An Appreciation of the Exhaust System Research of Prasad and Crocker

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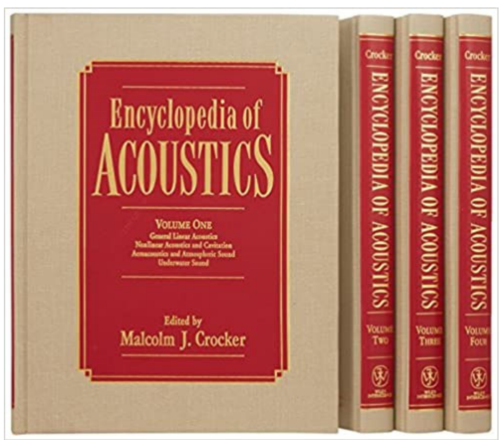
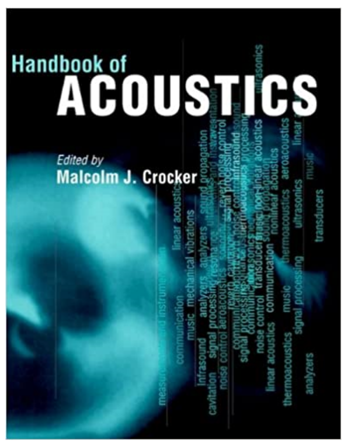
Marehalli G. Prasad

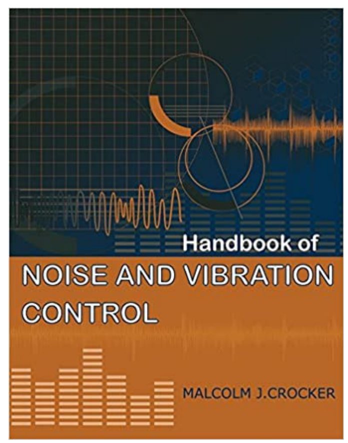
- Professor Emeritus at Stevens Institute of Technology
- Co-General Chair of Noise-Con 1991
- INCE-USA Outstanding Educator Award (2015)
- Ph.D. from Purdue University (1980)

Malcolm J. Crocker

- Professor Emeritus at Auburn University
- INCE-USA Outstanding Educator Award (1992)
- Editor of several outstanding noise and vibration reference books.



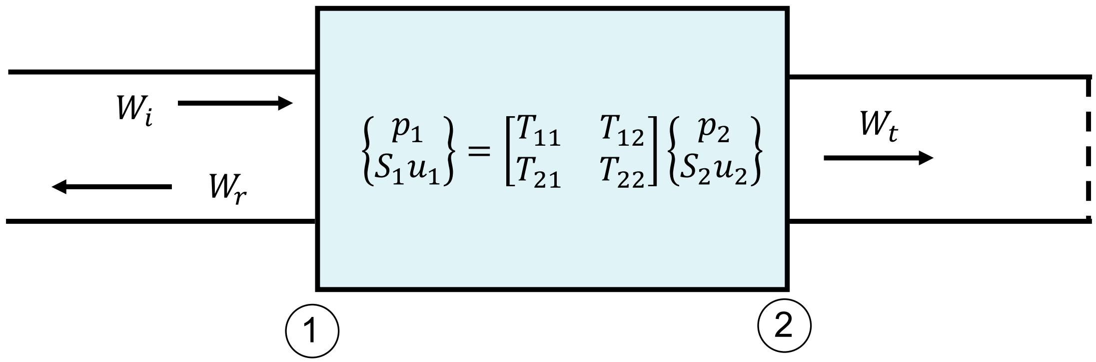




References

1. Prasad, M. G., and Crocker, M. J. “Insertion Loss Studies on Models of Automotive Exhaust Systems.” *The Journal of the Acoustical Society of America*., vol. 70, no. 5, 1981a, pp. 1339–1344.
2. Prasad, M. G, and Crocker, M. J. “A Scheme to Predict the Sound Pressure Radiated from an Automotive Exhaust System.” *The Journal of the Acoustical Society of America*, vol. 70, no. 5, 1981b, pp. 1345–1352.
3. Prasad, M. G., and Crocker, M. J. “Acoustical Source Characterization Studies on a Multi-Cylinder Engine Exhaust System.” *Journal of Sound and Vibration*, vol. 90, no. 4, 1983a, pp. 479–490.
4. Prasad, M. G., and Crocker, M. J. “Studies of Acoustical Performance of a Multi-Cylinder Engine Exhaust Muffler System.” *Journal of Sound and Vibration*, vol. 90, no. 4, 1983b, pp. 491–508.

Muffler Metrics – Transmission Loss

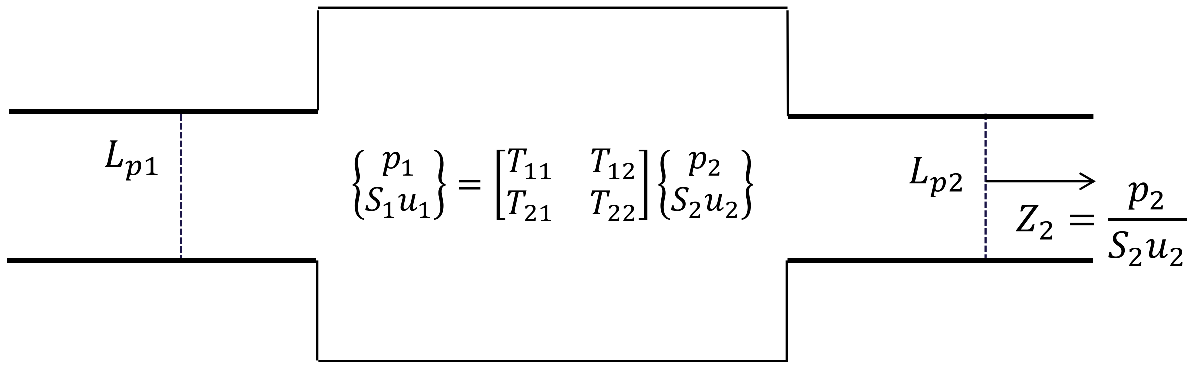


Transmission loss (TL) of the muffler:

$$TL = 10 \log_{10} \frac{W_i}{W_t}$$

$$TL = 10 \log_{10} \left\{ \frac{S_{in}}{4S_{out}} \left| T_{11} + \frac{S_{out} T_{12}}{\rho c} + \frac{\rho c T_{21}}{S_{in}} + \frac{S_{out}}{S_{in}} T_{22} \right|^2 \right\}$$

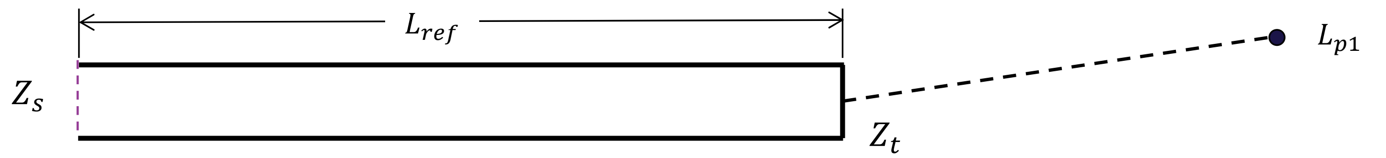
Muffler Metrics – Noise Reduction



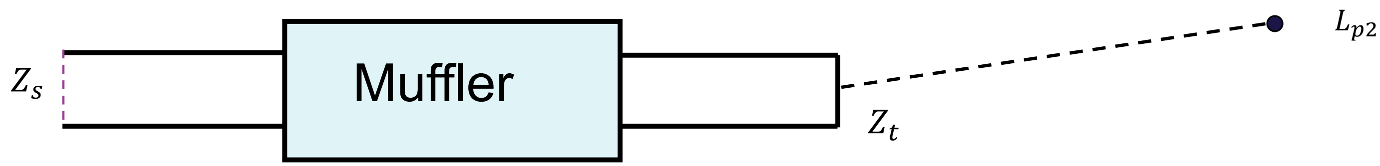
$$NR = L_{p1} - L_{p2} = 10 \log_{10} \left| T_{11} + \frac{T_{12}}{Z_2} \right|^2$$

Muffler Metrics – Insertion Loss

$$[T_0] = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}$$



$$[T] = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}$$



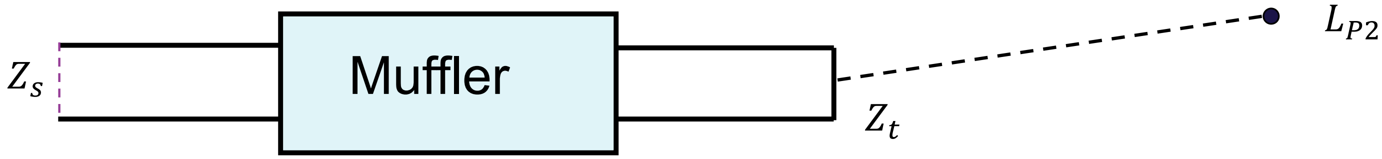
$$IL = 20\log_{10}\left\{\left|\frac{\frac{T_{11}}{z_s} + \frac{T_{12}}{z_t z_s} + T_{21} + \frac{T_{22}}{z_t}}{\frac{A_{11}}{z_s} + \frac{A_{12}}{z_t z_s} + A_{21} + \frac{A_{22}}{z_t}}\right|\right\}$$

Muffler Metrics

Neither TL or NR are very useful to muffler manufacturers since, although these measures may give some guidance, neither tell a manufacturer or designer the exact improvement (or reduction in sound pressure level) caused when a muffler system is installed on a certain engine or other machine source. The insertion loss, IL, of a muffler (the difference in sound pressure levels measured at one point in space without and with the muffler inserted between that point and the source) is thus the information of most use to the muffler manufacturer or designer. This quantity, IL, can be conveniently measured by using a single microphone mounted outside of the exhaust system in free space without and with the muffler in place. Both TL and NR measurements require mounting microphones upstream and downstream of the muffler inside the normally hot, hostile environments of exhaust or other gases. Unfortunately, although IL is somewhat easily measured, it is more difficult to predict, since not only must the muffler characteristics be known, but the source and tailpipe radiation characteristics (impedances) must also be determined from theory or experiment.

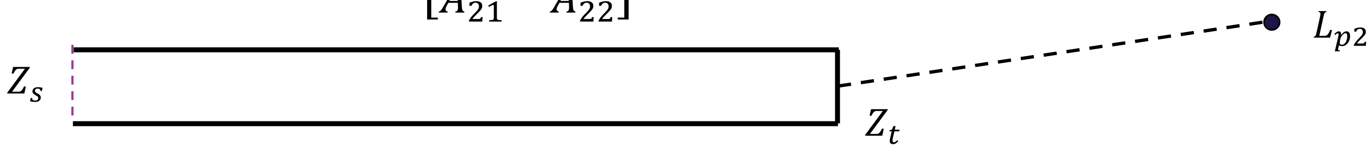
Prasad and Crocker (1981)

Derivation of Insertion Loss



$$\frac{p_2}{p_s} = \frac{1}{T_{11} + \frac{1}{Z_t}T_{12} + Z_s T_{21} + \frac{Z_s}{Z_t}T_{22}}$$

$$[T_0] = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}$$



$$\frac{p_2}{p_s} = \frac{1}{A_{11} + \frac{1}{Z_t}A_{12} + Z_s A_{21} + \frac{Z_s}{Z_t}A_{22}}$$

Insertion Loss

$$IL = 20\log_{10}\left|\frac{p_{2,no\ muffler}}{p_{2,muffler}}\right|$$

$$\frac{p_{2,no\ muffler}}{p_s} = \frac{1}{A_{11} + \frac{1}{Z_t}A_{12} + Z_s A_{21} + \frac{Z_s}{Z_t}A_{22}}$$

$$\frac{p_{2,muffler}}{p_s} = \frac{1}{T_{11} + \frac{1}{Z_t}T_{12} + Z_s T_{21} + \frac{Z_s}{Z_t}T_{22}}$$

$$IL = 20\log_{10}\left\{\left|\frac{\frac{T_{11}}{Z_s} + \frac{T_{12}}{Z_t Z_s} + T_{21} + \frac{T_{22}}{Z_t}}{\frac{A_{11}}{Z_s} + \frac{A_{12}}{Z_t Z_s} + A_{21} + \frac{A_{22}}{Z_t}}\right|\right\}$$

Source Impedance Measurement

Loudspeaker

Anechoic Source

Prasad and Crocker (1981a)

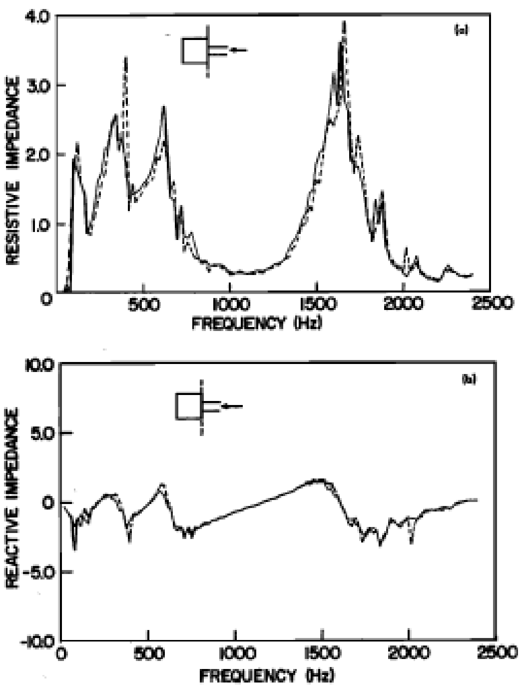


FIG. 3. Source impedance. (a) normalized resistive impedance, —— operating; ---- nonoperating and (b) normalized reactive impedance, —— operating; ---- nonoperating.

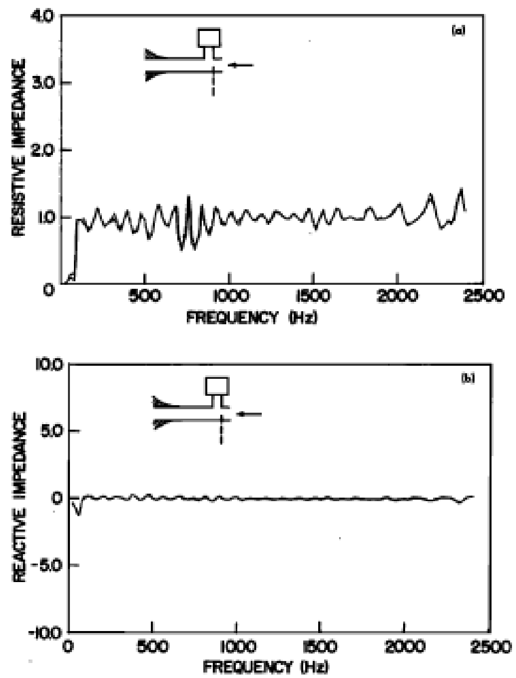


FIG. 4. Source impedance (with driver as side-branch and anechoic termination in-line). (a) Normalized resistive impedance, —— operating; ---- nonoperating and (b) normalized reactive impedance, —— operating; ---- nonoperating.

Termination Impedance Measurement

Anechoic Termination

Unflanged Open End

Prasad and Crocker (1981a)

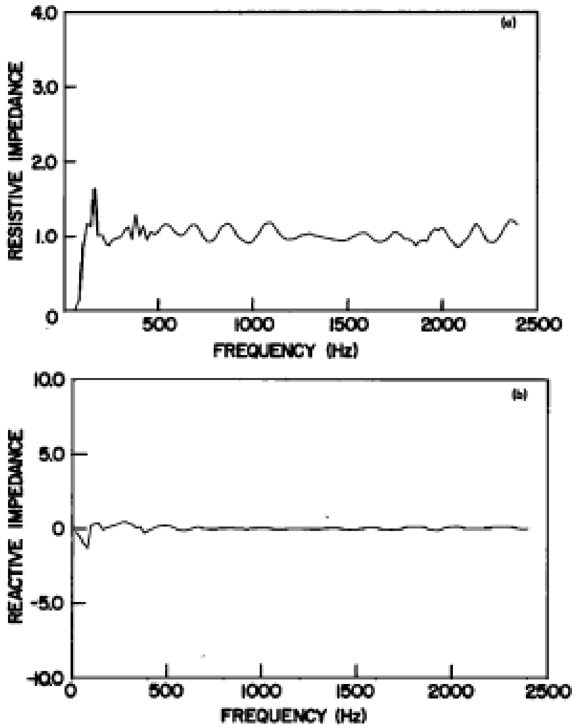


FIG. 5. Measured impedance of an anechoic termination. (a) Normalized resistive impedance and (b) normalized reactive impedance.

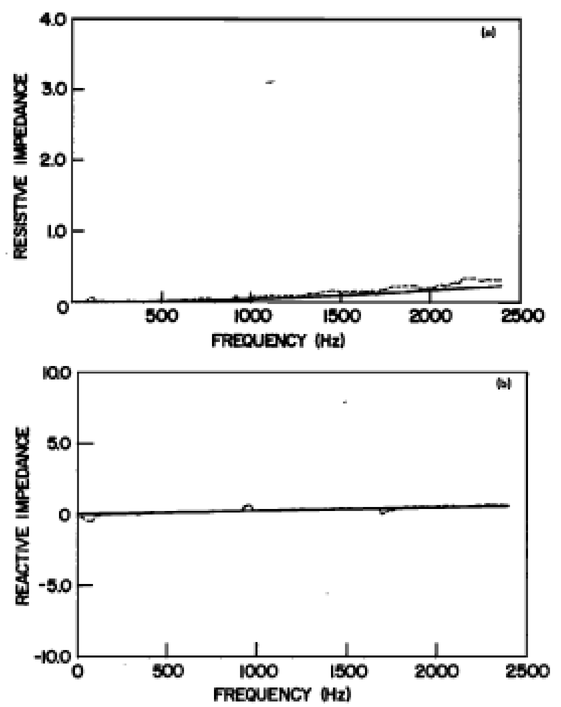


FIG. 6. Radiation impedance of an unflanged open-end. (a) Normalized resistive impedance, —— theory; ---- measured and (b) normalized reactive impedance, —— theory; ---- measured.

Insertion Loss Comparisons – Anechoic Termination

Prasad and Crocker (1981a)

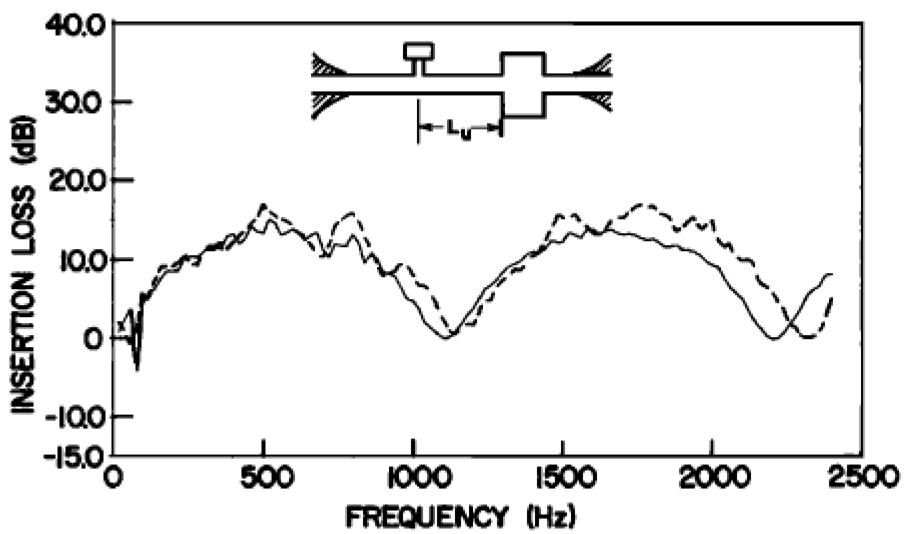


FIG. 7. Insertion loss of an expansion chamber muffler with the driver as a side-branch and anechoic terminations on the upsteam and downstream, L_u =0.502 m; —— theory; ----- measured.

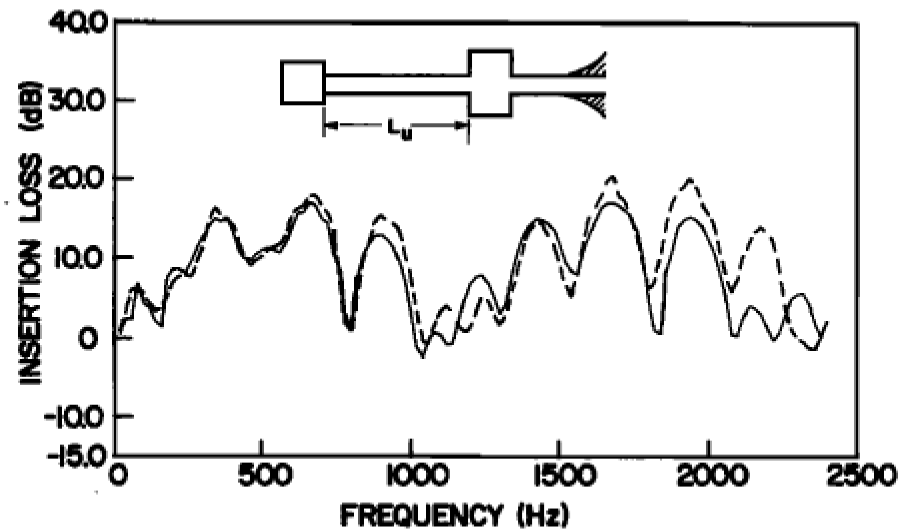


FIG. 9. Insertion loss of an expansion chamber muffler with anechoic termination, L_u = 0.508 m; —— theory; ---- measured.

Insertion Loss Comparisons – Loudspeaker Source and Open-End Termination

Prasad and Crocker (1981a)

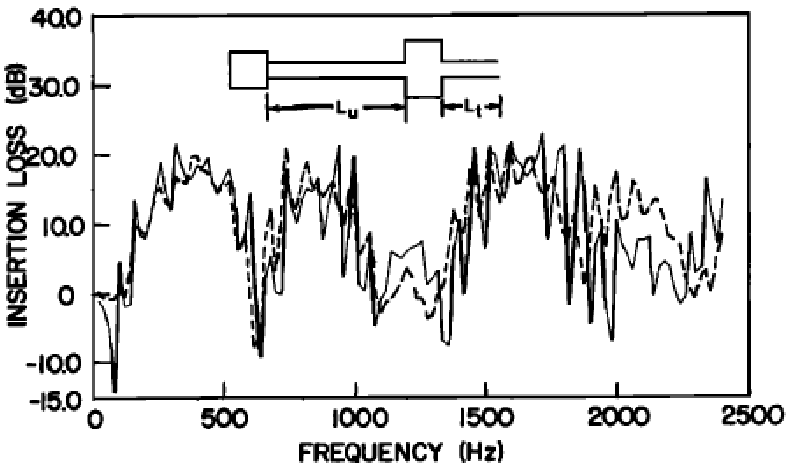


FIG. 11. Insertion loss of an expansion chamber muffler with unflanged open-end termination, $L_u = 2.02$ m, $L_t = 0.248$ m; —— theory; ---- measured.

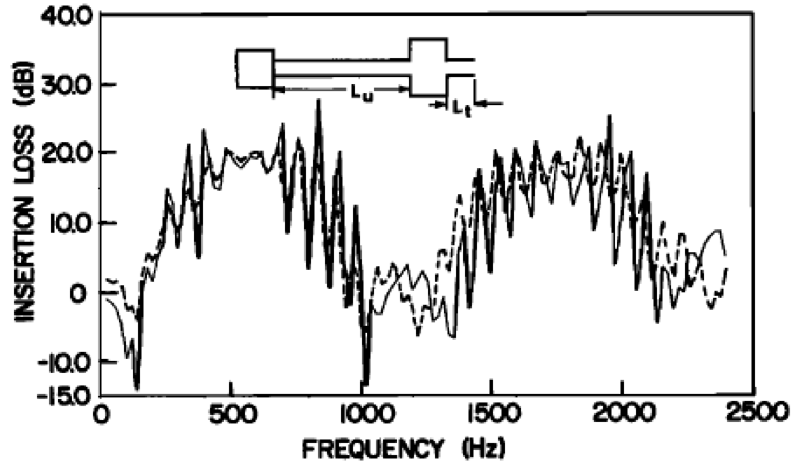


FIG. 12. Insertion loss of an expansion chamber muffler with unflanged open-end termination, $L_u = 2.02$ m, $L_t = 0.122$ m; —— theory; ---- measured.

Sound Pressure Level Comparison

Prasad and Crocker (1981b)

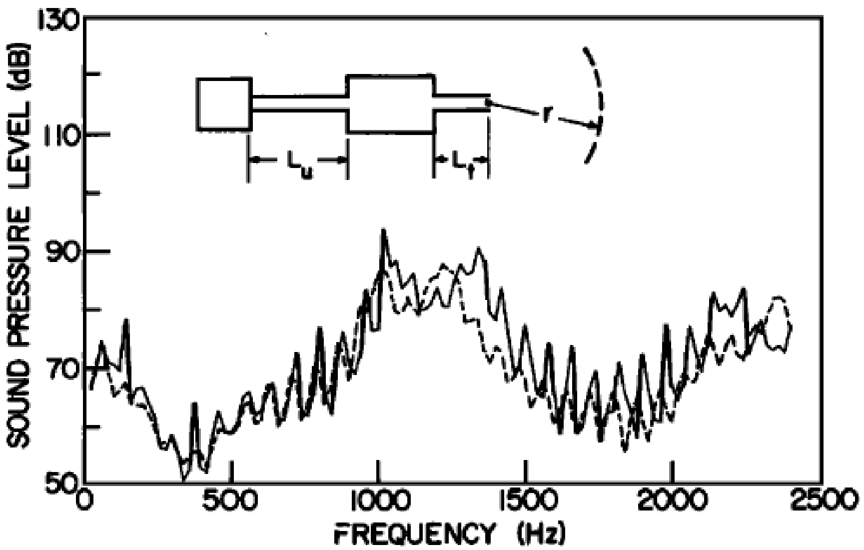


FIG. 5. Case 1, comparison of predicted and measured sound pressure level spectra. $L_u = 2.02$ m, $L_t = 0.122$ m, $r = 0.406$ m. ———— theory; ------------ measured.

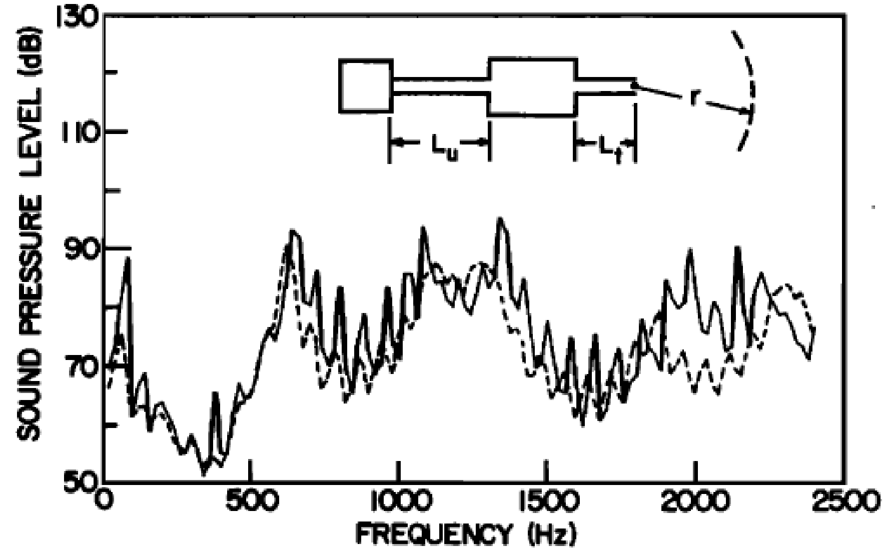


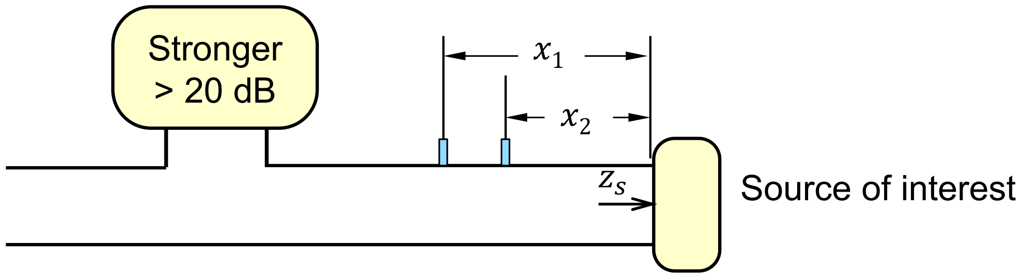
FIG. 7. Case 3, comparison of predicted and measured sound pressure level spectra. $L_u = 2.02$ m, $L_t = 0.248$ m, $r = 0.267$ m. ———— theory; ------------ measured.

Source Impedance

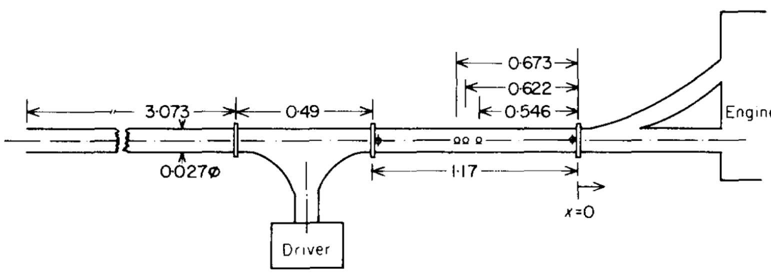
Characterization of the acoustic source in an exhaust system is of utmost importance in the proper evaluation of a muffler system. The descriptions of the exhaust system that require a knowledge of the source characteristics are the insertion loss and the radiated sound pressure level. Sources have been characterized in the literature in several ways, such as by assumption, simulation, and analysis. However, there are very few studies in existence in the literature on multi-cylinder engine exhaust systems which include consideration of the source itself. The chief reason is that a multi-cylinder exhaust system is quite complicated.

Prasad and Crocker (1983a)

Measuring Source Impedance on an Engine



Prasad and Crocker (1983a)



Measuring Source Impedance of an Engine

Prasad and Crocker (1983a)

Effect of Engine Speed on Source Impedance

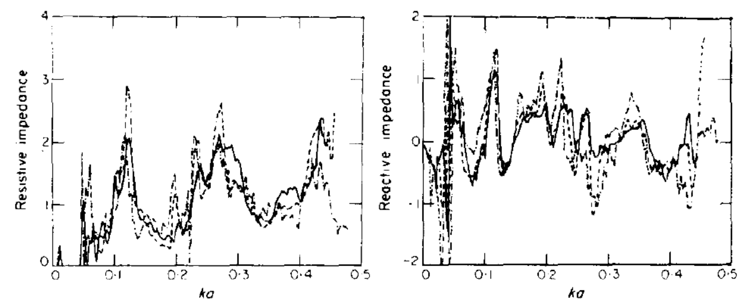


Figure 11. Effect of engine speed (with constant load) on the measured dimensionless specific acoustic internal source impedance of the engine. ——, 2000 rev/min, 10 in Hg; – – –, 1500 rev/min, 10 in Hg; — · —, 1000 rev/min, 10 in Hg.

Effect of Engine Load on Source Impedance

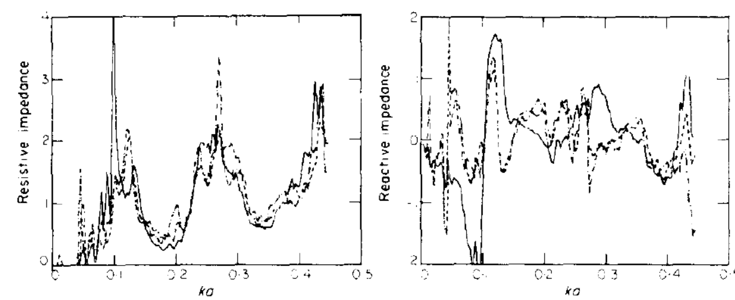


Figure 12. Effect of engine load (with constant speed) on the measured dimensionless acoustic internal source impedance of engine. ——, 2000 rev/min, 5 in Hg; – – –, 2000 rev/min, 10 in Hg; — · —, 2000 rev/min, 15 in Hg.

Prediction of Insertion Loss

Prasad and Crocker (1983b)

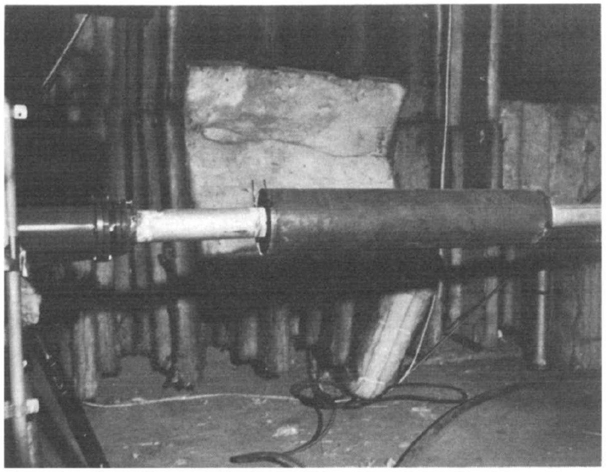
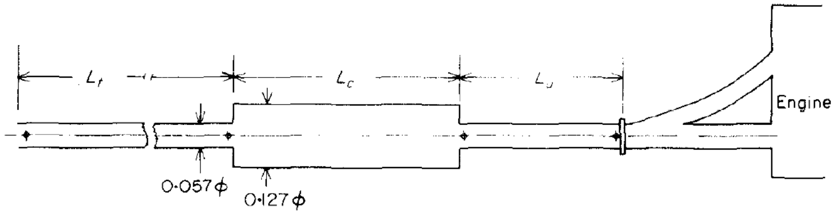


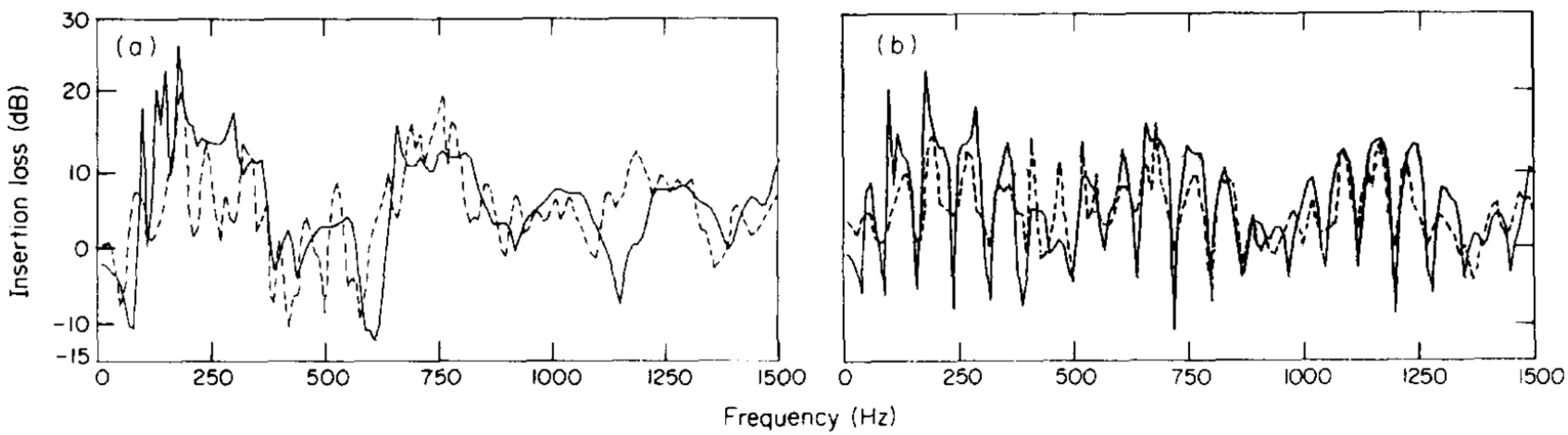
Figure 4. Test expansion chamber on the engine.



Insertion Loss of an Engine

Prasad and Crocker (1983b)

Dimensions of inlet and outlet ducts going into expansion chamber are varied.



Summary

Prasad and Crocker developed the theoretical framework and then demonstrated it would work for a realistic exhaust system in a string of publications over 5 years. Others have improved on the methods for simulating and measuring mufflers and measuring source impedance. The work by Åbom, Bodén, Selamet, Munjal, and others is especially notable in this regard.

Nonetheless, the body of work by Prasad and Crocker was foundational and quickly used by other authors. It made its way into muffler texts and noise control handbooks in less than a decade. Moreover, they significantly influenced the trajectory for the work that would follow, and their work still holds up well nearly 40 years later. For that, we should be grateful.