Measurement and Prediction of Exhaust Flow Noise

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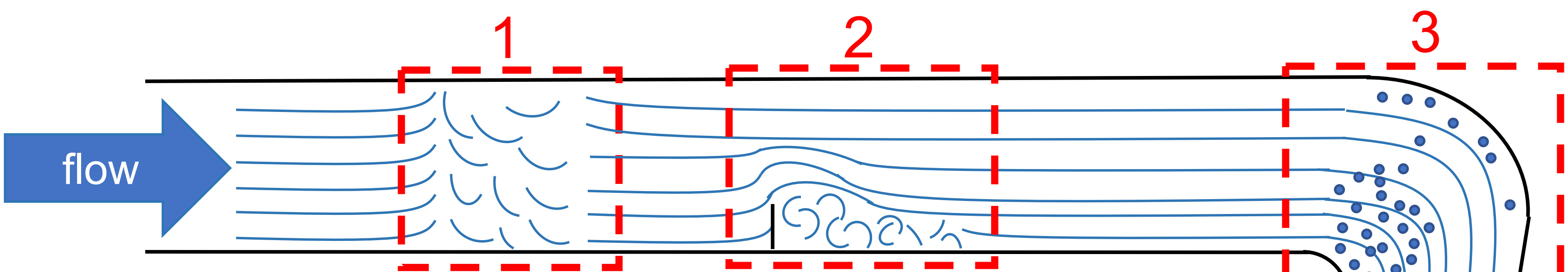
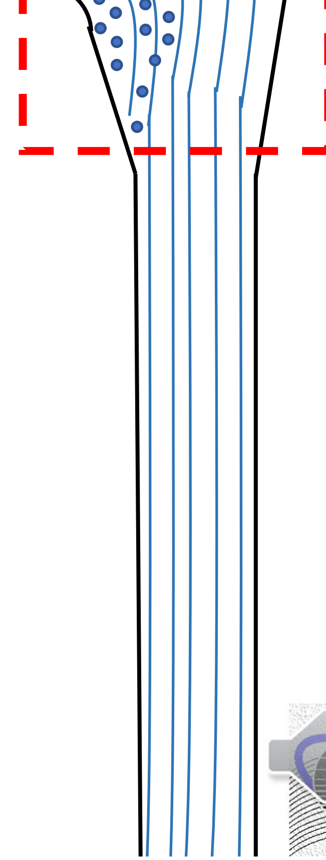
Sound Generation in a Pipe



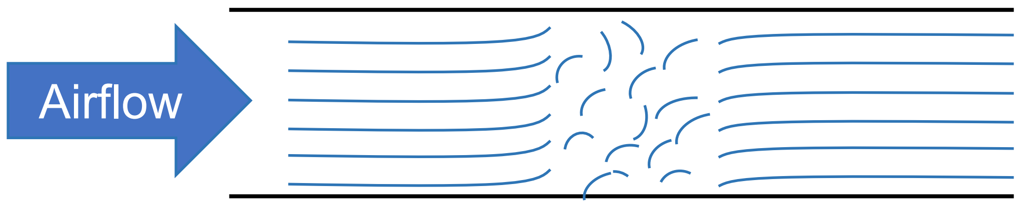


1. Flow
   - Turbulent flow at the pipe wall causing flow separation
2. Pipe Design
   - Obstacles in the flow path cause flow eddies at high flow rates
3. Cavitation
   - Static pressure =Vapor Pressure
4. Solids in the Fluid

VDI 3733 Overview

- VDI 3733, *Noise at Pipes*, Verein Deutscher Ingenieure (VDI) (1996).
- Guideline from the Association of German Engineers (Verein Deutscher Ingenieure (VDI)) concerned with noise due to pipes.
- Mostly for pipes with a round cross-section in industrial plants
- Covers sound generation, transmission, radiation and reduction measures.

Internal Sound Power From Flow



- Flow separation for Mach numbers ($M = U/c$) less than 0.3 is dominantly a dipole source
- Flow induced sound power proportional to U^6
- Semi-empirical model :

$$W_i = K_D \cdot \rho \cdot U^3 \cdot S \cdot M^3 = K_D \cdot \rho \cdot U^6 \cdot S \cdot 1/c^3$$

where $K_D \approx (2 \ldots 12)10^{-15}$ (Correction Factor)

Internal Sound Power From Flow

$$L_{W_i} = 10\log_{10}\frac{W_i}{W_0} = K + 60\log_{10}\frac{U}{U_0} + 10\log_{10}\frac{S}{S_0} + 10\log_{10}\frac{p}{p_0} \ldots$$
$$-25\log_{10}\frac{NT}{N_0T_0} - 15\log_{10}\frac{\gamma}{\gamma_0}$$

$K = 8 - 0.16U$	Correction Factor
W_i	Internal Sound Power (W)
U	Flow Rate (m/s)
S	Cross-sectional Area (m^2)
p	Static Pressure (Pa)
T	Temperature (K)
N	Gas Constant (J/kg·K)

Reference Values

$W_0 = 10^{-12}$ W

$U_0 = 1$ m/s

$S_0 = 1$ m^2

$p_0 = 101325$ Pa

$T_0 = 273$ K

$N_0 = 287$ J/kg·K

$\gamma_0 = 1.4$

Internal Sound Power From Flow

Simplified for Atmospheric Pressure and Room Temperature $(20°C)$

$$L_{W_i} = K + 60\log_{10}\frac{U}{U_0} + 10\log_{10}\frac{S}{S_0}$$

Internal Sound Power From Flow

ΔL_W is empirical adjustment which can be used to provide better frequency resolution.

$$L_{W_{i,oct}} = L_{W_i} + \Delta L_{W,oct}$$

Octave Band Correction

$$\Delta L_{W,oct} = 12\ \text{dB} - 15.5 \log_{10} \frac{f_m}{U}$$

1/3 Octave Band Correction

$$\Delta L_{W,1/3} = 7.23\ \text{dB} - 15.5 \log_{10} \frac{f_{m,1/3}}{U}$$

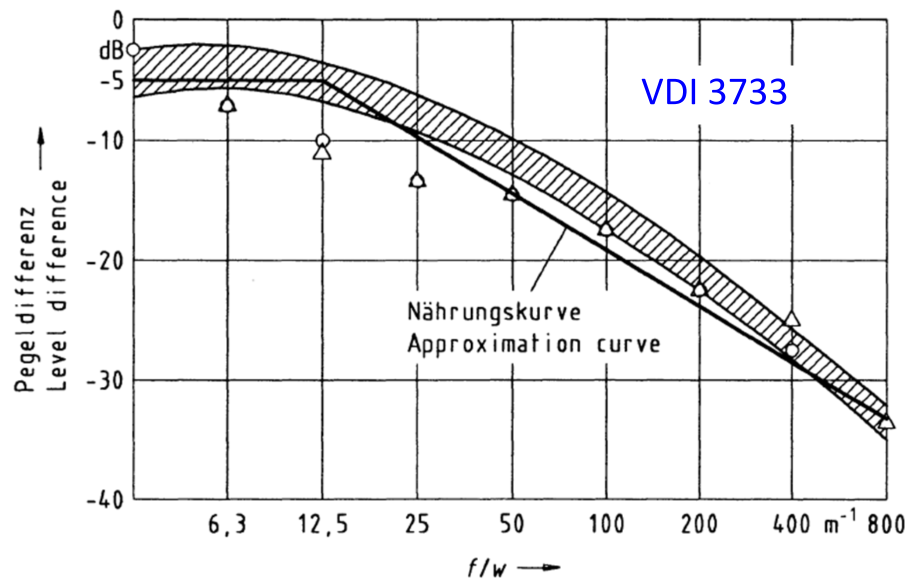
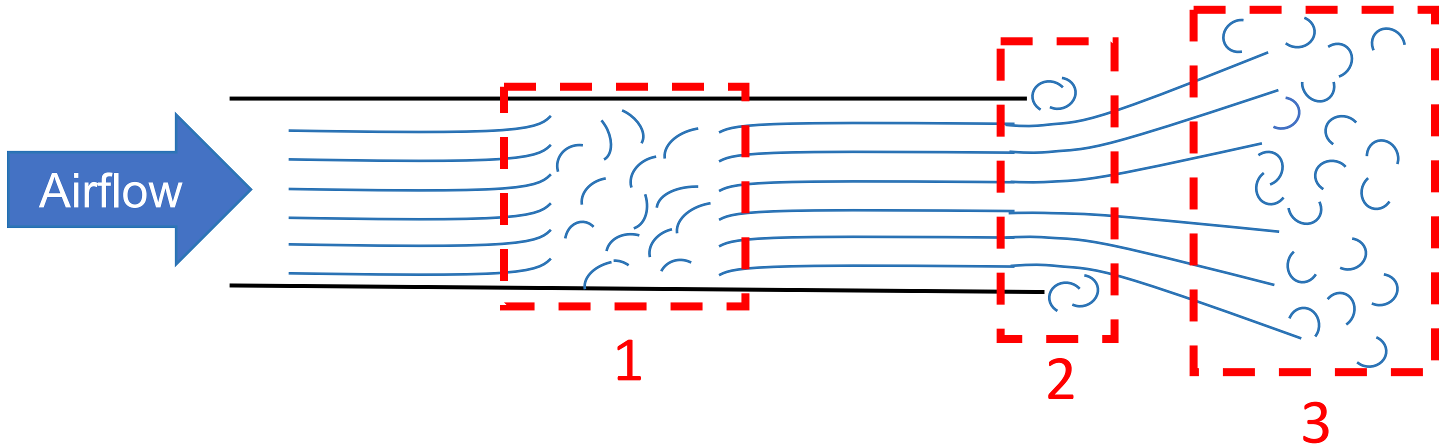


Bild 3: Relatives Frequenzspektrum des Strömungsgeräusches [104], [6]

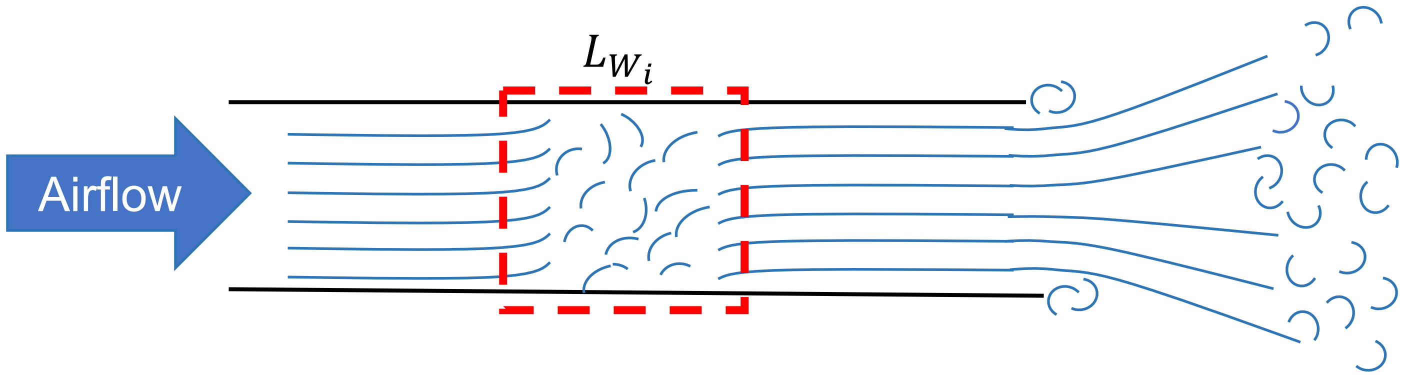
Figure 3: Relative frequency spectrum of the flow noise [104], [6]

Flow Noise Sources in an Exhaust



1. Flow separation inside the pipe
2. Lips
3. Jet mixing region outside of the pipe

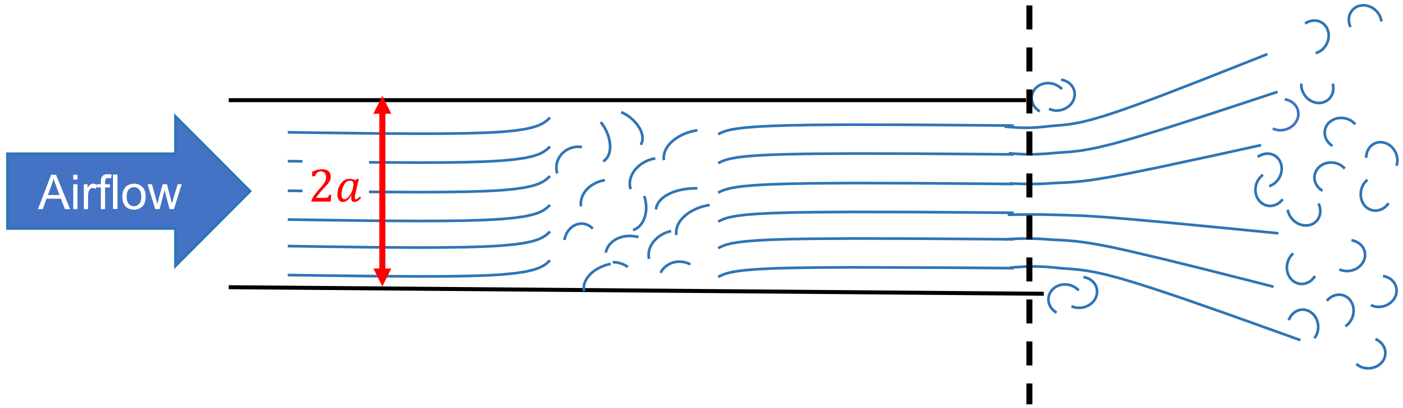
Flow Noise Sources in an Exhaust



- Assume the sound radiated results from the flow separation inside of the pipe.
- Previous work supports assumption for Mach Numbers less than 0.18. (Kuhn and Morfey,1975)
- Transmitted sound power (Ducret, 2006)

$$L_{W_t} = L_{W_i} + 10\log_{10}(1 - |R|^2)$$

Flow Noise Sources in an Exhaust



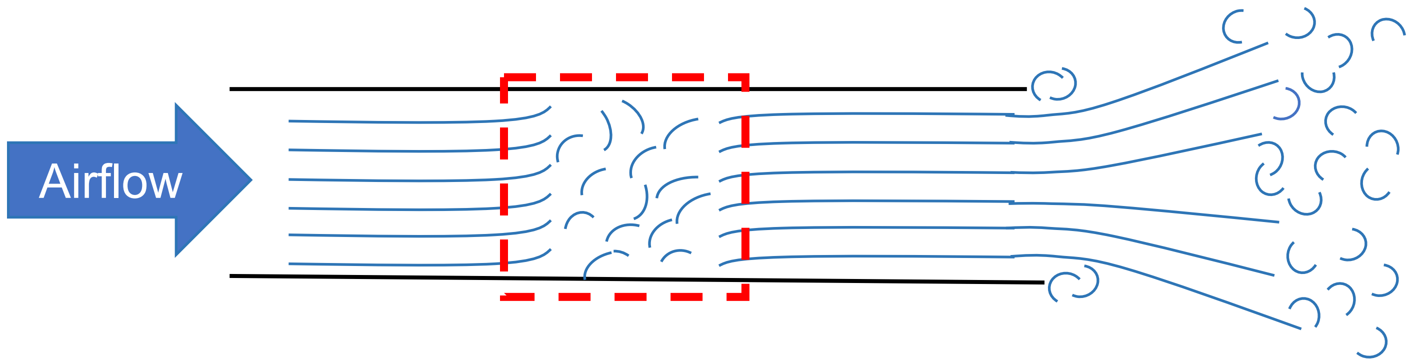
$$R = \frac{p_r}{p_i}$$

$$L_{W_t} = L_{W_i} + 10\log_{10}(1 - |R|^2)$$

$$R = 1 + 0.01336ka - 0.59079(ka)^2 + 0.33576(ka)^3 - 0.06432(ka)^4$$

Davies et al., 1980

Summary of Model (1/3rd Octave Bands)



Under the assumption that flow separation inside of pipe is the dominant flow noise source.

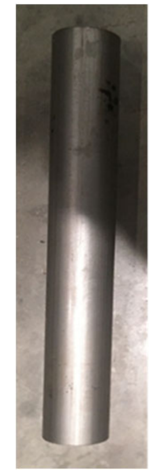
1. Internal sound power of flow separation → L_{W_i}
2. Convert to 1/3rd octave band → $\Delta L_{W_i,1/3}$
3. Reflection coefficient of the pipe opening → R
4. External flow noise sound power from the pipe

$$L_{W_t,1/3} = L_{W_i} + \Delta L_{W_i,1/3} + 10\log_{10}(1 - |\mathrm{R}|^2)$$

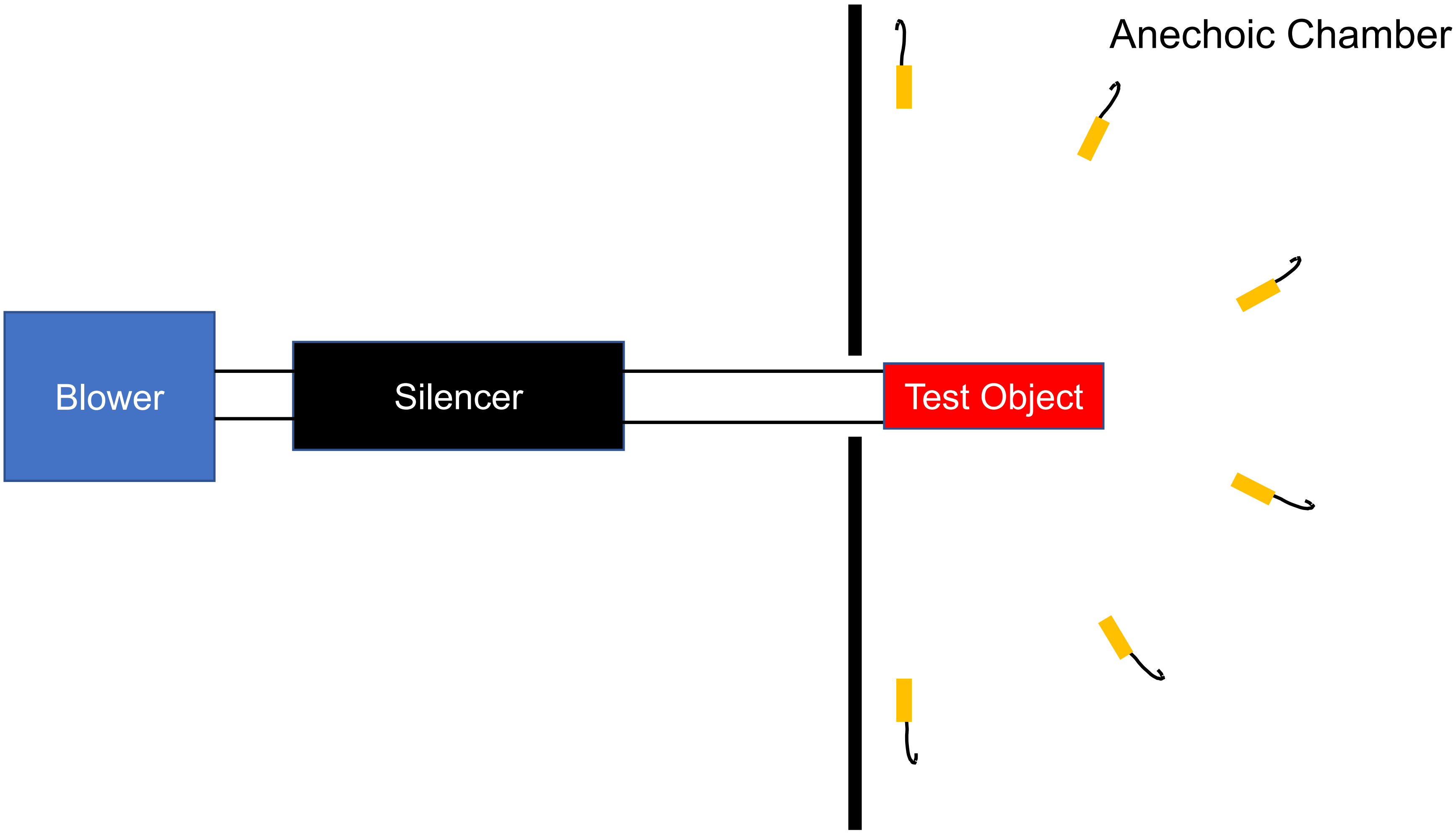
Verification of Model

- Measurements made using the UK flow rig
- Two sizes of pipes measured
- Mach numbers of 0.05 to 0.3 tested

Outer Diameter (in)	Inner Diameter (in)	Mach Numbers
2	1.8	0.05 0.10 0.15
1.5	1.3	0.10 0.15 0.30

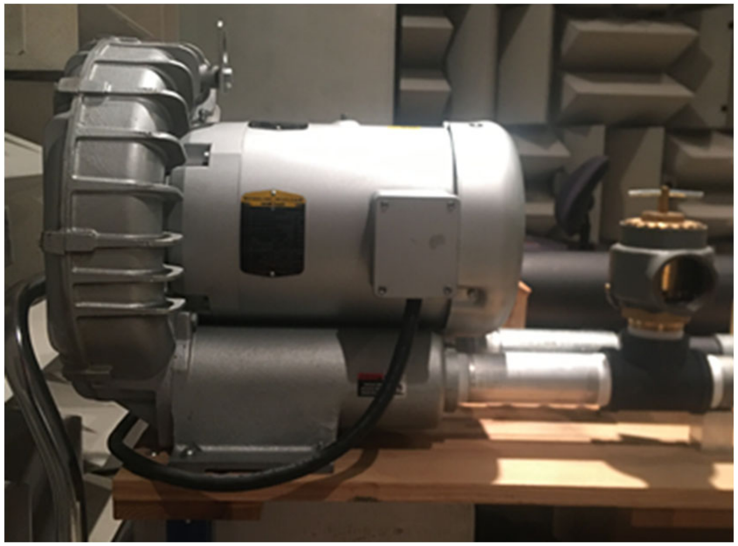


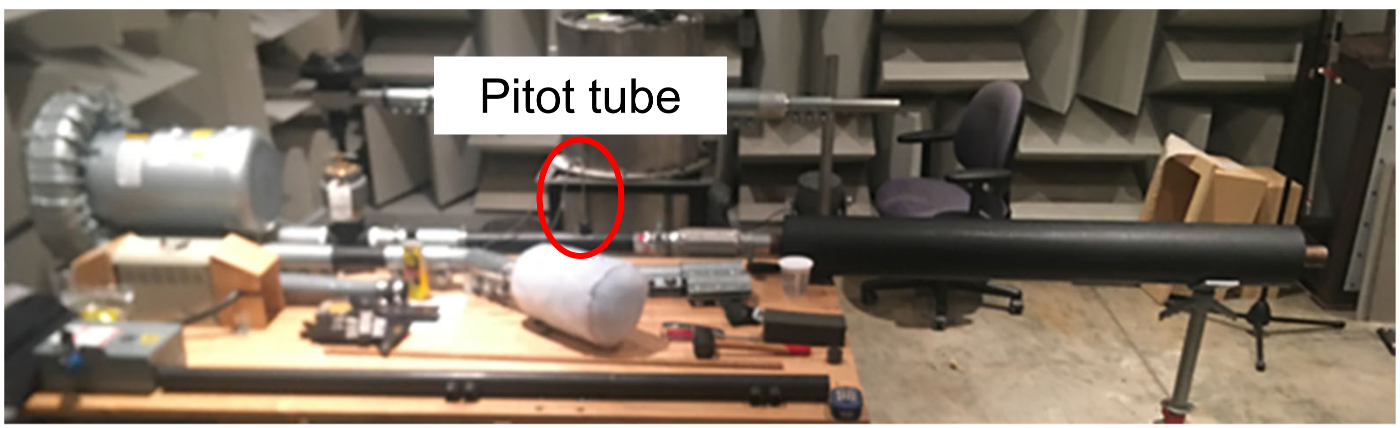
Measurement Setup



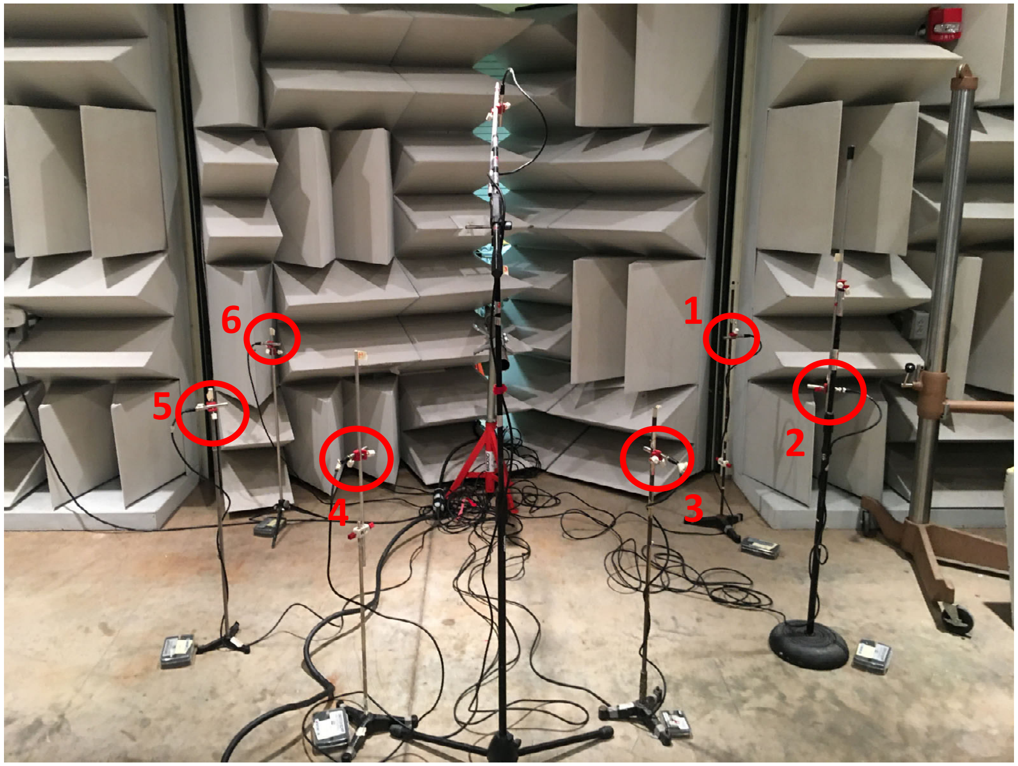
Measurement Setup

Verification of Model





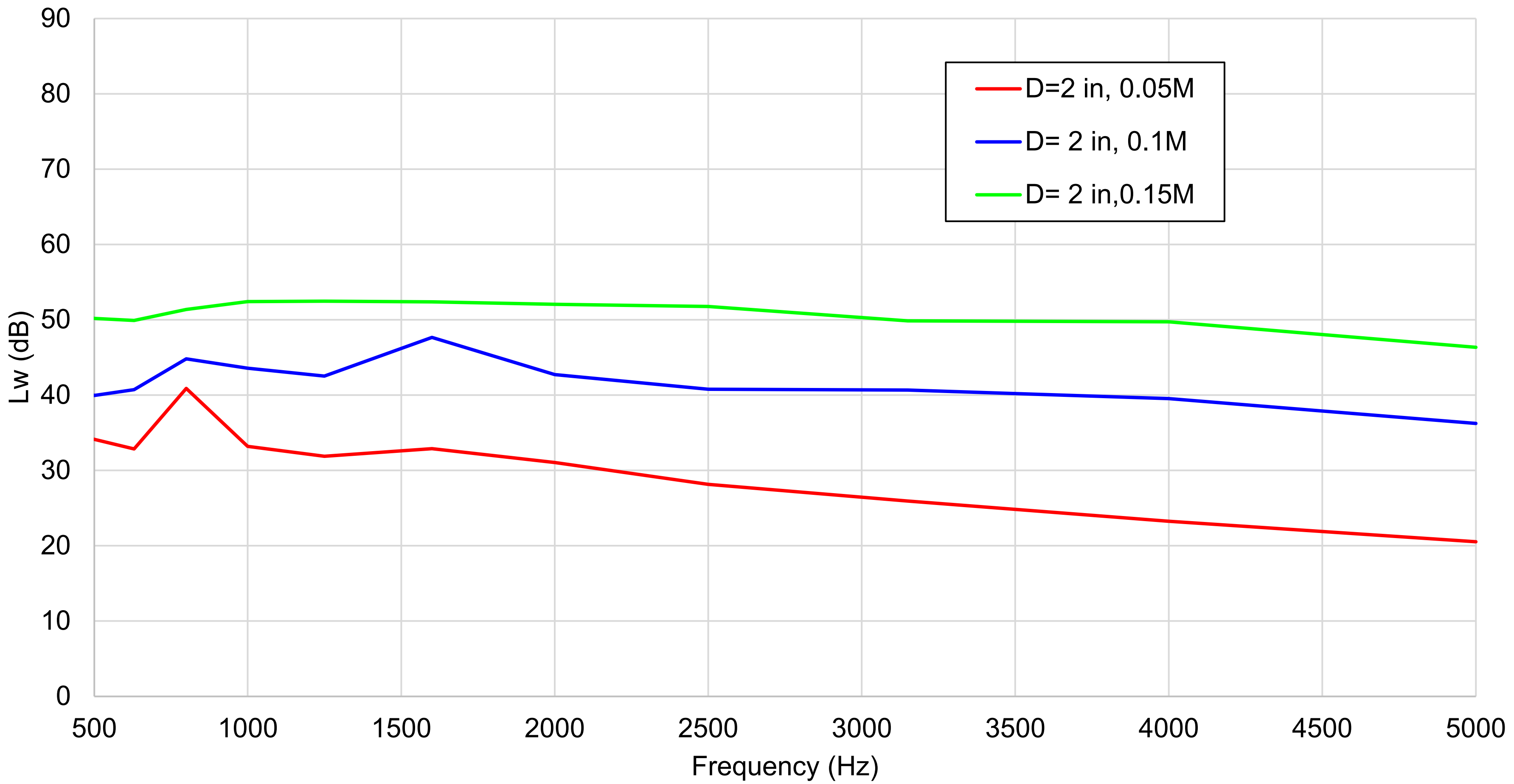
Measurement Setup



1-meter hemisphere with 7 microphones

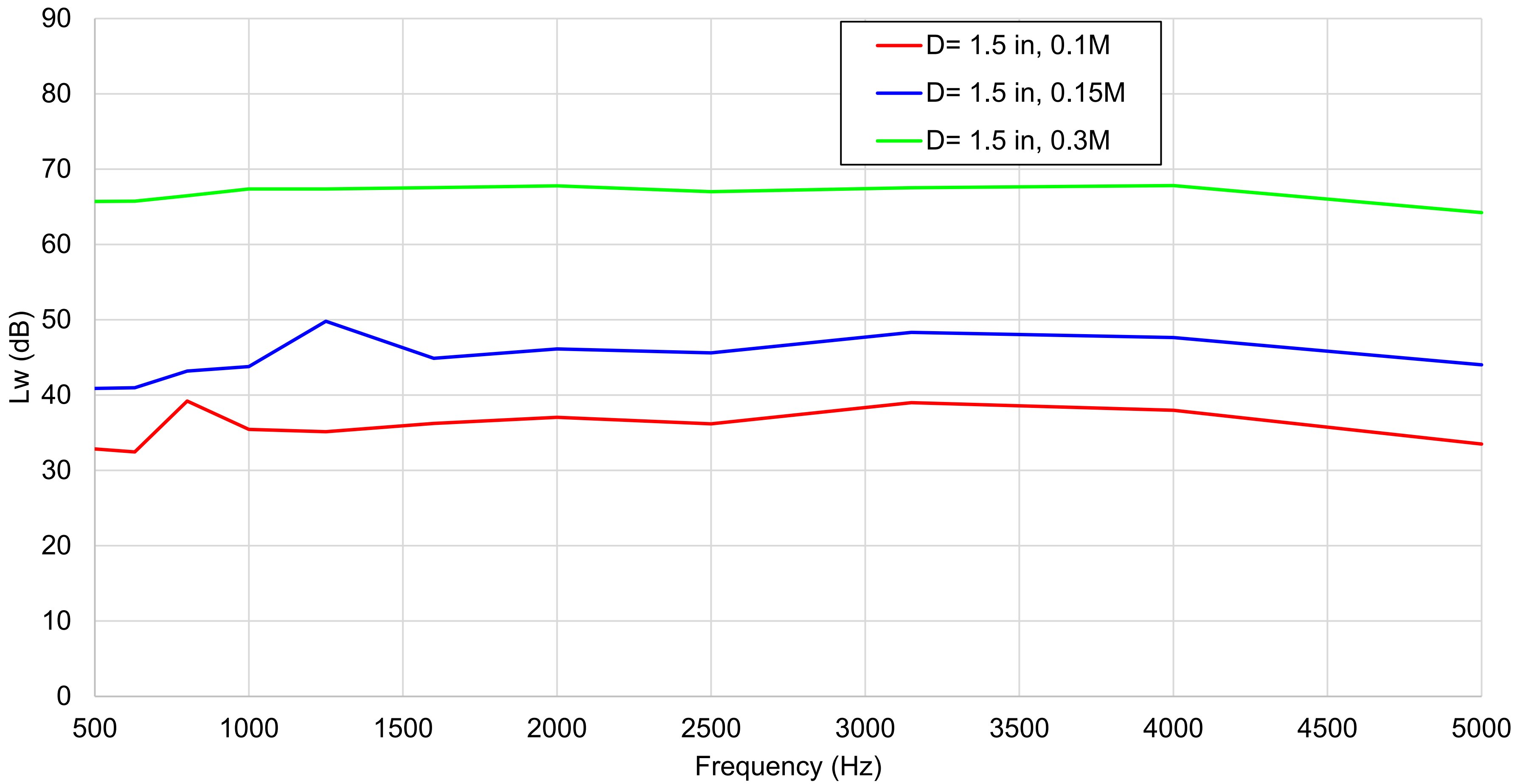
$$(L_W)_{source} \approx \left(\overline{L_p}\right)_{points} + 10\log_{10} S$$

Measurement Results (2 in Pipe)

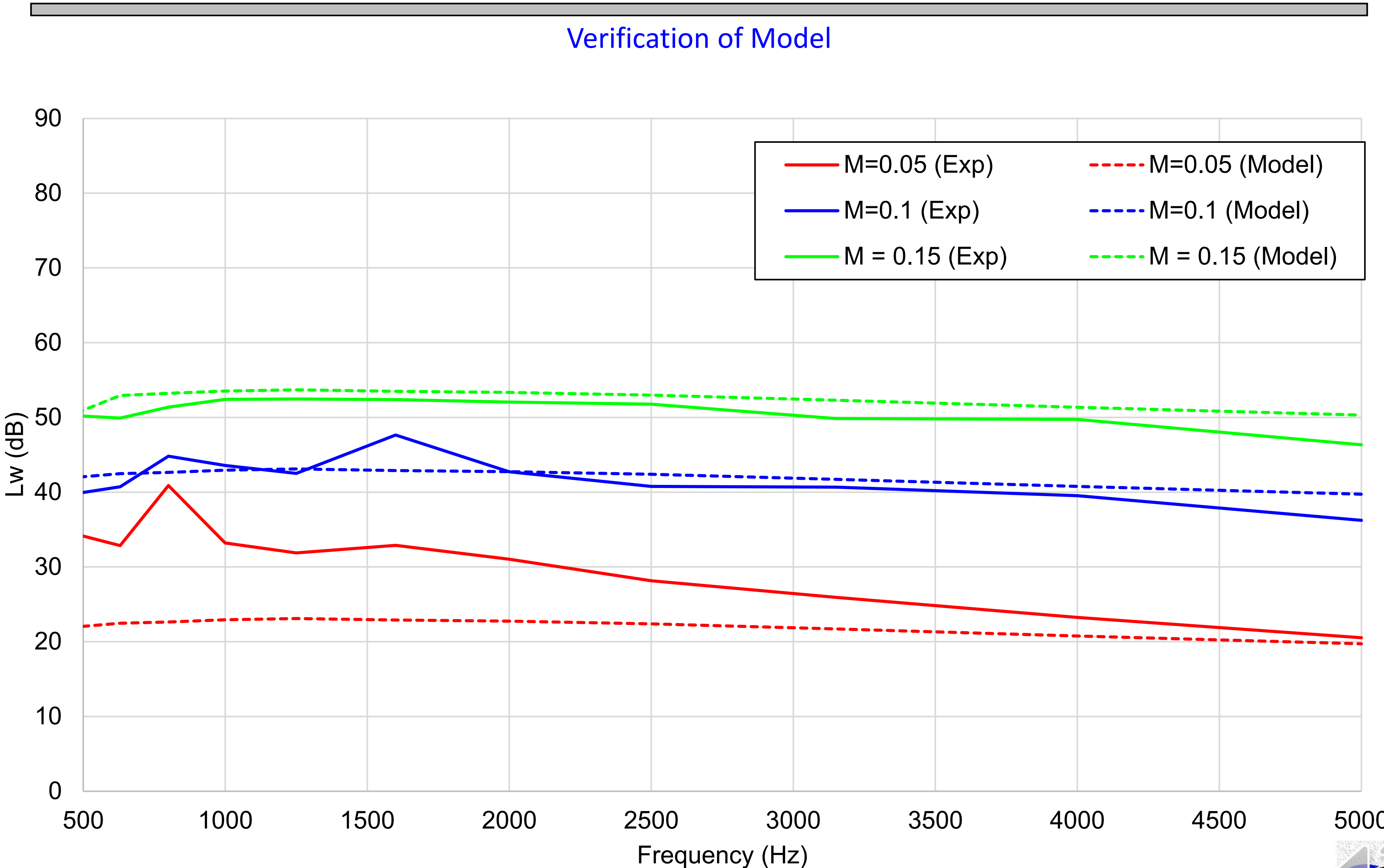


Measurement Results (1.5 in Pipe)

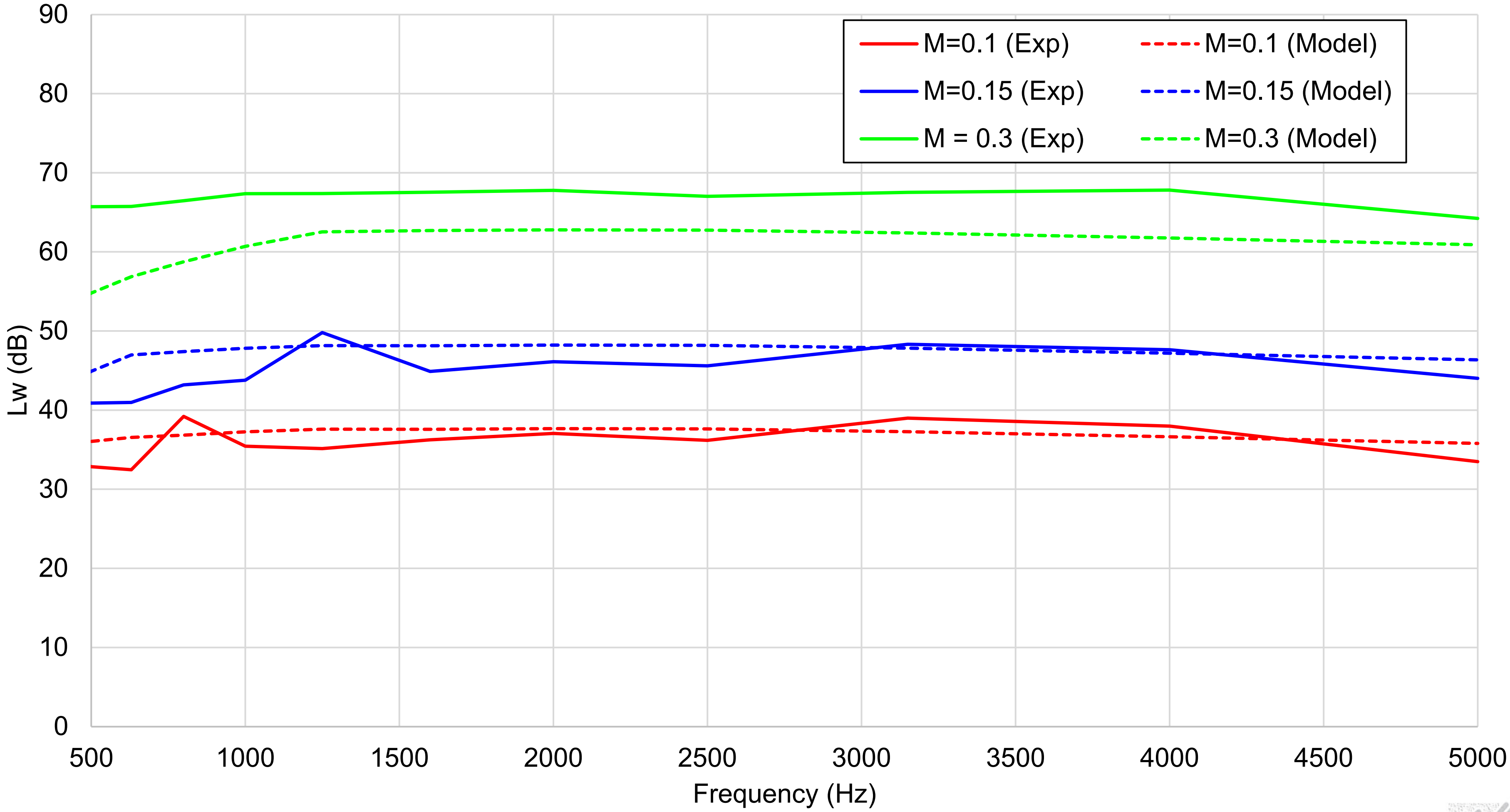
Verification of Model



Sound Power Results (2 in Pipe)



Sound Power Results (1.5 in Pipe)



Conclusions

- Sound power outside the pipe was predicted using an empirical equation in VDI 3733.
- The assumption that the flow separation inside the pipe is the primary flow noise source for Mach numbers between 0.1 and 0.2 seems valid on first inspection.

Future Work

- Test more Mach numbers and pipe diameters to define the limits of the model.

References

VDI3733,1996, "Noise at pipes", VDI manual noise reduction guidelines, http://www.vdi.de/vdi/kontakt/index.php, Verein Deutscher Ingenieure e.V., VDI Guidelines Department P.O. Box 10 11 39, 40002 Düsseldorf, Germany

Ducret, Fabrice. "Studies of Sound Generation and Propagation in Flow Ducts." *The Royal Institute of Technology (KTH)*, 2006.

Kuhn G.F., Morfey C.L., 1976, *Noise due to fully developed turbulent flow exhausting from straight and bend pipes,* Journal of Sound and Vibration, **44**, 27-35.