Research Journal of Applied Sciences, Engineering and Technology 6(1): 57-62, 2013
DOI:10.19026/rjaset.6.4034
ISSN: 2040-7459; e-ISSN: 2040-7467
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Submitted: October 17, 2012 Accepted: January 05, 2013 Published: June 05, 2013

Research Article

Noise Radiation Measure-Sound Power and its Test Methods

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Abstract: This study mainly aims to study the characteristics and theory of sound radiation of steady-state vibration. Study shows that sound radiation power of steady-state vibration is constant. And taking excavator for experimental object by hemisphere surface method, the radiated sound power of the excavator is the same as testing the sound pressure on various surfaces based on relevant international standard. Finally, a test method of radiated sound power for cylindrical vibration object is proposed.

Keywords: Radiation noise, sound power, test methods

INTRODUCTION

Control of noise has gradually drawn attention of many scholars with improved demand of living environment. Noise originates from vibration of objects. So measuring vibration radiation noise is the prerequisite to reduce vibration and noise. How is the vibration noise radiation reduced?

First of all, the main noise source should be identified. There are many researches about this. For example, Crocker *et al*. (2004) studied different noise source of air-conditioner by adopting frequency analysis method. Of course, there are other ways to identify the main noise sources, such as: the least square error method (Shih-Yi and Ying-Jong, 2005) and harmony search algorithm (Sungho and Zong, 2009) to determine the main noise source. Secondly, some noise reduction measures are conducted to control the noise radiation. The common way is to optimize the vibration source structure (Arup and Jog, 2012; Jung-sun *et al*., 2011), to reduce the noise radiation (Yanzhao and Stanescu, 2002; Joseph *et al*., 1998). At the same time, the measurement of radiation noise is also indispensable work. Measurement accuracy of radiation noise is different under different measurement method (Dae and Sungho, 2008; Kitagawa and Thompson, 2006). Finally, the researches about characteristics of noise radiation are in favor of the development of noise reductions. There are also lots of studies about noise radiation of engine fan (Wu *et al*., 1998), perforated plate (Putra and Thompson, 2010) and aircraft landing wheel (Peter *et al*., 2007). All the researches mentioned above make large contributions to the noise reductions.

So far, the researches and experimental work of the characteristics about the steady-state vibration noise radiation which is studied in this study and common being in actual life have not been published. Therefore, this study is of wide range of application projects and reference value. And this study is mainly conducted by theoretic analysis and experimental measurements.

ANALYSIS OF STEADY-STATE VIBRATION NOISE RADIATION

Basic concept of acoustics:

Sound pressure: At a point in a fluid, the pressure in the static state is p_0. Once disturbed by exterior environment, p_0 changes to p, and the excess pressure caused by the disturbance is expressed as:

$$P' = p - p_0$$

which is called sound pressure.

As the sound pressure is alternate, effective sound pressure p_e is used to describe it and expressed as:

$$p_e = \sqrt{\frac{1}{T}\int_0^T P^2 dt}$$

In steady-state sound field, p_e is related only to the space and location rather than time.

Sound power is the total sound energy radiated from a sound source per unit time. Sound intensity is the average sound energy flow per unit area perpendicular to the direction of propagation. It is expressed as:

$$I = \frac{1}{T}\int_0^T P(t)v(t)dt$$

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For the acoustic radiation of steady-state vibration, I is related only to the space and location rather than time.

Transient sound intensity is given as:

$$I(t) = p(t)v(t)$$

The acoustic energy for volume V_0 is:

$$E = E_k + E_p = \frac{1}{2}(\rho_0 V_0)v^2 + (-\int_{V_0}^{V} pdV) \tag{1}$$

Substituting the equation of state into Eq. (1), we get:

$$E = \frac{1}{2}\rho_0 V_0 (v^2 + \frac{p^2}{\rho_0^2 c_0^2}) \tag{2}$$

The sound energy density is defined as the acoustic energy per unit volume, and is expressed as:

$$w = \frac{E}{V_0} = \frac{1}{2}\rho_0 (v^2 + \frac{p^2}{\rho_0^2 c_0^2}) \tag{3}$$

Therefore, sound intensity is given as:

$$I(t) = wc_0 = \frac{dE}{dtdS} = \frac{p_i(t)dSdr}{dtdS} = p(t)v(t) \tag{4}$$

Basic acoustic equations:

- **Continuity equation (no endogenous):** Mass will neither increase nor disappear. Changes in the infinitesimal body mass should be equal to the rate of its change ratio:

$$-\rho(\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z})dxdydz = \frac{\partial}{\partial t}(\rho dxdydz) \tag{5}$$

It can be simplified as following:

$$\frac{\partial \rho'}{\partial \mathrm{t}} = -\rho_0 \nabla \bullet v \tag{6}$$

- **Equation of motion:**

$$\rho_0 \frac{\partial v}{\partial t} = -\nabla p \tag{7}$$

- **Equation of state:** Because the sound propagation speed is much faster than heat, the sound wave propagation process is adiabatic. And the adiabatic process of a certain mass of an ideal gas is expressed as follows:

$$\frac{p}{p_0} = \left(\frac{V_0}{V}\right)^{\gamma} = \left(\frac{\rho}{\rho_0}\right)^{\gamma} \tag{8}$$

If we expand the above equation using the Taylor series expansion and omit the higher-order infinitesimal, we get:

$$p' = c_0^2 \rho'$$

where $c^2_0 = \gamma p_0/\rho_0$ is taken as the differential on both sides; then, we can get:

$$dp' = c_0^2 d\rho' \tag{9}$$

Calculation of radiation sound power under steady-state vibration: Here, we only discuss noise radiation in fluid. Assuming a steady-state vibration object radiates noise into the air space. If the vibration surface area is S_1, and an arbitrary closed space in the radiated sound field is S_2. S_1 is included in the closed space S_2. Further, assume that V is the space surrounded by S_1 and S_2 . Then sound energy radiated by V, the sound energy radiated outward per unit time is:

$$\oiint_{S} Ids = (-\oiint_{S_1} Ids) + \oiint_{S_2} Ids \tag{10}$$

Therefore, the vibrating surface S_1 is transmitting the acoustic energy of the vibrating body to space, the outward radiation energy of the space body V has a negative value. By the Gauss theorem, we get:

$$\oiint_{S} I(t)ds = \iiint_{V} \nabla I(t)dv = \iiint_{V} \nabla(wc_0)dv = c_0 \iiint_{V} (\nabla w)dv \tag{11}$$

$$\nabla w = \nabla\left(\frac{1}{2}\rho_0 (v^2 + \frac{p^2}{\rho_0^2 c_0^2})\right) = \rho_0 (v\nabla v + \frac{p}{\rho_0^2 c_0^2}\nabla p) \tag{12}$$

According to the continuity equation, i.e., Eq. (6), we get:

$$\nabla v = -\frac{1}{\rho_0}\frac{\partial \rho'}{\partial t}$$

Then, substituting $\nabla p = -\rho_0 \frac{\partial v}{\partial t}$ from the equation of motion Eq. (7) into the above Eq. (12) gives:

$$\nabla w = -(v\frac{\partial \rho'}{\partial t} + \frac{p}{c_0^2}\frac{\partial v}{\partial t}) \tag{13}$$

According to the equation of state (Eq. (9)), we get:

$$\frac{\partial \rho'}{\partial t} = \frac{1}{c_0^2}\frac{\partial p}{\partial t}$$

If we substitute this into Eq. (13),
we get:

$$\nabla w = -(v\frac{\partial \rho'}{\partial t} + \frac{p}{c_0^2}\frac{\partial v}{\partial t}) = -\frac{1}{c_0^2}\frac{\partial (pv)}{\partial t} = -\frac{1}{c_0^2}\frac{\partial I(t)}{\partial t}$$

therefore, we get:

$$\oiint_S I(t)ds = \iiint_V \nabla I(t)dv = -\frac{1}{c_0^2}\iiint_V \frac{\partial I(t)}{\partial t}dv \qquad (14)$$

For the time-averaged sound energy flow, we get:

$$\oiint_S Ids = \iiint_V \nabla Idv = -\frac{1}{c_0^2}\iiint_V \frac{\partial I}{\partial t}dv \qquad (15)$$

For the sound radiation of the steady-state vibration, I is independent of time and is a function of only the spatial location. Therefore, when the partial derivative of time is 0, namely, $\partial I/\partial t = 0$.

Substituting this into Eq. (15) gives:

$$\oiint_S Ids = \iiint_V \nabla Idv = -\frac{1}{c_0^2}\iiint_V \frac{\partial I}{\partial t}dv = 0$$

Further, because

$$\oiint_S Ids = (-\oiint_{S_1} Ids) + \oiint_{S_2} Ids$$

we get:

$$\oiint_{S_1} Ids = \oiint_{S_2} Ids \qquad (16)$$

Therefore, the radiation power of the steady-state vibration sound source is

$$W = \oiint_{S_1} Ids = \oiint_{S_2} Ids \qquad (17)$$

where, S_2 is any closed-source envelope surface.

TEST METHOD OF SOUND POWER

Through above analysis, we know that the total radiation sound power of the vibration source can be calculated by integrating the sound intensity along the source of any closed-envelope surface. Therefore, we can test the sound intensity at several points on enveloping surface, and the radiation sound power can be calculated and equals the tested intensity by the area of closed – envelope surface.

Especially, supposing that the enveloping surface is a uniform-sound-intensity surface, the radiation power of the sound source is the product of the test sound intensity of the enveloping surface and the area of this surface. Because the testing of sound pressure is more straightforward than that of the sound intensity, the sound pressure level is usually converted into the sound intensity level.

Test methods for radiation sound power of point source and approximate point source: For external radiation noise of a point source, the sound pressure surface of the radiation sound field is considered to be a sphere with the sound source as the center and *R* as the radius. Therefore, to determine the radiation noise of a point sound source, it is necessary to average the sound intensity at several measurement points on the sphere, and the radiation sound power is calculated by taking the product of the spherical surface area and the averaged sound intensity. In real life, most of the sound sources are at the ground level. Therefore, the outward radiating space is the hemisphere field with the sound source as the center and *R* as the radius. We can use the hemisphere surface method, assuming that the ground is the total reflection surface. We consider several measurement points on the hemisphere surface to test the point sound intensity; then, we average these intensity values to subsequently calculate the radiation sound power by taking the product of the averaged sound intensity and the hemisphere surface area. The specific test method conforms to relevant international standards (Hickling *et al*., 1997).

Test method for radiation sound power of rectangular sound source: For the radiation acoustic field of a rectangular source, the sound pressure surface is a rectangular surface. We take the core of the rectangular sound source as the center, construct the rectangular surface, and select measurement points on the rectangular surface; the radiation sound power is then obtained by taking the product of the averaged sound intensity and the area of the rectangular surface. The specific test method conforms to relevant international standards.

Test method for radiation sound power of cylindrical sound source: For the radiation sound field of a finite-length cylindrical sound source, the uniform sound pressure surface is a cylindrical surface. We take the axis of the cylinder as the axis of the tested surface, construct a tested envelope cylindrical surface, and select the measurement points on the cylindrical surface. Make sure that the normal distances from tested surface to the surface of sound source is equal. The radiation sound power is obtained by taking the product of the averaged sound intensity of the measurement points and the area of the tested cylindrical surface. If the sound source is placed at ground level and it outwardly radiates noise, it is necessary to use a semi-cylindrical method. We take the projection on the ground level of the axis of the cylindrical sound source as the axis of tested surface, and construct a close-tested surface formed by the semi-cylindrical surface which axis is the same as the projected axis of the envelope sound source at the ground level, assuming that the ground is a total reflection surface. We select the measurement points on the semi-cylindrical surface we constructed, and obtain the radiation sound power of the sound source by taking the product of the average sound intensity and the area of the semi-cylindrical surface. The distance of the axis of the sound source from the ground should be far less than the radius of the semicircular cylinder envelope to ensure that the semicircular cylinder surface is the uniform sound pressure surface. The formula for calculating the sound power is given as:

$$W = I * (\frac{1}{2}\pi RL + \pi R^2) \cdot$$

EXPERIMENTAL TEST

It can be seen from the testing method that the selection of the tested sound pressure surface is independent of the distance between the sound source and tested surface. Namely, the radiation sound power tested by different sound pressure surfaces is the same, especially when we take an approximate point source (the radiation sound source outside the excavator). The hemisphere method is used to test the radiation noise of the source; the experiment was performed under conformance to relevant international standards.

Test conditions:

- Name of test: noise test
- Model: DS18 Excavator (Engine Model: 3TNV82A-SNN); Fig. 1
- Testing tools: tape measure, lift truck
- Test equipment: integrating sound level meter (HS5618A); Fig. 2

Basic process and test methods: The hemispherical method is used in the test, and radii (*R*) of 4 m and 10 m are considered. Figure 3 shows the microphone position on the hemisphere surface. Six measurement points are selected and the microphone position coordinates are as given in Table 1

Three sound pressure level tested values should be recorded from any microphone measuring points. A supplementary test is required if the difference between two out of the three values is more than 1 dB. The arithmetic mean of the two values with a difference of less than 1 dB are used as the reported values of the A-weighted sound pressure level. If there are more than one pairs calculated value of sound power level which meet the above requirements, then we take a greatest pair value on the arithmetic mean as the reported value of the A-weighted sound pressure level. The formula

Fig. 1: Test prototype

Fig. 2: Test equipment

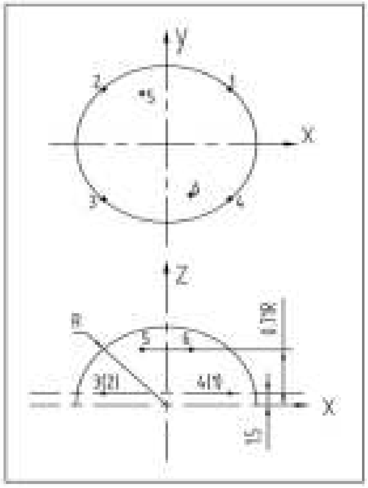

Fig. 3: Layout position of hemispherical microphone

Fig. 4: Measurement of noise at hemispherical space measurement points

Table 1: Microphone position coordinates

Microphone No.	X/R	Y/R	Z (Unit: m)
1	0.7	0.7	1.5
2	-0.7	0.7	1.5
3	-0.7	-0.7	1.5
4	0.7	-0.7	1.5
5	-0.27	0.65	0.71R
6	0.27	-0.65	0.71R

Table 2: Noise value at radiation measurement points outside the DS18 excavator (unit: dB)

No.	Test radius	Measurement point 1	Measurement point 2	Measurement point 3	Measurement point 4	Measurement point 5	Measurement point 6	Average energy	Sound power
1	A radius of 10 m	63.5	64.3	63.1	61.5	64.7	60.3	63.1552	91.1335
2		63.5	64.3	63.1	61.9	64.3	60.7	63.1482	
3	A radius of 4 m test	71.7	72.1	70.5	69.9	72.3	68.5	71.0303	91.0494
4		71.3	72.1	70.6	69.9	72.4	68.8	71.0224	

for the A-weighted sound power level is given in the appendix. Figure 4 shows the measurement of noise at the hemispherical space measurement points.

Test data and results: The test data and results are as given in Table 2. It is summed from the experimental data that: The calculated sound power level is 91.3335 dB when the testing radius is 10 m. And the calculated sound power level is 91.0494 dB when the testing radius is 4 m. Though differences of the pressure are large on different tested surfaces, the sound powers are basically the same.

CONCLUSION

After analyzing steady-state sound field radiation in this study, the conclusion has been drawn that the sound power source is a constant value, which can independently describe source noise. Namely, the sound power level of a steady-state source is the same as testing the sound pressure level on various surfaces. Experiments have been carried out on different tested surfaces and show that the sound power values are basically the same, though the sound pressure level is different on different surfaces.

Highlights:

- The Gauss theorem of steady-state sound radiation is deduced.
- Test methods for radiation sound power of a cylindrical vibrating body are shown.
- The sound power level of a source as testing the sound pressure level on various surfaces is the same.

APPENDIX

The average equivalent continuous A-weighted sound level is expressed as:

$$\overline{L_{PAeq,T}} = 10\lg\left[\frac{1}{6}\sum_{i=1}^{6} 10^{0.1L_{PAeqi}}\right]$$

where, L_{PAeqi} is the equivalent continuous A-weighted sound level measured at the microphone measurement point i (unit: dB).

The A-weighted sound power level of the machine L_{WA}, is given as (unit: dB):

$$L_{WA} = \overline{L_{PAeq,T}} + 10\lg\frac{S}{S_0}$$

where, $S_0 = 1m^2$, $S = 2\pi R^2$

ACKNOWLEDMENT

The study was supported by the Program for Graduate Student's Scientific Innovation Research of the Jiangsu Higher Education Institution of China (Grant No: CXLX12_0632).

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