technical monograph 33

Use of Pipewall Vibrations to Measure Valve Noise

Allen C. Fagerlund

Senior Research Specialist
Final Control Systems Research
Fisher Controls International, Inc.

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Acoustic energy generated by fluid flow through a control valve propagates through the piping and creates a fluctuating pressure field which forces the pipewalls to vibrate. These vibrations in turn cause pressure disturbances outside the pipe that radiate as sound.

When measuring the sound generated by a single control valve, multiple noise sources and reflected sound can make it difficult to determine what the measured value actually represents. In these instances, converting the vibration levels of the pipeline in which the valve is installed to an equivalent sound pressure level eliminates many of the measurement problems.

A study of sound transmission loss through the walls of commercial piping indicated the feasibility of converting pipewall vibrations to sound levels.[1] Further study resulted in a valid conversion technique.

Acoustic Power to Radiation Efficiency

Basic to the vibration-to-sound conversion technique is the relationship between acoustic power and radiation efficiency. Ideally, the pressure of an acoustic wave is proportional to the particle velocity of the medium through which the wave passes, with the constant of proportionality being the acoustic impedance of that medium. At the surface of a pipe, particle velocity is assumed equal to the velocity at which the pipe wall is vibrating. From this, acoustic wave pressure at the wall can be related ideally to wall velocity by:

$$p = \rho_o c_o v \qquad (1)$$

where p and v are root-mean-square values. (Note: all equation terms are defined in the nomenclature list.)

It is helpful when discussing the transfer of acoustic energy from one location to another to utilize the parameters *acoustic power* and *acoustic pressure.* Acoustic pressures exist as a result of a net acoustic power flow through a finite area. Given a power level, an increase in area through which the power flows results in a decrease in pressure acting on that area.

Acoustic power is related to acoustic pressure by the following general formula:

$$W = \frac{p^2 A}{\rho_o c_o} \qquad (2)$$

Substituting equation (1) into equation (2) yields the *ideal acoustic power* radiated by the vibrating pipe surface where the area of interest (A) is the surface of the pipe.

Therefore:

$$W_I = \pi D \ell \rho_o c_o v^2 \qquad (3)$$

An *actual acoustic power* can be calculated from equation (2) based on sound pressure level measurements at a point away from the pipe surface. The area term would be that of a cylinder with a radius equal to the distance (r) from the observer to the centerline of the pipe. The actual power may be written from equation (2) as:

$$W_A = \frac{2\pi r \ell p^2}{\rho_o c_o} \qquad (4)$$

A radiation efficiency term (σ) can be defined as the ratio of the actual acoustic power to the ideal acoustic power (W_A/W_I). Using this definition and equations (3) and (4) the relationship between the velocity of the pipe wall and the acoustic pressure at a point in space is:

$$p^2 = \rho_o^2 c_o^2 v^2 \frac{D}{2r} \sigma \qquad (5)$$

It now is evident that if the radiation efficiency is known, the conversion from wall vibration velocity to acoustic pressure at any point in a free field can be made easily.

The efficiency with which a surface radiates sound is a function of frequency. A coincident frequency (f_c) can be defined as the frequency at which the propagation velocity of a flexural wave in the pipe surface equals the velocity of sound in the acoustic medium. Coincident frequencies for many common steel pipes (air as the acoustic medium) are provided in Table 1.

Earlier studies[1,2] indicate that radiation frequency is equal to unity above the coincident frequency and is directly proportional to the frequency in the region below coincidence. This is shown in Figure 1.

In summary:

$$p^2 = v^2 \rho_o^2 c_o^2 \frac{D}{2r} \frac{f}{f_c} \qquad f < f_c \qquad (6a)$$

$$p^2 = v^2 \rho_o^2 c_o^2 \frac{D}{2r} \qquad f \geq f_c \qquad (6b)$$

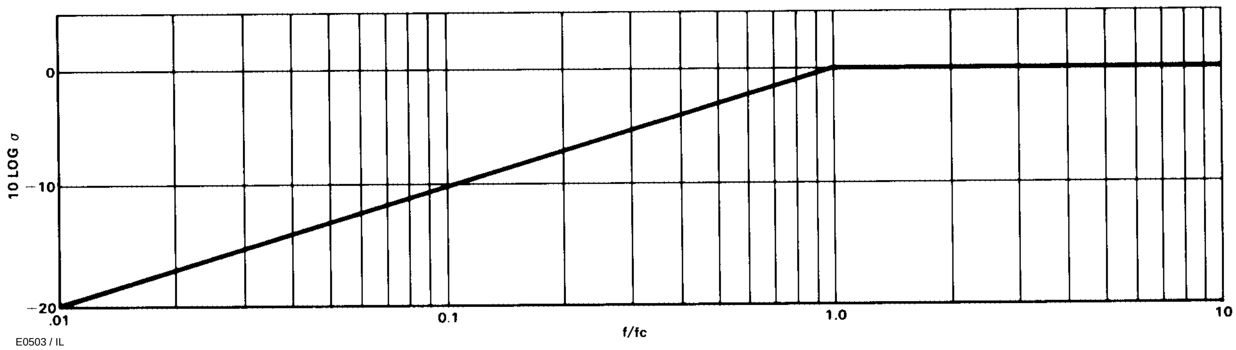

Figure 1. Above Coincident Frequency (f_c), Radiation Efficiency (σ) Equals Unity; Below, It Is Directly Proportional to Frequency

Acceleration measurements are often made rather than velocity measurements. The relationship

$$v^2 = \frac{a^2}{\omega^2} \qquad (7)$$

can be used in equations (6a) and (6b) to yield

$$p^2 = a^2 \frac{\rho_o{}^2 c_o{}^2}{4\pi^2} \frac{D}{2r} \frac{1}{ff_c} \qquad f < f_c \qquad (8a)$$

$$p^2 = a^2 \frac{\rho_o{}^2 c_o{}^2}{4\pi^2} \frac{D}{2r} \frac{1}{f^2} \qquad f \geq f_c \qquad (8b)$$

Table 1. Coincidence Frequencies (f_c in Hz) of Steel Pipe in Air

PIPE DIA.	PIPE SCHEDULE		
	40	80	160
2	3241	2290	1455
4	2106	1481	939
6	1783	1155	695
8	1550	998(2)	551
10	1367	998(2)	– – –
12	1331(1)	998(2)	– – –
16	1331(1)	998(2)	– – –
24	1331(1)	998(2)	– – –

1. Standard Wall.
2. XS Wall.

Considerations

Certain limitations must be recognized. As presented, the theory is appropriate for shell modes only. Shell mode response is what would be present if a flat vibrating plate were rolled into a cylinder. At low frequencies, however, the shell modes are not present and the response of the pipe is due to the entire length of pipe acting as a beam. These beam modes can vibrate with very high amplitudes; however, the efficiency of their coupling to the acoustic field on the outside of the pipe is extremely low. Recent studies[3] have shown that the radiation efficiency for shell modes is considerably greater than for the beam modes.

Table 2. 1st Shell Mode Frequencies (Hz)

PIPE DIA.	PIPE SCHEDULE		
	40	80	160
2	3115	4675	8289
4	1301	1940	3363
6	694	1124	2053
8	466	756	1517
10	338	475(2)	– – –
12	244(1)	332(2)	– – –
16	153(1)	208(2)	– – –
24	67(1)	90(2)	– – –

1. Standard Wall.
2. XS Wall.

This means a vibration measurement may indicate high energy content at low frequencies with very little contribution to the observed sound pressure level. Frequencies associated with the lowest shell mode are tabulated for each standard pipe size in Table II and should be considered as a low frequency cutoff for the direct application of the theory. This is generally not restrictive in evaluating control valve noise or other broadband high frequency noise.

In order to use the preceding formulation it is necessary to convert the mean-square values to decibels. This can be accomplished using the following definitions.

Sound pressure level in dB—SPL = $10 \log \frac{p^2}{p_o{}^2}$

Wall velocity level in dB—VdB = $10 \log \frac{v^2}{v_o{}^2}$

Wall acceleration level in dB— AdB = $10 \log \frac{a^2}{a_o{}^2}$

Widely accepted values for the various reference parameters are:

p_o = .0002 dynes/cm^2

$v_o = 10^{-6}$ cm/sec

$a_o = 10^{-3}$ cm/sec^2

Using the above definitions, equations (6a) and (6b) can be changed to decibel notation.

$$SPL = 10\log\frac{v^2}{10^{-12}} + 10\log\frac{D}{2r} + 10\log\frac{f}{f_c} - 13.7 \qquad f < f_c \qquad (9a)$$

$$SPL = 10\log\frac{v^2}{10^{-12}} + 10\log\frac{D}{2r} - 13.7 \qquad f \geq f_c \qquad (9b)$$

If the absolute value of the wall velocity is obtained with a vibration meter for example, then this value may be substituted directly in the first term (v) on the right hand side of the equations. This velocity must be expressed in cm/sec.

When velocity measurements are taken in decibels referenced to 10^{-6} cm/sec, this velocity dB may be substituted for the entire first term $\left(10\log\frac{v^2}{10^{-12}}\right)$.

In the same manner, equations (8a) and (8b) may be changed to decibel notation for acceleration measurements.

$$SPL = 10\log\frac{a^2}{10^{-6}} + 10\log\frac{D}{2r} - 10\log ff_c + 30.4 \qquad f < f_c \qquad (10a)$$

$$SPL = 10\log\frac{a^2}{10^{-6}} + 10\log\frac{D}{2r} - 20\log f + 30.4 \qquad f \geq f_c \qquad (10b)$$

Absolute values of the acceleration in cm/sec^2 can be substituted directly for (a) in the first term of equations (10a) and (10b). If acceleration levels are taken in decibels relative to 10^{-3} cm/sec^2 then this level may be substituted for the term $\left(10\log\frac{a^2}{10^{-6}}\right)$.

When vibration levels are taken in decibels relative to a reference value other than presented here it is then necessary to equate an absolute value using the definitions of velocity-dB or acceleration-dB and substituting for (v) or (a) in equations (9) or (10), respectively.

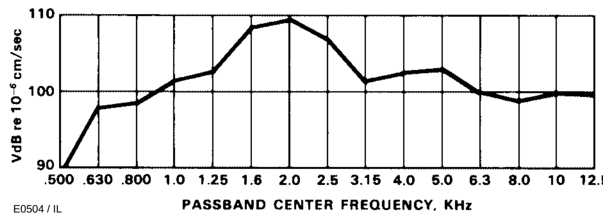

Figure 2. Velocity Level in dB as a Function of Frequency for 12" Standard Wall Pipe

The equations presented for velocity (9a, 9b) and acceleration (10a, 10b) allow conversion as a function of frequency. Ideally, to gain an overall equivalent sound pressure level from vibration measurements a summation of the corrected levels from each frequency band would be made. This is essential when acceleration is the quantity measured. However, when converting overall wall velocity to overall acoustic pressure, equation (9b) serves as a reasonable approximation as long as the velocity spectrum is not dominated by low frequency components.

Conversion Examples

Examples of converting velocity and acceleration level measurements to equivalent sound pressure levels illustrate the previous analysis.

Velocity

Determine — The equivilant sound pressure level that would be observed at a point 29" from the surface of the pipe.

Given — Velocity band levels measured on a 12" standard wall pipe are plotted in Figure 2.
— Equations (9a) and (9b) apply.
— From Table 1, f_c = 1331 Hz
— Pipe diameter = 12.75"; therefore r = 29" + 6.375"

Solving for the correction factor SPL-VdB—

$$SPL - VdB = 10\log\frac{D}{2r} + 10\log\frac{f}{f_c} - 13.7$$

$$= -7.4 + 10\log\frac{f}{f_c} - 13.7$$

$$= -21.1 + 10\log\frac{f}{f_c} \text{ when } f < f_c$$

$$= -21.1 \text{ when } f \geq f_c$$

Equivalent sound pressure levels for each 1/3-octave band are found by algebraically adding the SPL-VdB

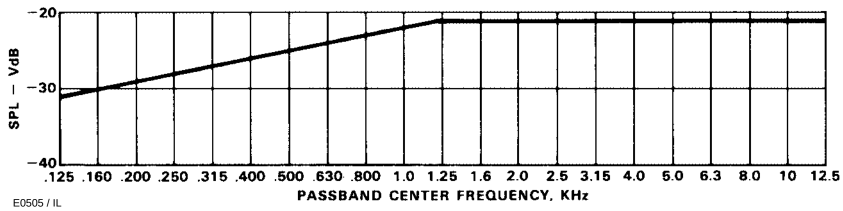

Figure 3. Typical Correction Factor Curve for Use with Velocity Level Measurement (Based on 12" Standard Wall Pipe)

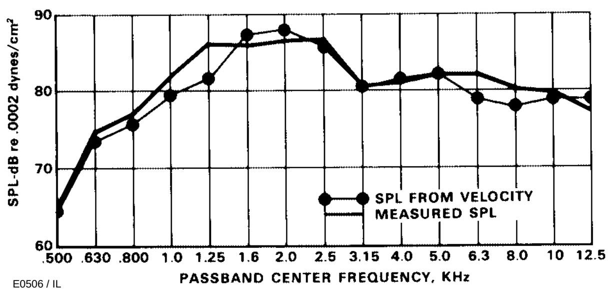

Figure 4. Comparison of Actual SPL Based on Velocity Measurements, 12" Standard Wall Pipe

factor to the velocity band level determined from Figure 2. For example, at 1331 Hz the measured VdB equals 106. Adding this to the SPL-VdB value yields an equivalent SPL of 84.9.

When faced with a number of conversions for a given pipe diameter, the task of solving the velocity equations can be lessened by developing a SPL-VdB factor curve as illustrated in Figure 3.

Figure 4 compares actual SPL and equivalent SPL as derived through use of equations (9a) and (9b).

Acceleration

Determine—The equivalent sound pressure level that would be observed at a point 29" from the surface of the pipe.

Given—Acceleration band levels measured on a 12" standard wall pipe are plotted in Figure 5.
—Equations (10a) and (10b) apply.
—From Table 1, f_c = 1331 Hz
—Pipe diameter = 12.75"; therefore r = 29" + 6.375"

Solving for the correction factor SPL-AdB—

$$SPL-AdB = 10\log\frac{D}{2r} - 10\log ff_c + 30.4 \qquad (10a)$$

$$= -7.4 - 10\log ff_c + 30.4$$

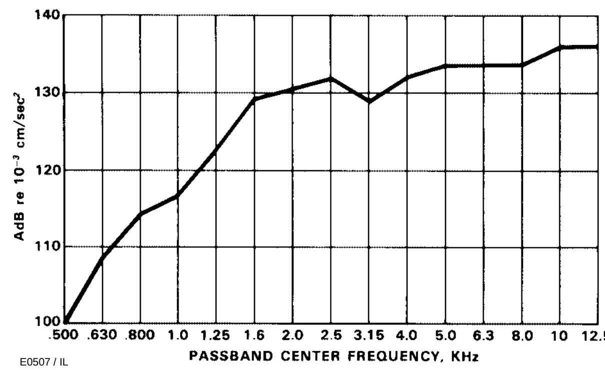

Figure 5. Acceleration Level in dB as a Function of Frequency for 12" Standard Wall Pipe

$$= 23.0 - 10\log ff_c \ \ when \ \ f < f_c$$

$$SPL-AdB = 10\log\frac{D}{2r} - 20\log f + 30.4 \qquad (10b)$$

$$= 23.0 - 20\log f \ \ when \ \ f \geq f_c$$

Equivalent sound pressure levels for each 1/3-octave band are found by algebraically adding the SPL-AdB factor to the acceleration band level determined from Figure 5. As with velocity measurement conversions, the equation solving task can be eased by developing a SPL-AdB factor curve as shown in Figure 6.

Figure 7 compares actual SPL and equivalent SPL as derived through use of equations (10a) and (10b).

Equivalent overall sound pressure levels can be obtained from the corrected vibration measurements by summing the energy in all frequency bands. This yields the following results for the data in the sample problems.

Total SPL (measured data) = 94.7 dB

Total SPL (corrected velocity) = 94.8 dB

Total SPL (corrected acceleration) = 94.6 dB

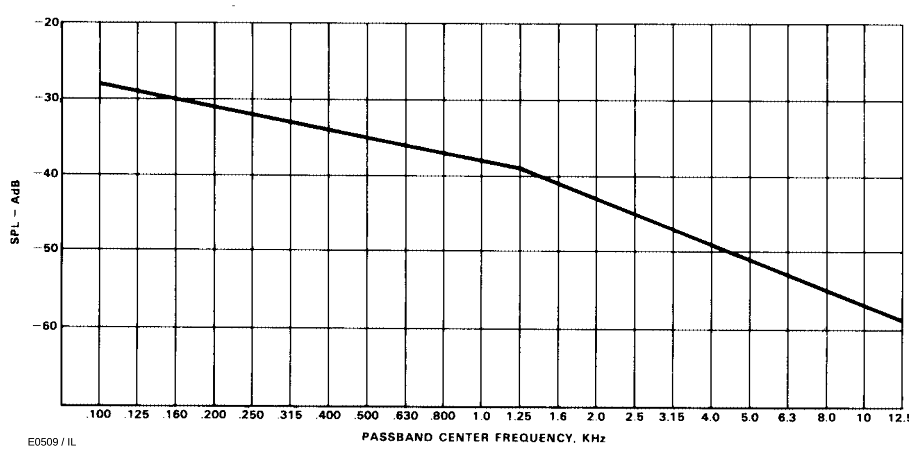

Figure 6. Typical Correction Factor Curve for Use with Acceleration Level Measurements (Based on 12" Standard Wall Pipe)

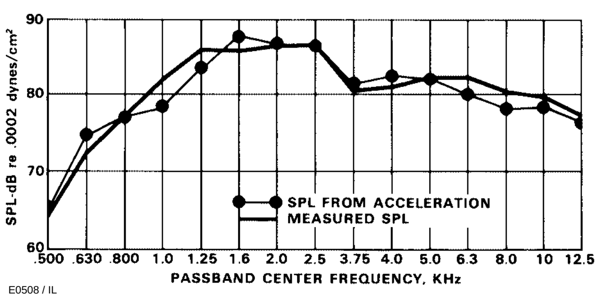

Figure 7. Comparison of Actual SPL to SPL Based on Acceleration Measurements, 12" Standard Wall Pipe

Measurement Techniques

The accuracy of the conversion method is a function of the accuracy with which the vibration measurements are taken. A typical vibration measuring system consists of an accelerometer to sense the vibrations plus analysis instrumentation for displaying or storing the information.

When making measurements care should be taken that the frequency response of the measuring equipment is compatible with the intended application.

Assuming that all equipment is operating properly, the important variable in making a measurement is the attachment of the accelerometer to the pipe wall. Rigid attachment to the pipewall is critical to accurate field results.

Ideally, the accelerometer should be rigidly attached to a small metal pad that is welded to the pipe. Also, some device should be used to electrically isolate the accelerometer from the pipe—such as an insulated stud or washer between surfaces. This attachment method will yield valid information over the entire frequency range for which the particular probe is specified.

An alternative is to attach pads or studs to the pipe wall using an adhesive. As long as a stiff, thin layered adhesive is used this method can be effective over the specified range of the probe. Different adhesives are necessary depending on the temperature of the application.

Magnetic attachments should be of special design to give a firm bond to a cylindrical surface. Even with a good magnetic attachment, the high frequency response is limited. If a magnetic base is used, then the surface should be clean of paint and dirt to ensure maximum contact.

Hand held accelerometers generally are limited to very low frequency measurements.

This theory cannot be used if the accelerometer is located on a flange, elbow, valve body, or other pipe fitting. Measurements should be taken a minimum of two diameters from the end of a straight run of pipe.

Nomenclature

a = rms wall acceleration

a_o =reference acceleration

c_o = ambient wavespeed

D = O.D. of pipe

f = frequency

f_c = coincident frequency

ℓ =pipe length

p = rms acoustic pressure

P_o = reference pressure

r = radial distance from centerline

v = rms wall velocity

v_o =reference velocity

W =acoustic power

W_A =actual acoustic power

W_I =ideal acoustic power

ρ_o =ambient density

σ =radiation efficiency

ω = angular frequency

SPL =sound pressure level

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Meet the Author...

Allen Fagerlund is a Senior Research Specialist in the Final Control Systems research group at Fisher Controls International, Inc. He holds a PhD degree in Mechanical Engineering from the University of Iowa, a MS Applied Mechanics degree from the University of Rhode Island, and a BS Ocean Engineering degree from Florida Atlantic University.

Fisher Controls International, Inc.
205 South Center Street
Marshalltown, Iowa 50158 USA
Phone: (641) 754-3011
Fax: (641) 754-2830
Email: fc-valve@frmail.frco.com
Website: www.fisher.com

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