A Velocity Measuring Method using M-sequence Signals

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M-sequence signal is a kind of random signals but has periodicity and its autocorrelation function has peaks periodically. M-sequence signal has strong noise immunity when used as a carrier signal because it can bear information in wide frequency band.

This paper reports a velocity measuring method using fringe pattern modulated by M-sequence signal. The experimental results of measuring the velocity of a turn-table and water flow are also described. The measurement error obtained was within 1.5 percent and slightly better than a normal error obtained in the case of Laser Doppler Velocimeter which employs equi-spaced fringe pattern in stead of M-sequence pattern.

The most significant advantage of this method is that we can measure the velocity precisely even when several particles come into the measuring volume at the same time. This point is very different from the case in the Laser Doppler Velocimeter.

1. Introduction

M-sequence signal means Maximum length linear shift register sequence signal[1]. It is one of the artificial random signals and it takes only two values,1 and -1. It has periodicity. This fact is great contrast with real random signals. The period is $N=2^n-1$ and n is often called as the degree of M-sequence signals. M-sequence signal is produced by following the generating functions given in Table 1. The autocorrelation function of the signal, $R(k)$, is given by next equations,

$$R(k) = \sum_{i=1}^{N} X_i X_{i+k} = \begin{cases} N & k=0,\ N,\ 2N,\ \cdots \\ -1 & k\neq 0,\ N,\ 2N,\ \cdots \end{cases} \quad (1)$$

Table 1. Generating Function of M-sequences

Period	Generating Function
7	$X_i = X_{i-3} \oplus X_{i-2}$
31	$X_i = X_{i-5} \oplus X_{i-3}$
63	$X_i = X_{i-6} \oplus X_{i-5}$
127	$X_i = X_{i-7} \oplus X_{i-6}$
255	$X_i = X_{i-8} \oplus X_{i-6} \oplus X_{i-5} \oplus X_{i-4}$

$\oplus$ is sum with modulo 2.

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M-sequence signal has been used as a quasi-white noise. The signal is produced by linear feed back circuit of shift registers. M-sequence signal has large entropy which is the significant character of random signals and it has strong noise immunity when used as a carrier signal because the M-sequence signal can transfer information with containing it in wide frequency band. M-sequence signal, then, has been used in the field of radar and ultrasonic Doppler measurement. This paper describes an application of the M-sequence signals for measurement of particle velocity. Some experimental results are also shown.

2. Method

There are two main methods to measure the velocity of particles by light wave[2]. One is the correlation method and the other is the fringe method. The former method is to know the velocity by measuring the time required for the particle to pass through a fixed distance. The latter is that a fringe pattern is formed in the measuring volume and we can know the velocity of particles by analysing the frequency spectrum of the scattered light from moving particles in the volume, because the scattered light signal is modulated by fringe pattern and the frequency components change with the particle velocity.

In our experiment, the fringe method was employed. The fringe method is divided into two techniques. The first one is fringe image technique. In this method, the image of fringe pattern is projected onto measuring volume as shown in Fig. 1. The second is spatial filter technique, in which the fringe pattern itself is put on the image surface of the particle flow as shown in Fig. 2. Both techniques can be employed and combined with M-sequence signal to measure particle velocity.

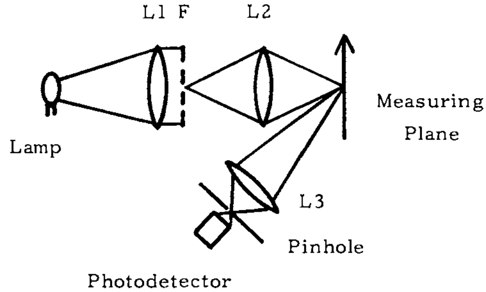

Fig.1 Fringe Image Technique
L1, L2, L3 : Lenses
F : Fringe

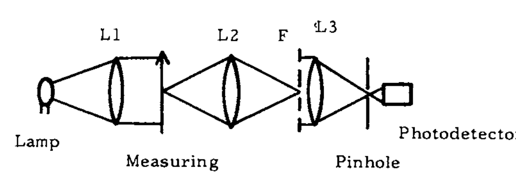

Fig.2 Spatial Filter Technique
L1, L2, L3 : Lenses
F : Fringe

The principle of measuring velocity proposed here is basically the same as that of the Laser Doppler Velocimeter (LDV). Only the difference lies in the following point that in our case the fringe is not equally spaced pattern but modulated by M-sequence signal. In a normal LDV system it has a disadvantage that the system can not measure the particle velocity correctly when several particles appear in the measuring volume at the same time. But in case of employing M -sequence signal as a fringe pattern, the disadvantage can be removed. This is because that M

-sequence signal has the character that when several M-sequence signals which have the same period are superposed randomly, the autocorrelation of this superposed M-sequence signal still shows peak values periodically.

The velocity of the scattering particle, V, is determined by the next equation,

$$V = \frac{kL}{\tau} \tag{2}$$

Here, L is the geometrical length of the period of M-sequence signal on a film, k is a scale factor when the pattern is projected onto a measuring volume and τ is the delay time at which autocorrelation function of the scattered light signal has the first peak value.

3. Experimental Apparatus

In the fringe image technique shown in Fig. 1, we put the infrared absorption filter behind the film in order not to damage the film by heat from a light source. A slide projector lamp (30W) was used as a light source to illuminate the measuring volume uniformly. In case of the spatial filter technique shown in Fig. 2, it was necessary for obtaining a good SN ratio to put a pinhole in front of the photodetector not to catch the direct irradiation light. Photomultiplier tube was used as a photodetector. The film sizes are $20 \times 32.5\text{mm}^2$ ($N=127$) and $20 \times 31.3\text{mm}^2$ ($N=31$), respectively. On the film ($N=127$), three cycles of the M-sequence signal pattern are printed, then one cycle length, namely a period, is 10.8mm and its minimum fringe space is 85.3μm. The film ($N=31$) has four cycles, so one cycle length is 7.83 mm and its minimum fringe space is 253μm. These two different films are prepared to choose and adapt the fringe space for an optimum fringe value which is determined by the scattering particle sizes. The optimum value of the minimum fringe space is estimated as the average size of the particles.

Fig. 3 shows the block diagram of the signal processing system. The photomultiplier tube is PM 49 (Hamamatsu TV Co., Ltd). The load resistance is 10 kΩ and applied voltage was normally 900V. The analog correlator is consisted of the Bucket Brigade Device (BBD) as a delay device. Block diagram of the analog correlator is shown in Fig. 4. The delay time is changeable from 0.512 msec to 25.6 msec. BBD is MN3001 (National) and multiplier is AD533 (Analog Device). Integrator is used as an averager of multiplier output. Another signal processing system is composed of a real time digital correlator which is almost the same system described by Asch et al[3].. The highest clock frequency is 20 MHz and the frequency can be controlled by 8 bit microcomputer. The correlator is of single clipping type and has 101 channels with the maximum 1200 pre-delay channels. The autocorrelation function is measurable up to 1300th channel by

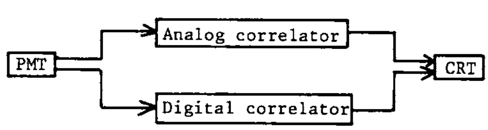

Fig.3 Block Digram of the Signal Processing System

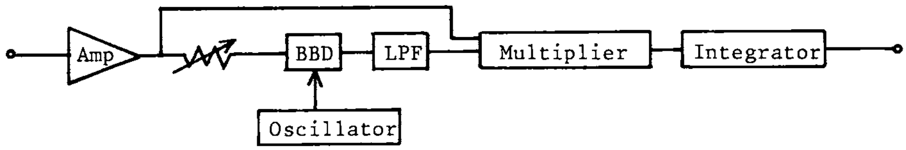

Fig.4 Block Diagram of the Analog Correlator

sequential measurement increasing the number of pre-delay channel by 100 after each measurement. The computer controls this sequential procedure automatically.

In the experiment we must find the delay time τ at which the output of correlator shows a peak value. But it takes long time to set and measure the delay time precisely. Therefore, we developed the automatic measuring system including 8 bit microcomputer, frequency synthesizer and digital voltmeter. Fig. 5 shows the block diagram of the system. On account of the automatic measuring system, the measurement can be done in shorter time and the accuracy is also increased.

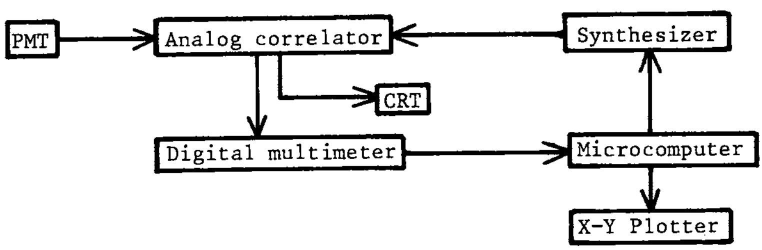

Fig.5 Block Diagram of the Automatic Measuring System

4. Results

Velocity measurement was made by the system of M-sequence signal. In the experiment, glass capillary rods were used as scattering particles, and the rods are attached on the edge of a turn-table as shown in Fig. 6. The rotational speed of the turn-table is controllable between 534. 7mm/sec and 1526.1mm/sec by the step of 0.1% with the fluctuation less than 0.025%. The diameter of rods was approximately 0.1mm～0.2mm. The autocorrelation functions of scattered light signals are measured under the condition of a stationary velocity. We also measured the velocity by the system of equally spaced pattern in stead of M-sequence signal. The results obtained by this system are considered as the same one of LDV system and we can compare the results obtained by these two methods. The fringe space of equally spaced pattern was 250μm.

The typical autocorrelation functions obtained by spatial filter technique are shown in Fig. 7～9. Fig. 7 is the one obtained by analog correlator. Fig. 8 is in the case of digital correlator and Fig. 9 is in the case of equally spaced pattern. Figs. 10～19 show the results obtained by spatial filter technique. Calculated velocity and errors are also shown in the figures. Figs. 16～19 show

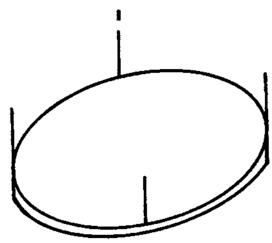

Fig.6 Scatterers on the Turn-Table

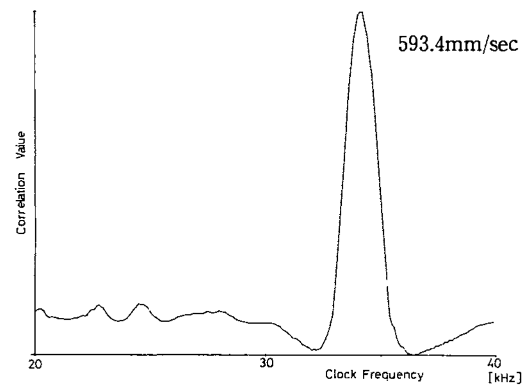

Fig.7 Autocorrelation Function
(N=31, 1 particle, Analog, Spatial Filter Technique)

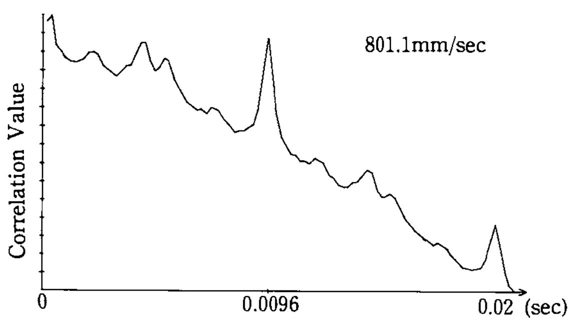

Fig.8 Autocorrelation Function
(N=31, 2 particles, Digital Spatial Filter Technique)

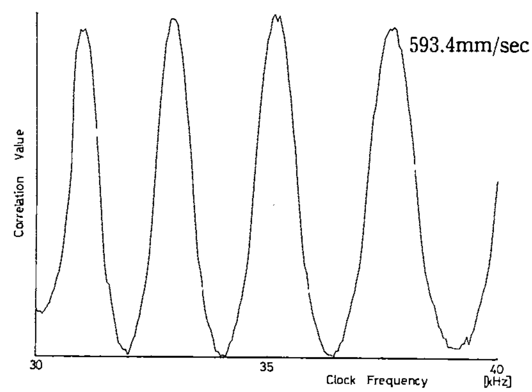

Fig.9 Autocorrelation Function
(Equi-spaced, 1 particle, Analog, Spatial Filter Technique)

the results in the case that two particles are in the measuring volume. In this experiment, two capillary rods separated by 5mm were attached on the turn-table. Other figures are all in one particle case. The measurement errors obtained by the systems are summarized and tabulated in Table 2.

Experiment was also made by fringe image technique. The results are similar to the one obtained by spatial filter technique. And only the measurement errors are tabulated in Table 3. In case of analog correlator, the experimental values are getting higher than the correct values as increasing the velocity. This is because of the influence of phase delay induced by low-pass filter (LPF) in the analog correlator. Hence, the measurement error is much reduced in this case by employing a better LPF.

The experiment of measuring water flow velocity was made to demonstrate that the system can measure the actual fluid flow velocity. Fig. 20 shows the experimental set up to measure the water flow. The acrylate pipe was 11 mm in diameter and small air bubbles are introduced to the water flow as a light scattering particles. The bubble sizes were 0.1～0.5 mm in diameter.

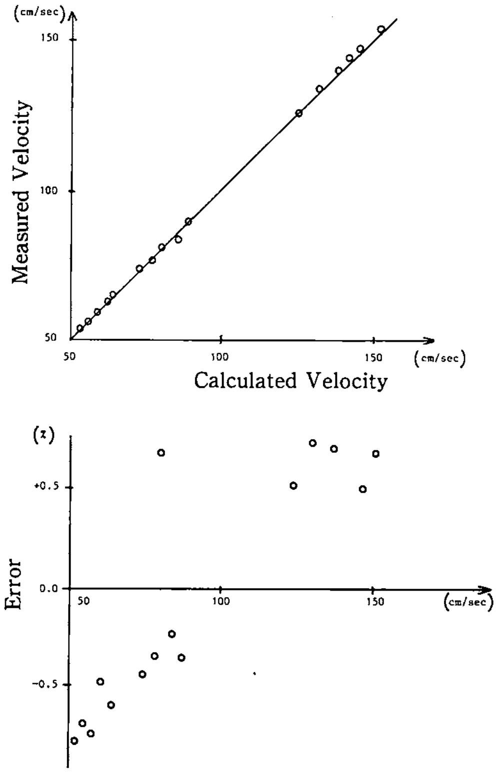

Fig.10　Experimental Results
(N=31, 1 particle, Analog, Spatial Filter Technique)

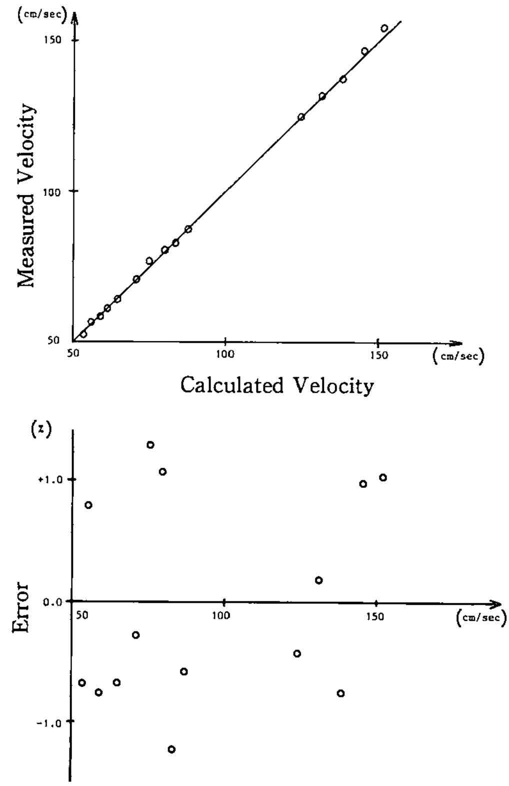

Fig.11　Experimental Results
(N=31, 1 particle, Digital, Spatial Filter Technique)

Table 2.　Measurement error obtained by spatial filter technique

	N=31	N=31	N=127	N=127	equi-spaced	equi-spaced
N. O. P. / correlator	1	2	1	2	1	2
Analog	−0.8 ~0.8	−0.3 ~0.5	−0.7 ~0.5	−0.8 ~0.8	−2.5 ~2.0	impossible
Digital	−0.8 ~1.2	−1.0 ~1.3	−1.0 ~1.0	−0.6 ~0.9	−2.25 ~1.5	impossible

N.O.P. is number of particle.
Error is given in per cent.

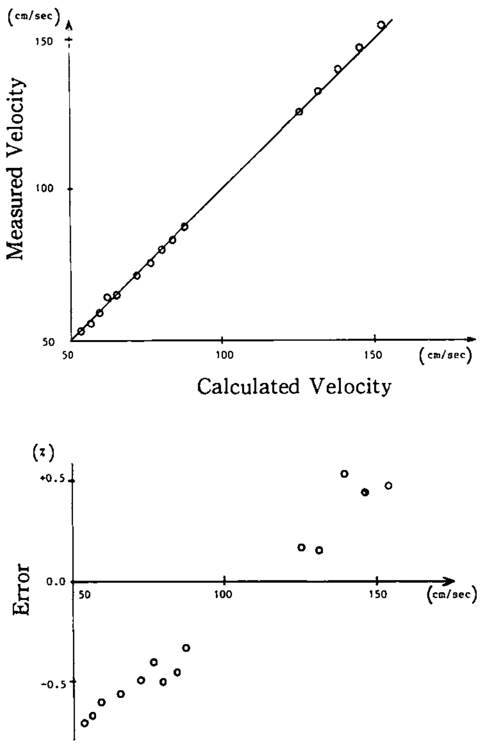

Fig.12 Experimental Results
(N=127, 1 particle, Analog, Spatial Filter Technique)

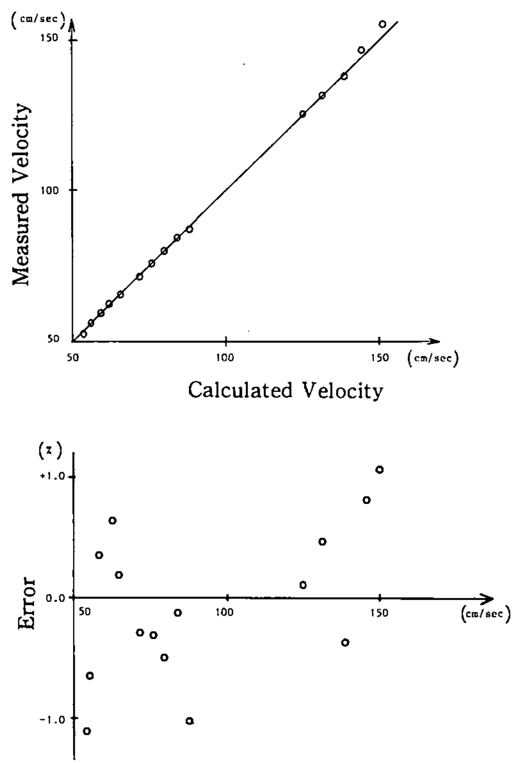

Fig.13 Experimental Results
(N=127, 1 particle, Digital, Spatial Filter Technique)

Table 3. Measurement error obtained by fringe image technique

	N=31	N=31	N=127	N=127	equi-spaced	equi-spaced
N. O. P. / correlator	1	2	1	2	1	2
Analog	−0.8 ~1.25	−1.0 ~1.5	−1.6 ~1.6	−1.0 ~1.5	−1.25 ~1.25	impossible
Digital	−1.5 ~1.25	−1.0 ~1.0	−0.25 ~1.25	−1.0 ~0.6	−1.0 ~1.0	impossible

N.O.P. is number of particle.
Error is given in per cent.

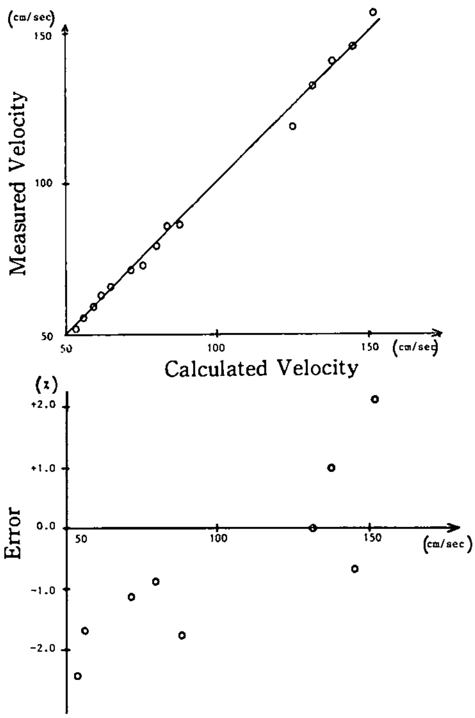

Fig.14　Experimental Results
(Equi-spaced, 1 particle, Analog, Spatial Filter Technique)

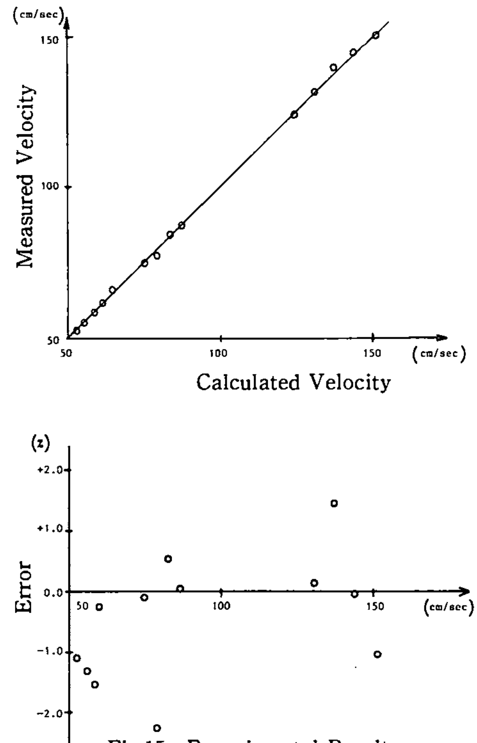

Fig.15　Experimental Results
(Equi-spaced, 1 particle, Digital, Spatial Filter Technique)

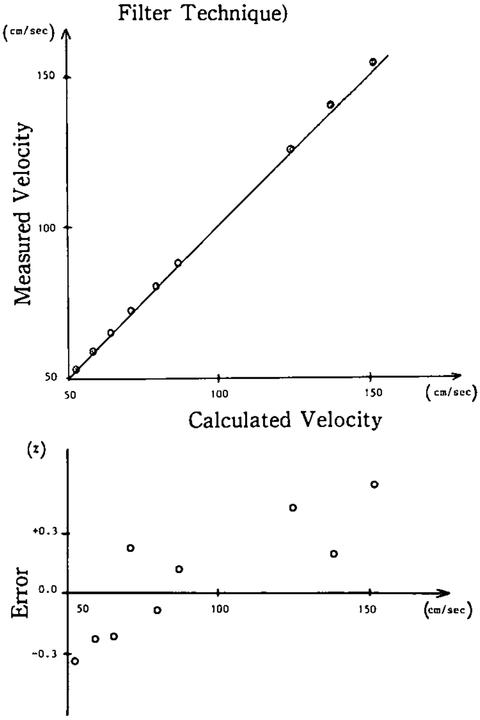

Fig.16　Experimental Results
(N=31, 2 particles, Analog, Spatial Filter Technique)

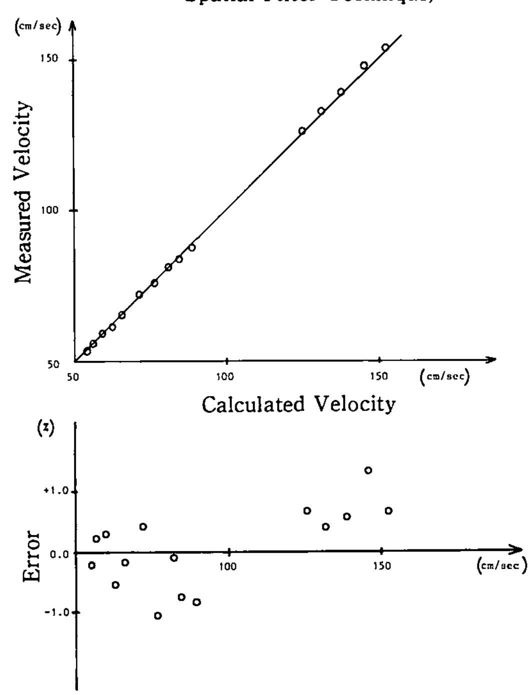

Fig.17　Experimental Results
(N=31, 2 particles, Digital, Spatial Filter Technique)

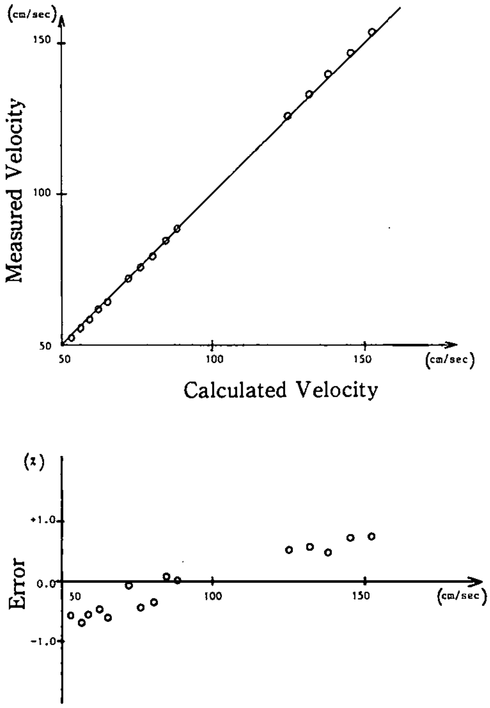

Fig.18 Experimental Results
(N=127, 2 particles, Analog, Spatial Filter Technique)

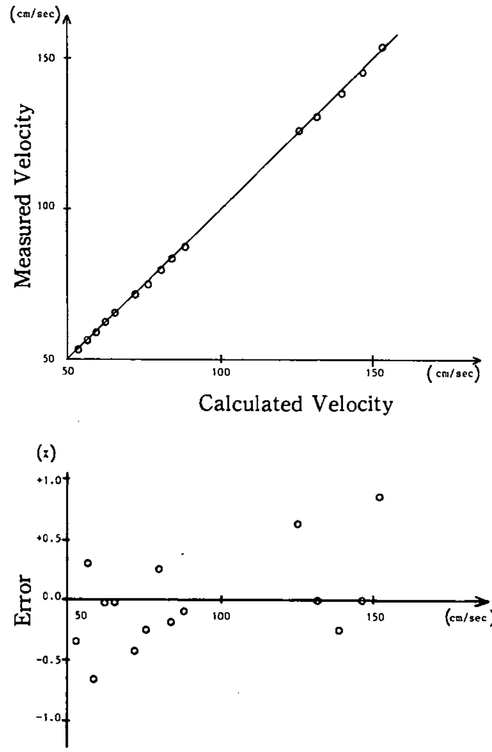

Fig.19 Experimental Results
(N=127, 2 particles, Digital, Spatial Filter Technique)

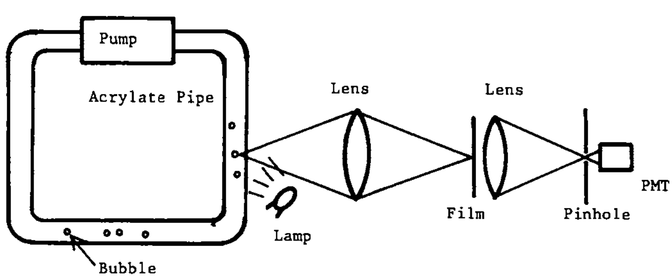

Fig.20 Experimental Set Up (Water Flow)

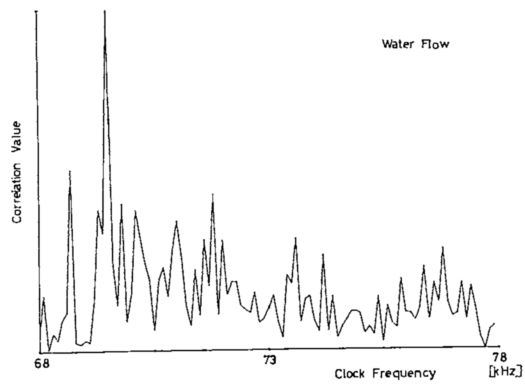

Fig.21 Autocorrelation Function in Case of Water Flow Measurem

The autocorrelation function is shown in Fig.21. The velocity of the water flow is calculated as 1260 mm/sec from it and the value is in good agreement with the calculated velocity

5. Conclusion

A velocity measuring technique of using M-sequence signal is proposed. And it was confirmed by experiment that the method has a better accuracy than that of a normal LDV system and also the system can measure the velocity even in the case that a few particles are in the measuring volume at the same time. This is a great advantage of the proposed method compared with LDV technique. Measuring error obtained by the pilot system was ±1.5%. In the method a projector lamp was used as a light source, this is another advantage compared with LDV in which expensive laser must be used.

References

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3) Asch, R. and Ford Jr., N. C.: Design of an ideal digital correlation computer, Rev. Sci. Instrum., **44**, p. 506 (1973).