω of another section is obtained, as shown in figure 5. The formed circle will be smooth and the defect at about 180 degree is obvious.

A standard pipe is stuck by a 0.3 mm filament on the inner wall, and the profile sensor is driven by a micro pipe robot to inspect the experiment pipe. Figure 6 describes a reconstructed part of the pipe inner surface, where A is the filament and B is the position of the signal cable passed. The experiments also show that the pipe inner diameter varied from 9.97 mm to 10.05 mm and the defect width varied from 0.25 mm to 0.36 mm.

Based on LD and PSD, we proposed a new non-contact laser method to inspect the inner surface of small-diameter pipes. The accuracy of the developed sensor for the measurement of the inner surface defect and pipe inner diameter is ±0.1 mm. This method is suitable for the pipe with an inner diameter of 9.5 mm~10.5 mm and a curvature radius of more than 100 mm.

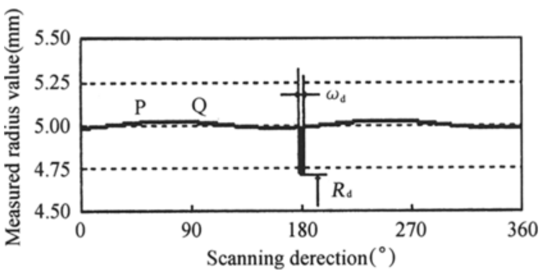

Fig. 5 Final relationship between R and W

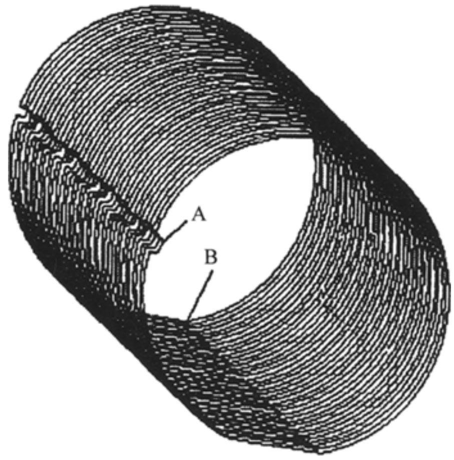

Fig. 6 3D reconstruction of pipe inner surface

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