The Design of Ocean Turbulence Measurement with a Free Fall Vertical Profiler

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Abstract. The newly designed instrument Free Fall Vertical Profiler (FFVP) developed by Ocean University of China (OUC) had been deployed in the Western Pacific in March 08, 2017 and succeed to collect turbulence signals about 350-m-deep water. According to the requirements of turbulence measurement, the mechanical design was developed for turbulence platform to achieve stability and good flow tracking. By analysing the Heading, Pitch and Roll, the results suggested that the platform satisfies the requirements of stability. The power spectrum of the cleaned shear signals using the noise correction algorithm match well with the theoretical Nasmyth spectrum and the rate of turbulence dissipation are approximately $10^{-8} W/kg$. In general, the FFVP was rationally designed and provided a good measurement platform for turbulence observation.

1. Introduction

The 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 [1], so turbulence should not only be correctly cognized, but also be predicted and controlled. The turbulence data obtained from turbulence observation instrument is important raw material to study the law of turbulence motion [2]. Accurate turbulence signals are the basis to analyze turbulence characteristics and set up marine macro motion simulation model correctly.

The measurement of turbulence in the open ocean is almost as much art as it is science, requiring specialized sensor platforms that are difficult to operate, complex data processing, and careful data analysis [3]. The platforms must be designed to suppress high frequency vibrations contaminating the measured turbulence shear signal and avoid the measurement useless. Traditional turbulence observation platforms are roughly divided into horizontal and vertical profilers according to their different trajectories through the water column. Ocean turbulence is usually measured by shear probes.
and/or fast response thermistors [4], which are fragile and easily destroyed by the rough handling that is inevitable on impetuous ships. Finally, the estimation of the dissipation rate of turbulent kinetic energy (TKE) [5] from the cleaned data involves many computational steps. As a result of these difficulties, the measurement of microstructure turbulence was in the past limited to a number of specialized research groups.

According to the demands of observation, this paper presents a newly developed instrument Free Fall Vertical Profiler (FFVP), which enables us to routinely measure microstructure turbulence. The instrument, the data acquisition system and the sensors are described in the next section. In the third section, the noise correction algorithm will be presented in details. The sea data collected by the FFVP in the Western Pacific will be used to validate the stability and flexibility of the instrument in the fourth section. Finally, conclusion remarks will be given.

2. Free Fall Vertical Profiler

Conventional turbulence observation platforms are roughly divided into horizontal and vertical profilers according to their 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. As shown in Figure 1 (a), the mechanical structure of FFVP is mainly divided into two parts: main structure and additional structure. The turbulence profiler is a cylindrical structure as a whole. The sensors are installed in the front of the movement direction so that they can firstly contact and collect data from the undisturbed fluid, and the cover protects the sensors from being destroyed. The instrument is designed to be streamlined to reduce resistance, the lower part is the electronic cabin and the upper part is the floating body. The balancing structure and damping brush is designed to meet the requirements of balance and stability.

The core component of FFVP is the turbulence observing part, which consists of two orthogonal shear probes (PNS06) provided by the ISW Washer Company, a fast response thermistors (FP07), a high-accuracy attitude sensor (MTI-300) provided by the Netherlands Xsens Company and an integrated Sea-Bird Electronics temperature-depth (TD) sensor. The configuration of the sensors is shown in Figure 1 (b).

![Figure 1](a) The three-dimensional structure modeling of the FFVP, (b) The configuration of the sensors

In the design of the instrument, the TD sensor is embedded to measure the mean temperature and pressure (depth) data. A MTI 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. The diagram of data acquisition system is shown as follows in Figure 2.

![Data Acquisition System Diagram](image_url)

**Figure 2**: The diagram of data acquisition system

### 3. Noise Correction Algorithm

When the shear probe is installed on the turbulence observation instrument to conduct measurement 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, an advanced motion compensation method is applied to remove the acceleration-coherent vibrations from the measured shear signal to minimize the vibration contamination. The detail processing steps are as follows [6-9]:

1. **Step1**: Remove the static pressure in triaxial acceleration \( A_i \) to get dynamix acceleration \( a_i \);
2. **Step2**: Use the low-pass filter to remove high frequency noise from shear signal;
3. **Step3**: Remove the singular value from the shear signal, which is caused by the impact of foreign bodies in the sea;
4. **Step4**: Resample the acceleration signal to ensure the length of the shear and acceleration data is same;
5. **Step5**: Assume that the measured shear signal is the summation of a desired environment shear signal plus a vibration signal measured by MTI:
   \[
   s(t) = \hat{s}(t) + h \ast a(t),
   \]
   where \( \hat{s}(t) \) is the true environmental shear signal, \( s(t) \) and \( a(t) \) 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;
6. **Step6**: Use the Wiener filtering function to remove the acceleration vibration signal from shear signal, where \( h_{op} \) is calculated by the Wiener-Hoff equation using the acceleration signal and shear signal. The vibration signal is removed and the cheaned shear signal is got:
   \[
   s'(t) = \int_{-\infty}^{\infty} h_{op}(\tau) \hat{s}(t-\tau) \, d\tau,
   \]
Step 7: Transform the signals from time domain ($t$) into frequency domain ($\omega$):

$$F_{\omega}(w) = \int_{-\infty}^{+\infty} s(t) e^{-jwt} dt,$$  \hspace{1cm} (3.3)

Step 8: Calculate the power spectrum $\phi(w)$ of the cleaned shear signal;

Step 9: Transform $\phi(w)$ into wavenumber spectrum using the Taylor frozen flow hypothesis:

$$\Phi(k) = 2\pi V \phi(w),$$  \hspace{1cm} (3.4)

Step 10: Calculate the dissipation rates of TKE terms:

$$\varepsilon = \frac{15}{2} \nu \int_{k_{\min}}^{k_{\max}} \Phi(k) dk,$$  \hspace{1cm} (3.5)

where $\nu$ is the kinematic viscosity coefficient, $k_{\min}$ is usually set to 2-5cpm and $k_{\max}$ is determined by the Kolmogorov wavenumber [10].

The flow chart of the algorithm is shown in Figure 3.

4. Results
The sea data used to verify the validity and feasibility of the improved denoising algorithm is collected in the Western Pacific with the Free Fall Vertical Profiler (FFVP) in March 08, 2017. In this experiment, the sinking depth of the instrument is about 350m. The shear signal sample processed is 3-min long. The shear signal sample processed is 3-min long.

4.1 The sinking velocity
Before the FFVP is deployed, it is required to stay on the water surface for a period of time, and release the cable after the turbulence instrument and the surrounding water flow being stable. As shown in Figure 4, we can see that the starting depth is not zero because of the instrument length 1.8m and about 10m water pressure produced by atmospheric pressure. The average sinking velocity is \(0.53 \text{ m/s}\). In the initial sinking time, the pressure fluctuation is large, leading to the calculation speed is inconsistent with the actual speed, but the speed begins to stabilize very soon.

![Figure 4: The relationship between sinking velocity and depth](image)

4.2 Attitude analysis
A MTI is installed in FFVP to collect the attitude information of Heading \((\psi)\), Pitch \((\theta)\) and Roll \((\phi)\). The time domain signal of attitude changes during the sinking as a sample in Figure 5.

The average Pitch \((\theta)\) and Roll \((\phi)\) is about -0.5° and -0.4° respectively. The variations of Pitch \((\theta)\) and Roll \((\phi)\) are very small, which validates that FFVP satisfies the stability requirements for turbulence measurement.
4.3 Vibration analysis

As a sample shown in Figure 6, 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 is caused by the phenomenon of Karman Vortex Street [11] and etc.. Triaxial accelerations signals (Accx, Accy, Accz) shown in Figure 6 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.

![Image](image_url)

**Figure 6:** Time series of the measured shear data and acceleration data for a 3-min-long sample

4.4 Noise Correction

To gauge the performance of the FFVP at turbulence levels for the oceanic range, the dissipation rates are computed using a recursive algorithm mentioned above. In Figure 7, the wavenumber power spectra are computed and compared with the Nasmyth theoretical spectrum. The red lines are the original shear spectra and the blue lines are the denoised shear spectra using the noise correction algorithm in this paper. It is very obvious that the vibration noise signals in the original spectra are apparent at low wavenumber. The vibration peaks of the denoised spectra before the cutoff wavenumber (the vertical dashed line) show a marked improvement, and agree well with the Nasmyth
theoretical spectrum. Furthermore, the dissipation rate of the turbulence kinetic energy computed with the denoised shear signals drops compared to the original data.

**Figure 7**: The comparison of the original spectrum, corrected spectrum and the Nasmyth theoretical spectrum

5. Conclusions

A newly designed instrument Free Fall Vertical Profiler (FFVP) developed by Ocean University of China (OUC) had been deployed in the Western Pacific in March 08, 2017 and succeed to collect turbulence signals about 350-m-deep water. According to analysing the attitude information of Heading, Pitch and Roll, the results suggested that the platform satisfies the requirements of stability. The power spectrum of the cleaned shear signals using the vibration noise correction algorithm matches well with the theoretical Nasmyth spectrum and the rate of turbulence dissipation are approximately $10^{-8}$ W/kg. In Conclusion, the noise correction algorithm is effective, the FFVP was rationally designed and provided a good measurement platform for turbulence observation.

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