AN IMPROVED PROCESSING ALGORITHM OF TURBULENCE SIGNAL BASED ON FRACTIONAL FILTERING

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ABSTRACT: The accuracy of ocean microstructure shear signal plays a vital role in turbulence measurement and cognizing. According to the characteristics of signal and the designed measurement instrument, this paper proposes an improved processing algorithm based on fractional filtering to improve the accuracy of the measured turbulence signals. On the basis of the time-frequency characteristic of fractional filtering, the algorithm takes triaxial accelerations signals and measured shear signals to structure the optimal filtering. The key point is to obtain the optimal estimation of vibration noise signals calculated by weight coefficient and eliminated them from the measured shear signals especially in low frequency. The improved algorithm is used to process the sea trial data obtained from the Free Fall Vertical Profiler deployed in the Western Pacific in March 08, 2017. The results show that the corrected signal spectra agree well with the Nasmyth theoretical spectra and the dissipation rates of turbulent kinetic energy drop near an order of magnitude compared with the original measured data, which indicate that the improved processing algorithm can effectively eliminate the vibration noise signals, improve the accuracy of the data and solve the key problem of ocean turbulence adaptive observation.

KEYWORDS: Fractional filtering, vibration noise, ocean turbulence, vibration noise signals

1 INTRODUCTION

Ocean turbulence research plays an important role in cognizing the ocean circulation and climate at a wide range of temporal and spatial scales. It also has a significant effect on the study of the marine ecological environment and the distribution of suspended material (Nikurashin, 2009). In the past few decades, Ocean turbulence has become a popular subject in marine science research. To study the law of turbulence mixing processing, oceanic turbulence measurements has been taken for more than 50 years since the pioneering work by Grant et al.

Conventional turbulence observation platforms are roughly divided into horizontal and vertical profilers according to their different trajectories through the water column. Vertical profilers are requisite to study the depth-dependent processes of ocean turbulence and the vertical diffusion coefficients. Ocean turbulence is usually measured by shear probes and/or fast response thermistors. However, noise is inevitable in the actual turbulence observation process because the oceanographic sensors work in complicated and changeable marine environments, which mainly includes vehicle motion and vibration, natural noise (usually due to the probes encountering plankton or other detritus in the water column) and the high frequency electronic system noise (Lueck, 1997; Ismail, 2015). The noise distributes at different frequency bands and leads to different effects on the measured signals. The Free Fall Vertical Profiler (FFVP) is an advanced vertical turbulence observation platform but susceptible to the vehicle motion and vibration, the signal measured by FFVP which is contaminated will lead to the wrong analysis of the turbulence characteristics. Therefore, it is crucial to eliminate the vibration signals from the measured turbulence signals before analyzing the turbulent kinetic energy (TKE) terms.

In recent years, many methods have been proposed to get rid of turbulence noise signals. Gregg presented estimating deviation method for the uncertainty and limitation of kinetic energy dissipation rate measured by shear probes. The spatial response model aiming at eliminating the high frequency contamination is proposed by Lueck in 2004, but have little effect on removing the noise distributed in low frequency. In 2006, cross-
spectrum denoising method is proposed to remove the noise signals caused by the instrument vibration. These methods all eliminate the vibration noise signals in the time/frequency domain, but the problem is that the shear signal is eliminated at some extent because of the signal overlap. In (Luan et al., 2018), we have already verified the stability and validity of FFVP for turbulence measurement by analyzing the sea trial data and presented an noise correction method, but this method still cannot solve the problem mentioned above. The Fractional Fourier Transform (FrFT) as the generalized formula for the Fourier Transform (FT) which transforms a function into an intermediate domain between time and frequency has good ability to solve the problem. The extra degree of freedom introduced by the choice of the transform order (angle of rotation) gives the FrFT a potential improvement in many applications, so FrFT is widely used in graphics, radar, sonar and others nowadays.

To take advantage of FrFT which has good performance in non-stationary signal analysis, this paper proposes a processing algorithm based on fractional filter transforming the turbulence shear signals from the time domain into fractional domain. This algorithm takes turbulence shear signals and the triaxial accelerations signals obtained from FFVP as the original data. The triaxial accelerations signals in the corresponding X, Y and Z directions can be got from a MTI sensor mounted in the FFVP. Based on the data analysis between triaxial acceleration signals and shear signals, the algorithm takes triaxial acceleration signal, shear signals as reference input signal, main input signal respectively to construct filter and estimates the vibration signals using the minimum mean square error (MMSE) of fractional filtering. Sea trial data is used to verify the validity of the algorithm, the results show that the algorithm is effective to eliminate the noise signals, improves the accuracy of turbulence data for further research.

In this paper, the concrete steps of the turbulence observation and the improved processing algorithm based on fractional filtering in detail are introduced in Section II. Section III mainly presents the data analysis between triaxial accelerations signal and shear signal and the sea trial data is used to verify the validity of the algorithm. Section IV makes a conclusion about the algorithm.

2 MATERIALS AND METHODS

2.1 Turbulence measurement

Traditionally, turbulence observation platforms are roughly divided into horizontal and vertical profilers for different trajectories through the water column. The Free Fall Vertical Profiler (FFVP) designed by OUC belongs to the latter form. The FFVP is 1.8m in length, whose maximum sinking depth is 6000m. The core component of FFVP is the turbulence observing part, which consists of two orthogonal shear probes, a high-accuracy attitude sensor (MTI) and a temperature-depth (TD) sensor. The configuration of the FFVP is shown in Fig.1 (a).

Fig.1 (a) The three-dimensional structure modeling of the FFVP. (b) The preparation before deployment. (c) The process of deployment

In the design of the instrument, the TD sensor is embedded to measure the mean temperature and pressure (depth) data. A MTI sensor is used to monitor the status of the instrument, which can measure the instrument vibration of the accelerations including the horizontal acceleration \( A_x \), the lateral acceleration \( A_y \) and the vertical acceleration \( A_z \), and collect the attitude information of Heading \( \psi \), Pitch \( \theta \) and Roll \( \phi \). With the sampling frequency set to 120 Hz, the output signal were digitized with a 16-bit A/D converter and stored in the SD card. One probe is oriented to sense horizontal velocity fluctuations \( u \) and the other responds to the lateral velocity fluctuations \( v \). The voltage output of the shear probes are converted to shear \( \partial u/\partial z , \partial v/\partial z \). The output voltage of the two shear probes were sampled at 1024 Hz, digitized by 16-bit A/D conversion and finally stored in the SD card.
When the shear probe is installed on the turbulence observation instrument to measure in the open sea environment, the vehicle motion and vibration are unavoidable to effect on the shear force. Then the output charge of the shear probe responds to the shear force and combines the true environment turbulence shear with the vibration noise. To get rid of the noise from the measured shear signal, we should minimize the contamination of the shear signals in the post-processing. In this paper, we estimate the vehicular motions and vibrations with the acceleration signals measured by the MTI. The diagram of data acquisition system is shown as follows in Fig.2.

![Fig.2 The diagram of data acquisition system.](image)

The whole procedure of the turbulence measurement and processing is shown in Fig.3. The core of the procedure is how to process the raw shear signal and acceleration signal to get the uncontaminated shear signal. In the next part, the detail of processing will be introduced.

![Fig.3 The procedure of the turbulence measurement and processing](image)

### 2.2 The improved algorithm

The key of processing is to eliminate the contamination from the measured shear signals by subtracting all coherent signals from the dynamic accelerations. The accelerations measured by MTI include an inertial component and a gravitational component. Thus, the inertial component of the signals used to describe the vibration of the instrument can be separated from the gravity signals with the independent pitch and roll attitude:

\[
Acc_z = A_1 + g \cos \theta \cos \phi, 
\]

(1)

where the angles $\theta$ and $\phi$ are the vehicle pitch and roll, $g$ is the acceleration of gravity. Similarly, the signals from the horizontal and lateral are deduced as

\[
Acc_x = A_1 + g \sin \theta, 
\]

(2)

\[
Acc_y = A_1 + g \sin \phi. 
\]

(3)

respectively.

We can get that the measured shear signals consist of the true turbulence shear and the noise measured by the MTI due to the body motion and vibration, so we assume that it can be expressed as:

\[
s = \hat{s} + h \ast a, 
\]

(4)

where $\hat{s}$ is the true environmental shear signals, $s$ and $a$ are the measured shear and acceleration signals. The weight value $h$ is the key to obtain uncontaminated shear signal, and the asterisk $(\ast)$ denotes a convolution.

The Fractional Fourier Transform (FrFT) is the generalized formula for the Fourier Transform (FT) that transforms a function into an intermediate domain between time and frequency [8]. The extra degree of freedom introduced by the choice of the transform order (angle of rotation) gives the FrFT a potential improvement in any application where the FT is used. To take advantage of FrFT, we transform the signals from the time domain into fractional Fourier domain.

The FrFT is defined [12] by means of the transformation kernel $K_p(t,u)$, and expressed as

\[
X_p(u) = \left\{ F_p \left[ x(t) \right] \right\}(u) = \int_{-\infty}^{\infty} x(t) K_p(t,u) dt, 
\]

(5)

where $p$ is the transform order $p \in (-2,2]$, $F_p$ is the FrFT operator and $K_p(t,u)$ is indicated by

\[
K_p(u,t) = \sqrt{\frac{j\cot \alpha}{2\pi}} \exp \left\{ j \left( \frac{1}{2} \cot \alpha \omega u - u \csc \alpha + \frac{1}{2} u^2 \cot \alpha \right) \right\}, \alpha = \frac{\pi}{n}
\]

(6)

where $n$ is an integer and $\alpha$ is the rotation angle, $\alpha = \frac{\pi}{2n}$. According to the fractional convolution theorem,

\[
S_p = \hat{S}_p + \exp \left( -j \frac{1}{2} \cot \alpha u^2 \right) H_p A_p
\]

(7)

where the uppercase symbols represent the FrFT of the corresponding lowercase symbols in Eq.(4).
As the general structure of filter [15], we assume that \( s(n) \) is the input signal,
\[
s(n) = \hat{s}(n) + a(n),
\]
which includes the signal \( \hat{s}(n) \) and the noise \( a(n) \). \( y(n) \) is the actual output signal of the filter,
\[
y(n) = \sum_{m} h(m) s(n-m),
\]
where \( h(n) \) is s sample impulse transfer function. And \( e(n) \) is the error of estimation,
\[
e(n) = s(n) - y(n).
\]
The mean square error between the original signal and the actual signal can be expressed as:
\[
E[e^2(n)] = E[\left( s(n) - y(n) \right)^2].
\]
The filtering is to make \( e \) minimum, which has a better processing performance. The key problem of MMSE is to determine the weight coefficient \( h_{opt} \), so we calculate it by the equation, which can be expressed easily in the matrix form as follows:
\[
[\phi_s] = [\phi_s][h],
\]
where \( \phi_s \) is the cross correlation matrix, \( \phi_s \) is the auto-correlation matrix.

In the fractional Fourier domain, the impulse transfer function in Eq.(12) can be derived as
\[
H_p = \Phi_{ss}^p(u)/\Phi_{aa}^p(u)
\]
where \( \Phi_{ss}^p(u) \) denotes the fractional cross correlation function, \( \Phi_{aa}^p(u) \) denotes the fractional autocorrelation function, and they are defined as
\[
\Phi_{ss}^p(u) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} K_p(u,t)K_p^*(u,\delta)r_{ss}(t,\delta)dtd\delta,
\]
\[
\Phi_{aa}^p(u) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} K_p(u,t)K_p^*(u,\delta)r_{aa}(t,\delta)dtd\delta,
\]
where \( r_{ss} \) represents the cross correlation function of the measured signal \( s \) and \( a \), \( r_{aa} \) denotes the autocorrelation function of \( a \). Then we use MMSE to calculate the \( H_{opt} \) for obtaining the \( h_{opt} \) to eliminate the vibration noise signal, finally the cleaned shear signal is derived as:
\[
\hat{s} = s - h_{opt} \ast a.
\]
The evaluation standard of the algorithm is to compare the size of turbulence kinetic energy dissipation rate [5]. The formula of turbulence kinetic energy dissipation rate is shown in Eq.(17).
\[
\varepsilon = 7.5\nu \left( \frac{\partial u}{\partial z} \right)^2
\]
where \( \varepsilon \) is turbulence kinetic energy dissipation rate, \( \frac{\partial u}{\partial z} \) is shear rate which is get from shear data, \( \nu \) is the coefficient of viscosity.

3 RESULTS

3.1 Spectral analysis

The sea data used to verify the validity and feasibility of the improved processing algorithm is collected in the Western Pacific in March 08, 2017 with the Free Fall Vertical Profiler (FFVP) (Fig.1(b)). In this experiment, the sinking depth of the instrument is about 350m. The shear signal sample processed is 3-min long. As a sample shown in Fig.4 (a) and (b), the raw shear signals have large and intermittent fluctuations in the microstructure because of the environmental turbulence and noise interference. The noise signals includes the low frequency vibration noise signals which are caused by the phenomenon of Karman Vortex Street [13] and other noise signals caused by the ambient plankton and instrument. In this paper, we mainly concentrate on processing the noise signals induced by the Karman vortex street. Triaxial accelerations signals (\( Accx, Accy, Accz \)) shown in Fig.5 (a)-(c) react real-time motions and vibrations of the instrument. The horizontal (\( Accx \)) and lateral (\( Accy \)) accelerations should be compared to \frac{\partial u}{\partial z} and \frac{\partial v}{\partial z} respectively. It is obvious that the temporal fluctuations of the \( Accx \) and \( Accy \) is larger than \( Accz \).
In the time domain, it is almost impossible to analyze the influence of the noise on the turbulence shear signals. Then we transform shear and triaxial acceleration signals into frequency domain. The measured shear signals are segmented into 4-s-long portions of each 3-min-long burst for data analysis. The comparison between the shear frequency spectra and the accelerations frequency spectra is presented in Fig. 6.

![Image](image1)

**Fig.4 Time series of the measured shear data for a 3-min-long sample.**

When the FFVP is in the deep ocean for turbulence observation, fluid flows through the bluff body such as the ropes and the instrument, will form the phenomenon of Karman Vortex Street and generate vibration signals. According to the average flow velocity \( U = 0.53 \text{m/s} \) and using the theory of Karman vortex street, we can calculate the shedding frequencies \( d = 0.006 \text{m}, d = 0.07 \text{m} \), which are 15Hz and 1.5Hz. Then at 1.5Hz and 15Hz, the power spectra of the acceleration and shear have larger fluctuation change, as shown in Fig. 6 (vertical line).

The power spectral densities (PSD) of acceleration and shear signal at two shedding frequencies have consistent changes, which indicate that acceleration signals and shear signals have a certain superposition [14]. So the improved turbulence processing algorithm based on fractional filter described above is used to eliminate the vibration noise from the measured shear signal, and we set \( p = 0.99 \) because of the measured turbulence shear signal characteristic.

### 3.2 Vibration Noise Correction

The improved processing algorithm mentioned above is used to eliminate the vibration noise from the measured shear signal and the cross-spectrum denoising algorithm [16] is used as the comparison method. In Fig. 7, the wavenumber power spectra are computed and compared with the Nasmyth theoretical spectrum. The red lines are the original shear spectra, the green lines and the blue lines are the processed shear spectra using the improved algorithm in this paper and the cross-spectrum algorithm respectively. It is very obvious that the vibration noise signals in the original spectra are apparent at low wavenumber. Compared with the cross-spectrum algorithm, the vibration peaks of the processed spectra using the improved algorithm before the cutoff wavenumber (the vertical dashed line) show a more marked improvement, and agree better with the Nasmyth theoretical spectrum. Furthermore, the dissipation rate of the turbulence kinetic energy computed with the processed shear signals using the improved algorithm drops near an order of magnitude compared to the original data and the cross-spectrum denoising data.
More dissipation rates are computed from the processed shear spectra and the original shear spectra to validate the improved algorithm. As shown in Fig.8, the processed dissipation rates (blue dots) using the improved algorithm have significantly decreased in magnitude compared to the original dissipation rates (red dots) and the cross-spectrum algorithm dissipation rates (green dots). In short, these show that the improved algorithm is feasible and effective. It effectively eliminates the vibration noise signals and improves the accuracy of turbulence data for the further analysis.

**4 CONCLUSION**

An improved processing algorithm of turbulence signal based on fractional filtering is put forward in this paper on the basis of the analysis of the characteristics of the vibration noise in the measured turbulence shear signals to acquire the high precision shear data. The algorithm transforms the signal into time-frequency domain using the fractional filtering to eliminate the vibration noise. The sea trial data collected in the Western Pacific with the Free Fall Vertical Profiler (FFVP) is used to verify the validity of the improved algorithm. Compared with the cross-spectrum algorithm, the improved algorithm works better in improving the denoising effect. The results indicate that the algorithm is effective and feasible. It effectively eliminates the pollution caused by low frequency vibration signals, and provides accurate data foundation for analysis turbulent characteristics correctly.

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**6 REFERENCES**


