Response of Borehole Strain Observation Data to Air Pressure Based on EEMD

Hongwei Li and Meiqin Song*
Shanxi Earthquake Agency, Taiyuan, 030021, Shanxi, China
*Corresponding author e-mail: lhw_one@163.com

Abstract. In this paper, based on the empirical mode decomposition (EEMD) method, considering the frequency dependent characteristics of the pressure response, the borehole strain observation data of Daixian station in Shanxi Province and the pressure observation curve of synchronous observation are decomposed, and the eigenmode function (IMF) sequences of different frequency bands are obtained. Then, on the same narrow frequency band of IMF, the one-dimensional regression analysis of borehole strain observation value and pressure change is carried out respectively, and the frequency dependent pressure response coefficient is obtained, which realizes the refined pressure correction of borehole observation data. The results show that this method can effectively deduct the influence of air pressure, and the frequency distribution characteristics of air pressure response are clear.

Keywords: Air Pressure, Borehole Strain, Frequency Dependence, EEMD

1 Introduction
At present, one of the main measuring instruments used for strain observation in the field of seismology is borehole strain gauge. The first borehole strain gauge in the world was successfully developed in the United States in 1968 [1-2], and then carried out earthquake related research in the United States, Japan, China and other regions. In the analysis of borehole strain data, the short-term fluctuation of the observation curve indicates that the observed crustal strain deviates from the normal background value, which may indicate that some degree of crustal deformation or anomaly has occurred near the observation point. The research shows that the pressure fluctuation on the earth's surface will produce the crustal strain of $10^{-9}$ magnitude, especially the high-precision strain gauge is more easily affected by the pressure change [3]. In the analysis of modern crustal strain observation data, this influence cannot be ignored. At present, the analysis of pressure fluctuation mainly depends on the shape ratio and rough correlation analysis, which can not accurately deduct the pressure influence. The micro dynamic changes of the observation curves usually carry a lot of information of tectonic activity and seismic anomalies. Therefore, it is of great significance to eliminate the pressure effect for effectively identifying the seismic anomaly information.

Some scholars at home and abroad have done a lot of research on the effect of atmospheric pressure response on the observation data. When Crossley et al [4], Hu et al [5] studied the influence of the fluctuation of air pressure on the measured value of gravity, he found that the distribution of the
movement energy of the gas varies with the frequency. Compared with the high frequency, the low frequency signal of the atmosphere has higher energy and wider spatial distribution range, so it will cause the influence of the variation of air pressure on the gravity observation to have a certain frequency dependence; It is found that the distribution of gas motion energy varies with the frequency. Compared with the high-frequency band, the low-frequency signal of atmosphere has higher energy and wider spatial distribution range, so the influence of pressure change on gravity observation will be frequency dependent; Wang[6] made quantitative research and Analysis on the air pressure interference in the observation of borehole body strain in Shandong Province; Zhou et al[7] deduced the calculation formula of the air pressure response coefficient of borehole body strain through theoretical analysis, and established the theoretical air pressure interference model of borehole body strain observation; Based on the EEMD decomposition method, Wang Dijin et al[8] proposed a pressure correction method with frequency dependent characteristics. In this paper, based on the research ideas of Wang Dijin et al[8], using the improved method EEMD (ensemble EMD) of empirical mode decomposition (EMD), the observed values of borehole strain are independently decomposed into some narrow-band frequency bands, at the same time, the same processing is carried out for the synchronous pressure observation sequence of the station, and the regression analysis of the strain observation value and the pressure change is carried out on the same frequency band, so as to obtain the frequency dependent pressure response coefficient, so as to carry out the refined pressure correction for the time series of the borehole strain observation.

2 Research Methods
Empirical mode decomposition (EMD) is an important part of Hilbert Huang transform (HHT) method [9]. HHT method is a new method to deal with non-linear and unsteady data, which has been widely used in various fields of Geophysics [10-11]. Compared with the traditional signal decomposition method, the decomposition method used in EMD is intuitive and self-adaptive, which does not include any prior information, and is directly carried out in the time domain on the basis of various inherent characteristics of the data itself.

EMD decomposition steps: first find out all the maximum and minimum points of the original signal \( S(t) \), then use cubic spline interpolation to get the upper and lower envelope lines of the original data series; calculate the mean value of the upper and lower envelope lines to get the average envelope line \( m(t) \), use \( S(t) \) to subtract \( m(t) \), and then get a new sequence \( c_i(t) \) without low frequency. If \( c_i(t) \) satisfies the mathematical conditions of IMF, \( c_i(t) \) is defined as a component of IMF, otherwise, the above steps are repeated with \( c_i(t) \) as the analysis signal until the requirements are met. After EMD, the signal is decomposed into \( n \) IMF components and a signal margin, as shown in Formula 1:

\[
S(t) = \sum_{i=1}^{n} C_i + r_n
\]  

Among them, \( C_i \) represents \( i \) IMF components and \( r_n \) is the residual term.

Wu and Hang[12] further improved the EMD method based on the theory of noise aided data analysis (Nada), and proposed the EEMD (ensemble EMD) method. The core of EEMD method is to add a white noise sequence to the target data in the EMD decomposition process; EEMD method successfully solves the mode mixing problem in EMD decomposition, so that the IMF obtained by decomposition has more centralized frequency information.

3 Experiment and Result Analysis
In order to evaluate the effect of air pressure on the observation curve of borehole strain correctly, it must be done on the basis of no other noise. In order to get the different effects of pressure changes on the observed values of borehole strain in each frequency band, the continuous observation signals of borehole strain in calm period are selected, and they are decomposed into the same frequency band by
using the pressure data synchronously observed with them, and then the correct pressure response coefficient is obtained by linear regression analysis.

Based on the above considerations, the minute value data of drilling strain and synchronous air pressure observation in Daixian station, Shanxi Province, from March 1, 2019 to March 30, 2019 are selected. After removing tide signal (Fig.1), EEMD decomposition is carried out for observation sequence and synchronous air pressure observation respectively. Fig.2 is the IMF result of EEMD decomposition of drilling strain in Daixian after removing tide and air pressure sequence in the same period (only imf2, imf6, imf10 and imf12 are shown in the figure, and 14 IMF sequences and a residual trend term are actually decomposed).

The results show that there is a certain correlation between the residual volume strain and the trend of synchronous pressure observation after tidal correction. Comparing the IMF time series of the two kinds of data, it can be found that the correlation between the borehole strain and pressure change in the low-frequency imf10 signal is very large. The center frequency of imf10 is about 5 days according to the Fourier spectrum analysis, it shows that after removing the influence of tide, the variation of pressure fluctuation in about 5 days has obvious influence on the borehole strain.

![Fig.1 Comparison of tidal effect removal from observation data and atmospheric pressure observation value in the same period](image1)

![Fig.2 EEMD decomposition diagram of borehole strain observation data to remove tide influence and air pressure observation value in the same period](image2)

Fig.3 shows the IMF sequence results of pressure change and borehole strain removal tide observation curve after EEMD decomposition (only imf2, imf3 and imf4 are shown in the figure). It can be seen from the figure that, on the one hand, the IMF of each signal decreases from the first to the second frequency in strict accordance with the decomposition sequence, and there is no modal aliasing; on the other hand, the IMF corresponding to the two signals is concentrated in the same frequency band, and the amplitude spectrum of each group of corresponding IMF has a high similarity, which shows that each IMF has the same frequency band after EEMD decomposition.
Fig. 3 Amplitude spectrum of IMF2-IMF4 obtained by EEMD decomposition of strain and pressure of synchronizer

Two types of observation signals are decomposed into the same narrow band (IMF), and then the correlation coefficients are calculated. The results show that (Fig. 4): the correlation coefficient of the pressure change and the body strain observation sequence with tide removed basically presents a monotonic downward trend from IMF1 to IMF7, that is to say, the lower the frequency is, the lower the correlation between the two signals is; the monotonic upward trend appears again from IMF7 to IMF10, and then the fluctuation decreases. According to the basic judgment relationship given by statistics: the correlation coefficient value between 0.1-0.3 is weak correlation, 0.3-0.5 is medium correlation, and 0.5-1.0 is strong correlation. It shows that the pressure fluctuation of IMF1 to IMF4, IMF10 and IMF11 frequency bands has obvious influence on the borehole strain observation data of Daixian, at the same time, it can be concluded that the response of borehole strain to air pressure changes with the change of frequency, showing a non-linear, non-monotonic correlation.

Using formula (2), calculate the frequency dependent barometric response coefficient for the corresponding IMF of each group of borehole strain observation and barometric observation, and count the energy percentage of each IMF. The calculation results are shown in Table 1 below (excluding the trend term IMF15).

\[ g_c(\Delta f) = g_0(\Delta f) + c(\Delta f) \times P(\Delta f) \] (2)

Where \( G_0(\Delta f) \) and \( P(\Delta f) \) are the observed and barometric changes in the sub frequency band \( \Delta F \). Using the least square method to solve the linear regression equation, the regression coefficient \( C(\Delta f) \) is calculated when \( |G_C(\Delta f)| \) is the minimum value, that is, the pressure response coefficient. The
pressure response coefficient calculated by this method is frequency dependent, so the effect of pressure variation on the observation of fixed-point deformation can be more effectively eliminated.

Table 1 Correlation coefficient, pressure response coefficient and percentage of energy

| Decomposition level | Correlation coefficient | Air pressure response coefficient | Energy percentage |
|---------------------|-------------------------|----------------------------------|------------------|
| 1                   | 0.924                   | 0.829                            | 0.05             |
| 2                   | 0.877                   | 0.768                            | 0.02             |
| 3                   | 0.760                   | 0.608                            | 0.01             |
| 4                   | 0.562                   | 0.366                            | 0.00             |
| 5                   | 0.377                   | 0.159                            | 0.00             |
| 6                   | 0.225                   | 0.048                            | 0.00             |
| 7                   | -0.003                  | 0.000                            | 0.00             |
| 8                   | 0.066                   | -0.001                           | 0.00             |
| 9                   | 0.402                   | 0.026                            | 0.03             |
| 10                  | 0.864                   | 0.350                            | 9.79             |
| 11                  | 0.724                   | 0.271                            | 12.19            |
| 12                  | -0.110                  | -0.203                           | 73.23            |
| 13                  | -0.685                  | -1.532                           | 4.67             |
| 14                  | -0.003                  | -0.001                           | 0.00             |

According to the calculation results in Table 1, take imf10 with the largest correlation coefficient, air pressure response coefficient and energy percentage (the cycle is about 5 days) as an example to conduct one-way regression analysis, and the results are shown in Fig.5. It can be seen from Fig.5(a) that the fluctuation curve of air pressure in this frequency band is relatively consistent with the curve trend of borehole strain observation value, which has a great influence on borehole strain observation value. Therefore, in the actual data analysis, it needs to be deducted quantitatively.

According to the judgment standard of correlation given by statistics, the decomposition layer with correlation coefficient greater than 0.5 is selected as the input data of atmospheric pressure correction, and the original observation curve is corrected according to the frequency of atmospheric pressure. Fig.5(b) is the comparison diagram between the observation curve corrected by atmospheric pressure and the original observation curve. It can be seen from Fig.5(b) that the observation curve corrected by air pressure is smoother than that before correction, and the trend change is more stable. The original short-term fluctuation change has disappeared, which provides a clearer basis for interference analysis.

![Fig. 5 Comparison between single regression results and actual observations (a) and Comparison between atmospheric pressure correction and original observation curve (b)](image-url)
4 Conclusion
In this study, based on the empirical mode decomposition (EEMD) method to correct the pressure effect in the borehole strain observation data of Daixian station, the minute value data of 30 consecutive days from March 1, 2019 to March 30, 2019 is selected as the research object, and the air pressure observation value and borehole strain observation value are decomposed into the intrinsic mode function (IMF) series of different frequency bands by using the adaptive decomposition characteristics of EEMD, then, the regression analysis of deformation observation value and pressure change is carried out on the same narrow frequency band of IMF, and the frequency dependent pressure response coefficient is obtained, so as to make fine pressure correction for the time series of drilling strain observation at Daixian station. The research results will directly serve for the establishment of subsequent abnormal interference database and quantitative prediction index, and also play a certain role in promoting the daily earthquake tracking work.

Acknowledgement
Research Project of Shanxi Earthquake Agency, No. SBK-1923; Youth Science Foundation of Shanxi Province, No. 201901D211550; The Earthquake Tracking Task of CEA, No. 2019010218; The Earthquake Tracking Task of CEA, No. 2018010214.

Reference
[1] Sacks I S, Suyehiro S, Evertson D W. 1971. Sacks-Evertson strainmeter, its installation in Japan and some preliminary results concerning strain steps[J]. Proc. Japan Acad., 47(9):707-712.
[2] Evertson D W. 1975. Borehole strainmeters for Seismology[J]. Rep. ARL-TR-77-62, Applied research Lab. University of Texas, Austin, Texas, 1-144.
[3] Roeloffs E. 2010. Tidal calibration of Plate Boundary Observatory borehole strainmeters: Roles of vertical and shear coupling [J]. JGR, 115, B06405:25.
[4] Crossley D J, Jensen O G, Hinderer J. 1995. Effective barometric admittance and gravity residuals. Phys. Earth Planet. Int., 90(3-4):221-241.
[5] Hu X G, Liu L T, Hinderer J, et al. 2006. Wavelet filter analysis of atmospheric pressure effects in the long-period seismic mode band [J]. Phys. Earth Planet. Int., 154(1):70-84.
[6] Wang M. 2002. Study on correlation of digital body strain data with atmosphere and well water level [J]. Journal of geodesy and geodynamics, 22(4):85-88.
[7] Zhou L S, Qiu Z H, Tang L. 2008. The response of crustal strain field to short-period Atmospheric pressure Variation[J]. Progress In Geophysics, 23(6):1717-1726.
[8] Wang D J, Liu Z W, Wei J, et al. 2018. Method to correct atmospheric pressure effects based on ensemble empirical mode decomposition [J]. Chinese J. Geophys, 61(2):504-520.
[9] Huang N E, Shen Z, Long S R, et al. 1998. The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis [J]. Proceedings A, 54(1971):903-995.
[10] Huang N E, Wu Z H. 2008. A review on Hilbert-Huang transform: method and its applications to geophysical studies [J]. Reviews of Geophysics, 46(2):1-23.
[11] Gu X, Jiang T X, Zhang W Q, et al. 2014. Anomalous signals before 2011 Tohoku-oki Mw 9.1 earthquake, detected by superconducting gravimeters and broadband seismometers [J]. Geodesy and Geodynamics, 5(2):24-31.
[12] Wu Z H, Huang N E. 2009. Ensemble Empirical Mode Decomposition: a noise-assisted data analysis method [J]. Advances in Adaptive Data Analysis, 1(1):1-41.