RESEARCH ON THE VIBRATION ISOLATION EFFECT BASED ON THE IMPEDANCE RELATION OF COMPLEX MECHANICAL SYSTEM

Wuhui Wu

China Ship Development and Design Center,National Key Laboratory on Ship Vibration & Noise,Hubei,Wuhan 430064,China
email: 623800318@qq.com

The complex mechanical system consists of elastic elements such as vibration isolators and flexible joints and rigid components such as mechanical equipment and support pipelines. In the steady operation state of complex mechanical systems, the multi-system impedance of elastic elements and rigid elements is the main factor that affects the system vibration isolation and transmission loss. In this article, a double-layer vibration isolation mechanical system was developed, and two kinds of system impedance mathematical models were established by the test method of hammer excitation to obtain the initial impedance of complex mechanical system which was used as a reference. By adjusting the structural strength of the mechanical system base and the supporting stiffness of the piping system, the relationship between the system impedance of the two types and the vibration isolation effect of the mechanical system and the transmission loss of the pipeline system were studied. The quantitative relation between the vibration isolation system of double-layer vibration isolation mechanical system and the transmission loss of pipeline and the system impedance of two types was obtained. The experimental results showed that the appropriate increase of the system impedance of the base was beneficial to the vibration isolation effect of the vibration isolation device. Concerning the system with weak base impedance, if the vibration isolation effect of vibration isolation system fails to meet the design requirement, the appropriate increase of the impedance of test base is an effective solution to satisfy the vibration isolation effect. By changing the properties and installation layout of the flexible components of the piping system, the transmission loss the vibration energy of the flexible piping system can be increased, reducing the base level of vibration isolation system effectively and increasing the vibration isolation effect of the system.
Keywords: double-layer vibration isolation system,transmission loss, impedance

1. Introduction

Complex mechanical system is generally composed of four parts including two or more auxiliary equipment, vibration isolation device, installation base and system piping. The vibration isolation effect generally refers to the difference between the total energy levels of the excitation source of auxiliary equipment and the installation base. As the vibration source, the auxiliary machine generates excitation, which will be transmitted to vibration isolation device through the elastic contact of the equipment foot and the vibration isolator. After the excitation source is transmitted through the vibration isolation device, it will be transmitted to installation base through the elastic contact surface between the vibration isolation device and installation base. Apart from being transmitted to the installation base through the vibration isolation device, the equipment excitation source can also be transmitted to the installation base through system pipeline. The equipment excitation will first be transmitted to the system pipeline from the flexible pipe and then transmitted by the pipe to the installation base through the support foot and the outlet valve. The whole mechanical vibration isolation system can be divided into four independent subsystems, and the impedance characteristics of each subsystem structure are the main factors influencing the energy level transmitted from equipment excitation source to installation base. By selecting objective parameters to describe the characteristics of each substructure, the expression method which describes mechanical vibration isolation system can be formed. The sub-structure method based on frequency response function (FRF) is an effective method to analyze complex composite structure. Its basic principle is to use a single uncoupled component FRF to form the total system response through impedance or admittance equation. This method can directly calculate the higher frequency bands by using the FRF from actual test without building accurate models for complex structural models. Therefore, this method is particularly suitable for the situations in which resolution or numerical models cannot be established or the actual structures are relatively complex. Besides, the method can also use the experimental data directly to avoid the additional loss caused by modal decomposition. It will be possible to use the multiple analysis methods such as theoretical analysis, finite element analysis and experimental data. While in the practical engineering application, concerning the examination of the vibration isolation effect of the complex mechanical vibration isolation system, the impedance between independent sub-system structures has very strong coupling. Carrying out the research on the impedance relation of the sub-structure of complex mechanical vibration isolation system is of great importance for the study on the optimal acoustic performance of the vibration isolation system.

2. The foot transmission theory of excitation source

As shown in Fig. 1, the equations of V_R, the transmission loss of the single-layer vibration isolator installed on non-rigid test base, L_V, the difference of vibration grades and V_2, the vibration speed of the base are:

$$V_R = \frac{V_2}{V_1} = \frac{Z_K}{Z_L + Z_K} \tag{1}$$

$$L_V = 20log\frac{1}{V_R} = 20log\frac{Z_L + Z_K}{Z_K} \tag{2}$$

$$V_2 = \frac{F_1}{(1+\frac{Z_m}{Z_k})Z_L + Z_m} \tag{3}$$

Wherein: F_1 is the input acting force; Z_K is the input impedance of the isolator; Z_m is the input impedance of the device, Z_L is the input impedance of the non-rigid test base, V_1 is the vibration speed of device foot after the isolator is installed.

It can be seen from Eq. (2) and Eq. (3), the influence of the impedance of installation base for vibration isolation effect and the vibration speed of the base is: when F_1, V_1 and Z_K are constant, if Z_L is reduced, V_R will increase, L_V will reduce and V_2 will increase. This means when the impedance of the base is reduced, the vibration speed of the installation base increases.

It can be found from Eq. (2) and Eq. (3), the influence of test installation impedance for vibration isolation effect and the vibration speed of the base is: when F_1, V_1 and Z_K are constant, if Z_L is reduced, V_R will increase, L_V will reduce and V_2 will increase. This means when the impedance of the base is reduced, the vibration speed of the installation base will increase.

Assume that L_{V1} and L_{V2} are the vibration grades of different installation bases, and Z_{L1} and Z_{L2} are the impedance of different installation bases, then:

$$\begin{gathered} L_{V1} = 20log\frac{Z_{L1} + Z_K}{Z_K}, L_{V2} = 20log\frac{Z_{L2} + Z_K}{Z_K} \\ L_{V1} - L_{V2} = 20log\frac{Z_{L1} + Z_K}{Z_{L2} + Z_K} \end{gathered} \tag{4}$$

Usually, when Z_{L1} and Z_{L2} are much greater than Z_K, then:

$$20log\frac{Z_{L1}+Z_K}{Z_{L2}+Z_K}\approx 20log\frac{Z_{L1}}{Z_{L2}}=L_{ZL1}-L_{ZL2}=\Delta L_{ZL} \tag{5}$$

In the frequency domain, the following can be concluded at a certain frequency point f:

$$L_{V1}(f)=L_{V2}(f)+\Delta L_{ZL}(f) \tag{6}$$

When the same vibration isolator is tested on two types of bases, the structural vibration of the bases are similar; if the impedance of the two bases are different, the structural vibration of the two bases are different, and the difference can be estimated based on equation (6).

According to the expression method of the single-layer vibration isolator, as shown in Fig. 2, the equation for the vibration effect of the double-layer vibration isolator installed on the non-rigid base can is:

Transmission loss V_R

$$V_R=\frac{V_4}{V_1}=\frac{Z_K}{T_{21}Z_L+T_{22}Z_K} \tag{7}$$

In the equation, V_1 is the vibration speed of the foot after the vibration isolator is installed, V_4 is the vibration speed of the base after the vibration device is installed, and Z_L is the input impedance of the non-rigid test base.

$$\begin{aligned}T_{21}&=HK_1\beta_{11}+\beta_{21}+HK_2(HK_1\beta_{12}+\beta_{22})\\T_{22}&=HK_1\beta_{12}+\beta_{22}\end{aligned} \tag{8}$$

HK_1 is the input transducer admittance of upper-layer isolator; HK_2 is the input transducer admittance of lower-layer isolator; β_{11}, β_{12}, β_{21}, β_{22} are respectively the four-way parameters of the middle vibration isolation device.

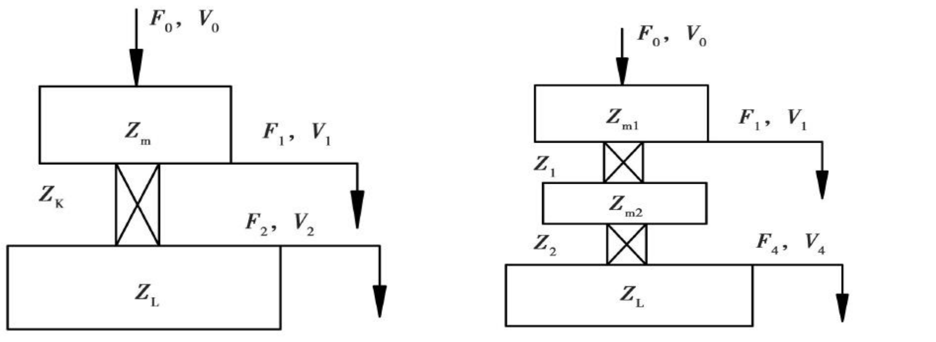
In general, $|T_{21}|>|T_{22}|$, and $|Z_L|>1$, if $|Z_L|$ is reduced, the basic installation ratio of V_R will increase, and the installation ratio of vibration isolation effect will reduce.

The difference of vibration grade L_V

$$L_V=20log\frac{V_1}{V_4}=20log\left\{\left[\mu\frac{f_t}{f_0}\right]^2+\left[\left[\mu\frac{f_t}{f_0}\right]^2-(\mu+2)\right]Q-1\right\} \tag{9}$$

μ is the ratio of the quality of the middle isolator and the device f_t is the dominant frequency of the device set. f_0 is the inherent frequency of the upper-layer vibration isolator in the vertical direction. And Q is the ratio of impedance of the base and the lower-layer isolator.

It can be seen from Eq. (8) and Eq. (9) that when μ, f_t, f_0 and Z_2 (the impedance of lower-layer vibration isolator is a certain value), when Z_L (the impedance of the base) is reduced, the transmission loss, V_R increases, and the difference of vibration level, L_V reduces. For the corresponding device set with constant vibration speed, the vibration speed of the bases increases.



a. Single-layer vibration isolation b. Double-layer vibration isolation

Fig. 1: Foot transmission loss of excitation source equipment.

3. The transmission theory of the flexible pipeline of excitation source

As shown in Fig. 2, assume face S1 is the installation surface of the flexible pipeline of the auxiliary equipment, and face S2 is the installation service of the flexible pipeline and rigid pipeline; face S3 is the support surface of rigid pipe and the base. The relationship between the transmission loss and mechanical impedance of the flexible pipeline is deduced based on the unidirectional movement along the coordinate direction of axis y. Without considering the mutual influence of the movement of other coordinate directions, the mechanical impedance and the transmission loss of energy of the three faces can be expressed as:

$$\begin{Bmatrix} F_1^y \\ \cdot \\ v_1^y \end{Bmatrix} = \begin{pmatrix} \dfrac{Z_{11e}^{yy}}{Z_{21e}^{yy}} & Z_{12e}^{yy} - \dfrac{Z_{11e}^{yy} \bullet Z_{22e}^{yy}}{Z_{21e}^{yy}} \\ \dfrac{1}{Z_{21e}^{yy}} & -\dfrac{Z_{22e}^{yy}}{Z_{21e}^{yy}} \end{pmatrix} \begin{Bmatrix} F_2^y \\ \cdot \\ v_2^y \end{Bmatrix} = \begin{pmatrix} a_{11e} & a_{12e} \\ a_{21e} & a_{22e} \end{pmatrix} \begin{Bmatrix} F_2^y \\ \cdot \\ v_2^y \end{Bmatrix} \tag{10}$$

$$\begin{Bmatrix} F_2^y \\ \cdot \\ v_2^y \end{Bmatrix} = \begin{pmatrix} \dfrac{Z_{11b}^{yy}}{Z_{21b}^{yy}} & Z_{12b}^{yy} - \dfrac{Z_{11e}^{yy} \bullet Z_{22b}^{yy}}{Z_{21b}^{yy}} \\ \dfrac{1}{Z_{21b}^{yy}} & -\dfrac{Z_{22b}^{yy}}{Z_{21b}^{yy}} \end{pmatrix} \begin{Bmatrix} F_3^y \\ \cdot \\ v_3^y \end{Bmatrix} = \begin{pmatrix} a_{11b} & a_{12b} \\ a_{21b} & a_{22b} \end{pmatrix} \begin{Bmatrix} F_3^y \\ \cdot \\ v_3^y \end{Bmatrix} \tag{11}$$

The relationship between the transmission loss of face 1 and face 3 is:

$$\begin{Bmatrix} F_1^y \\ \cdot \\ v_1^y \end{Bmatrix} = \begin{pmatrix} a_{11eb} & a_{12eb} \\ a_{21eb} & a_{22eb} \end{pmatrix} \begin{Bmatrix} F_3^y \\ \cdot \\ v_3^y \end{Bmatrix} \tag{12}$$

Wherein, F_1^y, F_2^y and F_3^y are the dynamic forces of face 1, face 2 and face 3; v_1^y, v_2^y and v_3^y are the vibration speeds of face 1, face 2 and face 3; Z_{11e}^{yy}, Z_{12e}^{yy}, Z_{21e}^{yy} and Z_{22e}^{yy} are the mechanical impedance from face 1 to face 2; Z_{11b}^{yy}, Z_{12b}^{yy}, Z_{21b}^{yy} and Z_{22b}^{yy} are the mechanical impedance from face 2 to face 3. It can be seen from the equation, that transmission loss of the flexible pipeline of excitation source is not only relevant to the mechanical impedance of the flexible pipeline but also the mechanical impedance of the metal path connecting the flexible pipeline. For a given vibration isolation system, the F_1^y and v_1^y of the excitation source of the auxiliary pipeline are constant, and the speed transmitted to the support base of flexible pipeline, v_3^y, is directly related to the impedance of pipeline system.

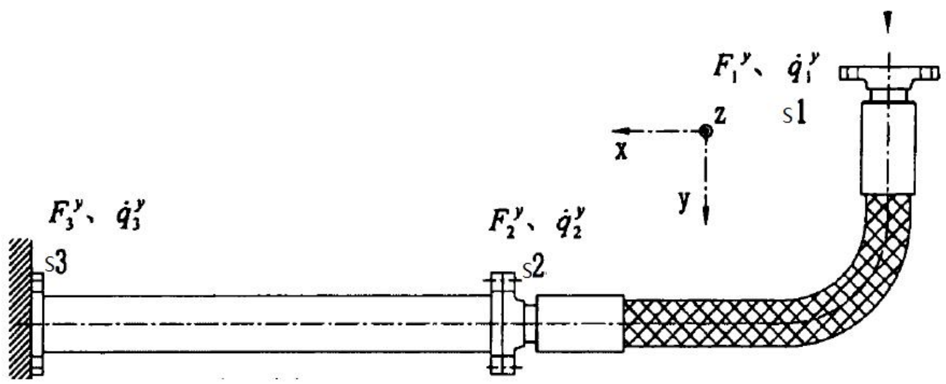


Fig. 2: Transmission loss of the flexible pipeline of excitation source.

4. Verification for the impedance and vibration isolation effect of the base

As shown in Fig. 3, the double-layer vibration isolation system was resiliently mounted on the T-base structure by four mounting surfaces, and base impedance of 4 installation faces were Z_1, Z_2,

Z_3 and Z_4. I was the original state of the installation base, which was a channel-type structure. II was the installation base after changes: 4 transverse ribs were added to the channel-type structure. Based on the test, the comparison of impedance characteristics of the base in two status is shown in Fig. 4~Fig. 7. Abscissa f was the center band corresponding to 1/3Oct, and ordinate Z was the impedance amplitude of corresponding center band. The RMS value of effective frequency within the bandwidth of 1/3Oct was drawn, and the reference of impedance was Z_0. The vibration characteristics of the base is shown in Fig. 8~Fig. 11. Abscissa f was the center band vale corresponding to 1/3Oct, and ordinate ALV was the acceleration amplitude corresponding to the center band. The RMS value of effective frequency within the bandwidth of 1/3Oct was drawn, and the reference of acceleration level was a_0.

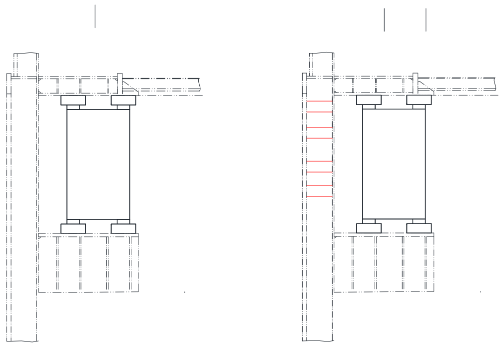


Fig. 3: Schematic of impedance of the mounting base.

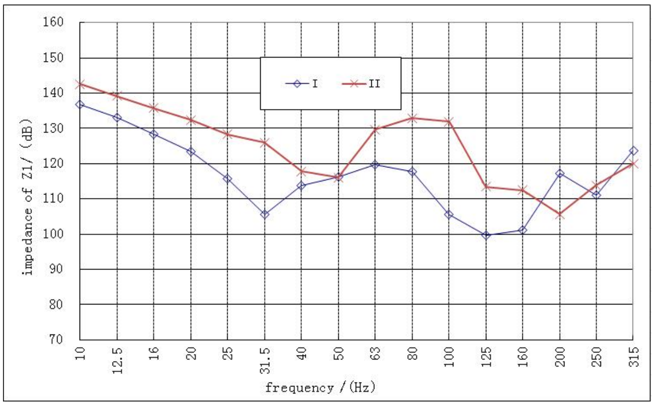


Fig. 4: Comparison of impedance of Z1.

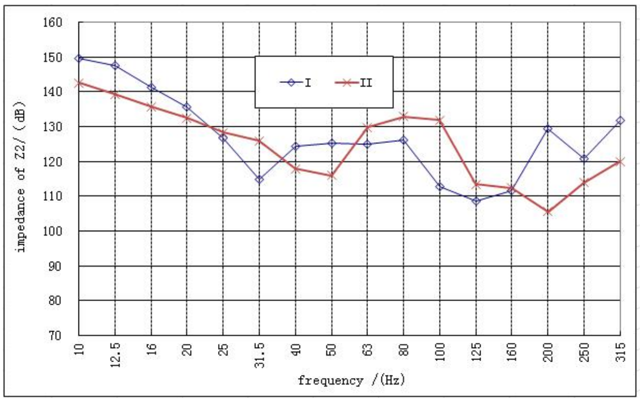


Fig. 5: Comparison of impedance of Z2.

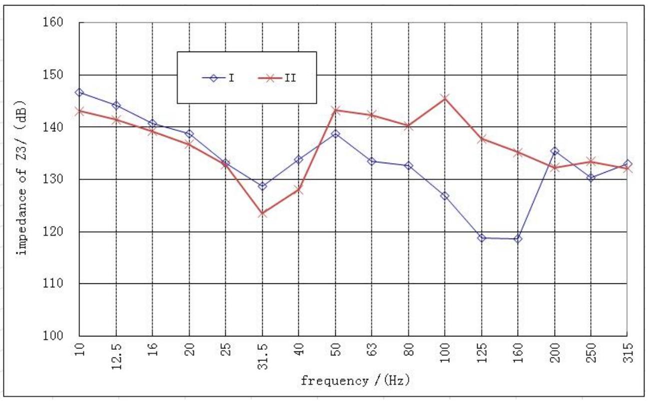


Fig. 6: Comparison of impedance of Z3.

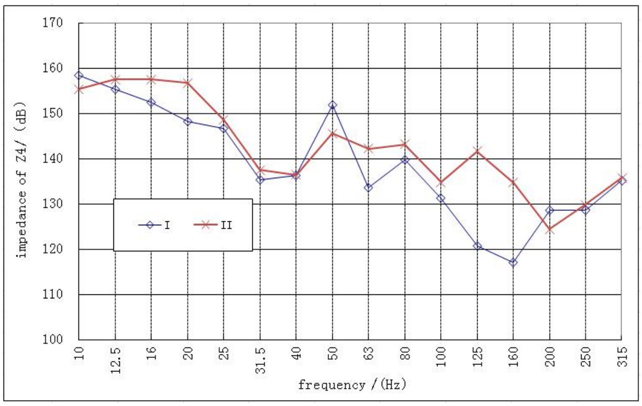


Fig. 7: Comparison of impedance of Z4.

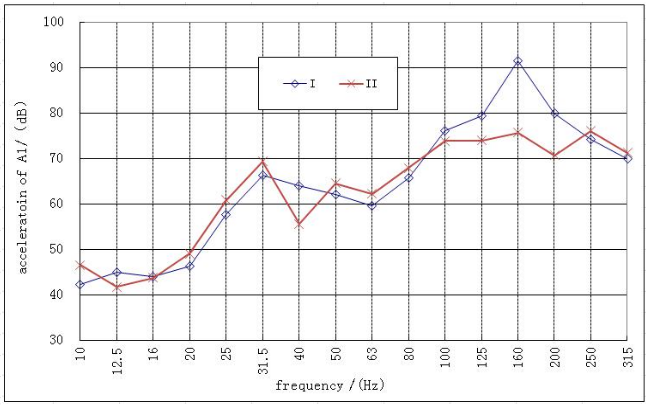


Fig. 8: Comparison of acceleration level of Z1.

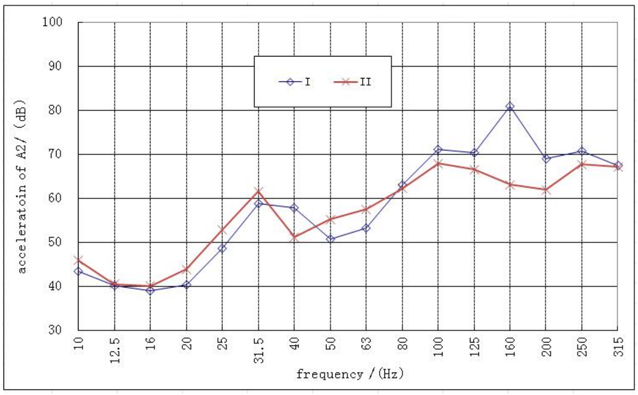


Fig. 9: Comparison of acceleration level of Z2.

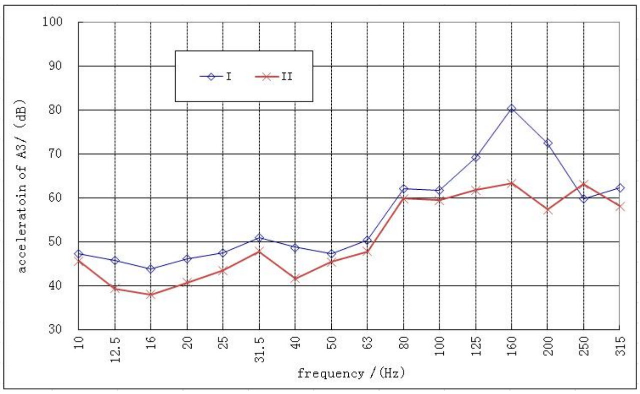


Fig. 10: Comparison of acceleration level of Z3

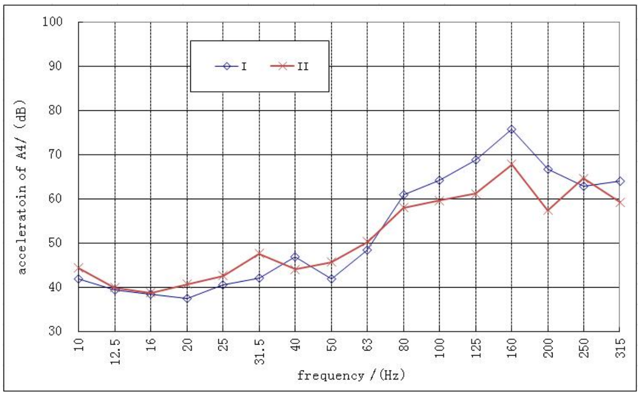


Fig. 11: Comparison of acceleration level of Z4.

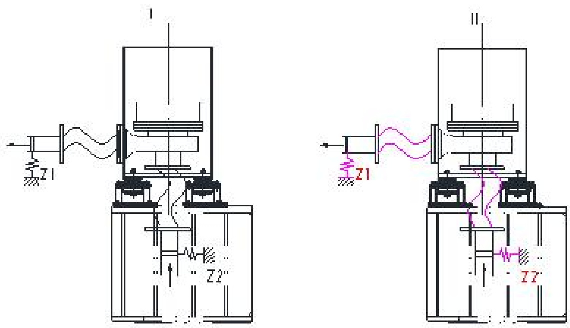


Fig.12: Schematic of impedance of piping system.

The experimental results show that within the center bandwidth of 50Hz~200Hz corresponding to 1/3Oct, the impedance amplitude of the four faces of Base II was larger than that of Base I, and the increase range was 5dB~20dB. When the excitation input of the device and the vibration isolation system were the same, the vibration energy of device foot was constant, while the vibration isolation effect was inversely proportional to the vibration acceleration level of the base. Based on Eq. (8) and Eq. (9), the vibration acceleration speeds of the four installation faces of Base II were smaller than those of Base I, and the bandwidth range of reduced frequency was within 80Hz~200Hz. At 160Hz, the amplitude of center band was reduced by 8dB~16dB, which was the most obvious. Therefore, for the structure with relatively weak base impedance, if the vibration isolation effect of the vibration isolation system cannot meet the design requirements, the appropriate increase of test base impedance is one of the effective ways to meet the requirements.

5. Verification for impedance and transmission loss of the flexible pipeline system

As shown in Fig. 12, the inlet and outlet flexible piping system were elastically mounted on the base through two support points, and the base impedance of the two support points were respectively expressed as Z_1 and Z_2 . I was the initial installation status of the flexible pipeline system, and II referred to the changed flexible pipeline system. The changes were mainly for the properties and installation layout of the elastic components. According to the test, the comparison of impedance characteristics of the two support points in two status is shown in Fig. 13 ~ Fig. 14. Abscissa f was the center band corresponding to 1/3Oct, and ordinate Z was the impedance amplitude of corresponding center band. The RMS value of effective frequency within the bandwidth of 1/3Oct was drawn, and the reference of impedance was Z_0 . The vibration characteristics of the support points is shown in Fig. 15 ~ Fig. 16. Abscissa f was the center band vale corresponding to 1/3Oct, and ordinate ALV was the acceleration amplitude corresponding to the center band. The RMS value of effective frequency within the bandwidth of 1/3Oct was drawn, and the reference of acceleration level was a_0.

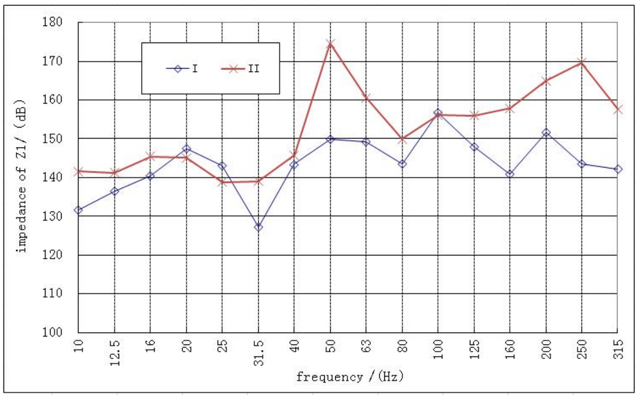


Fig. 13: Comparison of impedance of the Z1.

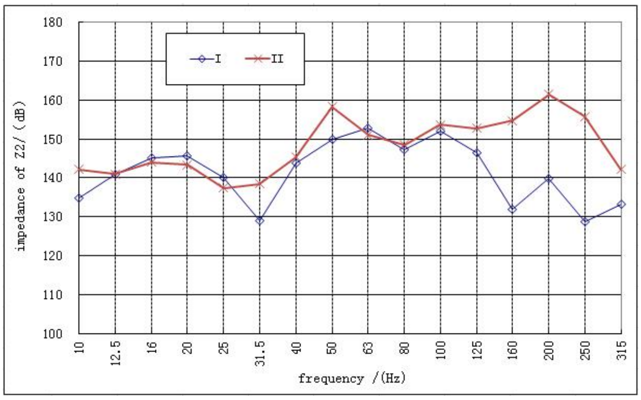


Fig. 14: Comparison of impedance of the Z2 point.

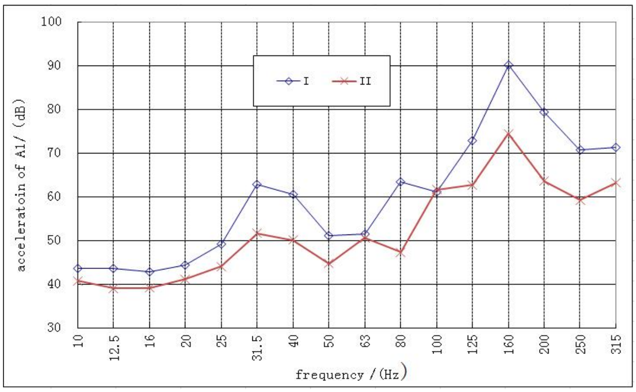


Fig. 15: Comparison of acceleration level of Z1.

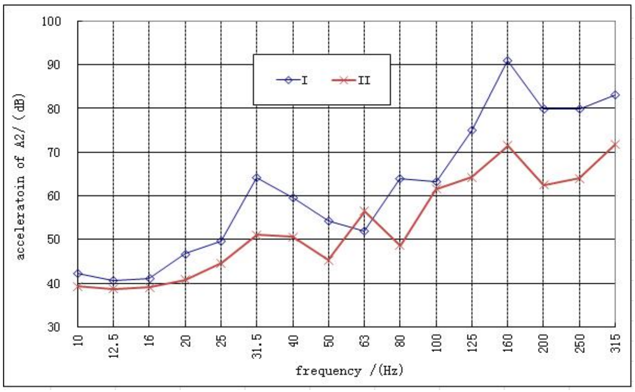


Fig. 16: Comparison of acceleration level of Z2 .

The experimental results show that within the center bandwidth of 40Hz~80Hz and 100Hz~ 315Hz corresponding to 1/3Oct, the impedance amplitude of support point II was larger than that of support point I, and the increase range was within 25dB. The increase was very obvious at the center bandwidth of 50Hz and 200 Hz. When the excitation input of the device and pipeline interface system were the same, the input vibration energy of the pipeline system was constant, while the transmission loss was inversely proportional to the vibration acceleration level of the pipeline support points. Based on Eq. (12), the vibration acceleration speeds of pipeline system II were smaller than those of pipeline system II. The bandwidth range of reduced frequency was within 10Hz ~ 315Hz, and the reduced amplitude was within 20dB. Therefore, in order to increase the transmission loss of the vibration energy of the flexible pipeline system, changing the properties and layout of the elastic element of the pipeline system can effectively increase the impedance of the system and realize the expected transmission loss effect.

6. Conclusions

The complex mechanical system consists of elastic elements such as vibration isolators and flexible joints and rigid components such as mechanical equipment and support pipelines. In the steady operation state of complex mechanical systems, the multi-system impedance of elastic elements and rigid elements is the main factor that affects the system vibration isolation and transmission loss. In this article, a double-layer vibration isolation mechanical system was developed, and two kinds of system impedance mathematical models were established by the test method of hammer excitation to obtain the initial impedance of complex mechanical system which was used as a reference. By adjusting the structural strength of the mechanical system base and the supporting stiffness of the piping system, the relationship between the system impedance of the two types and the vibration isolation effect of the mechanical system and the transmission loss of the pipeline system were studied. The quantitative relation between the vibration isolation system of double-layer vibration isolation mechanical system and the transmission loss of pipeline and the system impedance of two types was obtained. The experimental results showed that:

The appropriate increase of the system impedance of the base was beneficial to the vibration isolation effect of the vibration isolation device. Concerning the system with weak base impedance, if the vibration isolation effect of vibration isolation system fails to meet the design requirement, the appropriate increase of the impedance of test base is an effective solution to satisfy the vibration isolation effect.

By changing the properties and installation layout of the flexible components of the piping system, the transmission loss the vibration energy of the flexible piping system can be increased, reducing the base level of vibration isolation system effectively and increasing the vibration isolation effect of the system.

7. Acknowledgement

The work is founded by the National Science Foundation of China under grant numbers 61503354.

REFERENCES

1 H.L. Sun, H.B. Chen, K. Zhang, P.Q. Zhang, Research on performance indices of vibration isolation system, *Applied Acoustics* 69(9) , 789-795,(2008).

2 Z.Q. Lang，X.J. Jing，S.A. Billings , G.R. Tomlinson，Z.K Peng, Theoretical study of the effects of nonlinear viscous damping on vibration isolation of sdof systems, *Journal of Sound & Vibration* 323(1–2) , 352-365,(2009).

3 A.N. Bart，J. Clark，J. Young，Y. Zohar, Underwater ambient noise measurements in aquaculture systems: a survey, *Aquacultural Engineering,* 25(2) ,99-110, (2001).

4 W.C. Peng, Y. Liu, C.H Yuan, FRF-Based substructure technique for modeling machinery isolation system. *Chinese Journal of Ship Research* 7(1),65-70,(2012) .

5 Z.D. Wu, Research of the analysis method for the raft system based on the frequency response function coupling method, *Shanghai Jiaotong University* ,(2007).

6 J. Liang, Transferring relationship of vibration-acoustic energy under different mounting conditions, *Chinese Journal of Ship Research* ,2(2) ,52-56,(2007) .

7 G.M. Wu, R.Y. Shen, H.X. Hua, Mode mechanical impedance synthesis method and its application in flexible isolation system, *Journal of Ship Mechanics,* 8(6) ,(2004).

8 Y.T. Ma, Yan. Zhou, Q.N. Zhang, Z.P. Tong, L.G. Yin, A new modeling method for floating raft system,*Chinese Journal of Ship Research* , 28(7),28-32,(2009).