www.s2is.org
International Journal on Smart Sensing and Intelligent Systems
ISSN 1178-5608

IN-SITU TEST OF PRESSURE PIPELINE VIBRATION BASED ON DATA ACQUISITION AND SIGNAL PROCESSING

Huimin Hou[1], Cundong Xu[2], Hui Liu[2], Rongrong Wang[2], Junkun Nie[2] and Lianying Ding[2]

[1]School of Energy and Power Engineering, Lanzhou University of Technology, Lanzhou, China

[2]School of Water Conservancy, North China University of Water Resources and Electric Power / Collaborative Innovation Center of Water Resources Efficient Utilization and Protection Engineering, Henan Province, Zhengzhou, China

Emails: xucundong@ncwu.edu.cn

Submitted: Nov. 1, 2014 ***Accepted: Jan. 29, 2015*** ***Published: Mar. 1, 2015***

Abstract- Pipeline vibration of high frequency and large amplitude is an important factor that impacts the safe operation of pumping station and the efficiency of the pumps. Through conducting the vibration in-situ test of pipeline system in the pumping station, we can objectively analyze the mechanism of pipeline vibration and evaluate the stability of pipeline operation. By using DASP (data acquisition & signal processing) in the in-situ test on the 2# pipeline of the third pumping station in the general main line of Jingtaichuan electric-lifting irrigation project in Gansu Province (later known as "the general trunk third pumping station in Jingtai electric project") and then adopting time-domain

analysis and cross-spectrum analysis to deal with collected data, we can acquire the vibration state in different positions of pipeline. Tests have shown that, the application of DASP in the vibration test of pressure pipeline of the pumping station, compared to the traditional test systems, can not only obtain higher test accuracy and efficiency, but can also provide theory basis and technical support for solving the vibration problems of the same-type pipeline operation. It has a good promotion value in the engineering practice.

Index terms*:* DASP software, time-domain analysis, cross-spectrum analysis, pressure pipeline.

I. INTRODUCTION

In the large-scale pumping station project in China, the vibration problems of pressure pipeline commonly exist. The long-term and large-amplitude vibration of pressure pipeline can result in fatigue damage to the pipeline, which has a serious influence on the safety operation of water-pumping system and the normal benefit, and even leads to the failure of the structure function of pipeline as well as of its ancillary equipment [1]. So attention must be paid to it. There are many reasons for the vibration of pumping station pressure pipeline, including special operation states, the flow pattern inside pipe, and the arrangement form of buttresses etc. According to the pipeline vibration theory, pipeline vibration is divided into two systems: pipeline system and fluid system [2]. Many scholars at home and abroad have been studying vibration problems for a long time, and achieved considerable progress [3, 4, 5, 6]. Paidoussis [7] reviewed the research results of the analysis for nonlinear vibration of fluid-solid coupling of pipeline [8, 9, 10] in detail; Wood [11] and Williams [12] conducted the theoretical and experimental researches on the influence of pipeline movement respectively, and found that pipeline movement had a great influence on water hammer pressure; Vardy [13] made experiments and calculations to “T”-sharped pipeline system and discovered that coupling effects between liquid and pipeline seriously influenced pipeline vibration response.

Although theoretical researches on pipeline vibration have already achieved remarkable progress, the practical vibration problems of pressure pipeline are very complex. For the constructed pipeline structures, in order to improve the anti-vibration performance, the needed structure parameters including damping coefficients and boundary conditions can be determined by tests.

In addition, intensity, spectrum and even dynamic response of pipeline vibration can also be determined by tests so that we can find the source of vibration and analyze the feasibility of applying vibration isolation, vibration absorption, vibration resistance and other damping technologies to practical engineering. Thus, the research on the in-situ test[14] for vibration of pressure pipeline in the pumping station has great significance for obtaining accurate design parameters and achieving the safety and economic operation of pumping stations.

The common methods for the test of pipeline vibration are electric measurement, mechanical method, optical method and so on, most of which are applicable to the test of crack position, welding defects, corrosive wear, instability and other problems of pipeline and its equipment [15]. However, for the vibration in-situ test of pressure pipeline of the running pumping station, the researchers are still a few, and they are not as deep and extensive as those on the test and analysis of equipment vibration. There is no assessment standard for pipeline system vibration either, and the test systems are relatively few. In addition, traditional test devices of pipeline vibration mainly consist of various hardware instruments. Besides the sensor and amplifier, specialized equipment for vibration recording and analyzing are also needed, such as oscilloscope, signal analyzer, and spectrum analyzer and so on. Therefore the entire system is complicated and costly and only has single function and weak reconfiguration [16, 17]. Thus, this article abandons traditional test methods, applies DASP system to the vibration in-situ test of pressure pipeline of pumping station and analyzes the vibration of pipeline under specific running conditions.

II. DASP TEST SYSTEM

DASP is the integrated test and processing system for vibration, noise test and engineering. It is a virtual instrument storehouse integrating data acquisition, data display, oscilloscope, signal processing, vibration analysis, model analysis, fault diagnosis and many other functions. It has the features of high-integration, multi-function, simple-operation, and high-measurement precision etc. [18, 19, 20]. The system mainly consists of vibration pickup, data line, acquisition front, DASP analysis software, and computer. Figure 1 shows the system connection.

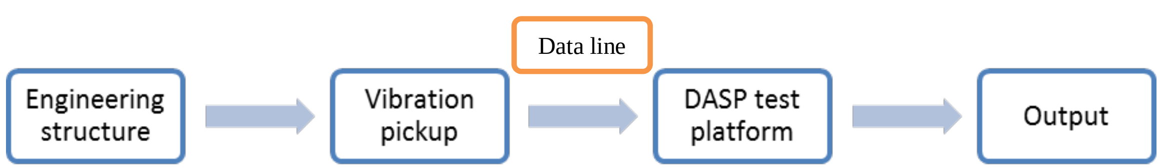


Figure 1 Flow chart of DASP test system

III. TEST OBJECT

This article takes the pressure pipeline of the general trunk third pumping station in Jingtai electric project as the test object for the vibration in-situ test. The layout diagram of the pressure pipeline is shown in Figure 2. The layout of the 2# pressure pipeline of this pumping station can represent the layout patterns of multi-machine single pipe of large-scale pumping stations. On turning on/off the machine, the vibration noise and amplitude are very large, and the long-term vibration would pose a threat to the structure safety of buildings. Therefore it is more representative and universal to use this pressure pipeline as the test object to study.

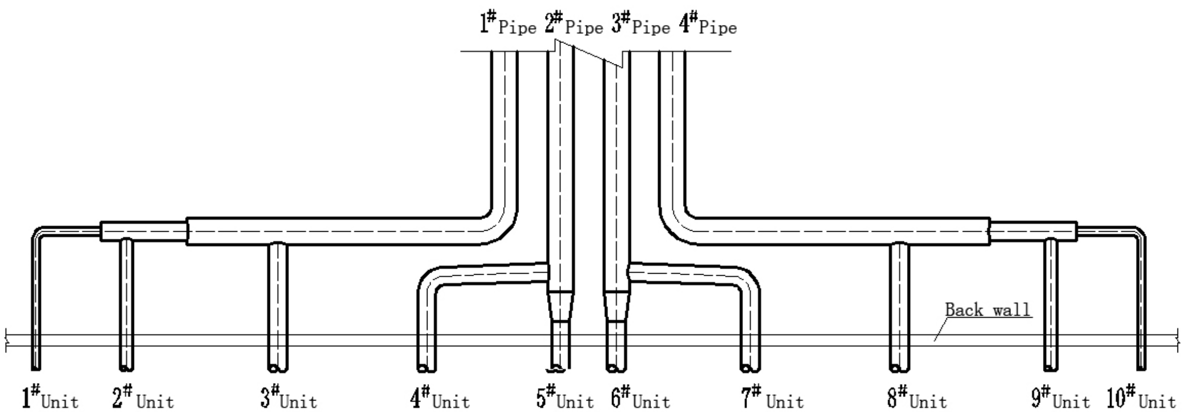


Figure 2 Layout diagram of the pressure pipeline of general trunk third pumping station in Jingtai electric project

The 2# pipe is a bifurcation pipeline. It is a general outlet pipeline aggregated by the outlet of 4# unit and 5# unit, and their diameters are 1700mm, 1200mm, 1200mm respectively. The layout diagram is shown in Figure 3.

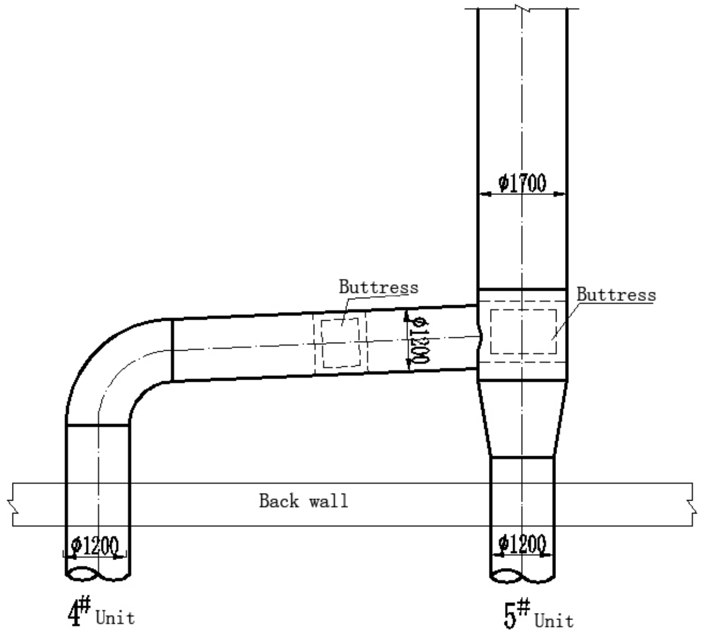


Figure 3 Layout diagram of the 2# pressure pipeline of general trunk third pumping station in Jingtai electric project

IV. TEST MATERIAL AND METHOD

The test object of vibration in-situ test is 2# pipeline; testing conditions are startup condition and stable-operation condition; and the test adopts ADSP-10 (the updated version of DASP) system. Through the vibration signal acquisition of the representative positions of 2# pipeline and the automatic processing for the signal data, we can obtain the oscillogram of the typical measurement points of the pipeline and analyze the vibration state of the measured objects.

a. Vibration sensor

Vibration sensor adopts the 891-2 vibration pickup, the configuration of DASP-V10 system, which can be connected with the recording instrument and data acquisition system. It can be set at accelerated-speed, medium-speed, high-speed and low-speed, respectively corresponding to 1#~4# gears. According to the site conditions and test purposes of the vibration in-situ test of pressure pipeline of pumping station, the gear is switched to 2#, and the corresponding measurement parameters are shown in Table 1.

Table 1: Technical indexes of 891-2 vibration pickup in 2# gear

Sensitivity / $\left(V \cdot s \cdot m^{-1}\right)$	7
Damping constant	0.65
Maximum displacement / m	70
Maximum speed/（m·s^{-1}）	1.4
Passband / $\left(Hz, {}^{+1}_{-3}dB\right)$	1～100
Output load resistance value / $k\Omega$	300
Displacement after connected with the 891 amplifier / m	1×10^{-7}
Speed after connected with the 891 amplifier / (m·s^{-1})	1×10^{-7}

The vibration pickups are placed at the positions which need to be tested. The geometric axis of horizontal vibration pickup should be as horizontal as possible, and the geometric axis of vertical vibration pickup should be as perpendicular as possible to the one of horizontal vibration pickup. Then the vibration pickups are bonded firmly by adhesive.

b. Test method

The arrangement of test points is very important. Generally, test points are selected according to the following principles: try to test the whole pipeline system; test points should include important positions of the pipeline, such as elbows, welds, junction positions of two pipes, and buttresses; select appropriate number and location of test points; and the installation of vibration pickups should be convenient.

Based on the comprehensive consideration of various factors, such as the selection of test points, layout of vibration pickups, and arrangement forms of pipeline and so on, this test selects 6 positions to carry out the vibration test. In order to better test the vibration situation of 2# pipeline under the conditions of startup and stable-operation, a 3-dimension coordination system is established along radial, axial and vertical directions of the pipeline, namely the directions of x, y, z. Three vibration pickups as a group are put together as close as possible, of which two horizontal (x, y), one vertical (z). 6 groups of vibration pickups are placed at the representative positions of the pressure pipeline, for example, near the back wall, elbows, junctions of different-sized pipes, gradients, and buttresses etc.

Before the test, 6 groups of vibration pickups, totally 18, should be encoded and registered one by one. The 1#~3# data lines correspond to the first group of vibration pickups, and respectively correspond to the three directions of the vibration pickups, namely x, y and z. The others are put in the similar way. The specific arrangement is shown in Figure 4.

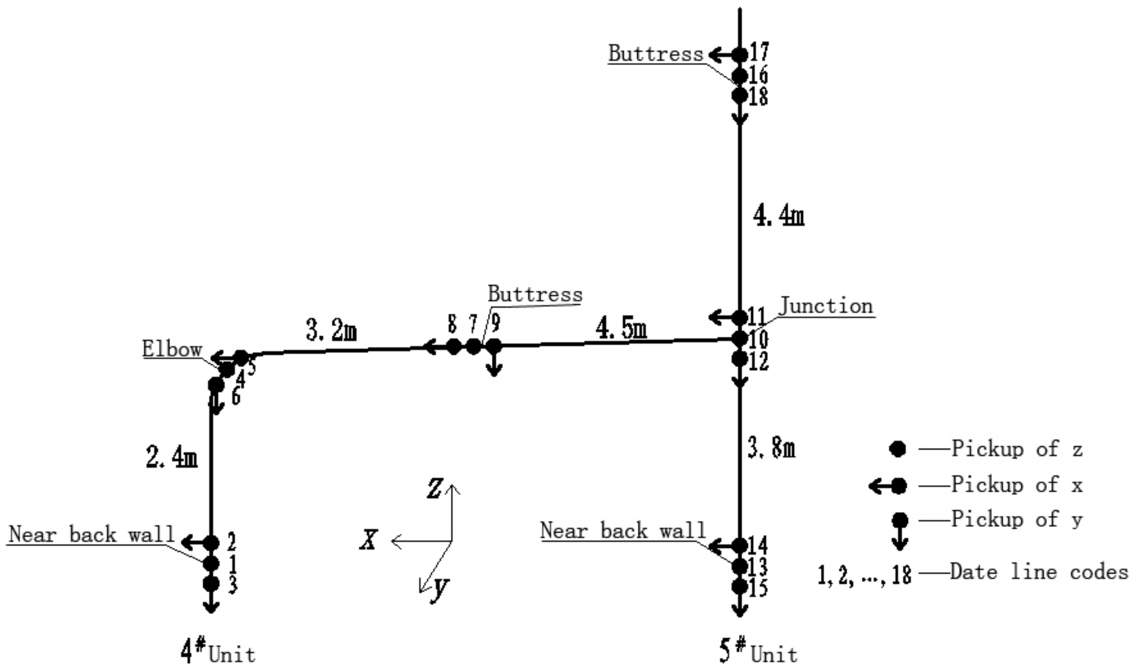


Figure 4 Arrangement diagram of the vibration pickups of DASP test system

V. TEST DATA ACQUISITION AND SIGNAL ANALYSIS

According to the conditions that need to be tested, the whole period from the startup of the 4# unit to its stable-operation is selected as the test time. The vibration signals of each test position in the directions of x, y, and z should be recorded at the same time.

a. Data acquisition

Before sampling the analysis module with the DASP software, we should enter the engineering unit and calibration value of each channel in the parameter setting table of the sampling program. This test uses the 891-2 vibration pickup and sets the engineering unit to be mm/s.

Because the excitation of the in-situ test of pipeline vibration adopts the natural pulse signal, the test uses random sampling method. The test time is 3 minutes and the sampling frequency is 204.8 Hz.

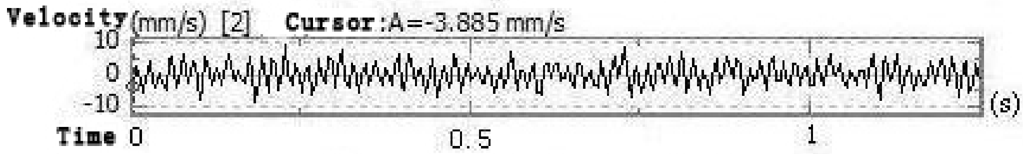
b. Signal analysis

After 180-second sampling test, DASP software system can accurately detect the different-amplitude signals of the representative test points under different conditions, automatically process the data, and generate oscillograms.

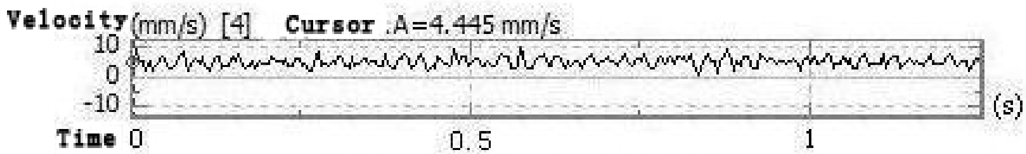
This article uses time-domain analysis and cross-spectrum analysis to analyze the collected vibration signals. Time-domain and frequency-domain are the essential properties of signals, and two observation aspects for the analog signal. They analyze signals from two different perspectives, respectively time and frequency. Time-domain analysis [21, 22] uses timeline as the coordinate to show the relationship of the dynamic signals, which is more visual and intuitive; while frequency-domain analysis [23, 24] expresses the signals with the frequency-axis coordinate, which is more concise and convenient, and the cross-spectrum [25] is one kind of frequency-domain analysis.

b.i. Time-domain analysis

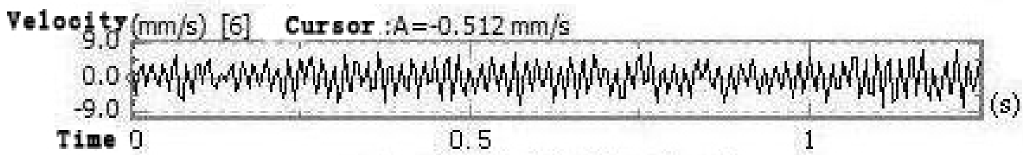
The collected data of the 18 vibration pickups correspondingly generate 18 oscillograms, which can be analyzed with time-domain analysis. This paper selects 4 of them as the representatives, and intercepts the waveforms of 0~1.2s to generate images, as shown in Figure 5.



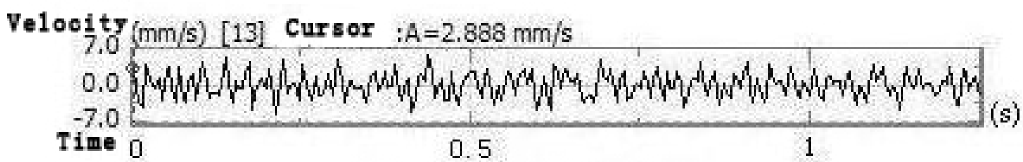
(a) No. 2 point time domain analysis waveform figure



(b) No. 4 point time domain analysis waveform figure



(c) No. 6 point time domain analysis waveform figure



(d) No.13 point time domain analysis waveform figure

Figure 5 Generated images of waveforms of time-domain analysis

In Figure 5, the differences among oscillograms of test points are obvious. We use DASP analysis software to conduct the cross-correlation analysis on the vibration signals in the directions of x, y, z of each position of the pipeline, and use instantaneous rolling analysis in parameter setting. Table 2 shows the calculation results of correlation.

Table 2: Correlation coefficients of the test points vibration in the directions of x, y, z

Test point	**Correlation coefficient**	**Test point**	**Correlation coefficient**
1&2	-0.377	10&11	0.043
1&3	-0.29	10&12	0.26

2&3	0.068	11&12	0.216
3&4	0.327	13&14	0.058
3&5	-0.388	13&15	0.109
5&6	-0.653	14&15	-0.389
7&8	-0.17	16&17	-0.091
7&9	-0.298	16&18	-0.021
8&9	0.059	17&18	0.01

It can be seen from Table 2 that, all of the vibration signals in the directions of x, y and z have correlation with each other. If the correlation coefficient is bigger, the vibration states in two directions are synchronous; and if it is smaller, the vibration in one direction is intense while another weak. We can know from Table 2 that the correlation coefficient of 5#&6# test points is the biggest one and vibration signals in axial and radial directions of would superimpose. 5#&6# test points are located at elbow in the plane position, which indicates that the vibration of 5#&6# test points is stronger and resonance phenomenon may occur.

In order to further analyze the test points accurately, the time-domain indexes are calculated by statistics. The results are in Table 3.

Table 3: Calculated results of sectional time-domain indexes

point	**Mean /(mm·s^{-1})**	**Standard deviation /(mm·s^{-1})**	**Kurtosis index**
1	-0.21	1.84	32.01
2	-0.01	3.85	487.94
3	0.01	1.89	24.61
4	5.1	1.94	41.74
5	0	2.84	168.18
6	-0.02	3.59	343.89
13	-0.03	2.56	121.75
14	-0.49	3.23	301.69
15	0	1.19	6.33
16	-0.11	2.75	154.37
17	0	1.9	34.11
18	0.16	0.57	0.29

Note: Kurtosis index is a numerical statistics that reflects the distribution property of vibration signals, which is used in the diagnosis of surface damage fault.

From the analysis on the means, the mean velocities of all the test points except 4# are near zero. In Figure 5, it can also be seen that the waveform of 4# test point is rather special, deviating from zero baseline. The mean velocity of 4# test point is 5.10 mm/s. From Table 2, we can know that the vibration of 4# test point is stronger. It makes the vibration pickups vibrate intensively and slightly slid off the relative positions of the test points, which leads to the signal baseline-drifting. We can compile the waveform through waveform pluses/subtraction a direct-current value, and then the signal baseline can be moved to zero, which has no influence on signal analysis.

From the analysis of standard deviation which can reflect the degree that the data of each signal deviate from mean value, the standard deviation of 2# test point is the biggest, indicating that the vibration of 2# test point is relatively stronger than others or the pipeline vibration of 2# test point is the strongest. From the analysis of Kurtosis index, the Kurtosis index of 2# test point is the biggest. In other words, 2# test point is the position where the damage of pipeline vibration is the most serious. In addition, the damage at the positions of 6#&13# test points is also more serious. In the horizontal plane, 2#&13# test points are near the back wall and connected with the outlets of pumps. It shows that the vibration at the pumps' outlets is the strongest and the damage caused by vibration is also the most serious.

b.ii. Cross-spectrum analysis

Through the time-domain analysis on the vibration signals, it can be known that the vibration amplitudes of 2#&6# test points are larger and located in the same plane. In order to study the cyclical fluctuation and interrelationship of the various frequency components of the two signal sequences, this article makes cross-spectrum analysis of the signals and analyzes the vibration problems of pressure pipeline from the aspect of frequency-domain, which can reduce the difference of the results due to the analyzers' subjectivity judgment, and make the conclusions more scientific and objective.

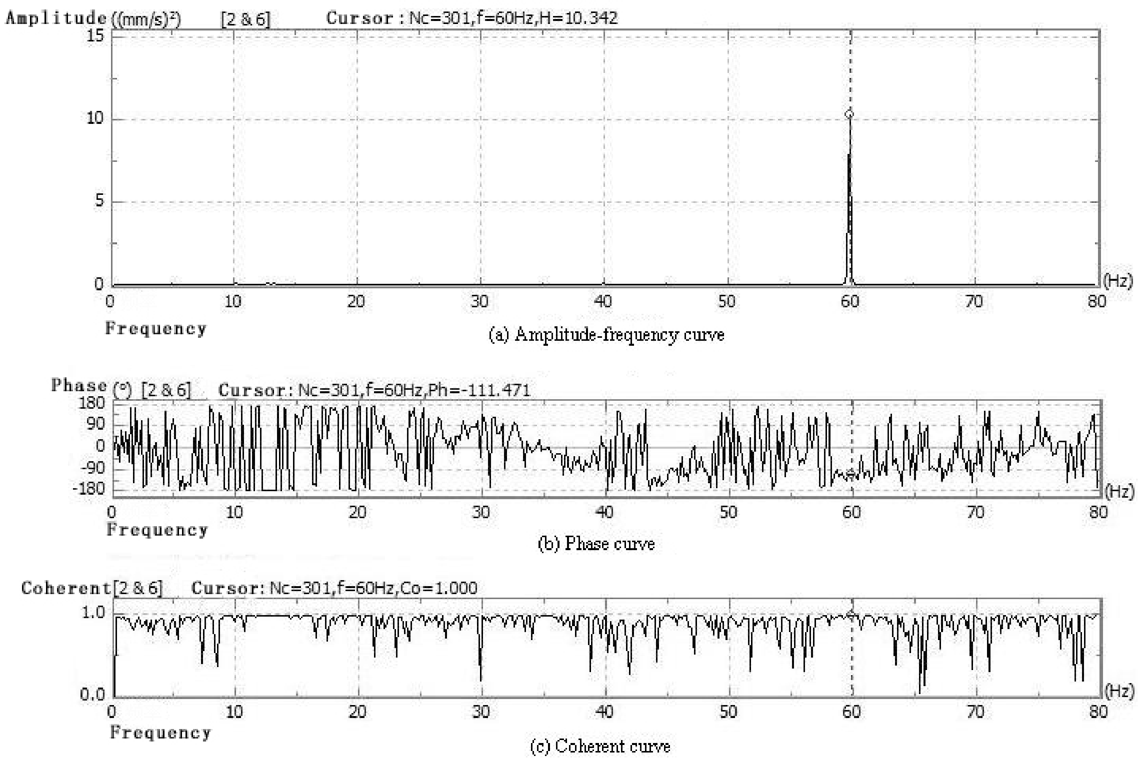


Figure 6 Output of cross-spectrum analysis results of 2#&6# test points

Cross-spectrum analysis indicates the common components and the relationship of phase difference of the two spectrums obtained by the two time-domain signal sequences in the frequency-domain. That is to make cross-spectrum calculation to the two signals, including amplitude-frequency, phase-frequency and other coherent calculations, as shown in Figure 6. Graph (a) the amplitude-frequency curve has an obvious peak, namely H = 10.342 (mm/s) corresponding to frequency f = 60 Hz, phase ph = -111.471˚, and coherent coefficient C0 = 1.0.

Phase cross-spectrum represents the mean of phase change of the components whose frequencies are f in the two signal sequences, expressed in radian and valued in [-π,"π"]. It reflects the relationship of precedence or lag between the two signal sequences in each frequency. If the value of phase cross-spectrum is negative, in the frequency f, 2# test point precedes over 6# test point; conversely, 2# test point lags behind 6# test point. In Graph (b) the phase curve, when Ph = -111,471˚ and f = 60 Hz, 2# test point precedes 6# test point and the phase difference is 111.471, which indicates that the signal sequence change of 2# test point is ahead of that of 6#. It quantificationally proves that the vibration of 2# test triggers that of 6#.

Coherent cross-spectrum is the standardized mean of the amplitude products of the components, of which the frequencies are f in the two signal sequences and valued in (0, 1). It reflects the influence level of the external incoherent noise in the cross-spectrum calculation for the two signal sequences. The larger the coherent is, the smaller the external influence is. In Graph (c) the coherent curve, when the coherent coefficient C0 = 1.0, it can be analyzed that 2#&6# test points have a great coherence in the frequency f = 60 Hz, namely correlation. Meanwhile, it indicates that noise has tiny influence on the vibration of 2#&6# test points. This proves the intimate correlation between 2# and 6# test points from the aspect of frequency-domain in time series.

It can be seen from the above analysis of data that the vibration signals of pressure pipeline of pumping station can be well observed, and the tested signals of different test points have certain differences. Through the time-domain analysis on the vibration signals of different test points, the vibration states at different positions of pipeline can be acquired. The vibration amplitudes of 2#, 6#, and 13# test points are larger, corresponding to the outlets of pumps and elbows, which agrees with the observed phenomenon. The potential safety hazards are serious, so attention must be paid. The cross-spectrum analysis on 2#&6# test points indicates that the noise produced by the running of pumping station has tiny influence on the vibration of pressure pipeline. The vibration of 6# test point has great relation to the vibration of 2# test point, showing that solving the vibration problems of elbows can mainly start from the outlets of pumps.

VI. CONCLUSIONS

The vibration signals of 2# pipeline of the general trunk third pumping station in Jingtai electric project have good observability and some differences. The vibration of 5#&6# test points located at elbow is stronger and the vibration of 2#&13# test points at the pumps' outlets is also intense. If resonance, it will causes serious harm to the pipeline. While it can be seen from the cross-spectrum analysis that the running noise of pumping station has little influence on the vibration of pipeline, thus it should focus on the pumps' outlets to solve the vibration problem of pipeline.

Through the in-situ test and analysis of 2# pipeline of the general trunk third pumping station in Jingtai electric project, it is shown that, under the condition that pressure pipeline of pumping station is under the coupling influence of multi excitation sources, real-time monitoring of pipeline vibration can be realized by applying DASP system to signal acquisition and real-time analysis of pipeline vibration. Besides, the rapid acquisition and analysis of signal data can come true. It overcomes the problem that the vibration sources of pressure pipeline are hard to identify under natural excitation sources. Compared to the traditional test systems, it has higher test accuracy and efficiency.

By adopting DASP test system to carry out the in-situ test of pipeline vibration, we can make correlation analysis of the signals of different positions and directions from the aspects of time-domain and frequency-domain, and obtain the vibration states of different positions. The analysis results of the test are in agreement with the practical situation. Therefore it can be seen that the test is reliable. Thus, the research achievement can not only offer powerful theoretical foundation and technical support for the safety operation and management of the general trunk third pumping station in Jingtai electric project, but also provide helpful reference for vibration problems of pressure pipeline of the same-kind hydraulic structure, such as water pump station and hydroelectric station and so on. It is well worth being promoted in the engineering practice.

VII. ACKNOWLEDGEMENT

This work was financially supported by the “Natural Science Foundation of China (51279064; 31360204)”, the “Supported by Program for Science & Technology Innovation Talents in Universities of Henan Province (14HASTIT047)” and the “Supported by Program for Innovative Research Team (in Science and Technology) in University of Henan Province (14IRTSTHN028)”.

REFERENCES

[1] Alavinasab Ali, Jha Ratneshwar, Ahmadi, Goodarz. “Damage identification based on modal analysis of prestressed concrete pipes”, Pipelines 2011: A Sound Conduit for Sharing Solutions - Proceedings of the Pipelines 2011 Conference, 2011, pp.12-23.

[2] Li Gong-fa, Gu Yue-sheng, Wu Ze-hao, et al., “Vibration model of pipe conveying fluid considered fluid structure interaction”, Sensors and Transducers, Vol.16, no.SPEC.1, 2012, pp.197-202.

[3] Li Shuai-jun, Liu Gong-min, Kong Wei-tao, et al., “Vibration analysis of pipes conveying fluid by transfer matrix method”, Nuclear Engineering and Design, Vol.266, 2014, pp.78-88.

[4] Fan, D., Tijsseling A., “Fluid-structure interaction with cavitation in transient pipe flows”, Journal of Fluids Engineering, Transactions of the ASME, Vol.114, no.2, 1992, pp.268-274.

[5] Singh, Mayand Pratap, Tripathi et al., “FPGA based vibration control of a mass varying two-degree of freedom system”, International Journal on Smart Sensing and Intelligent Systems, Vol. 4, no. 4, 2011, pp. 698-709.
[6] Zhang Xiaoming, Liu Jianmin, Qiao Xinyong, et al., “The Analysis on the High-pressure Pipe Vibration Signal of 12150L Fuel Injection System with Wavelet Transform”, Proceedings of the International Symposium on Test and Measurement, Vol.3, 2003, pp.2565-2568.
[7] Paidousis M P. Issid N T, “Dynamics stability of pipes conveying fluid”, Journal of Sound and Vibration, Vol. 33, no. 2, 1974, pp. 267-294.
[8] Du Jian-Hua, Ouyang Zhi-wei, Zhao Yang-dong, “Damage identification method with structural frequency data from modal test”, Komunikacie, Vol.11, no.1,2009, pp.50-54.
[9] Xu Yuan-zhi, Johnston D. Nigel, Jiao Zong-xia, et al., “Frequency modelling and solution of fluid-structure interaction in complex pipelines”, Journal of Sound and Vibration, Vol.333, 2014, pp.2800-2822.
[10] Keramat A, Tijsseling, Tijsseling A. S., Hou Q, et al., “Fluid-structure interaction with pipe-wall viscoelasticity during water hammer”, Journal of Fluids and Structures, Vol.28, 2012, pp.434-455.
[11] D J Wood, “A Study of Response of Coupled Liquid Flow-structural Systems Subjected to Periodic Disturbances”, ASME Journal of Basic Engineering, Vol. 90, no. 5, 1968, pp. 532-540.
[12] D J Williams, “Waterhammer in Non-rigid Pipes: precursor Waves and Mechanical Damping”, ImechE Journal of Basic engineering Science, Vol. 19, no. 1, 1977, pp. 237-242.
[13] A E Vardy, D Fan, “Fluid Structure Interaction in a T-piece Pipe”, Journal of Fluids and Structures, Vol. 10, no. 1, 1996, pp. 763-786.
[14] Chen Hao, Nan Zhuo-tong, “Wireless sensor network applications in cold alpine area of west china: Experiences and chanllenges”, International Journal on Smart Sensing and Intelligent Systems, Vol. 6, no. 3, 2013, pp. 932-952.
[15] Peng Xue-Lin, Hao Hong, “A numerical study of damage detection of underwater pipeline using vibration-based method”, International Journal of Structural Stability and Dynamics, Vol.12, no.3, 2012.
[16] Ren Liang, Jia Zi-guang, Ho, Michael Siu Chun, et al., “Application of fiber Bragg grating based strain sensor in pipeline vortex-induced vibration measurement”, Science China-Technological Sciences, Vol.57, no.9, 2014, pp.1714-1720.
[17] Gao, Y., Brennan, M.J., Joseph, P.F., et al., “On the selection of acoustic/vibration sensors for leak detection in plastic water pipes”, Journal of Sound and Vibration, Vol.283, no.3-5, 2005, pp.927-941.
[18] Liu Xiang, Gao Zhenning, Kong Jiangtao, “Research on dynamic behaviour of wind tower under ambient excitation based on DASP”, Advanced Materials Research, Vol.243-249, 2011, pp.1248-1252.
[19] Zhang Ming, Jiao Feng, “Ultrasonic vibration characteristics of nano-composite ceramic in the ultrasonic polishing process”, Key Engineering Materials, Vol.522, 2012, pp.147-151.

[20] Shuai Wang, Dezhi Zheng, Shangchun Fan, “Analysis on vibration characteristics of coriolis mass flow sensor”, ICEMI 2009 - Proceedings of 9th International Conference on Electronic Measurement and Instruments, 2009, pp.2842-2845.

[21] Sharan, S.K., “Time-domain analysis of infinite fluid vibration”, International Journal for Numerical Methods in Engineering, Vol.24, no.5, 1987, pp.945-958.

[22] Cao Bochao, Sarkar Partha P., “Extraction of rational functions by forced vibration method for time-domain analysis of long-span bridges”, Wind and Structures, An International Journal, Vol.16, no.6, 2013, pp.561-577.

[23] T.Ohji, S.C.Mukhopadhyay, M.Iwahara and S.Yamada, "Permanent Magnet Bearings for Horizontal and Veryical Shaft Machines - A Comparative Study", Journal of Applied Physics, Vol. 85, No. 8, pp 4648-4650, April 1999.

[24] Khoa Viet Nguyen, “Dynamic Analysis of a Cracked Beam-Like Bridge Subjected to Earthquake and Moving Vehicle”, Advances in Structural Engineering,Vol.18, no.1, 2015, pp.75-95.

[25] T.Ohji, M.Kano, S.C.Mukhopadhyay, M.Iwahara and S.Yamada, “Characteristics of Rotating Vibration of Repulsive Type Magnetic Bearing Using Permanent Magnet”, Journal of Magnetic Society of Japan, Vol. 24, No.4-2, pp. 1011-1014, 2000.

[26] Hou Ji-lin, Jankowski Lukasz, Ou Jin-ping, “Frequency-Domain Substructure Isolation for Local Damage Identification”, Advances in Structural Engineering, Vol.18, no.1, 2015, pp.137-153.

[27] S.C.Mukhopadhyay, T.Ohji, T.Kuwahara, M.Iwahara, S.Yamada, F.Matsumura, "Comparative Studies of Levitation and Control Performances of Two Types Single Axis Controlled Repulsive Type Magnetic Bearing", NASA periodicals, Vol. NASA/CP-1998-207654, pp 393-405, May 1998.

[28] Liu Jie, Wang Wilson, Ma Fai, “Bearing system health condition monitoring using a wavelet cross-spectrum analysis technique”, Journal of Vibration and Control, Vol.18, no.7, 2012, pp.953-963.