A New Method for Purification of Rayleigh Wave Signal Based on GSTTF-MT

Kunnan Qiu, Feimin Shen

***Abstract*—**It is a difficult problem to purify the Leibo signal from the seismic record. In order to purify the Rayleigh wave signal from seismic records, a new method for purification of Rayleigh wave exploration signal is proposed, which is based on the combination of multiple-filter technique and time-frequency filtering of generalized S transform (GSTTF-MT). GSTTF-MT calculation is described in this paper. It illustrates that the GSTTF-MT can be effectively applied to the Rayleigh wave purification through the simulation experiments and engineering examples. After analyzed and compared the advantages and disadvantages of GSTTF-MT and other methods. In conclusion, the method of GSTTF-MT is reliable and stable, and the experience and conclusions can be for reference to extraction of Rayleigh wave dispersion Curve in practical engineering.

***Keywords*—**Rayleigh wave, dispersion curve, Generalized S-transform, Multiple-filter technique.

I. INTRODUCTION

As a non-destructive seismic exploration method, Rayleigh exploration has been widely used in many fields such as subgrade detection [1], advanced geological prediction of tunnels[2-6] and so on. The main principle of Rayleigh wave exploration technology is to extract the Rayleigh wave dispersion curve according to the signal actually detected by Rayleigh wave instrument and to make a reasonable explanation of the physical and mechanical properties of the rock mass according to the dispersion characteristics. However, the signals of Rayleigh waves, P waves, S waves, reflected waves, refracted waves and noises are included in the actual exploration record signals. Therefore, how to eliminate the interference waves and effectively identify the Rayleigh wave signals is the key to Rayleigh wave exploration technology.

At present, there are many methods to extract Rayleigh wave dispersion curve, which are mainly divided into three methods of single track[7], double tracks[8] and multiple tracks[9], but basically based on multi-channel Rayleigh wave technology. Multi-channel Rayleigh wave technology requires a long line survey detector, however, in underground engineering Rayleigh wave test, the underground engineering face surface limited special restrictions, therefore, in this paper, the multiple filtering method and the generalized S-transform time-frequency filtering method are introduced to the purification of Rayleigh wave signals with two channels of data, and a novel Rayleigh wave signal filtering and filtering method based on generalized S-transform time-frequency multiple filtering (hereinafter referred to as GSTTF-MT) is proposed.

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II. GENERALIZED S-TRANSFORM MULTI FILTERING METHOD

The generalized S-transform multiple filtering method is a new Rayleigh wave signal purification method based on the combination of multiple-filter technique and generalized S-transform time-frequency filtering (hereinafter referred to as GSTTF-MT).

The main steps of the method for Rayleigh signal purification are as follows:

1）Read Rayleigh wave original signal and parameters and conduct pretreatment;

2）Multi-filter the signal to get the arrival time of the wave group;

3）According to the obtained information of the arrival time of wave group, contract a time-varying filter based on GST transform;

4）The signal is filtered by a time-varying filter based on a GST transform to obtain a mode-separated fundamental mode signal;

5）Find Rayleigh wave dispersion curve.

The process is shown in Fig. 1.

A. *Multiple filtering method*

Multiple filter method is a frequency time analysis method proposed by scholars such as Dziewaonski and Bloch in 1969~1972[10-11], the basic idea is: the seismic signal is filtered by Gaussian non-phase shift bandpass filter (center frequency is), then the inverse Fourier transform to the time domain, to get the maximum amplitude of the arrival of the frequency group velocity package. Represented as:.

$$h_n(t)=\frac{1}{2\pi}\int_0^{+\infty}\tilde{U}(\omega)H(\omega_n,\omega)e^{-i\omega t}d\omega \quad (1)$$

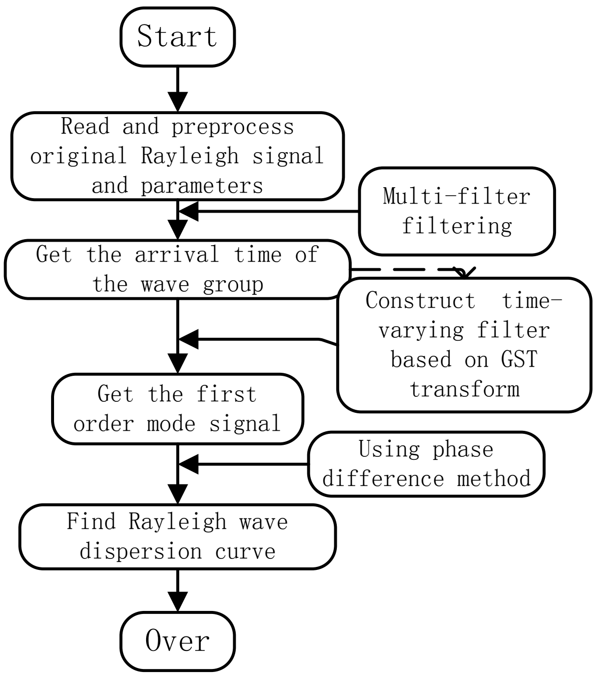


Fig. 1. GSTTF-MT-based filtering flow diagram

In the formula: $U(\omega)$—Rayleigh wave time domain signal Fourier spectrum, $H(\omega_n,\omega)$— Gaussian non-phase shift bandpass filter with center frequency of ω_n, Since no phase-shifted band-pass filter must be conjugate symmetric, filtered to ensure that the time domain signal is real, so its specific expression:

$$H_n(\omega)=\exp\left[-\eta\left(\frac{\omega-\omega_n}{\omega_n}\right)^2\right]+\exp\left[-\eta\left(\frac{\omega+\omega_n}{\omega_n}\right)^2\right] \qquad (\omega>0) \tag{2}$$

After filtering the $h_n(t)$ envelope is:

$$A_n(t)=\sqrt{\{\mathrm{Re}[s_n(t)]\}^2+\{\mathrm{Im}[s_n(t)]\}^2} \tag{3}$$

Which, $s_n(t)=h_n(t)+i\bar{h}_n(t)$, In the formula: $\bar{h}_n(t)$ is the Hilbert transform (HT) of the filtered signal.

B. Time-varying filtering method based on Generalized S-transform

The Generalized S-transform (GST) is proposed in the window of the S-transform (ST) to solve the problem of ST: Only Gaussian windows are considered for use and there are some parameters in the window function that make the time-frequency window width freely adjustable. The mathematical expression:

$$S(\tau,f)=\int_{-\infty}^{+\infty}h(t)\frac{\alpha|f|^{\beta}}{\sqrt{2\pi}}e^{-\frac{\alpha^2 f^{2\beta}(\tau-t)^2}{2}}e^{-i2\pi ft}dt \tag{4}$$

In the formula: f is frequency, τ,t is time, the transformation of τ controls the position of Gaussian window on the time axis, α is Gaussian window amplitude stretch factor, β is frequency scale factor. In practice, when α =1, β =1, GST is ST, when α > 1 or β > 1, the signal time resolution is improved and the frequency resolution is decreased. When α < 1 or β < 1, the frequency resolution of the signal is improved and the time resolution is decreased[12-14]. Due to α and β are real number, so the inverse transformation is the same as that of ST.GST focuses on the advantages of short time Fourier transform (STFT), wavelet transform (WT) and S transform (ST)[15-16]. At the same time, the GST and its inverting change also have the characteristics of nondestructive. GST inverse transformation of mathematical expressions:

$$h(t)=\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}S(\tau,f)dte^{i2\pi ft}df=\int_{-\infty}^{+\infty}X(f)e^{i2\pi ft}df \tag{5}$$

Knopoff and other scholars [17] first proposed a time-varying filter in 1964 and applied it to the analysis of surface wave dispersion. The so-called time-varying filtering is the filtering of the frequency characteristic changing with the recording time. The purpose is to filter the unnecessary information through the time-varying filter, so as to improve the accuracy of Rayleigh wave speed (group velocity and phase velocity). Its mathematical expression is :

$$h(t)=\frac{1}{2\pi}\int_{-\infty}^{+\infty}W(\tau_\omega,\omega)U(\omega)e^{-i\omega t}d\omega \tag{6}$$

In the formula, τ_ω — The frequency of a group of ω waves (or the arrival of a group of waves), $U(\omega)$— Rayleigh wave spectrum, $W(\tau_\omega,c)$ is filter, its mathematical expression is:

$$W(\tau_\omega,\omega)=\begin{cases}B(t-\tau_\omega) & -L(\omega)\le t-\tau_\omega\le L(\omega)\\ 0 & Other\end{cases} \tag{7}$$

In the formula, $B(t-\tau_\omega)$ is time domain window function, $L(\omega)$ is time width.

III. Experimental Study on Refinement of Rayleigh Wave Signal GSTTF-MT

In order to verify the purification effect of GSTTF-MT Rayleigh wave, the simulation experiments were carried out by using the dynamic software LS-DYNA and LS-PREPOST. The stratigraphic model (the main parameters of the model is shown in Table 1) is designed. The LS-DYNA dynamics software is used to simulate the waveform under transient impact of a variety of geological models and then extracted by

LS-PREPOST Under the impact of the load state. Use the accelerated time curve data.

The design of the stratum model mainly refers to the simulation method of Liu Mingxue [18]. Model parameters: The base model is a cylinder of , . Source parameters: loading surface, Duration of action0.5ms、 . In the post-processing software LS-PREPOST, we extract the acceleration time history curve of the particle vibration. The number of sampling points is 1000, the number of recording tracks is 24, the channel spacing and offset are 0.5m and 5m respectively, the sampling interval is 0.2ms and the record length is 0.2s. The formation model parameters are shown in Table 1:.

Table 1 Stratigraphic model parameters

Sequence	H /m	P （Kg/m³）	Modulus of elasticity /（Pa）	Poisson's ratio	Velocity of transverse waves /（m/s）
1	3	2000	3×10^8	0.3	222.87
2	∞	2068	6×10^8	0.45	299.72

A. Rayleigh Wave dispersion Curve extraction

For the above model, two channels are selected for modal separation to extract the dispersion curve. The calculation process is as follows：

1) Multiple filtering, access to its wave group information. The filter used in the multiple filter method is set according to the formula (2), in which the parameter η in the filter is selected based on the experience of Dziewaonski et al., use 50.3[10]. After processing, the arrival information of the wave group is obtained.

2) According to equation (7), we construct GST-based time-varying filter:

$$W(\tau_\omega,\omega)=\begin{cases}\cos\dfrac{\pi(t-\tau_\omega)}{2\Delta t} & -\Delta t\le t-\tau_\omega\le\Delta t\\ 0 & Other\end{cases} \tag{8}$$

In the formula, Δt is the time-varying filter window length, the mathematical expression is：

$$\Delta t=\frac{2\pi}{\omega}\left(\alpha+\beta\left|\frac{dV_g(\omega)}{d\omega}\right|\right) \tag{9}$$

In the formula, $V_g(\omega)$ is the approximate group velocity can be obtained by empirical formula.

$$V_g(\omega)=r/\tau_\omega \tag{10}$$

In the formula, r is the source distance.

GST-based time-varying filter filtering process is as follows: First, the 18th original signal (shown in Fig. 2) is transformed into the domain $f-t$ by GST (shown in Fig. 3).And then time-varying filtering. Wave processing, and then by GST inverse transform to get the first order modal signal (shown in Fig. 3).

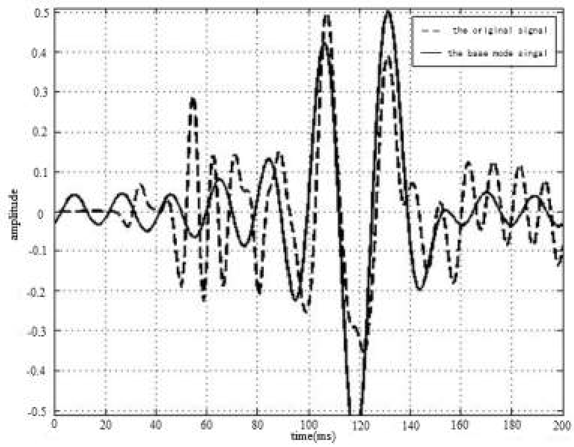


Fig. 2. The original signal of the 18th channel of the model and the fundamental mode signal

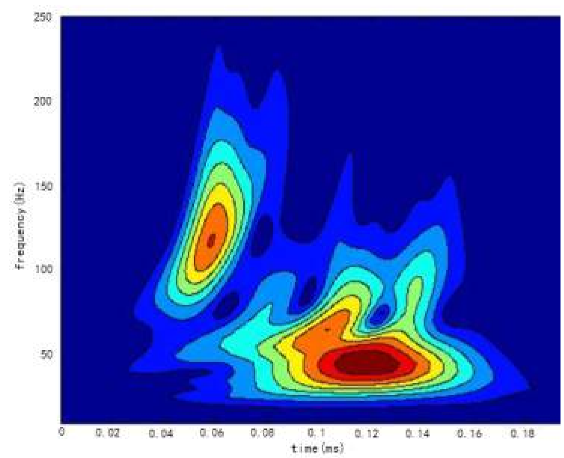
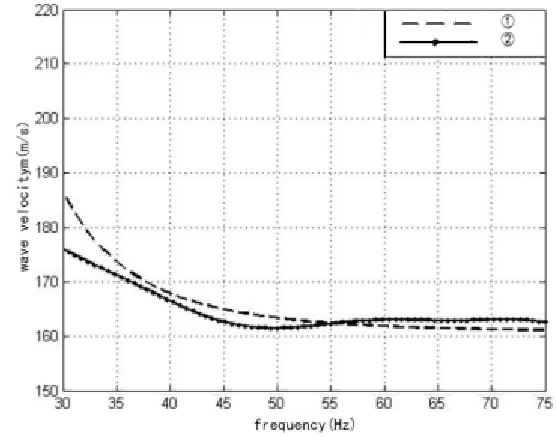


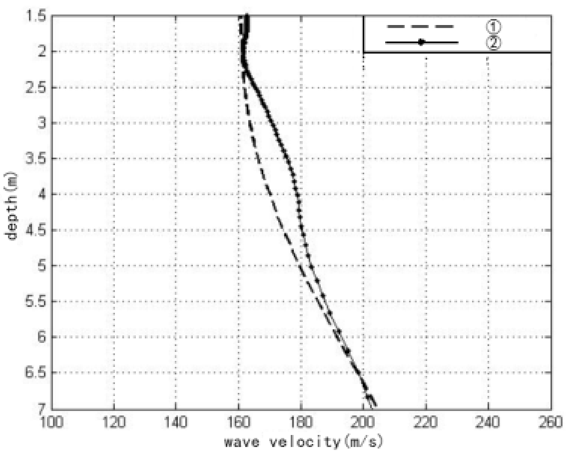
Fig. 3. Model 18th channel signal s domain contour diagram

3) The phase difference method is used to process the fundamental modal signal and the Rayleigh wave dispersion curve is extracted.



(Note: ①-theoretical calculation of dispersion curves; ②-base order modal dispersion curve

(a)

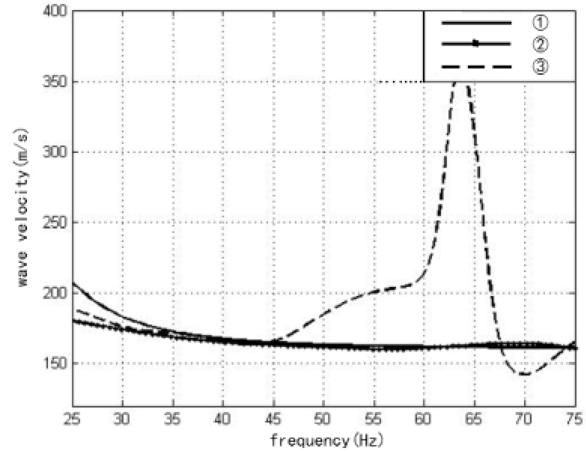


(Note: ①-theoretical calculation of dispersion curves; ②-base order modal dispersion curve

(b)

Fig. 4. Model 18th ~ 19th channel dispersion curve

The result of the frequency dispersion curve extracted from the basic order mode signal after the theoretical calculation, the original signal and the filtering processing is shown in Figure 5. It can be seen from the graph that the dispersion curve of the fundamental mode signal after filtering is almost the same as that of the theoretical curve after 35Hz. The error is less than 5%, but there are still some errors in the part less than 35Hz. The reason may be that the part less than 35Hz is caused by the error of the arrival of the wave group at the arrival of the multiple filter processing. The obtained dispersion curves differ greatly from the theoretical values. Therefore, GSTTF-MT contributes to the extraction of Rayleigh dispersion curve, and proves that it is feasible to apply GSTTF-MT to Rayleigh dispersion curve.



(Note: ①-theoretical calculation of dispersion curves; ②-base order mode dispersion curve; ③- original signal dispersion curve)

Fig. 5. Comparison and Analysis of extracting dispersion Curve

IV. Project Cases

In a section of Xiamen high speed Dehua, the site around the site is relatively flat, and the foundation is rammed and rammed by stratified compaction. The SWS-MS2000 type surface wave meter is used to explore it. The number of tracks is 24, the channel spacing is 1 m, the sampling interval is 1/5 ms, the number of sampling points is 2048, the offset distance is 10 m, and the artificial earthquake signal is excited by the vertical direction of the iron hammer.

The detected time frequency signal and its corresponding $f-k$ domain energy spectrum are shown in Fig. 6 and Fig. 7, respectively. The energy spectrum shows that the fundamental mode energy accounts for most of the energy. Therefore, the number of data is chosen by GSTTF-MT. The results were analyzed and compared, and several representative groups were selected to extract the frequency dispersion curve of Rayleigh wave. As shown in Fig. 8-10. The corresponding comparative analysis of the curves in Fig. 8-10 can be drawn: The GSTTF-MT-based modal separation of the first order modal dispersion curve is nearly consistent with the dispersion curve obtained by solving the $f-k$ method, the error is less than 5%. It can be concluded from the above analysis that the modal separation based on GSTTF-MT is feasible and feasible to extract the fundamental mode dispersion curve and can be used in practical engineering.

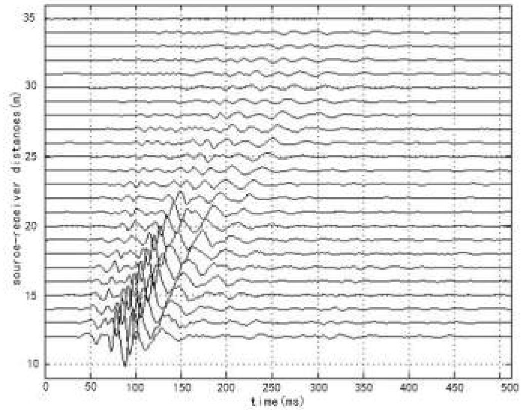


Fig. 6. Rayleigh wave exploration original signal

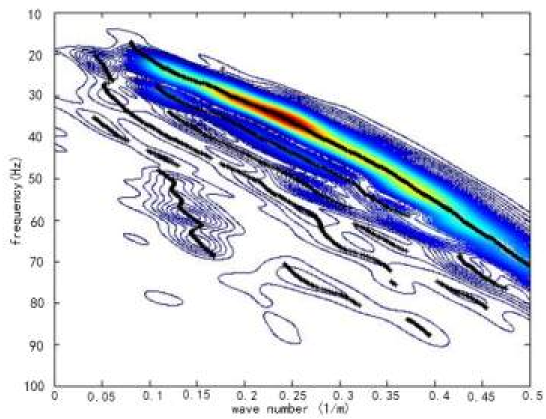
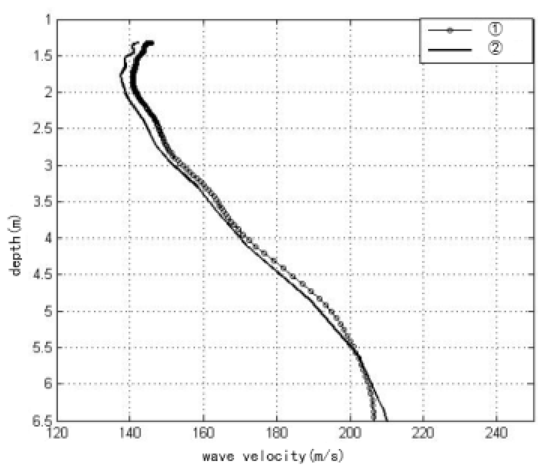
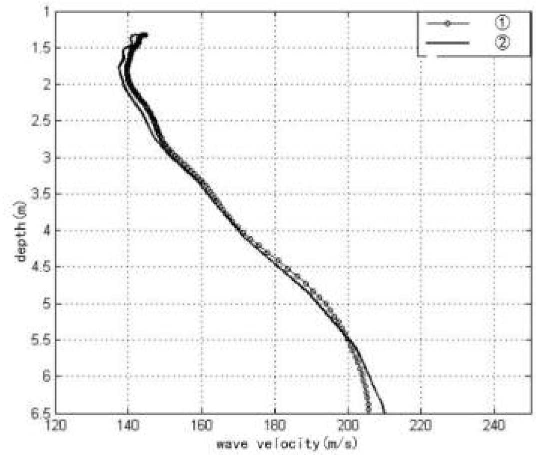


Fig. 7. $f-k$ Domain energy spectrum



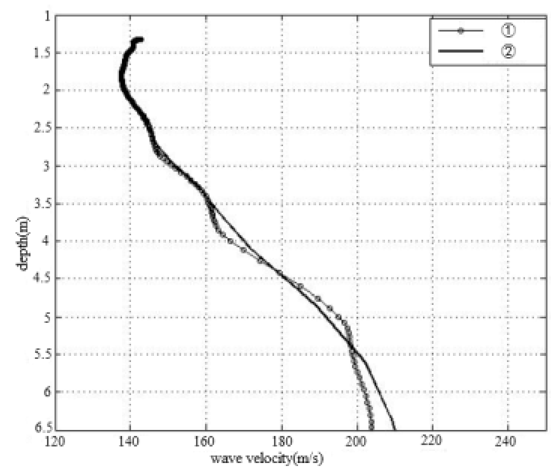
(Note:①- filtering method; ②- $f-k$ method)

Fig. 8. The dispersion curve Chart of the model 17th and 18th data



(Note:①- filtering method; ②- $f-k$ method)

Fig. 9. The dispersion curve Chart of the model 19th and 20th data



(Note:①- filtering method; ②- $f-k$ method)

Fig. 10. The dispersion curve Chart of the model 21th and 22th data

V. The Result and Discussion of Rayleigh Wave Dispersion Curve Extraction

Using the GSTTF-MT method, the dispersion curves of the first order modal extraction $f-V_R$ and the dispersion curve of the theoretical $f-V_R$ are processed by the 18th and the 19th signal of the model as shown in Fig. 4 (a). It can be seen from the figure that the dispersion curve is within 5% of the 35-75 Hz error, which shows that the application of GSTTF-MT can improve the accuracy of dispersion curve extraction. Fig. 4 (b) shows the dispersion curves of the theoretical V_R-H dispersion and the dispersion of the fundamental modal V_R-H obtained from the 18th and 19th signals of the GSTTF-MT method.

VI. Conclusion

This paper presents a new method based on generalized S-transform multiple filtering method for Rayleigh wave signal purification of two channels of data. The result of the frequency dispersion curve extracted from the basic order mode signal after the theoretical calculation, the original signal and the filtering processing is shown in Figure 5. It can be seen from the diagram that the dispersion curve of the base order mode signal after filtering is almost identical with the theoretical curve after the 35Hz, and its error is less than 5%. However, there are still some errors in the part less than 35Hz. The reason may be that the information that is less than 35Hz is caused by the error of the information obtained by multiple filter processing. In addition, the frequency dispersion curve extracted from the original signal is very different from the theoretical value. Therefore, GSTTF-MT is helpful to the extraction of the frequency dispersion curve of Leibo. It is proved that it is feasible to apply GSTTF-MT to the extraction of the frequency dispersion curve of Leibo. The theoretical calculation, simulation and engineering examples show that the GSTTF-MT processing of detection signal is a very effective method to purify two Rayleigh waves and has the advantages of reliability, stability and simple calculation.

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