August 12, 2021

Hydraulic Fluidborne Noise Measurements

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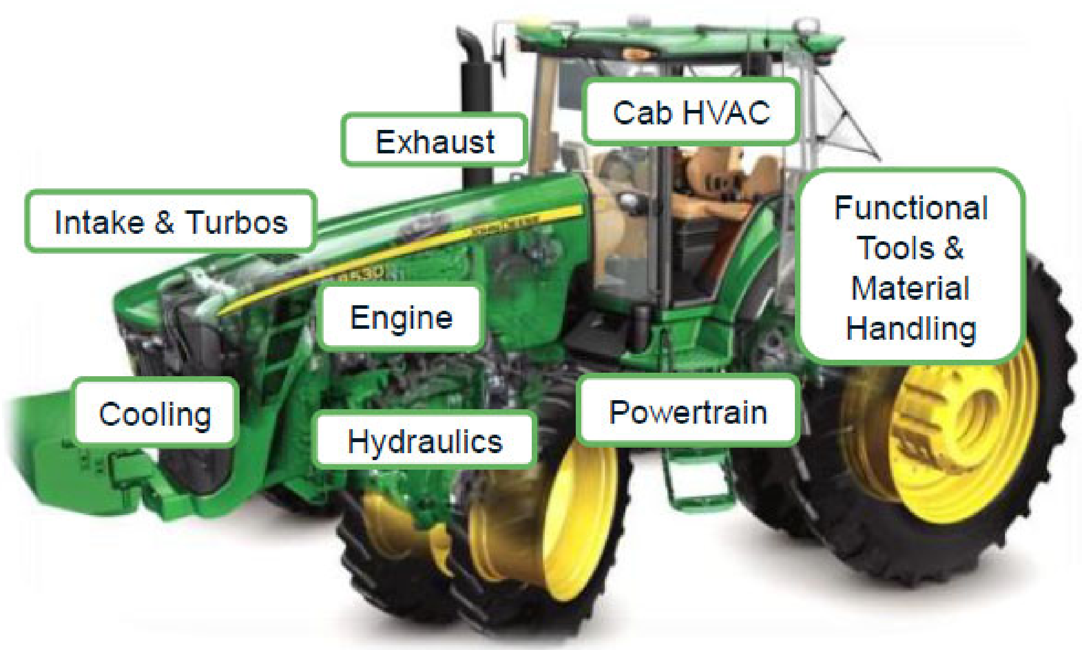
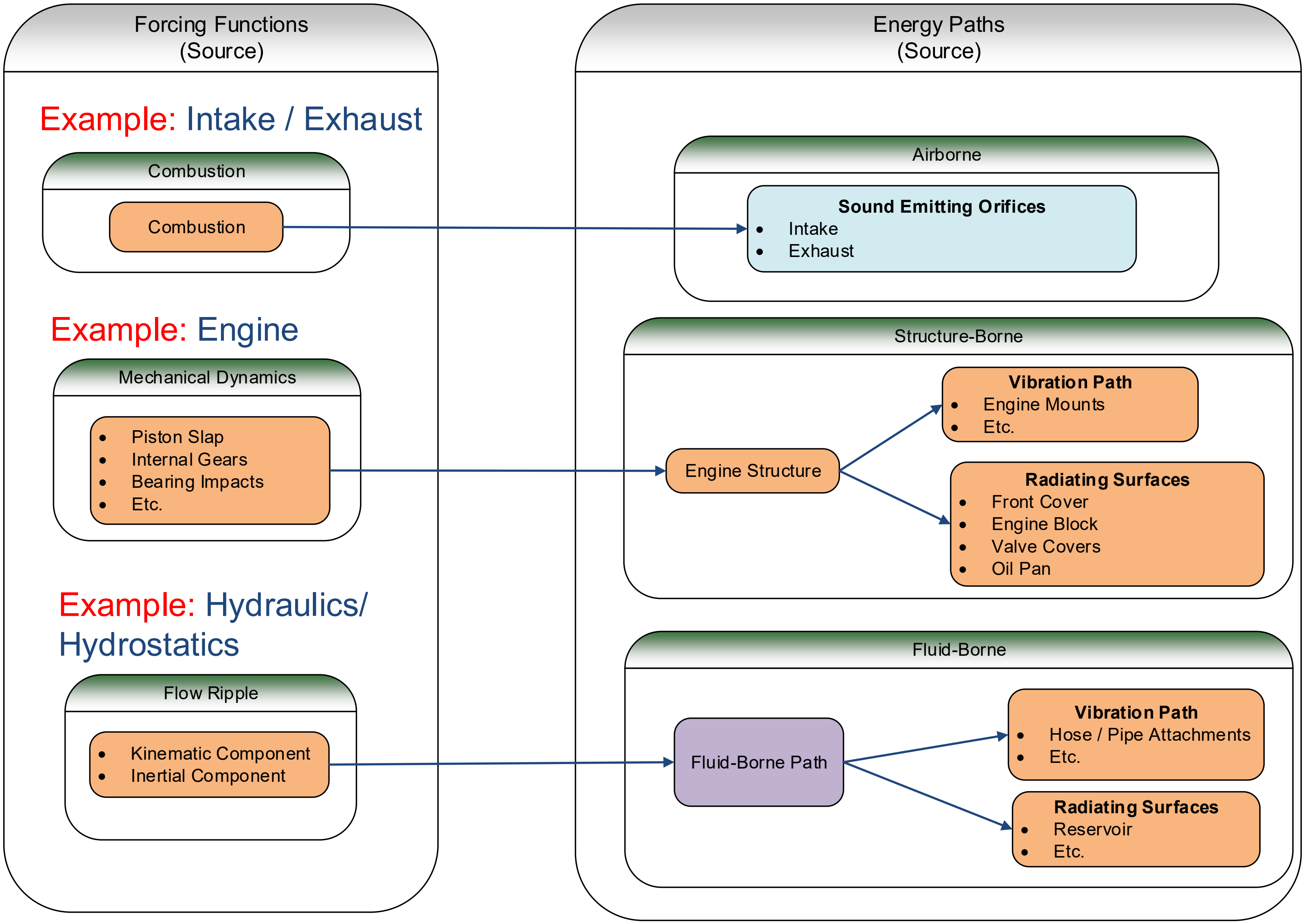
University of Kentucky

Heavy Equipment Multiple Sources

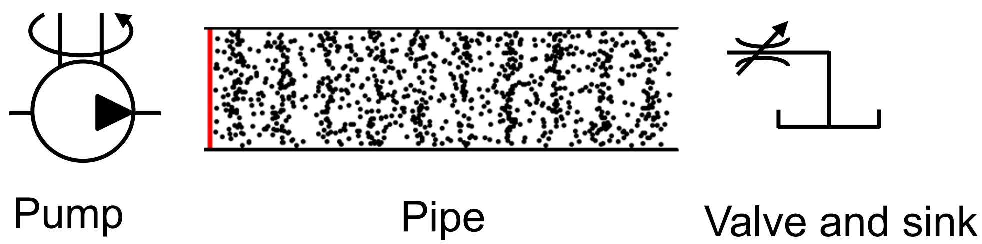




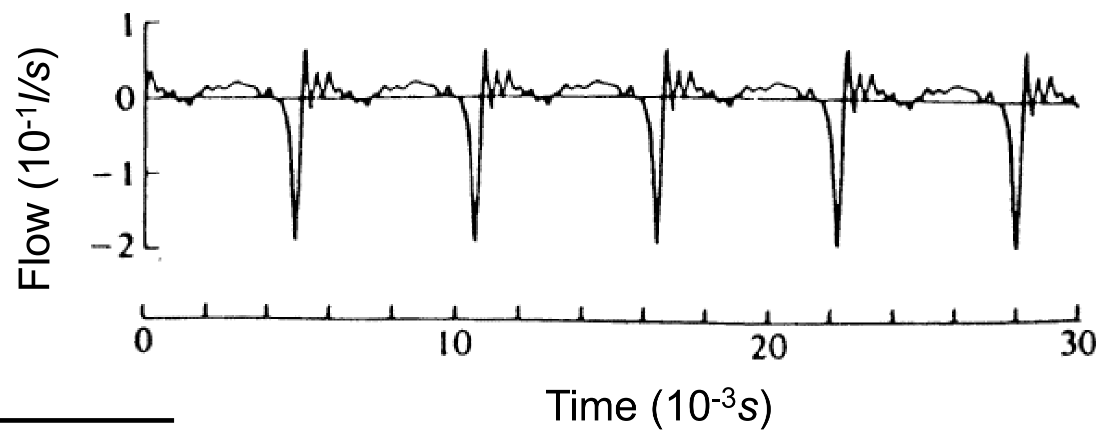
The source energy paths are characterized by the whether the forcing function is airborne, structure-borne, or Fluid-Borne.

Flow Ripple

- Kinematic Component
- Inertial Component



Typical flow ripple for a piston pump:



Standards

ISO 15086 Hydraulic fluid power – Determination of fluid-borne noise characteristics of components and systems

- ❖ Part 1 (2001): Plane wave model in hydraulics
- ❖ Part 2 (2000): Measurement of speed of sound
- ❖ Part 3 (2008): Measurement of hydraulic impedance

ISO 10767 Hydraulic fluid power – Determination of pressure ripple levels generated in systems and components

- ❖ Part 1 (1996): Measurement of source flow ripple and source impedance
- ❖ Part 1 (2015): Measurement of source flow ripple and source impedance

Plane Wave Model

Acoustic Pressure

$$P(x) = p_i e^{-jkx} + p_r e^{jkx}$$

$$k = \frac{2\pi f}{c}$$

Pressure Ripple

$$P(x) = p_i e^{-\gamma x} + p_r e^{\gamma x}$$

$$\gamma = j\frac{2\pi f}{c}\,\xi$$

ξ: viscosity coefficient

Viscosity Coefficient

$$\xi(\omega) \approx \left(1 + \sqrt{\frac{\nu}{2r_0^2\omega}}\right) - j\left(\sqrt{\frac{\nu}{2r_0^2\omega}} + \frac{\nu}{r_0^2\omega}\right)$$

Plane Wave Model

Acoustic Particle Velocity

$$Q(x) = \frac{1}{Z_c}\left(p_i e^{-jkx} - p_r e^{jkx}\right)$$

Characteristic Impedance

$$Z_c = \frac{\rho c}{S} \quad \text{(in air)}$$

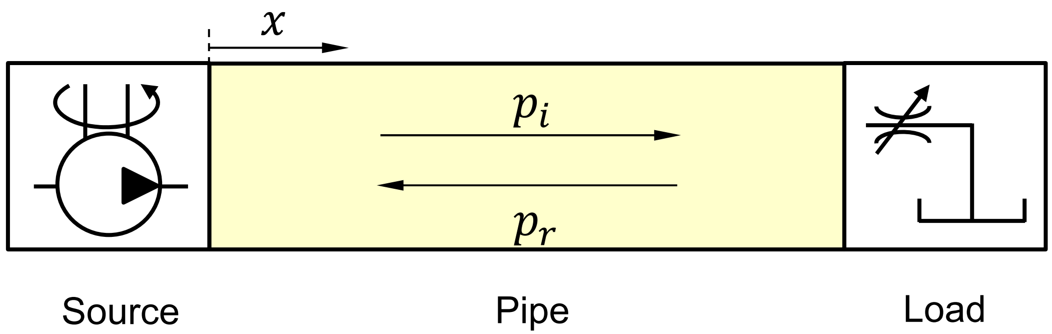
Flow Ripple

$$Q(x) = \frac{1}{Z_c}\left(p_i e^{-\gamma x} - p_r e^{\gamma x}\right)$$

Characteristic Impedance

$$Z_c = \frac{\rho c \xi(\omega)}{S}$$

Plane Wave Model



$$P(x) = p_i e^{-\gamma x} + p_r e^{\gamma x}$$

$P(x)$: fluid pressure at location x

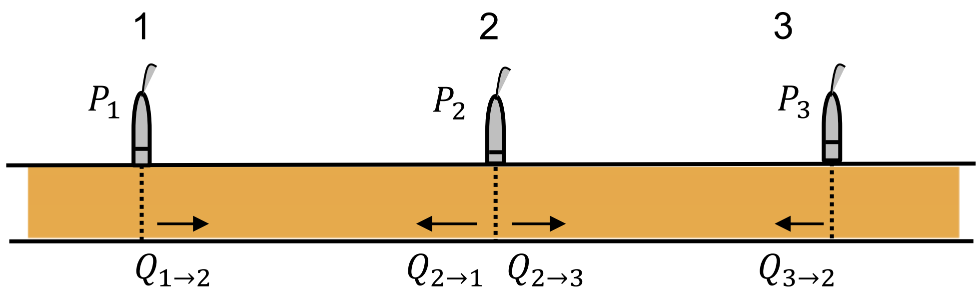
p_i: incident wave amplitude

p_r: reflected wave amplitude

γ: wave propagation coefficient

x: location in the pipe

Hydraulic Transfer Matrix



$$\begin{bmatrix} P_1 \\ Q_{1\to2} \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} P_2 \\ Q_{2\to1} \end{bmatrix}$$

$$\begin{bmatrix} P_2 \\ Q_{2\to3} \end{bmatrix} = \begin{bmatrix} T_{22} & T_{23} \\ T_{32} & T_{33} \end{bmatrix} \begin{bmatrix} P_2 \\ Q_{3\to2} \end{bmatrix}$$

$$Q_{2\to1} + Q_{2\to3} = 0$$

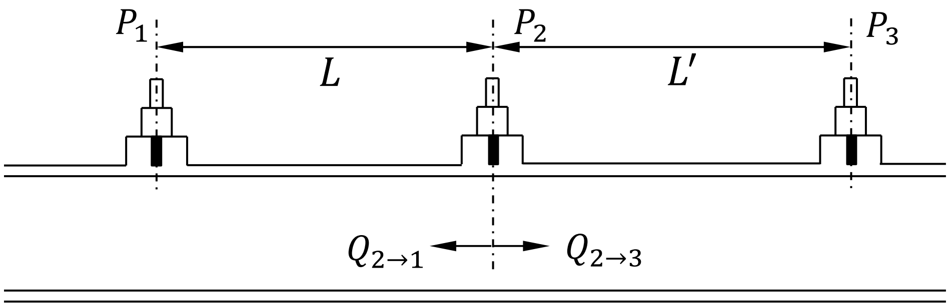
Property Calculations

From handbooks:
- Viscosity of fluid in pipe ν
- Density of fluid ρ

From measurement: Speed of sound c

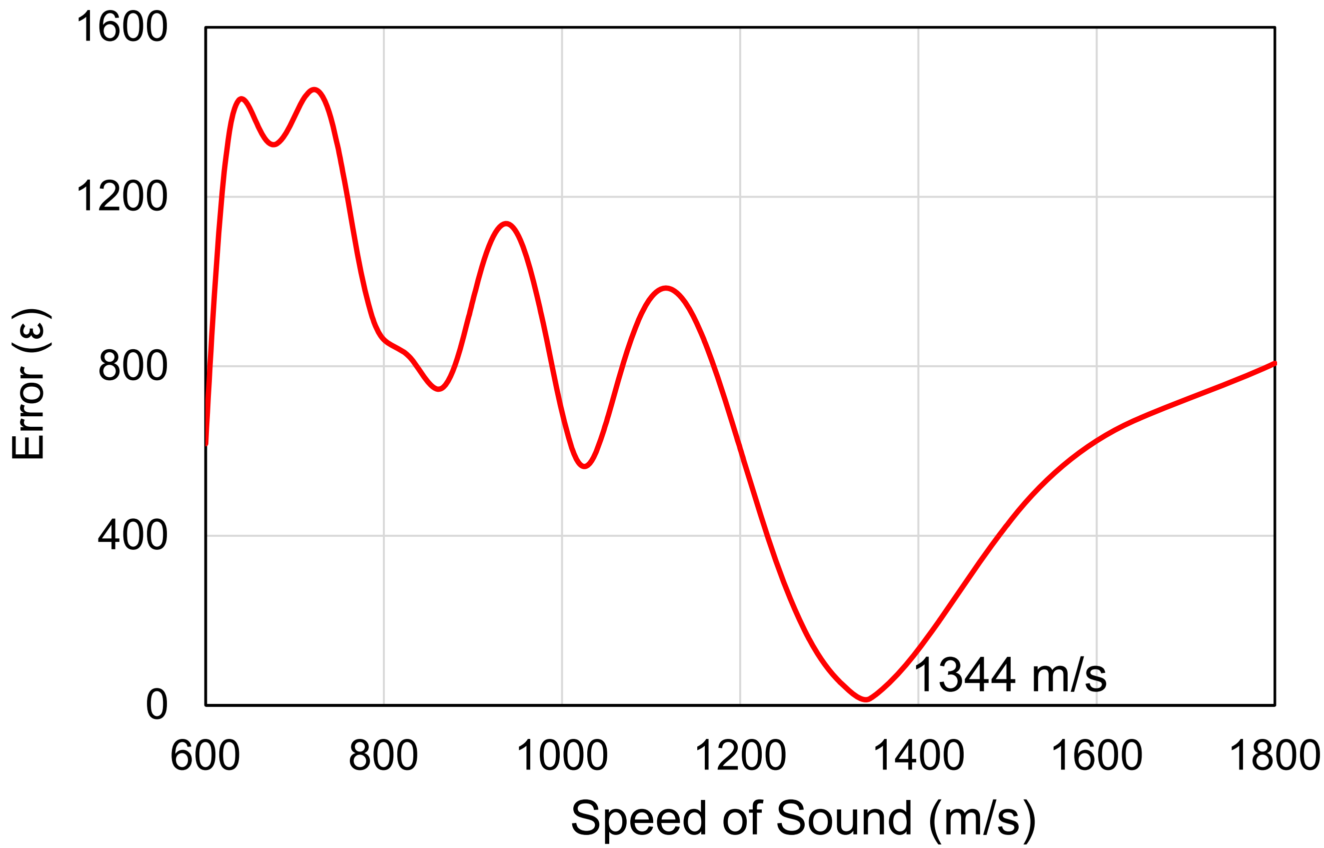
→ Wave propagation coefficient $\gamma = j\dfrac{\omega}{c}\xi$

Speed of Sound ISO 15086-2

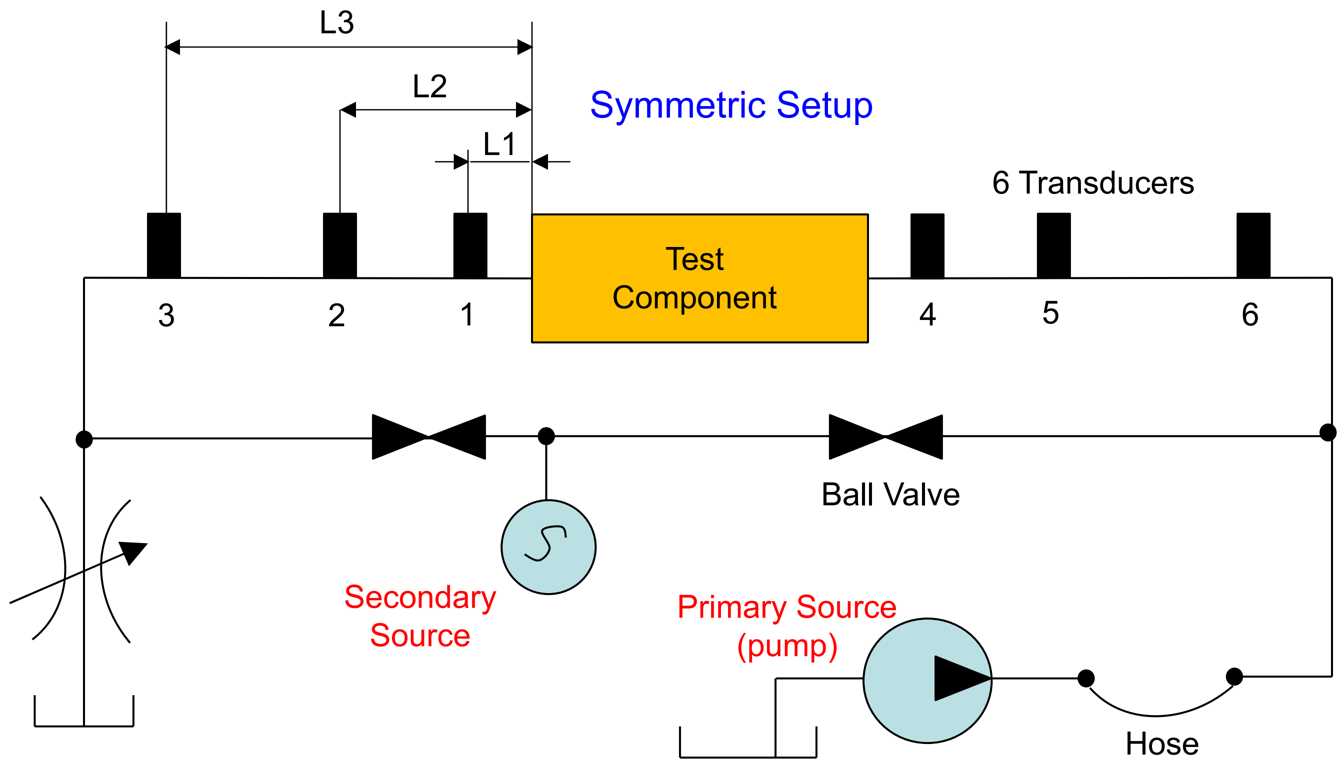


1. Assume speed of sound to determined incident and reflected wave using p_1 and p_2.
2. Determine p_3 and compare to measured p_3.
3. Iterate c until error is minimized.

Speed of Sound ISO 15086-2

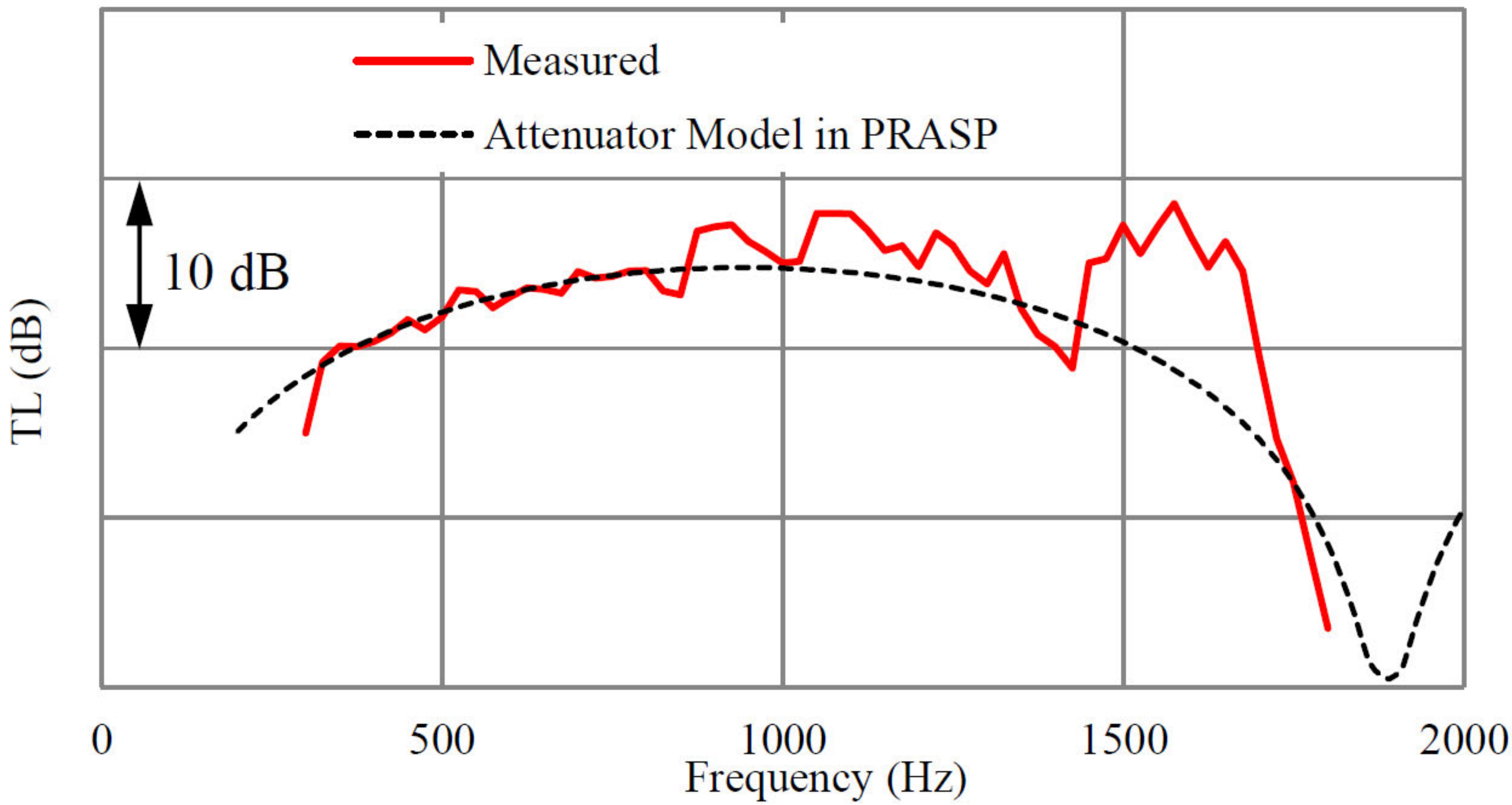


Transmission Loss Two Source Approach



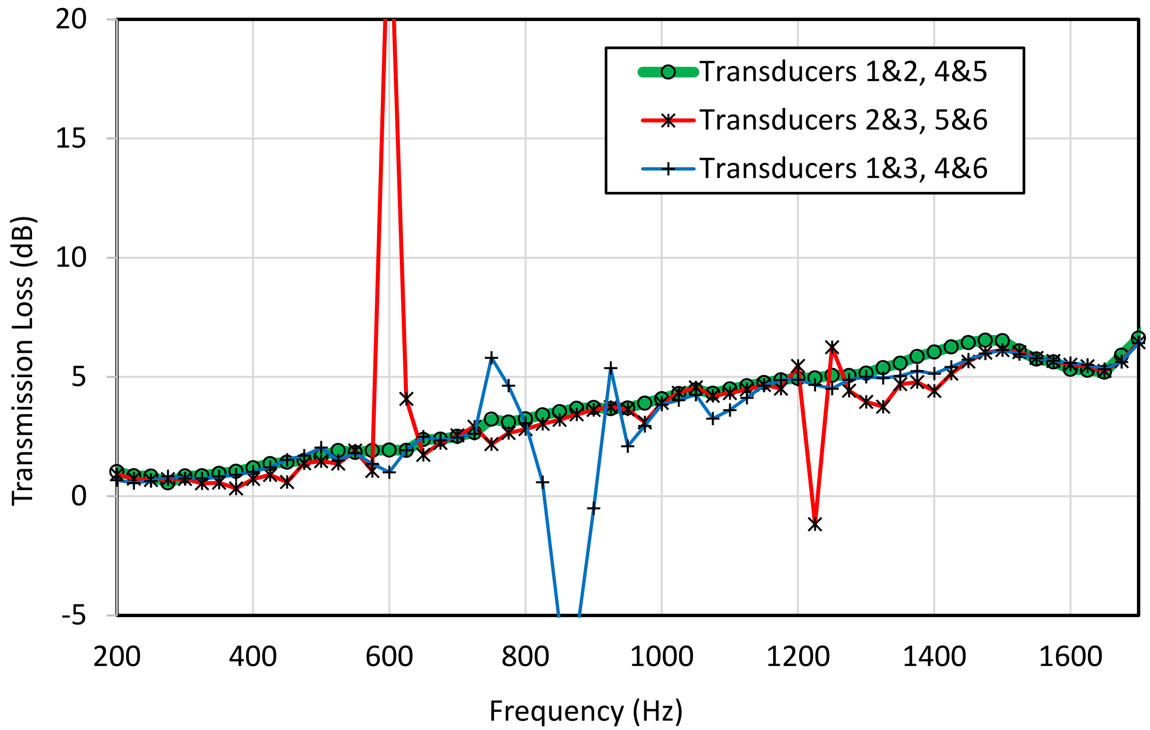
Notes: primary pump is to provide the mean flow pressure and is running at 270 Hz.

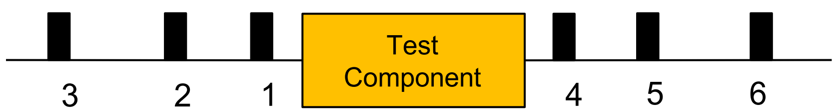
Transmission Loss ASTM E2611



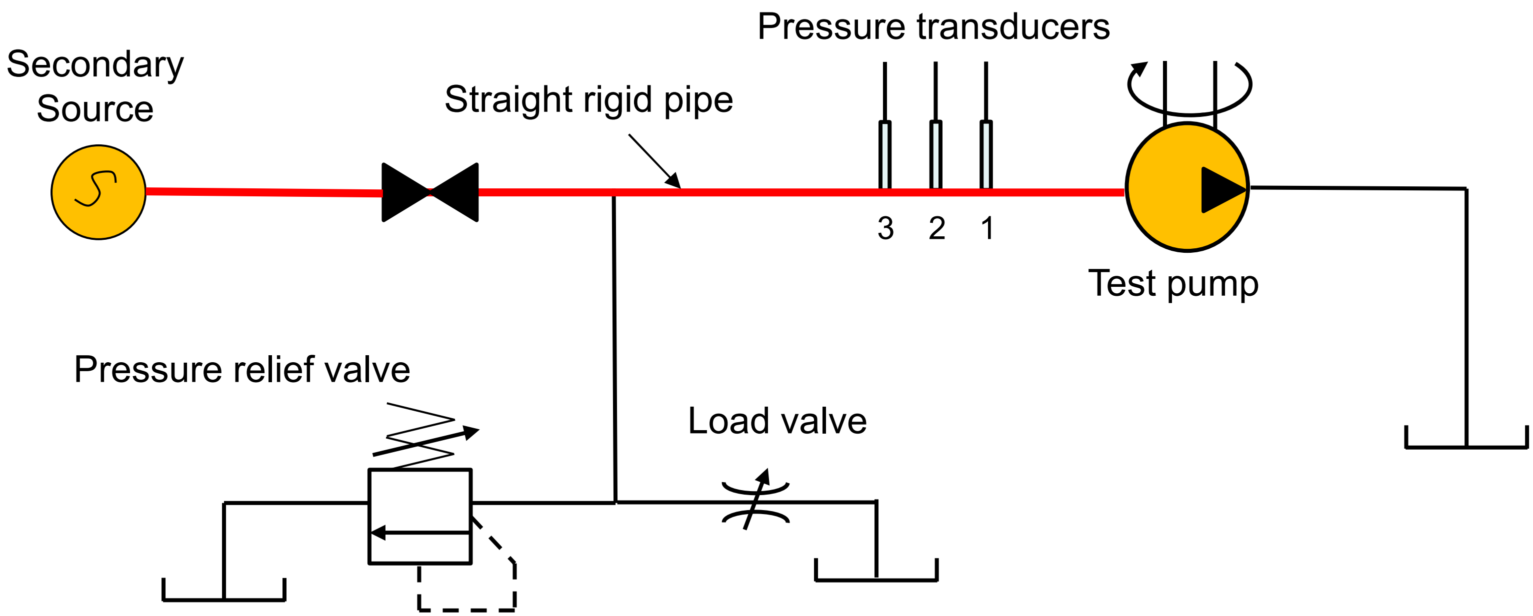
Liu, Suh, and Yang (2017)

Transmission Loss ASTM E2611





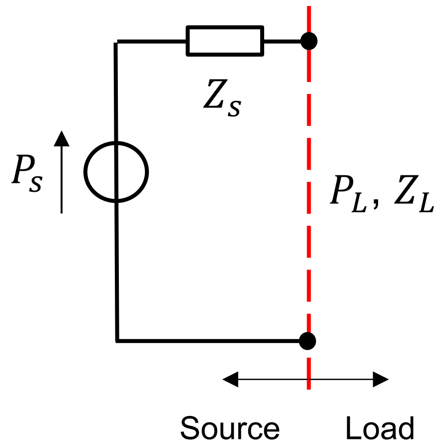
Source Impedance ISO 10767-1 (1996)



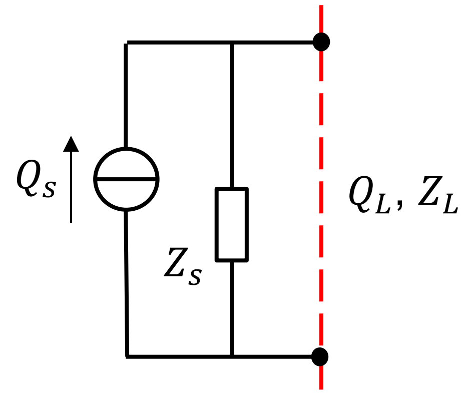
- More than 2 pressure transducers can be used for accuracy.
- Q_S and Z_S are solved at the harmonics of the secondary source.

Source Impedance ISO 10767-1

Voltage source: P_s and Z_s



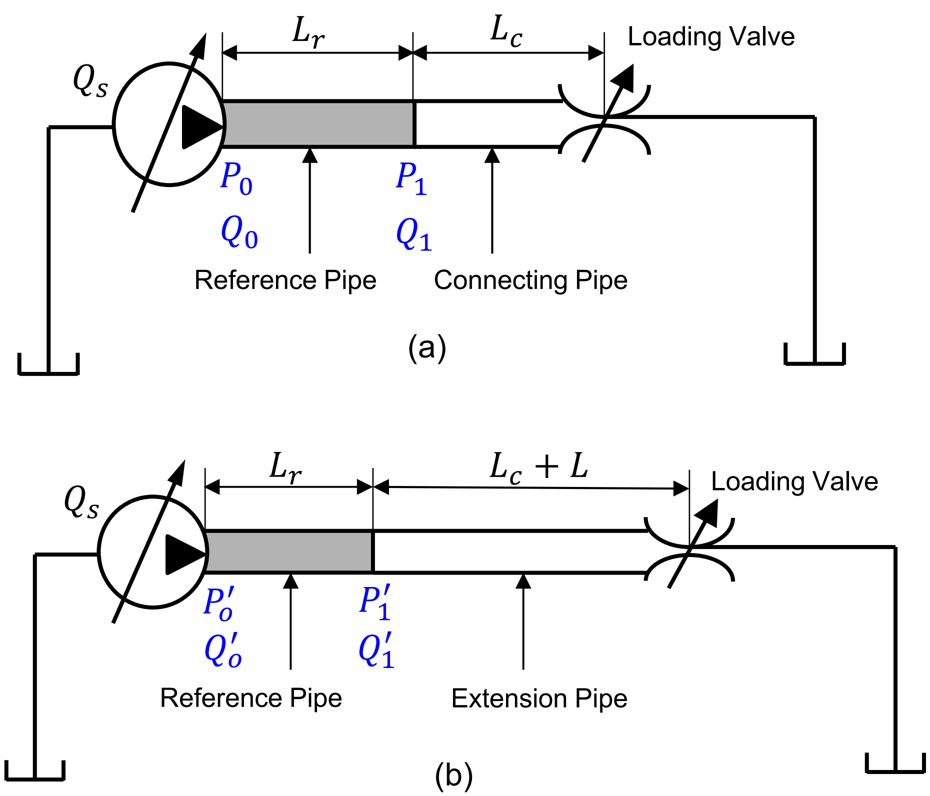
Current source: Q_s and Z_s



$$\frac{P_s}{Z_s + Z_L} = \frac{P_L}{Z_L}$$

$$Q_s \frac{Z_s}{Z_s + Z_L} = Q_L$$

Source Impedance ISO 10767-1



$$Q_s - \frac{P_o}{Z_s} = Q_0$$

$$\begin{bmatrix} 1 & -P_{L1} \\ 1 & -P_{L2} \end{bmatrix} \begin{Bmatrix} Q_s \\ Y_s \end{Bmatrix} = \begin{Bmatrix} Q_{L1} \\ Q_{L2} \end{Bmatrix}$$

Where $Y_s = 1/Z_s$

Multi-load approach can be used, and source properties can be solved by least square approach.

Liu, Suh, and Butts (2018)

Source Impedance Load Selection

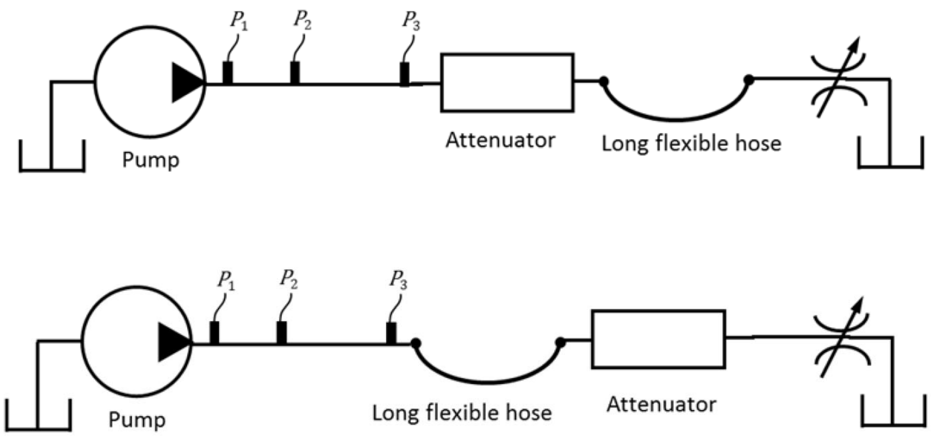


Fig. 2 – Modified Two-pressure/two-system Test Setup.

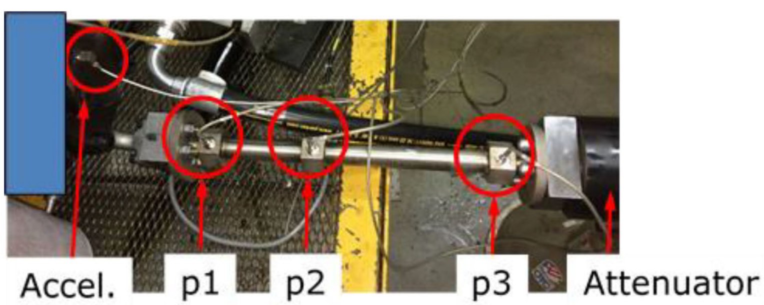
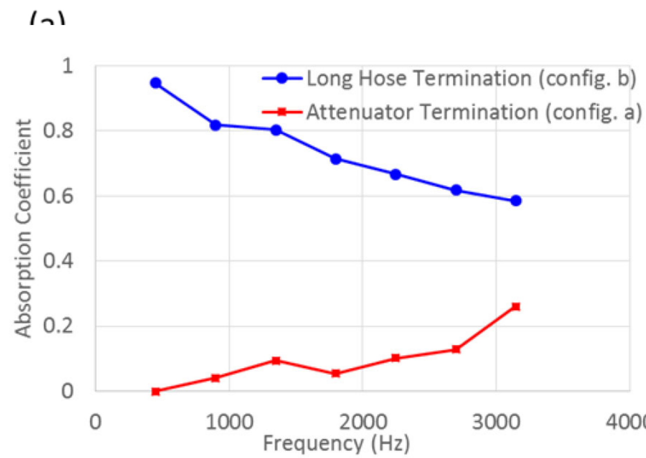


Fig. 3 – Physical Test Setup for Modified two-pressure/two-system configuration (a).



Liu, Suh, and Butts (2018)

Source Impedance ISO 10767-1

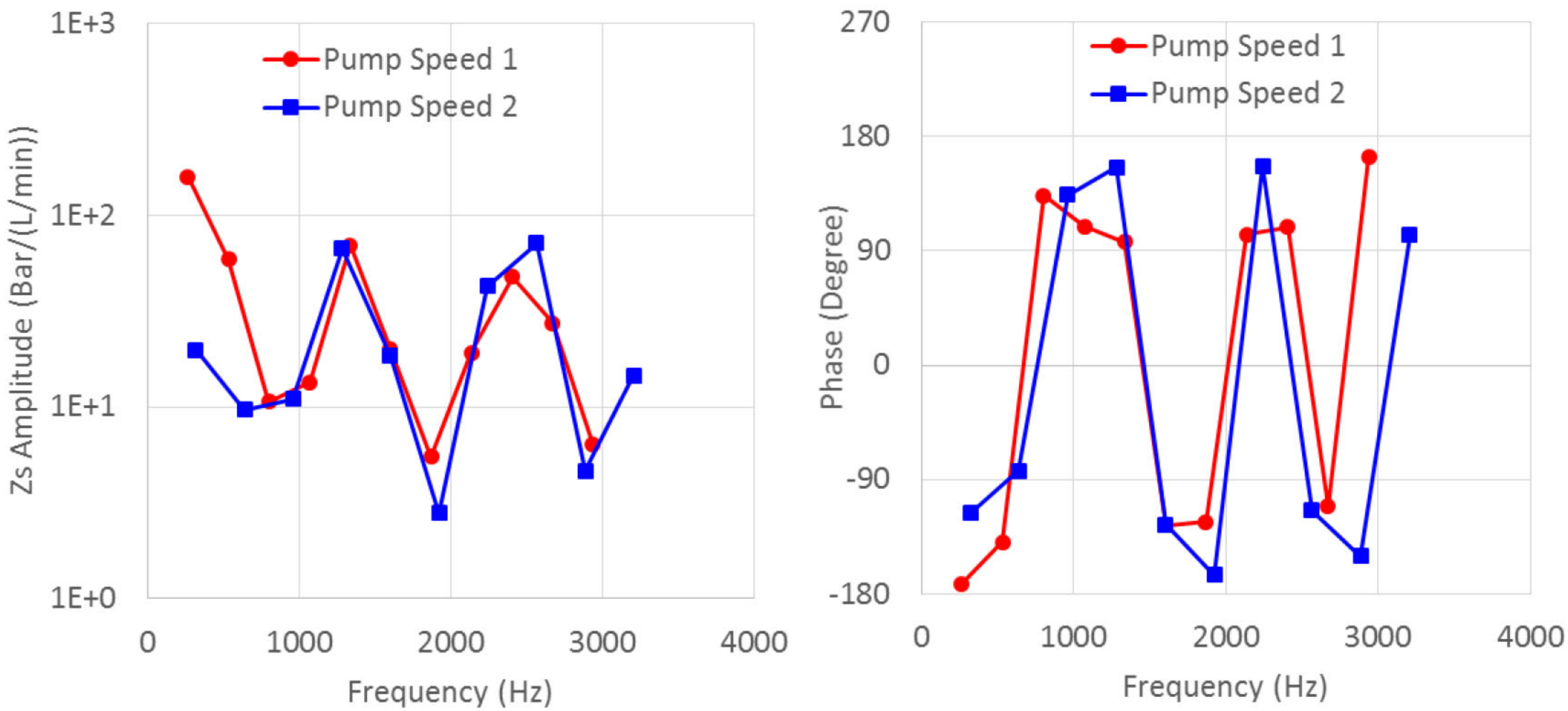


Fig. 6 – Pump impedance amplitude (left) and phase (right) measured under two different pump speeds.

Liu, Suh, and Butts (2018)

Flow Ripple ISO 10767-1

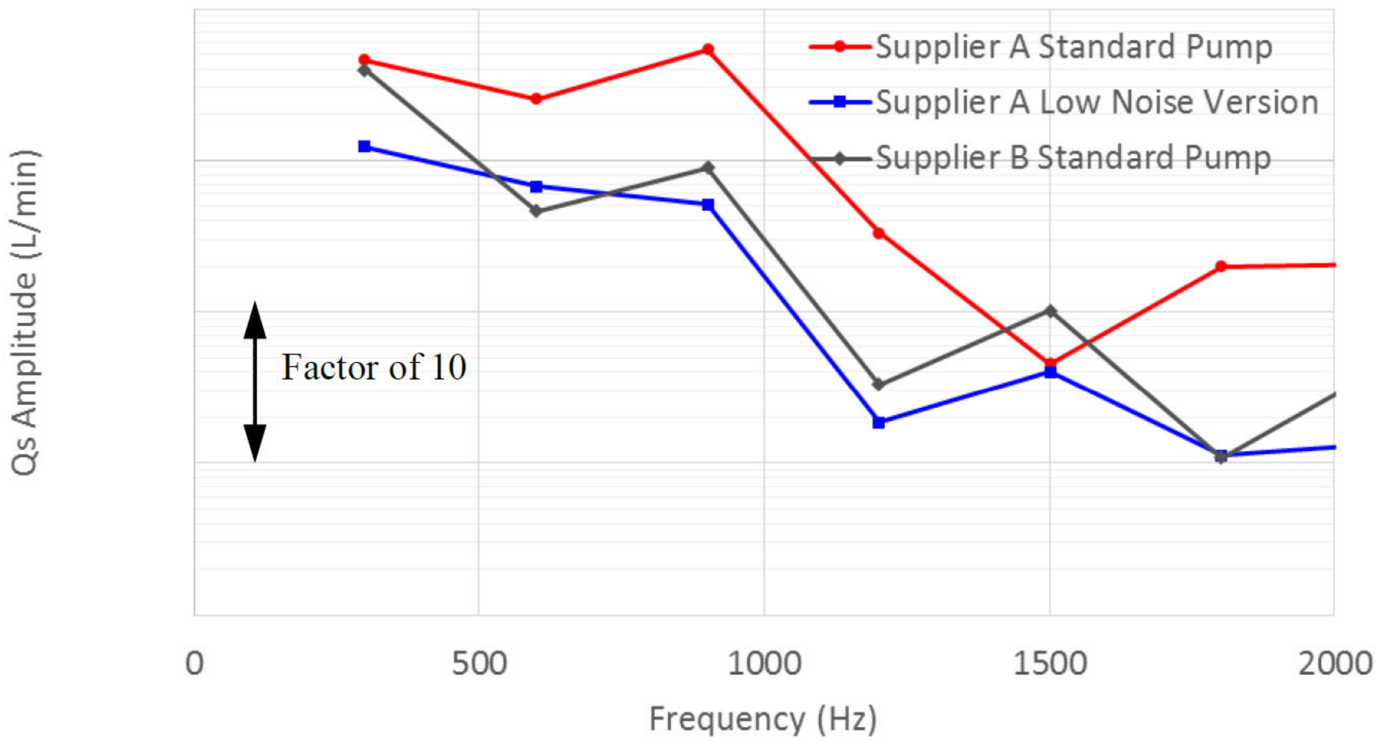


Fig. 9 – Pump flow rippled measured at medium pressure and medium speed condition.

Liu, Suh, and Butts (2018)

Flow Ripple ISO 10767-1

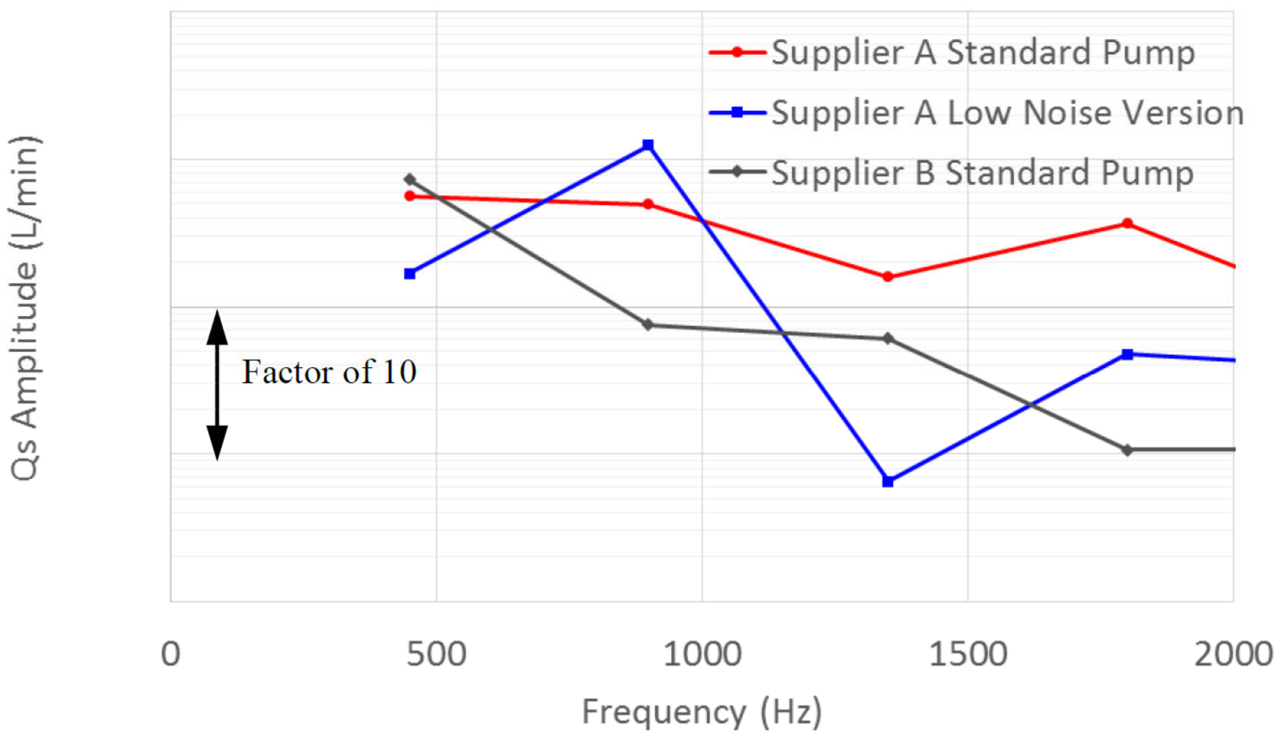


Fig. 10 – Pump flow rippled measured at maximum pressure and maximum speed condition.

Liu, Suh, and Butts (2018)

References

- J. Liu, S. Suh, and Y. Yang, Hydraulic Fluid-borne Noise Measurement and Simulation for Off-Highway Equipment, *Noise-Con*, Grand Rapids, MI, June 12-14 (2017).
- J. Liu, S. Suh, and T. Butts, Source Flow Ripple and Source Impedance Measurement for Different Hydraulic Pumps, *Inter-Noise*, Chicago, IL, August 26-29 (2018).