THE TRANSFER PATH ANALYSIS METHOD OF SHIP VIBRATION AND EXPERIMENTAL RESEARCH

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The ship is a complex noise source, mainly composed of mechanical noise, hydrodynamic noise and propeller noise. The key to reduce the radiated noise level and improve the acoustic performance is to control and reduce mechanical noise of ship. In order to control ship mechanical noise, it's essential to carry out the research on the transfer path analysis method of ship vibration. With the partial coherence and conditional power spectrum analysis, the thesis carries out the research of operational transfer path analysis on ship vibration noise and build the mathematical model, accomplishes the validity emulation of operational transfer path analysis that uses coupling noise source. By using the experimental platform of cabin model, analysing the transmission characteristics of cabin vibration noise with the established operational transfer path analysis model. Experimental data processing results prove that operational transfer path analysis can accurately accomplish noise evaluation, identify main noise source and transfer path, and estimate the contribution of each source to target response. Meanwhile, the method can supervise the working condition of device, and accomplish the fault diagnosis of device. The results of emulation and experiment both verify the feasibility of operational transfer path analysis method that optimized by partial coherence analysis.
Keywords: ship; mechanical noise; operational transfer path analysis; partial coherence

1. Introduction

Ship is a very complex noise source, which is mainly composed of mechanical noise, hydrodynamic noise and propeller noise [1]. Generally, when being in the medium and low speed, mechanical noise is the main source, and makes the most contribution to ships' radiation noise. Mechanical noise is mainly composed of operational mechanical equipment (engine, air compressor, reducer, air-condition, all kinds of pump etc.) in the ship. These equipment produce vibrations during the working process, then vibration transfers to ship's shell by equipment base or internal brackets, then sound waves are radiated to the ocean [2][3]. The ship mechanical noise is always controlled from two aspects, which are vibration source control and transfer path control. As the amount of mechanical noise source is large and complicated, and the coupling among noise sources is serious [4], meanwhile, the transfer path of vibration noise source is extremely complex. Therefore, the precondition of mechanical vibration noise control is to take research on Transfer Path Analysis (TPA) of ship vibration noise [5]. On the one hand, it can identify the main vibration noise source and transfer path of ship vibration noise, and can direct the reasonable implementation of vibration damping and noise reduction measures. On the other hand, it can accomplish the mechanical noise evaluation and fault diagnosis of equipment, and improves acoustic performance of ship.

Transfer Path Analysis (TPA) is a kind of research and control method on energy transfer path in the vibration system, which is based on tests and develops rapidly in recent years [6]. Its rudiment was proposed by Van der Linden P J G, Fun J K and other people in 1993, and was applied to structure borne noise diagnosis of cars [7-9]. After experiencing more than 20 years' research and development, this method is extensively applied to NVH of cars, ships, spaceflight and other fields, with its core of studying system transfer characteristic, and solving any problems of vibration noise source-transfer path-response point. Aiming at characteristics of the large amount of ship equipment, the serious coupling among noise sources and others, through combining with partial coherence analysis method[10], adopting operational transfer path analysis(OPA) and analysing transfer characteristic of ship vibration noise, the thesis determines the proportion and contribution that each vibration noise source occupied in MIMO (multiple input, multiple output) system[11][12], after reaching the target response point through different transfer paths, and therefore, determines the main vibration noise source and the main transfer path in the system, in order to realize the compound of vibration noise, and provides theoretical direction for ship's noise control, fault diagnosis and noise evaluation, which is verified through the cabin model experiment in the anechoic tank[13].

2. Theoretical Analysis

2.1 The Operational Transfer Path Analysis

In the test system of ship vibration transfer path analysis, through designing a number of combined conditions, study the transfer characteristic of ship system transferring to multiple target response points in different transfer paths as receiving extrinsic stimulations under different combined conditions, and set up the transfer relation between target response point and vibration source [14][15]. Assuming that the vibration source signal $x(t)=\{x_1(t),x_2(t),\cdots x_m(t)\}$ is produced by the stimulation of mechanical equipment or secondary vibration source, and the response signal measured by target response point is $y(t)=\{y_1(t),y_2(t),\cdots y_n(t)\}$. Here the environmental noise of ship test system is ignored. Considering the time delay of signal propagation, then the i^{th} signal measured by the sensor in the target point is:

$$y_i(t)=\sum_{j=1}^{m}\sum_{r=0}^{N-1}h_{ij}(\tau)x_j(t-\tau) \tag{1}$$

Where h_{ij} expresses the transfer path between vibration source j and target point i. The equation (1) can be expressed in frequency as:

$$Y_i(w)=\sum_{j=1}^{m}H_{ij}(w)X_j(w) \tag{2}$$

Equation (2) can also be expressed in matrix form as:

$$\begin{bmatrix} H_{11}(w) & \cdots & H_{1m}(w) \\ \vdots & \ddots & \vdots \\ H_{n1}(w) & \cdots & H_{nm}(w) \end{bmatrix} \begin{bmatrix} X_1(w) \\ \vdots \\ X_m(w) \end{bmatrix} = \begin{bmatrix} Y_1(w) \\ \vdots \\ Y_n(w) \end{bmatrix} \tag{3}$$

In the system of ship vibration noise transfer path analysis, assuming that the transfer path is linear, and it has no significant change during the experimental process, then the equation (2) is workable under all kinds of operation. While designing and choosing working operation, ship mechanical device can be opened separately (the mechanical device opened simultaneously can be treated to be equivalent to a set of equipment). For example, if vibration source k is opened separately, then $x_j(t)=0(j\neq k)$. For every working operation r, if the vibration source is opened separately, then the equation (3) is workable that expressed in the following:

$$\begin{bmatrix} H_{11}(w) & \cdots & H_{1m}(w) \\ \vdots & \ddots & \vdots \\ H_{n1}(w) & \cdots & H_{nm}(w) \end{bmatrix} \begin{bmatrix} X_1^1(w) & \cdots & X_1^r(w) \\ \vdots & \ddots & \vdots \\ X_m^1(w) & \cdots & X_m^r(w) \end{bmatrix} = \begin{bmatrix} Y_1^1(w) & \cdots & Y_1^r(w) \\ \vdots & \ddots & \vdots \\ Y_n^1(w) & \cdots & Y_n^r(w) \end{bmatrix} \quad (4)$$

which can also be expressed as:

$$H_{n\times m} X_{m\times r} = Y_{n\times r} \quad (5)$$

Then the OPA matrix of ship vibration can be expressed as:

$$H_{n\times m} = Y_{n\times r} X_{m\times r}^{-1} \quad (6)$$

While choosing working operation, follow the principle of $r \ge m$. The chosen working operation should be applied different structural loads, such as engines or other device under different revolving speed and different load. While taking experiment, the measuring sensors also should be placed nearby the excitation source as much as possible, so as to maximally obtain unrelated drive signals. In addition, when the loading operation combination causes the following situations that each row vector of matrix X has strong correlation, or the additive noise is contained in the measured vibration signal matrix X or sound pressure signal matrix Y, then the accuracy of transfer path matrix H will be influenced greatly[16]. Under this condition, partial coherence analysis method can be used firstly to decouple[4], identify the main noise source and characteristic frequency, and then optimize the ship operational transfer path analysis model.

2.2 Partial Coherence Analysis

In short, assuming to adopt a set of orderly time domain signals $x_1(t)$, $x_{2\cdot 1}(t)$, $\cdots$, $x_{n\cdot(\mathrm{n}-1)!}(t)$ to represent the obtained condition input with partial coherence analysis method in ship vibration transfer path analysis system[17], representing the known original input. Thus $X_{i\cdot(\mathrm{i}-1)!}(w)$, $i = 1, 2, \cdots n$, and $Y(w)$ respectively represent Fourier Transform of input signal under orderly condition input, Fourier Transform of system noise and Fourier Transform of output signal, $L_{x_i y}(w)$ represents a set of optimal system transfer function under orderly condition input, the subscript $i \cdot (i-1)!$ represents the i th conditional input after removing the linear effect of the former $(i-1)$ input signals by applying Least Square Method. At this time, system output can be represented as:

$$Y(w) = \sum_{i=1}^{n} L_{x_i y}(w) X_{i\cdot(\mathrm{i}-1)!}(w) + N(w) \quad (1)$$

Let $X_{(n+1)}(w)$ represents $Y(w)$, and $X_{(n+1)\cdot n}(w)$ represents system output noise $N(w)$, j represents $(n+1)$, $r < j$, then under orderly condition input, the conditional cross-power spectrum density function can be expressed as

$$G_{ij\cdot r!}(w) = G_{jj\cdot(r-1)!}(w) - L_{x_i x_j}(w) G_{jr\cdot(r-1)!}(w) \quad (2)$$

Let $i = j$, the power spectral density function can be expressed as:

$$G_{jj\cdot r!}(w) = G_{jj\cdot(r-1)!}(w) - L_{x_i x_j}(w) G_{jr\cdot(r-1)!}(w) \quad (3)$$

At this time, the mean square error of $L_{x_i y}(w)$ is

$$G_{n_i n_i}(w) = G_{yy}(w) - L_{x_i y}^*(w) G_{iy\cdot(i-1)!}(w) - L_{x_i y}(w) G_{iy\cdot(i-1)!}^*(w) + L_{x_i y}^*(w) L_{x_i y}(w) G_{ii\cdot(i-1)!}(w) \quad (4)$$

And the optimal system here is the linear system that generates minimum mean square error, it can be solved with the partial derivative of equation (11) $L_{x_i y}(y)$ being zero by fixing $L^*_{x_i y}(w)$, that is:

$$L_{x_i y}(w) = \frac{G_{iy\cdot(i-1)!}(w)}{G_{ii\cdot(i-1)!}(w)} \quad (5)$$

The partial coherence function between input signal $x_i(t)$, and output target signal $y(t)$ is defined as ordinary coherence function of their condition spectral density. Obtaining collocate equation (9) and equation (11), the partial coherence be expressed as:

$$\gamma^2_{iy\cdot(i-1)!}(w) = \frac{\left|G_{iy\cdot(i-1)!}(w)\right|^2}{G_{ii\cdot(i-1)!}(w)G_{yy\cdot(i-1)!}(w)} \quad (6)$$

If there is coherence among various input signals, thus system output power spectrum can be expressed as:

$$G_{yy}(w) = \gamma^2_{1y}(w)G_{yy}(w) + \gamma^2_{2y\cdot 1}(w)G_{yy\cdot 1}(w) + \cdots \gamma^2_{ny\cdot(n-1)!}(w)G_{yy\cdot(n-1)!}(w) + G_{yy\cdot n!}(w) \quad (7)$$

Where the first term represents the coherent output power spectrum of $x_1(t)$ to $y(t)$; the second term represents the partial coherent output power spectrum of $x_2(t)$ to $y(t)$ under the effect of removing the impact of $x_1(t)$ to $y(t)$, the following and so on.

Through the analysis above, applying partial coherence analysis and conditional power spectrum analysis can solve the coupling input signals problem, which will not change the intrinsic coherency between original input signal and output signal. Which can optimize the OPA model, improve the accuracy of transfer path matrix T, and solve the ship vibration transfer path analysis problem among coupling noise sources.

3. Simulation Analysis

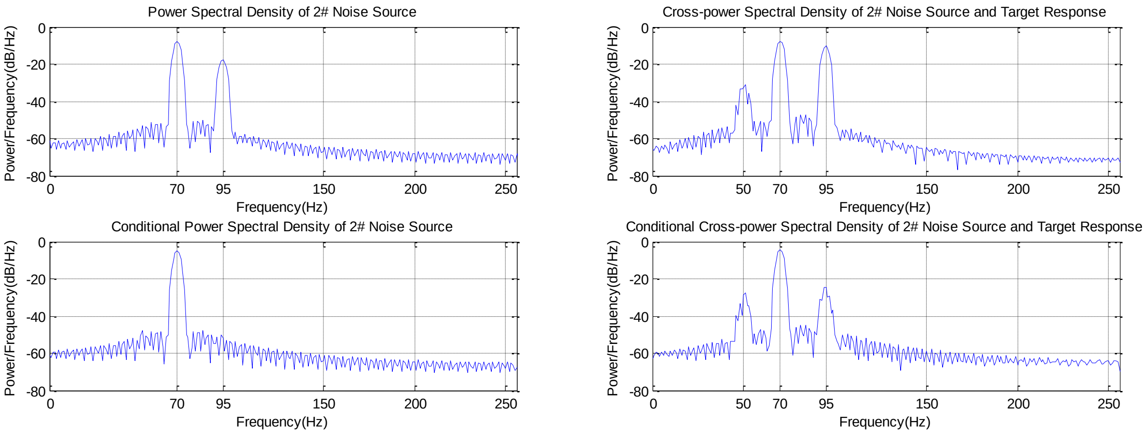
3.1 Simulation Sondition

$x_1(t)$ represents 1# noise source, and $x_2(t)$ represents 2# noise source. They are respectively transferred to target point $y(t)$ by transfer path $H_1(w)$ and by $H_2(w)$, the $H_1(w)$ is a low passing digital FIR filter with a gain of -10dB, while the $H_2(w)$ is a band passing digital FIR filter with a gain of -3dB. The presupposed gains of two transfer path are different, which is applied to simulate the decrement of vibration source passing through different transfer paths and transferring to different target points. Signal length is 10 seconds, sampling frequency is 512Hz. System output noise $N(w)$ is represented with Gaussian White Noise.

$$\begin{aligned} x_1(t) &= 2*\sin(2\pi 50t) + 2*\sin(2\pi 95t) \\ x_2(t) &= 1.5*\sin(2\pi 70t) + 0.5*\sin(2\pi 95t) \end{aligned} \quad (8)$$

$$Y(w) = H_1(w)X_1(w) + H_2(w)X_2(w) + N(w) \quad (9)$$

3.2 Conditional Power Spectrum and Partial Coherence Analysis



a. The power spectral density and conditional power spectral density of 2 # noise source

b. The cross-power spectral density and conditional cross-power spectral density of 2 # noise source

Figure 1: The power spectral density of 2# noise source

As shown in Figure 1, from the comparison of two figures in Figure (a), it can be seen that, through conditional power spectrum analysis, the corresponding condition of spectrum peak can be clearly seen, the spectrum peak at 95Hz frequency point is obliterated in noisy environment, therefore, the part of 1 # noise source that affects 2# noise source can be removed, which will not change the inherent main component information of 2# noise source. Then observing Figure (b), it can be seen that when 2# noise source and target point exclude the effect of 1# noise source, the spectrum peak at 95Hz falls to -24.79dB from -10.27dB, the information of other frequency points is not changed, thus the effect of 1# noise source can be excluded.

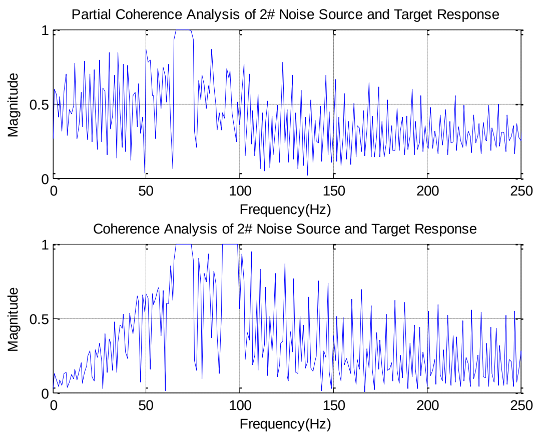


Figure 2: The coherence analysis of 2# noise source and target

Comparing the ordinary coherent graphics and partial coherent graphics in Figure 2, it can be seen that applying partial coherent analysis will not change the inherent coherence of vibration signal of 2# noise source and the output signal of target. In addition, combining with the conditional cross-power spectrum and conditional power spectrum analysis of 2# noise source and target, partial coherent analysis method also accurately identifies that 70Hz of 2# noise source is the main frequency contributing to target. Aiming at characteristic frequency point, then analysing contribution on all vibration sources that pass through different transfer paths to target, as shown in Figure 3.

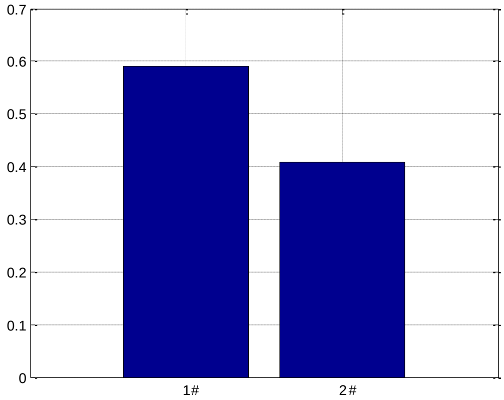


Figure 3: Contribution analysis of all vibration sources to target

It can be seen from Figure 3 that the energy of 1# noise source transfers to target point is greater than the energy of 2# noise source after system attenuation, the noise contribution is relatively larger for target point. Through comparing with the presupposed vibration source and system gain of transfer path, the emulation results fit well with theoretical value.

Emulation research shows that the optimized ship operating condition transfer path analysis method is feasible in theory, firstly through partial coherent and condition power spectrum analysis, it separates and linkages the vibration noise source, secondly conduct transfer characteristic analysis research, so as to analyze the contribution amount of all vibrations sources to target point, meanwhile identify the main noise source.

4. Experimental Analysis

4.1 Experimental System

Operational transfer path analysis experiment is carried out in anechoic tank, which makes the scaled cabin model as experimental object. The length of model is 3.5 m, the outer diameter is 2.5 m, and the model structure is shown in Figure 4. The floating raft vibration isolation mounting is installed at the bottom of model, and there is are two vibration motors installed at both ends, vibration motor is connected with vibration isolation mounting through vibration isolator. In the middle of cabin, exciter is installed in the base of horizontal beam through the vibration absorber, vibration absorber can select rigid connection or resilient soft connection through screw, which can simulate the fault of vibration absorber. The exciting force of vibration absorber is 500N, frequency is adjustable, and the highest frequency of vibration is 5000Hz.

Figure 4: The model structure used in the experiment

The experimental system is mainly composed of two parts, including vibration launching system and vibration measuring system, and the specific model and quantity of instrument and equipment contained in system are showed in Table 1. In order to improve the accuracy of experiment, the experimentalist reduce the coupling signals and placing accelerometers on the location where reflects the same vibration information, the location of sensors is shown in Figure 5.

Table 1: The composition of experimental system

System	Device	Type	Quantity
Vibration measuring system	Accelerometer（including used in wet-end）	PCB M352C68	30
	Data acquisition collector	NIPXIe-1082crate +4499acquisition card	1
	Amplifier	B&KTYPE2694	1
	Hydrophone	B&K8106	2
	Synchronized-signal generator	PS-02	1
Vibration launching system	Function signal generator	AFG3022C	1
	Oscillograph	DSO7034B	1
	Power amplifier	GF-800W	1
	Exciter	JZ-50	1
	Motor	JZO2.5-2	2

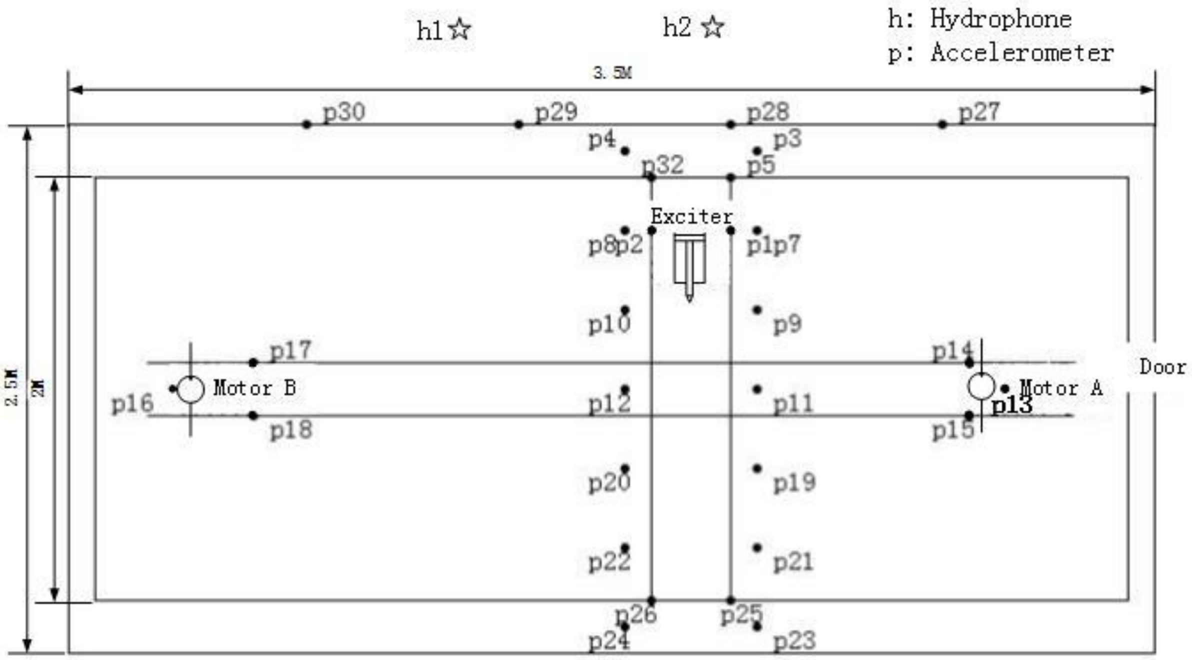


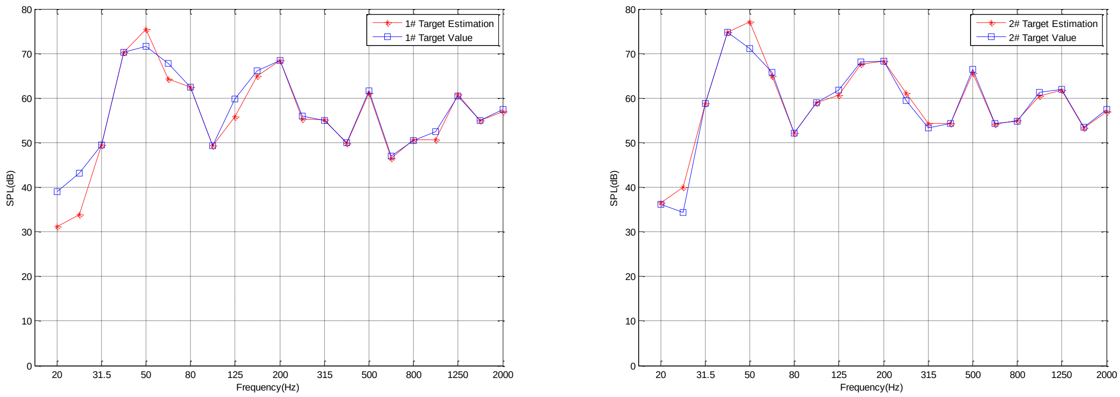
Figure 5: The location of sensors

During the process of experiment, designing the unit operation and combination operation of device, simulating the operation condition of vibration motor, such as absorber failure, then respectively conducting experiment ashore and underwater. The sampling frequency of experiment is 20 kHz, its sampling length is 70s, and then the date are stored in computer with *tdms format.

4.2 Experimental Results

4.2.1 Noise Evaluation

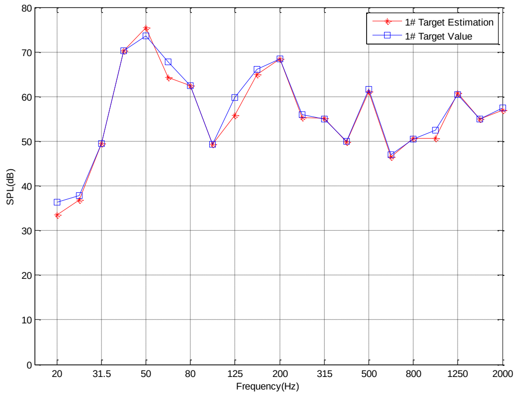
In the process of experiment, it should be followed that simultaneously open exciter and vibration motor. And the exciter transmits 1/3 octave signal from 20 Hz to 2000 Hz, under the excitation of different amplitudes and frequencies, which analyzes the transfer characteristic of device from absorber to bulkhead, and then from bulkhead to hydrophone of 1# and 2# object point in cabin model. Conducting synthesis of noise in object point with the OPA model, experiment also assumes that changes of transfer path function not to follow the changes of excitation amplitude of drive signal and sequential order of excitation, and the cabin model satisfies the linear invariance correlation.



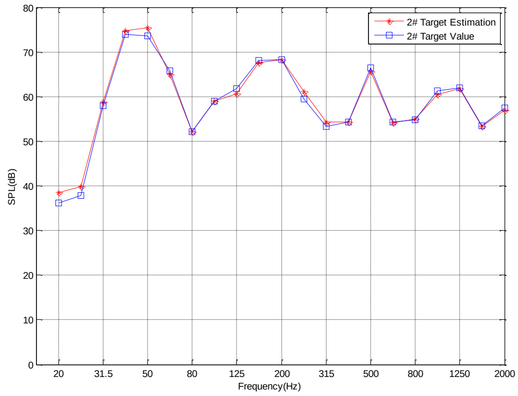
a. Contrast of 1/3 octave spectrum at 1#　　　a. Contrast of 1/3 octave spectrum at 2#

Figure 6: Contrast of targets' 1/3 octave spectrum

It can be seen from Figure 6 that there are several points, such as 50 Hz, 25 Hz and 20 Hz, suffered greater coupling effect of system from system and device, and there are larger effort noise between noise evaluation value and measured value. While, the noise evaluation fits well with the measured value at the other frequency points, and the difference valueless than 2 dB. In experiment, on the one hand, the narrow-band signal generated by vibration motor which takes 49.96 Hz as center frequency, and adding the electrical interference of 50 Hz power frequency, both of them will affect the noise evaluation. On the other hand, when exciter transmits low-frequency signal to conduct excitation of shell, the resonance happened on shell also affect the synthesis, of noise. Therefore, opening exciter alone and combining with the partial coherence analysis to conduct decoupling first, then conduct analysis on the characteristic of vibration transmission of ships. As shown in Figure 7.



a. Contrast of 1/3 octave spectrum at 1#



a. Contrast of 1/3 octave spectrum at 2#

Figure 7: Contrast of targets' 1/3 octave spectrum by optimized model

It can be seen from Figure 7 that the absolute error of 1# target noise between evaluation and measured value are less 2dB at 50Hz, and the absolute error of 2# target noise between evaluation and measured value are less 1.8dB at 50Hz, and the precision of noise synthetic has a certain improvement in the rest of low-frequency, of which the absolute error is less than 3 dB. After optimality, the evaluation value fits well with measured value by optimized OPA model, which meets the basic requirement of underwater noise analysis.

4.2.2 The Diagnostic Analysis of Absorber

It is possible to supervise the working condition of part of devices, through the analysis on the transfer path of ships, such as absorber failure in engine. In Experiment, it can be supposed that 4# absorber of exciter doesn't work (rigid connection), by which to simulate absorber failure. When exciter transmitting broadband and the application of absorber is normal, conducting synthesis, of sound pressure contribution amount with calculated transfer characteristic, and then compared with the result when device isolated operation respectively, as shown in Figure 8.

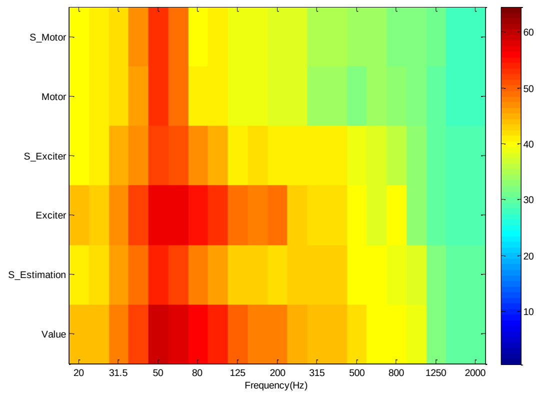


Figure 8: Contrast of 1/3 octave spectrum at 1#

It can be seen from the Figure 8 that when exciter and vibration motor are simultaneous operation, the composite value of majority of frequency points at 1# target point less than measured value; while combining with analysis on working condition of exciter and vibration when they respectively isolated operation, the absolute error that the evaluation value and measured value of vibration motor's noise is identical, which the evaluation value of noise in each frequency point is less than measured value, by which the absorber of exciter is preliminarily judged as failure.

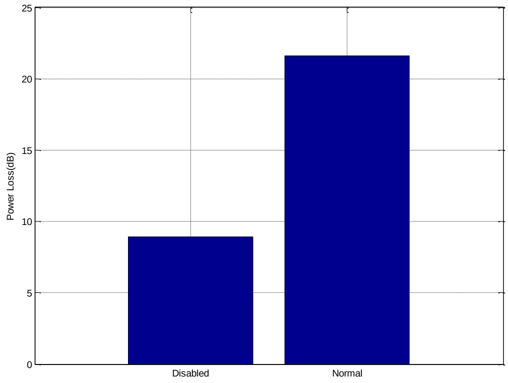


Figure 9: Contrast of absorber’s power attenuation

Respectively calculating the vibration attenuation when absorber works normally and doesn’t work, which is showed in Figure 9 that absorber is rigid connection, the vibration attenuation of vibration less than that of elastic connection from under-chassis to substrate, there is a 15.4 dB between them, thus it can be confirmed that absorber of exciter failure. Experiment indicates that the working condition of device can be judged by the evaluation analysis on sound pressure contribution amount of object point in different devices, which can supervise the working condition of device, and accomplish the fault diagnosis of device.

5. Conclusion

(1) Under the necessity of ships, the thesis simulates multiple noise source, and build the model of ship operational transfer path analysis with partial coherence analysis. Meanwhile, the results of emulation and experiment both verify the feasibility of the method.

(2) The results of emulation and experiment both prove that partial coherence analysis can accurately separate noise source. The noise evaluation by operational transfer path analysis model based on source separation is better than that based on coupling signals, which the former fits well with true value, and the absolute error is less than 3 dB.

(3) The ship operational transfer path analysis method can accurately accomplish noise evaluation, and identify the main noise source and transfer path. Meanwhile, the method can supervise the working condition of device, and accomplish the fault diagnosis of device.

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