New Method to Measure Pulp Flow Velocity Based on Time-frequency Analysis of Pulp Consistency Noise

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***Abstract*—A novel method of measuring flow velocity is put forward, which need no equipment or hardware. Utilizing the Doppler-effect that pulp flow velocity (PFV) causes effect upon pulp consistency noise signal, we can determine PFV carrying out time-frequency analysis of the noise of pulp consistency signal on the basis of pulp consistency measurement. The detailed calculating steps are proposed, firstly, noise signal is separated from pulp consistency signal, then it is analyzed by means of the short time power spectrum (STPS) or wavelet transform (WT), finally the PFV can be obtained according to the scale change of STPS or the period change of WT. The corresponding tests show that the measurement method is feasible with high precision.**

***Keywords*—pulp flow velocity, short time power spectrum, pulp consistency noise, correlation meter**

I. INTRODUCTION

In paper-making process, the pulp flow velocity (PFV) is the most frequently measured parameter, so it has great significance to the paper production line such as the workshop sections of pulp beating, pulp washing, pulp filtrating and pulp mixing as well as to the finished paper sheet's quality [1]. At present, the four main methods for PFV measurement include electromagnetism, ultrasonic, image processing and correlation theory [2].

The electromagnetic measurement is a nontouched measuring method which can convert PFV to inductive electromotive force by the use of principle of electromagnetic induction, and its precision can reach 1.0%, but this method brings many disadvantages such as the expensive price, the rigorous install-conditions and the complex processes of anti-jamming [3]. The ultrasonic measurement is a method that takes advantage of the change of ultrasonic spreading speed in pulp with the change of PFV to measure PFV, but it also has disadvantages of low precision, rigorous install-conditions and pulp pipeline's cleanness [4]. The third method is based on image processing which carry out pattern recognition and feature extraction of the pulp fibre image, it not only can obtain PFV, but also can acquire the distribution of PFV in different position, but its cost is extremely high [2]. The method based on correlation theory is to work out PFV by cross-correlation calculation, it's precision can reach as high as 0.2% and it's anti-jamming capacity is very excellent, but the expensive cost is also flaw [5]. In sum, we need a low cost and high precision measuring method for PFV in paper-making process presently.

During the measurement of PFV, pulp consistency is always measured at the same time, so we consider whether there is a way to determine the PFV by the analysis of pulp consistency signal on the basis of mature and advanced pulp consistency measuring technology.

It is found that the fluctuation property and the velocity-frequency property of the pulp consistency provide possibility for the assume that PFV is obtained by consistency sensor, the former property was discussed in [6], and the latter property was discovered by textual author and have been validated by a great deal of corresponding tests [7].

(1) Fluctuation property (see Section 2.2): Pulp is unhomogeneous mixture with pulp fibre agglomeration and water, which causes the uneven of pulp consistency and brings the fluctuant components in pulp consistency signal [6].

(2) Velocity-frequency property (see Section 2.3): The instantaneous frequency of the fluctuation components f follows normal distribution, and its average frequency $\bar{f}$ is approximately invariable when PFV v is constant. It is Doppler Effect in the signal of pulp consistency that the velocity-frequency property of pulp consistency signal is, i.e. $\bar{f}$ is high when the PFV v is high, and vice versa. There are nearly linear relation between the PFV and the average frequency, it can be expressed as follows [7].

$$\frac{v_1}{v_2} = \frac{\bar{f}_1}{\bar{f}_2} \tag{1}$$

In (1), $\bar{f}_1$ and $\bar{f}_2$ are respectively the average frequency of the fluctuation components of the pulp consistency signal when the PFV are v_1 and v_2.

A new method by which consistency sensor is employed to measure PFV is proposed by virtue of these two properties. The core technique of the measurement method is how to carry out STPS or WT to get average frequency $\bar{f}$ or average period $T(t)$ after fluctuation components is extracted from the pulp consistency signal, then to calculate PFV v through (1). The study which is performed in a set of pulp recycling experiment device shows high precision and good dynamic performance of the method.

II. Principle of New Pulp Flow Velocity Measurement Method

In order to study measurement principle of the new PFV method, the definition and measurement principle of pulp consistency must be understand firstly, and the pulp flow fluctuation and velocity-frequency property are introduced subsequently.

A. *Principle of pulp consistency measuremen*

Pulp is two-phase fluid of pulp fiber and water. Pulp consistency c is the percentage of the dried fiber in the compound of water and pulp fiber, and it can be determined by the following formula.

$$c = \frac{weight\ \ of\ \ dried\ \ fiber\ \ of\ \ pulp}{weight\ \ of\ \ pulp} \times 100\% \qquad (2)$$

Fig. 1 shows the measurement principle of consistency sensor. The principle shows that the friction force F will be produced when the pulp flow through the consistency sensor according to the boundary layer theory of two-phase fluid. The $F\ (= f(c))$ is a function of c. Therefore, we can gain the pulp consistency c by measuring the friction force F [8].

B. *Fluctuation property and components of pulp consistency*

It is found that pulp consistency contains fluctuation components because the pulp fibre agglomerations are not distributed homogeneously in water, and the distances between different agglomerations follow normal distribution with a small variance. So this nonhomogeneous mixture causes the pulp consistency signal $c(t)$ to be a normal nonstationary stochastic signal, which mainly consists of the following components [9]:

$$c(t) = d(t) + s(t) + r(t) \qquad (3)$$

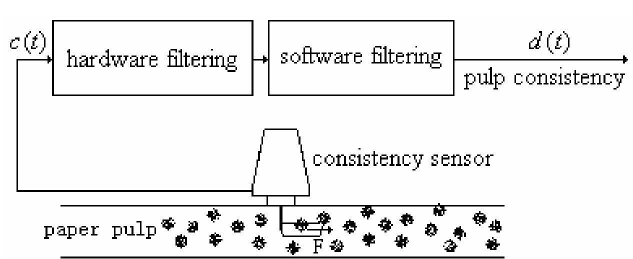


Figure 1. Schematic diagram of the principle of measuring pulp.

Where $d(t)$ is the mean pulp consistency; $s(t)$ is the fluctuation components in the consistency signal, which can be measured by the high-accuracy consistency sensor, and we can regard it as a noise signal; $r(t)$ is the measurement noise which produced in the measurement process of consistency sensor. All current consistency measurement systems want to eliminate the noise, $r(t)$ and $s(t)$. In this study, noise signal $s(t)$ is reserved and used to measure PFV according to its velocity-frequency property.

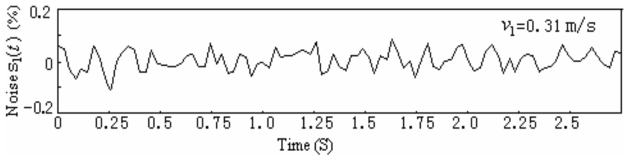
C. *Velocity-frequency property of pulp consistency*

During the calibration processes of consistency sensor, a phenomenon which arouses author's attention is that the average frequency of $s(t)$ is high when PFV is high, and vice versa. This is the velocity-frequency property which expressed by (1), essentially it is Doppler Effect which is caused by the relative motion between pulp transmitted in pipe and consistency sensor [7]. It is found that the change of average frequency of $s(t)$ can be reflected by some time-frequency transform or analysis like power spectrum, WT, STPS and so on.

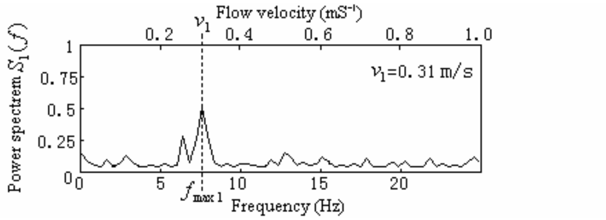
For example, if we analyze $s(t)$ employing power spectrum, when average frequency is altered with the change of PFV, obvious scale change of $S(f)$ which is the power spectrum of $s(t)$ will take place, and this change can be shown in Fig. 2, and the datum which is used to draw Fig. 2 derived from consistency sensor. Fig. 2a is the curve of $s_1(t)$ which is divided from $c(t)$ while the PFV following 0.31 meters per second, and in Fig. 2b $S_1(f)$ is the power spectrum of $s_1(t)$. Fig. 2c is the curve of $s_2(t)$ when the PFV is 0.36 meters per second, and $S_2(f)$ is the power spectrum of $s_2(t)$ in Fig. 2d. $f_{\max 1}$ (in Fig. 2b) and $f_{\max 2}$ (in Fig. 2d) are the peak frequency of $S_1(f)$ and $S_2(f)$ respectively, here the peak frequency is define as the frequency where power spectrum reaches maximum.

Comparing the power spectrum Fig. 2b with Fig. 2d, we can find that, when the PFV change from ($v_1 =$) 0.31 meters per second to ($v_2 =$) 0.36 meters per second, power spectrum $S_1(f)$ extend along f axis to become $S_2(f)$, and with the extension of power spectrum, peak frequency $f_{\max 1}$ is shifted to $f_{\max 2}$, furthermore, the peak frequency $f_{\max}$ vary linearly with the PFV v, i.e.

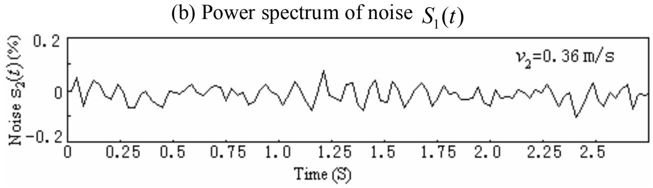
$$\frac{v_1}{v_2} = \frac{f_{\max 1}}{f_{\max 2}} \qquad (4)$$



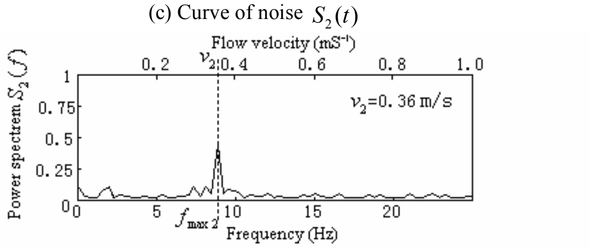
(a) Curve of noise $S_1(t)$



(b) Power spectrum of noise $S_1(t)$



(c) Curve of noise $S_2(t)$



(d) Power spectrum of noise $S_2(t)$

Figure 2. Power spectrum of pulp consistency noise following different PFV.

The certification of (4) is omitted in the paper because of the limit of text length.

Reference [10] indicates that, because the statistic property of the power spectrum, the peak frequency $f_{\max}$ is an accurate estimation of average frequency $\bar{f}$, so also yield $f_{\max 1}/f_{\max 2} \approx \bar{f}_1/\bar{f}_2$ which proves (1) to be a equivalent of (4). Because $f_{\max}$ which can be determined by means of time-frequency transform or analysis is obtained more easily than $\bar{f}$, we can substitute $f_{\max 1}$ and $f_{\max 2}$ for $\bar{f}_1$ and $\bar{f}_2$ respectively to reduce the calculation workload.

D. The principle of pulp flow velocity measurement

According to (4), if $f_{\max 1}$ and v_1 respectively be known as a peak frequency which have been calculated by means of a time-frequency transform or analysis and a PFV which have been calibrated before PFV measurement, the current PFV v_2 could be resolved by known $f_{\max 2}$, the peak frequency of the current power spectrum, i.e.

$$v_2 = \frac{v_1}{f_{\max 1}} f_{\max 2} = K f_{\max 2}. \quad (5)$$

This is the measurement principle of PFV, in (5), $K\,(= v_1 / f_{\max 1})$ is a constant coefficient.

III. EXPERIMENT DEVICE AND CONDITIONS

A. Experiment conditions

In the study we employ a set of pulp recycling system which shows in Fig. 3, the system consists of headbox, pulp pool, transmission pipeline, consistency sensor and flow sensor. In headbox control system we add a pulp location parameter and a pulp pressure parameter which couple each other to constitute subsystems. Pulp location control subsystem whose modulation can obtain constant pulp location is composed of decoupling controller, pulp height meter, frequency converter and lifting pulp pump. Pressure control subsystem whose modulation can obtain constant air pressure is composed of decoupling controller, pressure sensor, frequency converter and Ltz.blower. According to the principle of constant pressure with constant flow velocity, the constant air pressure and pulp height of headbox aim at obtaining constant and continuously adjustable PFV.

The measurement range of consistency sensor is 1.2—3.6%, measurement precision is 0.02%. The precision of electromagnetic flow velocity sensor is 1.0%. The Ltz.blower can provide 0—0.3 MPa air pressure. The pulp consistency of the whole recycling system ranges from 1.5% to 3.5%, PFV can continuously modulate in the range of 0-2.2 meters per second and its fluctuation is less than 0.1%.

Anyway, the pulp recycling system can perfectly provide stable and reliable conditions for the project's research.

B. PFV measurement device based on correlation theory

In fact, in the pulp circulation system, the standard PFV is not offered by electromagnetic sensor but by correlation meter which is composed of consistency sensor 1, consistency sensor 2 and secondary instrument. Secondary instrument collect the consistency signals transmitted from two consistency sensors, and the experienced time T in which pulp flows from sensor 1 to sensor 2 is yielded by secondary instrument according to cross-correlation calculation of the two consistency signals, and

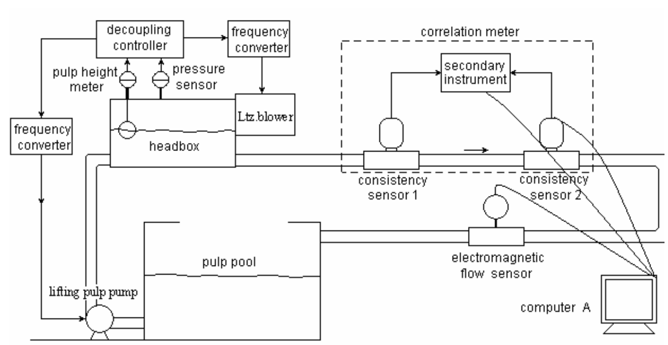


Figure 3. Schematic diagram of pulp circulation system.

the detailed calculation steps were is elaborated in [5]. The distance of the two sensors is 2 meters, so PFV v is 2/T. The correlation flow meter can reach the precision to 0.1% and be used to provide the standard PFV, while the electromagnetic flow meter is just only to provide a PFV reference. At the same time, consistency sensor 2 also provides initial signal $c(t)$ for this paper's method.

IV. TIME-FREQUENCY ANALYSIS OF PULP CONSISTENCY NOISE SIGNAL

$c(t)$ is preprocessed and analyzed by computer A in Fig. 3.

A. pre-processing of pulp consistency signal

The preprocessing includes two steps: noise extraction and stationarizing signal $s(t)$.

1) Noise extraction

$c(t)$ is derived from consistency sensor 2, among which only the system noise $s(t)$ contains the information of PFV, so we must separate $s(t)$ from the other components of $c(t)$. The procedure is as follows: remove the mean consistency $d(t)$ from $c(t)$, and the remained $s(t)$ and $r(t)$ are both nonstationary noises which are difficult to separate from each other, while we can see in [9] that $r(t)$ with finite amplitude and small energy has little influence to power spectrum of $s(t)$, therefore we omit the influence of $r(t)$ to the result of time-frequency analysis.

2) Stationarizing noise

If we employ short time power spectrum (STPS) as the method of time-frequency analysis, $s(t)$ can not to be an nonstationary stochastic signal, otherwise $s(t)$ need to be stationarized by time window function $h(T)$, hence the new signal $s_T(t)$ can be attained as follows:

$$s_T(t) = s(T)h(T-t) \tag{6}$$

Because of the inertia of colored noise $s(t)$, the extent of nonstationarizing in short time interval is finite, hence $s_T(t)$ can approximate to be stationary stochastic signal within the observation window $h(T)$.

B. Short time Fourier transform of pulp consistency noise

Stationary noise $s_T(t)$ has invariable average frequency which can be used to determine PFV but is obtained difficultly. Therefore we substitute peak frequency of STPS for average frequency of $s_T(t)$ to determine PFV according to above knowledge.

1) Calculation of short time Fourier transform and its peak frequency

Though STPS as well as short time Fourier transform (STFT) is confined to Heisenberg-Gabor's uncertainty principle with its time resolution and frequency resolution restricted to each other, it combines with the periodicity of STFT and statistics property of power spectrum. So in relatively long time STPS has its advantage in the aspects of estimating average frequency or average period of quasi-periodic and some stochastic signal like consistency noise $s(t)$ [11]. The STPS formula of $s(t)$ is:

$$P(t,f) = \left| \frac{1}{2\pi} \int_{-\infty}^{\infty} s(T)h(t-T)e^{-j2\pi fT} dT \right|^2 \tag{7}$$

But from (7), the error mean square of STPS is relatively large and its spectrum line is very rough, we need employ average filtering to $P(t,f)$, and yield the average STPS $\overline{P}(t,f)$ of $s(t)$.

$$\overline{P}(t,f) = \frac{\int_{t-\frac{T}{2}}^{t+\frac{T}{2}} P(t,f)dT}{\int_{t-\frac{T}{2}}^{t+\frac{T}{2}} \int_{-\infty}^{\infty} P(t,f)dfdT} \tag{8}$$

Then we can yield the peak value $\overline{P}_{\max}(t)$ of $\overline{P}(t,f)$ at every time t from (9).

$$\overline{P}_{\max}(t) = \max\{\overline{P}(t,f), f \in [0,+\infty)\} \tag{9}$$

substitute $\overline{P}_{\max}(t)$ for $\overline{P}(t,f)$ in (8), then yield the equation

$$\frac{\int_{t-\frac{T}{2}}^{t+\frac{T}{2}} P(t,f)dT}{\int_{t-\frac{T}{2}}^{t+\frac{T}{2}} \int_{-\infty}^{\infty} P(t,f)dfdT} = \overline{P}_{\max}(t). \tag{10}$$

We can solve (10) and obtain the corresponding peak frequency $f_m(t)$ of $\overline{P}_{\max}(t)$.

2) Determination of pulp flow velocity based on the peak frequency of STPS

Here $f_m(t)$ is an exact estimation of the average frequency $\bar{f}$ of $s(t)$ at time t [10], so substitute $f_m(t)$ for $f_{\max 2}$ which is presented in (5) and can not reflect the change of peak frequency at different time, so yield

$$v(t) = \frac{v_1}{f_{\max 1}} f_m(t) = K f_m(t) . \quad (11)$$

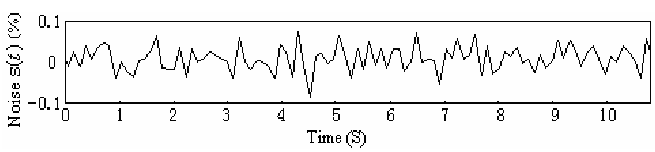
Hence we can acquire the instantaneous PFV from (11).

To curry out time-frequency analysis to the consistency noise $s(t)$ in Fig. 4a employing STPS, the width of Hamming window function $h(T)$ T is 1.8 seconds. Fig. 4b is the time-frequency distribution of $s(t)$'s average STPS which is based on the time t as X-axis, frequency f as Y-axis and $\overline{P}(t,f)$ the value of average STPS at (t, f) as gray level. Fig. 4c is the curve of peak frequency $f_m(t)$ as well as the curve of PFV $v(t)$ yielded from (11), in Fig. 4c the symbol $\times$ designates the PFV measured by correlation flow meter.

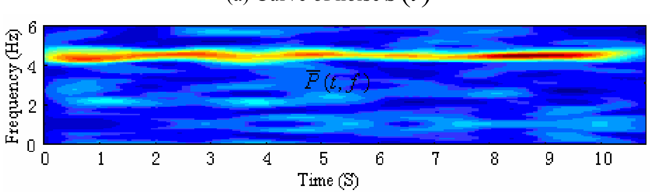
From the Fig. 4a we can see the remarkable fluctuation of $s(t)$. In Fig. 4b the average STPS $\overline{P}(t,f)$ is seemed to have preferable time-frequency resolution, which means with striking peak value $\overline{P}_{\max}(t)$, peak frequency $f_m(t)$ and its corresponding PFV $v(t)$ can be determined accurately. And Fig. 4(c) shows the PFV measurement precision based on STPS is in the order of 0.5%.

C. Wavelet transform of pulp consistency noise

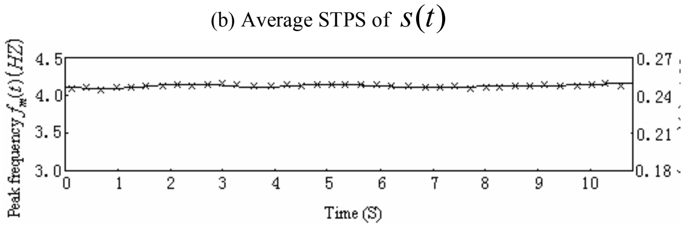
Wavelet transform(WT) is a method of time-frequency localization which has perfect capacity of time-frequency analysis to nonstationary signals. So before time-frequency analysis, $s(t)$ is not necessarily to be stationarized. Furthermore, wavelet analysis has excellent capacity of noise removal which can eliminate the influence of measurement noise $r(t)$. Therefore, according to the successive wavelet



(a) Curve of noise $s(t)$



(b) Average STPS of $s(t)$



(c) Curve of peak average STPS frequency of and PFV

Figure 4. Measurement PFV by STPS of pulp consistency noise.

transform to $s(t)$ we can determine $T(t)$ which is the average period of $s(t)$.

1) Calculation of Wavelet transform and its period

According to the characteristics of $s(t)$, Morlet wavelet $h_{a,b}(t)$ is selected as mother wavelet

$$h_{a,b}(t) = \pi^{-1/4} \frac{1}{\sqrt[4]{\pi a^2}} \left(e^{j\omega_0 (\frac{t-b}{a})} - e^{-\frac{\omega_0^2}{2}}\right) e^{-\frac{(t-b)^2}{2a^2}} . \quad (12)$$

WT is employed to analyze $s(t)$, we can develop

$$WT_S(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} s(t) h^*\left(\frac{t-b}{a}\right) dt . \quad (13)$$

In (13), scale factor a and shift factor b represent the X-axis and Y-axis in time-frequency space respectively. It is found that $WT_S(a,b)$ has periodicity if only $T(t)$ exist, and its period T_a is different at different scale a, furthermore, the relation between $T(t)$ and T_a can be expressed as:

$$\frac{T(t)}{k'} = \frac{T_a}{a} \quad (14)$$

Where k' is a coefficient.

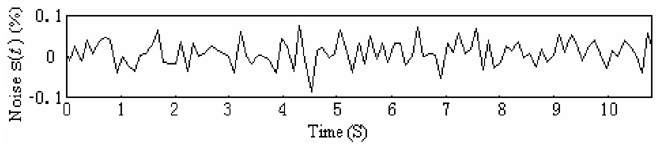
2) Determination of pulp flow velocity based on the period of WT

Because of the inverse relation of average period $T(t)$ and average frequency $\bar{f}$ ($\bar{f} = 1/T(t)$), as well as the fact that $f_m(t)$ is an exact estimation of $\bar{f}$ ($\bar{f} \approx f_m(t)$) [10], we substitute these relationships and (14) into (11) to yield

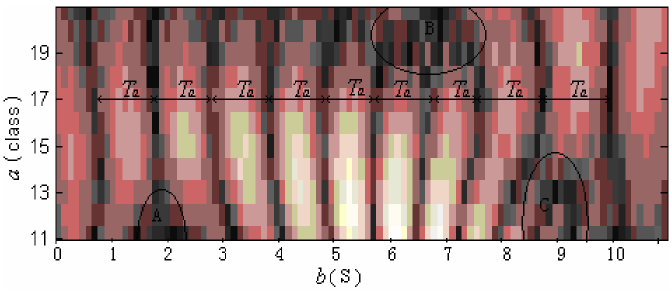
$$v(t) = K f_m(t) = \frac{K}{k'} \cdot \frac{a}{T_a} . \quad (15)$$

Here T_a can be easily determined according to $WT_S(a,b)$, hence we can acquire the PFV from (15).

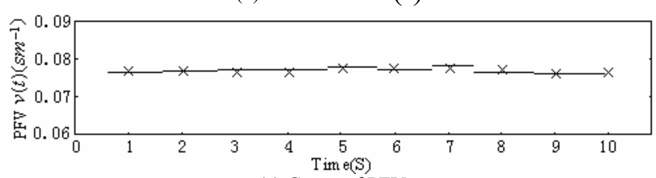
The consistency noise $s(t)$ which is shown in Fig. 5a is analyzed employing WT. Fig. 5b is the WT of $s(t)$, in the region A, B and C, though the nonstationary component of $s(t)$ and measurement noise $r(t)$ cause a certain effect on time-frequency analysis, The strong anti-disturbance capability



(a) Curve of noise $s(t)$



(b) WT of noise $s(t)$



(c) Curve of PFV

Figure 5. Measurement PFV by WT of pulp consistency noise.

of WT make clear period acquired at scale a =17 in the X-axis direction. Fig. 5c is the curve of PFV $v(t)$ yielded from (15) according to the measurement of period T_a, in this figure the symbol × designates the real PFV. By this way the measurement precision can reach 1.2% according to Fig. 5c, but after average filtering at the expense of partial calculation rapidity, the precision also can arrive at the value below 0.7%.

V. Experiment Result and Its Analysis

The method to measure PFV by means of STPS and WT are performed on the pulp recycling system which shows in Fig. 3, the partial results of experiment are recorded in the table 1, we can see that the measurement precision of method based on STPS or WT is higher than method based on electromagnetic flow meter, and the inertia time which reflect the rapidity of calculation process is shorter as well.

Comparatively, the precision of STPS is higher than that of WT, but the dynamic performance of WT is better than that of STPS.

VI. Conclusion

The preceding pulp flow velocity (PFV) measurement method has been studied several times and the experiment results have validated the existence of Doppler-effect in pulp consistency system noise. According to the STPS or WT of consistency system noise, we can acquire PFV perfectly. Of course STPS has higher precision and WT has better dynamic performance. So as a result STPS can be applied to the occasion where flow velocity fluctuation is slow and requirement of measurement precision is high, while WT can be employed to the place where flow velocity varies rapidly.

TABLE I. COMPARING THE EFFECT OF PFV MEASUREMENT

PFV measured by correlation meter (ms-1)	**PFV Measured by electro-magnetic sensor (ms-1)**	**PFV Calculated by STPS**		**PFV Calculated by WT**	
		Calculated value (ms-1)	***inertia time (s)***	***Calculated value (ms-1)***	***inertia time (s)***
0.0827	0.0821	0.0825	3.37	0.0821	0.45
0.4714	0.4734	0.4724	2.62	0.4730	0.42
0.6459	0.6397	0.6483	2.48	0.6495	0.41
1.0836	1.0717	1.0811	2.25	1.0904	0.40
1.4660	1.4786	1.4702	2.16	0.4634	0.37
1.6075	1.5940	1.6022	1.70	1.5969	0.31
2.1725	2.1861	2.1628	1.63	0.2181	0.30

Acknowledgment

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References

[1] G. G. Duffy, "Flow of Medium Consistency of Wood Pulp Fibre Suspensions, "Appita, vol. 48, pp. 51–55, January 2003.

[2] Y. Shen Yi, J.Q. Zhang and S.Z. Wang, "A New Method for Nonlinear Estimation and Dynamic Calibration of Pulp Consistency Sensors," Chinese Journal of Scientific Instrumentation, vol. 27, pp. 1-7 February 1997.

[3] Y. Yan, J.M. Zhang and J. Bao, "Research on On-line Signal Analysis for Electromagnetic Flowmeter," Chinese Journal of Scientific Instrumentation, vol. 25, pp. 53-57, April 2005.

[4] Y. Sato, M. Mori, Y. Takeda and K. Hishida, "Signal processing for advanced correlation ultrasonic velocity profiler," Third International Symposium on Ultrasound Doppler Methods for Fluid Mechanics and Fluid Engineering (EFPL). Lausanne. Switzerland, pp. 235-240, September 2002.

[5] H. Kikura, Y. Takeda and T. Taishi, "Flow Mapping Using Ultrasonic Doppler Method," Proc. FEDSM'98, ASME Fluids Eng, Division, Summer Meeting, USA, pp.563–569, July 2003.

[6] Q. Zhou, J.Q. Han and Y. Wang, "New Approach to Measure Pulp Flow Based on Cross-correlation Theory," China Pulp and Paper, vol. 35, pp. 27-31, July 2005.

[7] J. Li and K.F. Chen, "Fluctuation Property of Medium Consistency MEDIUM Consistency Fiber Suspension and Practice in Pulp mixing," Journal of Shannxi University of Science & Technology, vol. 25, pp.5-9, May 2005.

[8] Q. Zhou and J.Q. Han, "The New Research on the Property of Pulp Consistency," China Pulp and Pap, in press.

[9] G.Q. LU, N.C. FU and Z.S. Zheng, "A New Method for On-Line Measuring the Concentration of Pulp," Acta Metrologica Sinca, vol. 16, pp. 74-80, January 2001.

[10] Q. Zhou, "The research on improving consistency measurement precision of pulp by dynamics method," Control and Instrument in Chemical Industry, in press.

[11] H.M. Tang, "Stationarizing Two Classes of Nonstationary Process by Wavelet," Journal of Beijing University, vol..36, pp.19-28, February 2004..