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Design and Verification of a Noise Test Device for Water-jet Propulsion Pumps

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ABSTRACT

Based on the hydrodynamic testing facility for water-jet pump models, a measurement device is developed for measuring the intensity of underwater noise by means of a two-dimensional linear array which consists of two one-dimensional vector hydrophones and works in circular arc scanning mode. Both the array and the test model are set up in a water tank without sound elimination. The device can measure the sound intensity and calculate the acoustic power radiated from the pump. Verification tests via standard sound sources indicate that the absolute measurement error is less than ±2dB, and the repeatability error is less than ±1.5dB.

The noise characteristics of a water-jet pump model which is 300mm in diameter and operates at rated speed of rotation are measured in a series of tests. The test results indicate that the repeatability error of measured total level of radiated sound power is less than 1dB, and the repeatability errors in all the 1/3 octave bands are less than 2dB. As a means of conducting comparative measurements of water-jet propulsor radiated noise, this testing device is essential for the research and control of water-jet pump noise.

Keywords

Water-jet pump, sound intensity, sound power, scanning test, vector hydrophone

1 INTRODUCTION

As a kind of fluid machinery, pumps are widely used in various areas such as naval architecture and aerospace engineering. They need to have high efficiency and high resistance to cavitation so as to induce less vibration and noise. In the field of water-jet propulsion, the radiated noise underwater generated by the pumps is one of the most important technical issues (Mu et al 2003).

Currently, the pump-induced noise, especially that in low-frequency range, is scarcely measured in the hydraulic performance tests of water-jet pump models. Consequently, the measuring system for the comparative tests of radiated noise underwater is also rare to see as compared with the hydraulic performance test system, which makes it difficult to evaluate the effectiveness of noise reduction measures at design stage.

In this paper, the development of an experimental system is presented for the comparative measurements of the radiated noise intensity of pump models. The system is based on the non-anechoic tank built on the hydraulic test rig for water-jet propulsion pump models. The system is designed for the qualitative assessment of noise reduction measures by evaluating the radiated sound power, and it is expected to serve as an important tool in the research of noise control for water-jet propulsion pumps.

2 SYSTEM PRINCIPLE AND IMPLEMENTATION

2.1 Method of Low-frequency Noise Measurement

The noise in mid- and low-frequency ranges is of interest in the radiated noise characteristics of pump models. The length, width, and depth of the non-anechoic tank are 3.5m, 2.6m, and 2.7m, respectively. It is open to the air and filled with water. In such a tank the sound waves generated by the vibration of the test model will reflect repeatedly between the side and bottom walls, the water surface, as well as the model surfaces. Besides, the sound in low-frequency range loses little energy during the propagation process. So, an interfering field consisting of radiated and reflected sound waves exists in the tank.

The sound power in such a field can be acquired by different methods, such as the reverberation method based on sound pressure measurement, and the sound intensity measurement method. However, the former method is not suited for low-frequency sound measurement as it is difficult to form an effective reverberation field in a limited non-anechoic space. In the latter method, the sound intensity distribution is measured on an envelope surface surrounding the sound source. The radiated sound power is evaluated by integrating the sound intensities over the envelop surface (Fang et al 2009). As illustrated in Figure 1, when there are no sound-absorbing surfaces inside the envelop surface, the sound waves coming from outside the envelop surface due to reflection or any other sound sources will go into and then come out of the envelop surface, and the sound power due to these sound waves is zero theoretically. Therefore, the sound power obtained from the sound intensity measurement method is not influenced by interface reflections and other noise sources outside the envelop surface.

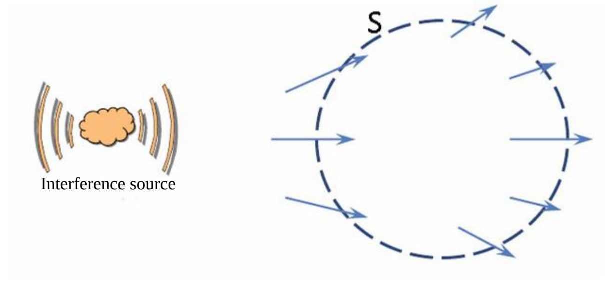

Figure 1 Propagation of sound waves through the envelop surface from interference sources outside

To implement the method, the sound intensity field perpendicular to the envelop surface (referred to as the measuring surface hereinafter) is obtained from the measurements at discrete points. The sound power of the noise source is evaluated by numerical integration of the sound intensity amplitudes over the measuring surface.

2.2 Methods for Sound Intensity Measurement

There are mainly two methods for measuring the intensity of radiated sound underwater. One is based on the dual-hydrophone technology and the cross-spectrum method. The other, the combined vector hydrophone method, measures sound intensity vectors by means of an array of vector hydrophones.

In the dual-hydrophone method, a pair of conventional hydrophones for measuring the sound pressure are placed face to face, and the sound intensity at the center between the pair of hydrophones can be calculated according to the cross-spectrum method. The error in calculated sound intensity depends upon the ratio of the spacing between the hydrophones to the wave length corresponding to the upper limiting frequency of the hydrophones. For a fixed hydrophone spacing, the phase difference between signals from the two hydrophones becomes smaller at lower frequency of the signal, and the signal-to-noise ratio of the sound pressure gradient decreases, too. Therefore, the dual-hydrophone method is not suitable for measurements in low-frequency range.

The combined vector hydrophone method is base on the latest technology in the field of noise measurement (Zhang et al 2001). The upper and lower limits of the working frequency range depend on the size of the hydrophone and the resonant frequency of the system, respectively. Furthermore, with this method homogeneous noise can be suppressed, and the detectable signal-to-noise ratio is lower than -6dB. When the size of the vector hydrophone is very small compared with the sound wave length, its directivity is of an '8' shape or a cosine shape, and becomes independent of the frequency. Therefore, the combined vector hydrophone system possesses prominent performance in low-frequency range, and can be easily miniaturized.

2.3 Sound Intensity Measurement Techniques

According to the layout of the test section of hydraulic test rig for water-jet propulsion pump models, a semi-cylindrical measuring surface is selected, as shown Figure 2. The nominal diameter of pump model is 300mm, and the radius of the measuring surface is no less than 700mm. To reduce acoustic leakage, the length of the measuring surface is no less than 1000mm.

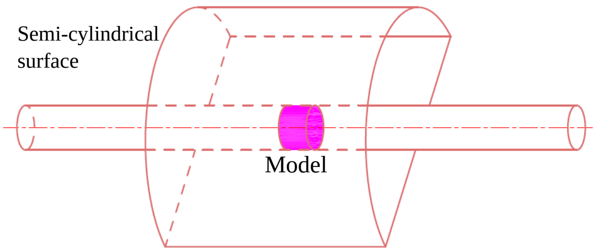

Figure 2 The semi-cylindrical measuring surface

For such a semi-cylindrical surface, two measurement techniques are feasible, *i.e.* measuring the sound intensity field using multiple hydrophones at discrete locations, or by scanning the measuring surface with a hydrophone array or just a single hydrophone.

In the discrete sound intensity measurement technique, an array of hydrophones are fixed at selected locations on the measuring surface, as illustrated in Figure 3. Although the measurement error can be decreased by reducing the ratio of hydrophone spacing to sound wave length, the free sound field would be affected by wave scattering if the hydrophone spacing is too small. Apparently the number of hydrophones determines system cost. But there is no way to accurately predict the error caused by reducing the number of hydrophones. According to a rough estimate (Shirahatti et al 1988) , the measurement error increases by around 3dB when the density of discrete measuring locations is reduced by half.

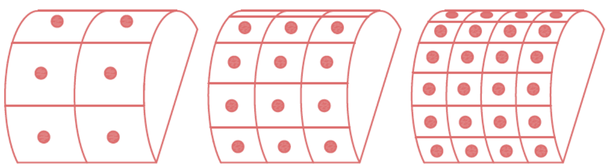

Figure 3 Discrete sound intensity measurement

There are two ways to implement the scanning technique. As illustrated in Figure 4, an array of hydrophones can be installed on a semi-circular arch which is driven by stepping motors to move along the rails. The measuring surface is scanned by moving the hydrophone array in one direction (1-D) only. The other way is to install two hydrophones at one end and the top of the arch respectively, as illustrated in Figure 5. To scan the measuring surface, one needs to scan a half of the semi-circumference by moving the hydrophones along the arch, and then move the arch along the rails to the next position and perform the circumferential scan again.

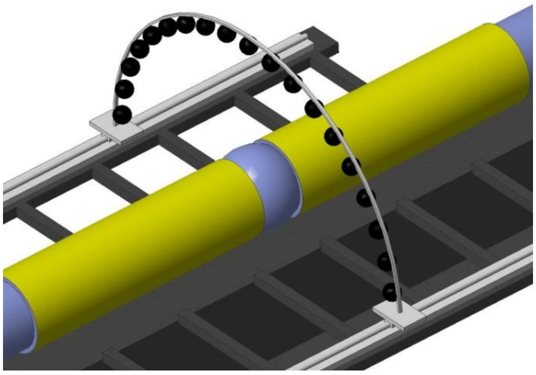

Figure 4 1-D scan using an array of hydrophones

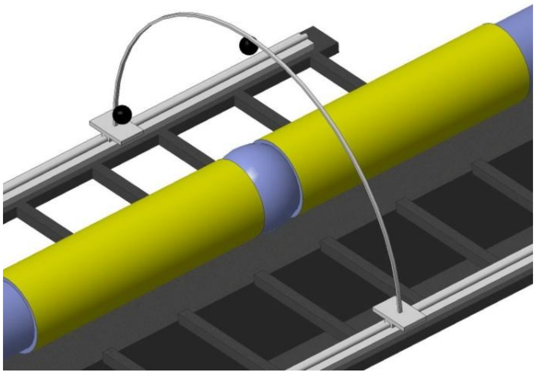

Figure 5 2-D scan using a single hydrophone

In the case of 1-D scan, the measuring accuracy depends on the spacing between hydrophones for the same reason as discussed in the discrete measurement technique. On the contrary, in the 2-D scan there is no problem of sound interferences between the two hydrophones, therefore the measuring accuracy can be made very high. The spacing between measuring points along the arch depends on the motor's stepping size, and can be set by the controller. Likewise, the spacing between measuring points along the length of the measuring surface is also variable in both 1-D and 2-D scan.

By comparison of the above measuring techniques, it is obvious that the density of measurement points is the main factor affecting the measuring accuracy.

For the discrete measurement method, the error level decreases as the density of measuring points increases. However, too many measuring points would make the interference among hydrophones nonnegligible, the installation of hydrophones more difficult, and the system cost very high.

In the 1-D and 2-D scanning methods, the error levels are similar by using the same scan interval. For a 2-D scanning system, if the scanning pitch is sufficiently small, the error level will be small enough. However, the circumferential scanning mechanism becomes necessary, and the measurement time is also greatly increased.

According to China national standards and the researches abroad, it is difficult for the discrete measurement method to achieve adequate precision. The scanning methods are more feasible. The 2-D scanning method is adopted in our system in order to fulfill the requirements for precision measurements.

2.4 Calculation of Radiated Sound Power

The vector intensity measurement technique is to measure sound pressure and particle velocity simultaneously, so as to obtain the energy output in a specific direction, namely the sound intensity vector, which is expressed as

$$\vec{I} = P \cdot \vec{U} \tag{1}$$

where $\vec{I} = (I_X, I_Y, I_Z)$ is the sound intensity vector, P is the sound pressure, and $\vec{U} = (U_X, U_Y, U_Z)$ is the particle velocity vector.

One-dimensional vector sensors are used which measures U_X only. Therefore, in the process of measurement, it is necessary to ensure that the direction of the maximum directivity index of the vector channel is the same as the normal direction of the measurement surface. By doing so the normal sound intensity can be calculated by means of Equation (1).

To calculate the sound power based on sound intensity measurements, the measuring surface is divided into N small elements, and in each element there is a measuring point, so N is also the number of measuring points. The acoustic power through a surface element is defined as the local sound power (Li et al 2008), and calculated as

$$W_i = I_{ni} \cdot S_i \tag{2}$$

where I_{ni} is the real part of the sound intensity measured at the center of the i^{th} surface element, and S_i is the area of the i^{th} surface element.

The total sound power through the measuring surface is expressed as

$$W_a = \sum_{i=1}^{N} W_i \tag{3}$$

The sound power level

$$L_w = 10\lg(W_a / W_0) \tag{4}$$

where the reference sound power $W_0 = 0.67 \times 10^{-18}$.

3 SYSTEM COMPONENTS AND TEST PROCEDURE

3.1 Test System Components

The comparative test and analysis system for the noise of propulsion pumps consists of a linear hydrophone array, a two-dimensional scanning motion mechanism, multi-channel data conditioner and data acquisition module, and the data analysis module. The block diagram in Figure 6 shows the system composition.

The test system uses two combined vector hydrophones to form a linear array fixed on the scanning mechanism. The sound intensity radiated from the pump model is measured by scanning. The working frequency range of the VH-2000 type vector hydrophone is 20Hz ~2kHz. Table 1 shows the main parameters of the hydrophone.

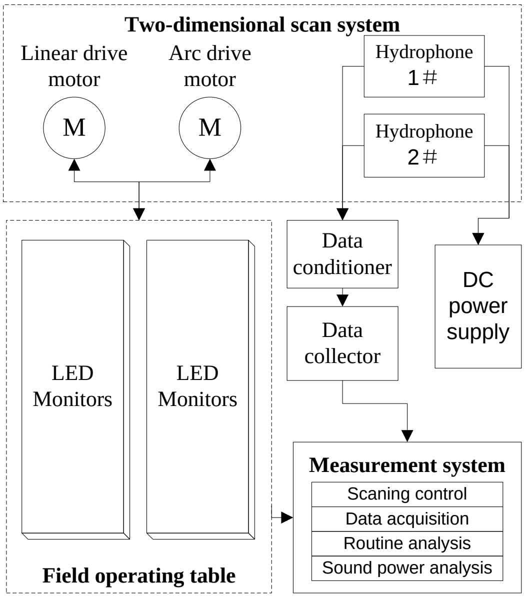

Figure 6 Composition of the comparative test and analysis system for the noise of propulsion pumps

Table 1 Main parameters of vector hydrophones

Type	Sound pressure channel		Acceleration channel	
	Sensitivity (1kHz)	Preamplifier (dB)	Sensitivity (1kHz)	Preamplifier (dB)
VH-C2000-1	-194.1	20	-183.7	0
VH-C2000-2	-195.7	20	-182.5	0

Figure 7 shows the two-dimensional scanning motion mechanism. The half-circular arch moves along the rails, and the hydrophones installed on the 1/4-arch move along the half-circular arch. In this way, the hydrophones can scan the entire measuring surface over the pump section.

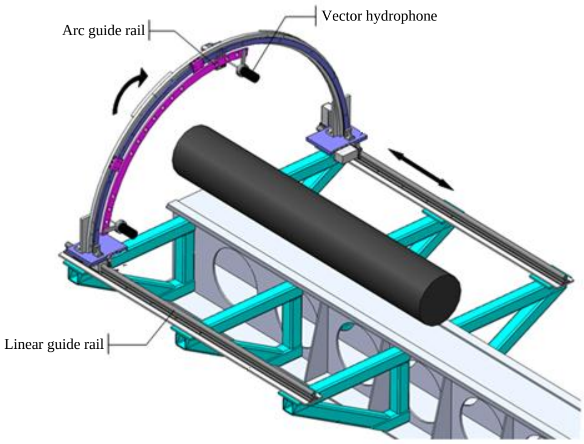

Figure 7 Two-dimensional scanning motion mechanism

The mechanical scanning mechanism consists of linear motion guides (rails), the rotary motion guide, the rotary drive mechanism, stepping motors and other components. With this mechanism the hydrophones can move to desired positions on the measuring surface. Figure 8 shows the main dimensions of the mechanism.

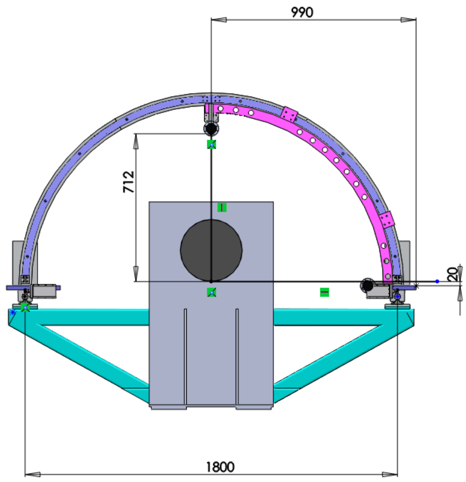

Figure 8 Main dimensions of the scanning mechanism

3.2 Test Procedure

The underwater radiated noise test of the propulsion pump model is carried out at a specified flow rate, which should be kept stable during the test. All the environmental parameters should also remain unchanged. The test steps are as follow:

1) Install the pump model and test drive it. Operate and debug the scanning mechanism in the air.

2) Fill the tank with water to the depth of 2.5m. Remove the air remaining in between the guides and gears, operate and debug the mechanism underwater.

3) Check the electronic measuring equipments, including the hydrophones, signal conditioner, data acquisition module and industrial computer, etc. Then debug the whole system to ensure that the equipment is working normally.

4) Start the model pump, adjust the flow rate, and wait until the pump operate stably. Set the control system parameters and start the measurement.

5) After the test, start the analysis module to perform routine analysis, and calculate the radiated sound power level at the tested flow rate.

6) Repeat steps 4 and 5 at other flow rates, or the tested one to check for system repeatability.

4 VERIFICATION OF THE TEST SYSTEM

To verify the noise test system, the sound power levels are measured by means of a standard sound source, Agilent 33220A, which launches single-frequency signals as listed in Table 2.

Table 2 Frequencies and levels launched by the standard sound source Agilent 33220A

f (Hz)	500	600	700	800	900	1000	1100	1200
Level (dB)	150.8	153.1	154.3	156.9	157.8	158.5	156.9	158.1

The scanning system operates within a range of 1500mm along the linear guides, and perform measurements at an interval of 150mm. The moving speed of the arch is 20mm/s. Along the semi-circular arch, the hydrophones cover a range of 170°, and perform measurements at an interval of 17°. The hydrophones move along the arch at a speed of 1.5°/s. The data acquisition starts with a 3s delay after the hydrophones reach at specified positions in order to avoid the impact of scanning system movements.

The measurement at each frequency is repeated five times. Based on the comparison with standard sound source levels, the measurement errors are as shown in Table 3.

Table 3 Comparison of measurement errors (dB)

Frequency (Hz)		500	600	700	800	900	1000	1100	1200
Standard sound source level (dB)		150.8	153.1	154.3	156.9	157.8	158.5	156.9	158.1
Test No.	1	152.2	152.2	152.8	155.8	156.4	158.0	156.5	157.8
	2	151.6	152.9	152.9	155.6	156.5	157.8	155.7	157.5
	3	151.6	153.0	154.2	156.7	156.5	156.9	156.1	157.3
	4	150.8	153.1	154.5	156.6	156.6	157.1	156.1	157.3
	5	150.6	152.5	153.3	155.9	156.5	156.9	157.2	157.1
Max error (dB)		1.4	0.9	1.5	1.3	1.4	1.6	1.2	1.0
Statistical Analysis (dB, 5 times)		151.4	152.7	153.5	156.1	156.5	157.3	156.3	157.4
Statistical error (dB)		-0.6	0.4	0.8	0.8	1.3	1.2	0.6	0.7
Repeatability error (5 times)		≤±0.8	≤±0.5	≤±1.0	≤±0.6	≤±0.1	≤±0.7	≤±0.9	≤±0.4

The measurement errors in radiated sound power are shown in Figure 9.

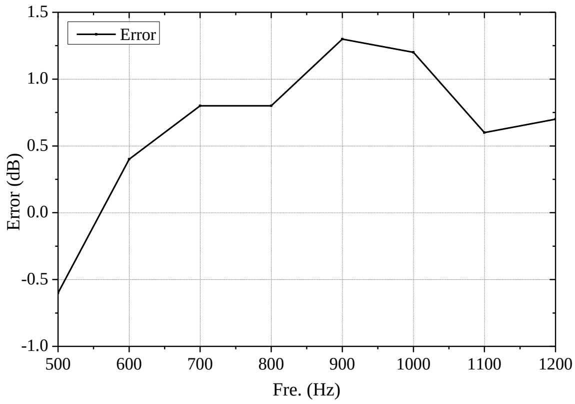

Figure 9 Measurement errors in radiated sound power

From the analysis results, the absolute errors are within ±2dB, while the repeatability errors are within ±1.5dB in the sound power levels measured in the frequency range of 500Hz ~ 1200Hz. It is verified that the principle of the test system is correct, and the test procedure is feasible.

5 TEST AND ANALYSIS OF A MODEL PUMP

The model pump has a seven-bladed rotor, and a set of axial guide vanes. Its outer diameter is 300mm. The rotor speed is 1450r/min at the flow rate of 0.42 m^3/s. Figure 10 shows the test setup for the model pump.

The longitudinal and circumferential scanning ranges are 1100mm and 170°, respectively. The intervals of measuring points in the two directions are 110mm and 17°, respectively.

According to the test procedure, signal acquisition is delayed by 3 seconds after the hydrophones reach at the measuring points. The 3kHz low-pass filter is used in the signal conditioner. The sampling frequency is 8192Hz for data acquisition.

Figure 10 Model pump test setup

The sound power level of the model pump is measured seven times. For each measurement, data analysis is made in the 40Hz~1600Hz frequency range. The statistical value of the total radiated sound power level is obtained by averaging the seven measurement results. Figure 11 shows the repeatability error of each measurement by comparing with the statistical value.

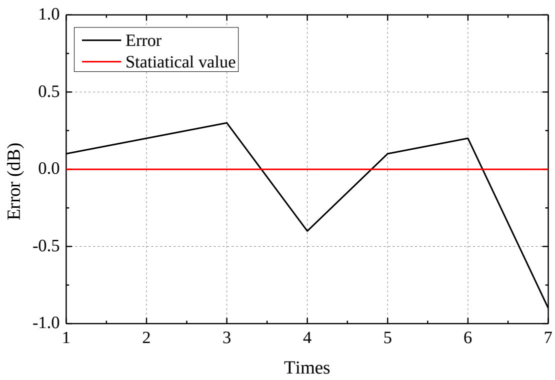

Figure 11 Errors in total radiated source level

Table 4 shows the repeatability error in radiated sound power level for each 1/3 octave band within the measuring frequency range of 40Hz ~ 1600Hz.

Table 4 Measurement errors in 1/3 octave bands

Center frequency (Hz)	40	50	63	80	100	125
Repeatability error (dB)	≤ 0.3	≤ 0.7	≤ 0.9	≤ 1.1	≤ 1.5	≤ 0.5
Center frequency(Hz)	160	200	250	315	400	500
Repeatability error (dB)	≤ 0.8	≤ 0.8	≤ 1.2	≤ 1.6	≤ 1.0	≤ 0.8
Center frequency(Hz)	630	800	1000	1250	1600	Max error
Repeatability error (dB)	≤ 1.6	≤ 1.2	≤ 1.2	≤ 0.8	≤ 0.4	≤ 1.6

Through the measurement and analysis of the radiated sound power of the model pump, it is seen that the repeatability error in total sound radiation power level is within 1dB, while the repeatability errors in different 1/3 octave bands are within 2dB. The test system can be used for the qualitative assessment of underwater radiation noise from propulsion pump models.

6 CONCLUSION

The design and verification of a test system for the comparative measurements of the underwater sound radiated from water-jet propulsion pumps are presented.

Based on the verification tests by using the standard sound source, it is shown that the absolute measurement errors are within ±2dB, and the repeatability errors are within ±1.5dB.

Through the tests for a model pump, it is shown that the repeatability errors in total radiation sound power level are below 1dB, and the repeatability errors in the 1/3 octave bands from 40Hz to 1600Hz are below 2dB.

The test system is expected to be widely applied to the qualitative assessment of the underwater noise from water-jet propulsion pump models, as well as the comparison of noise performance of conventional pump models.

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