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Sound Power Measurements for Hot Exhaust Stacks

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ABSTRACT

The measurement of the noise emitted by hot gases, issuing from exhaust stacks, has been of particular interest to the power industry for many years. A method adopted by the ISVR uses two separate probes, positioned axially in the duct, with condenser microphones fitted to the probes outside the exhaust duct away from the hot flow gases. The paper describes the measurement method as refined and tested in the laboratory. Measurements are then reported for an exhaust stack, with typical exhaust gas temperatures of 250°C and velocities of greater than 50 m/s.

The laboratory tests used two adjoining reverberation rooms with a test duct positioned between the two rooms. The tests were undertaken at ambient conditions. The in-duct measurements of the sound power were compared to measurements taken in the receiving room using the method described by ISO 3743. The two measurements were found to be in close agreement. Errors incurred by the techniques have been demonstrated in this low-turbulence experiment to be within ± 3 dB.

It was shown that separating the sensors axially (with respect to the duct) gave less rejection of the unwanted signal caused by the turbulent flow compared with that with the sensors orientated radially. The effects of temperature on the probe's frequency response are predicted and incorporated into the analysis of in-stack data.

When the technique was used in the field there was good repeatability of the in-duct exhaust stack measurements when measured on different days, using slightly different design refinements of the probes and different transducers. The sound pressure level was found to be greatest near the duct wall although the variation in level with radial position was small. Variations in plant operating conditions gave changes in in-duct sound power levels that were expected.

1 THE PRINCIPLE OF THE TWO MICROPHONE TECHNIQUE

Sound power measurements made inside hot exhaust ducts are problematic because of the generally high temperature and flow velocity of the exhaust gas. The problem is to separate the flow noise associated with the incompressible turbulent flow from those associated with the acoustic signal using high-quality transducers that are not damaged by the high temperature of the exhaust gas.

The basis of the power measurement technique proposed in this paper is to predict the relationship between sound power and pressure based upon an assumed mode-amplitude-distribution and then to apply this correction to the measured pressure. Here, we make the assumption that, in a narrow frequency band, the sound power *W* transmitted along the duct is

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shared equally amongst the propagating duct modes. By making this assumption, Joseph et al[2] have shown that there is a simple relationship between sound power and the mean squared pressure averaged over a duct cross-section $\left\langle \overline{p^2} \right\rangle_S = \frac{1}{S}\int_S \overline{p^2}(\mathbf{y},x)dS$. They have shown at sufficiently high frequencies, $ka > 5$, and for flow Mach numbers M less than 0.2 (flow velocities less than 70 m/s)

$$\overline{W} = \frac{S\left\langle \overline{p^2} \right\rangle_S}{2\rho_0 c} \qquad (ka > 5, M < 0.2) \tag{1}$$

where S is the duct cross-sectional area, ρ_0 is the mean fluid density and c is the speed of sound, k is the acoustic wavenumber ω/c and a is the duct radius. This result suggests that, once the area-averaged mean square is determined, the sound power transmitted along the duct can be deduced. However, this measurement poses two difficulties. First, it requires an extensive number of pressure measurements to be quantified accurately, and second its measurement is susceptible to contamination by non-acoustic pressure fluctuation due to unsteady turbulent flow. The first of these difficulties can be easily circumvented by making the assumption that the sound field in the duct is axi-symmetric, i.e. it varies only with radial distance from the centre of the duct. This is valid when the mode amplitudes in the duct are uncorrelated. In this case the area-averaged pressure may be deduced from the radial variation of mean square pressure, using $\left\langle \overline{p^2} \right\rangle_S = \frac{2}{a^2}\int_0^a \overline{p^2}(r) r\,dr$, where a is the duct radius. In practice, this integration is approximated by a discrete summation of mean square pressure measurements at N positions along a duct radius. To overcome the turbulent flow generated non-acoustic pressure fluctuations $\overline{p^2}(r)$ is deduced from the pressure cross spectrum between two microphones in order that uncorrelated turbulence contributions are suppressed. Note that the sensor separation distance should be generally smaller than $\lambda/4$ to ensure that the acoustic signal at the two microphones signal is well correlated. Combining the above leads to the final expression for the spectrum of sound power,

$$W(\omega) \approx \frac{S}{\rho_0 c a^2}\sum_{n=1}^{N} S_{12}(r_n,\omega) r_n \,\Delta r_n \qquad (ka > 5, M < 0.1) \tag{2}$$

where r_n refers to the average radial distance between the two microphones, $r_n = \frac{1}{2}(r_{n2} + r_{n1})$. The American Society of Testing and Materials (ASTM) is currently independently investigating the method (1).

2 LABORATORY VALIDATION TESTS

2.1 Outline of the Method

For the laboratory tests aimed at validating the sound power measurement technique, a circular duct was used of 0.3 m radius and 2 m in length. The duct protruded through a sound insulating panel between two adjacent reverberation chambers. One reverberation chamber contained the sound source (source room). The second reverberation chamber contained a rotating microphone for measuring the sound pressure in the receiving room and thereby deducing the transmitted sound power according to ISO 3743. The sound source was either a loudspeaker or a centrifugal fan. Initial tests, without flow, were made with the loudspeaker as the source. In this case the microphones were positioned inside the duct without the probes. For the with-flow tests the centrifugal fan was used as the source with the fan outlet aligned with the duct but not connected to it. The arrangement is shown in Figure 1.

For measurements with flow the microphones were fitted into the probes. Each of the ISVR probes comprised a nose cone, which was inserted into the duct, a long tube with a T-piece and an anechoic termination. The T-piece, which was outside the duct, supported the microphone and the anechoic termination which was used to damp standing waves in the tube and hence smooth the natural frequency response of the tube.

The frequency responses of the probes, as used in the laboratory tests at ambient temperature, were checked before each set of tests so the processed results were unaffected by the type of anechoic termination. Later the effects of temperature on the probe's frequency response were determined.

The sound power measurements obtained from the in-duct technique were compared against those obtained using the conventional method for measuring sound power described in ISO 3743. Figure 2 shows the arrangement in the receiving room with the probes in position.

Three sets of laboratory tests were carried out with and without air flow. Different microphone configurations and separation distances were tested in order to identify the most accurate arrangement of probes for accurate sound power measurement. The discrete integration of intensity was performed from pressure measurements made at eight positions equally separated along a duct radius.

2.2 Extrapolating of test results to a different duct radius and temperature

The analysis of broadband multi-mode ducted sound fields described in Ref (2) shows that the important non-dimensional frequency in this measurement technique is *ka.* Thus, measurements made in two ducts of different sizes at the same *ka* – value are similar. This leads to the relation below, which may be used to relate the power measurements at frequencies f_{ISVR} in the laboratory (a_{ISVR} = 0.3 m) to the measurements at frequencies $f_{Exhaust}$ on the exhaust stack ($a_{Exhaust}$ = 1.5 m), $(f_{Exhaust} / f_{ISVR}) = (a_{ISVR} / a_{Exhaust}) \approx 0.2$. Thus, the lower frequency limit of 100 Hz of the laboratory tests corresponds to a lower frequency limit of approximately 20 Hz in the exhaust, whilst the upper frequency limit of 3 kHz relates to about 600 Hz in the exhaust stack.

The results have shown that acoustic signals are not rejected by the two-microphone technique provided $k\Delta r < 2$, where k is the acoustic wavenumber and Δr is the probe separation distance. At temperature T (in centigrade), this condition may be written in the form,

$$\Delta r < \frac{c_0 \sqrt{1 + T/273}}{\pi f} \tag{3}$$

where c_0 is the speed of sound at 0°C, which is approximately 332 m/s. Solving for the probe separation distance Δr predicts that, for a maximum frequency of 500 Hz, and a temperature of 300°C, the probe separation distance should be approximately 30 cm to provide a good level of turbulence rejection.

2.3 Effects of a partial radial traverse

The diameter of the exhaust stack in which the field tests were to be carried out was 2.9m so the probes could not traverse across the complete radius. Laboratory tests were carried out to assess the error incurred by an incomplete radial traverse. Figure 3 shows a comparison between the sound power measured for a full radial traverse of the duct (crosses) and a radial traverse of the duct between $a/2 \leq r \leq a$ (circles). Measurements obtained from a full radial traverse are observed to be closer to the measured sound power by approximately 1 dB. The error incurred by restricting the radial traverse to the outer radius was found to be small.

2.4 Results of the Laboratory Tests

- The probe measurements, shown in Figure 4, are in close agreement with measurements of sound power deduced from the conventional measurement procedure described by ISO 3743 in a no-flow test with the noise provided by a loudspeaker.
- Separating the sensors axially (with respect to the duct) gave greater rejection of the non-acoustic signal compared with that with the sensors orientated radially.
- It was shown that the coherence between the two probe microphone signals is generally good for $k\Delta r < 2$, where k is the acoustic wavenumber ω/c and Δr is the probe separation distance.
- In the presence of air flow a significant drop in coherence occurred but levels remained reasonably good overall. Good agreement was obtained between the ISO 3744 results and those from the probe, as shown in Figure 5.
- The effects of the temperature on the probe's frequency response are predictable and can be incorporated into the analysis of in-stack data.
- Errors incurred by the techniques have been demonstrated in this low-turbulence experiment to be within ± 3 dB.

3 IN-DUCT FIELD TESTS

Having validated the sound power measurement technique, field testing was carried out in an oil refinery between a large Tertiary Cyclone Vessels (TCV) and the stack silencers. Figure 6 shows the three measurement positions that were used: position 1 is above the three Multi-Holed orifice plates (MHO), position 2 is between the MHO and the TCV, and position 3 is inside the TCV.

The sound power measurements showed:

- Good repeatability when measured on different days for the same process conditions.
- The sound pressure levels were greatest near the duct wall although the variation in level with radial position was small.
- The highest sound power levels were found inside the TCV.
- Diverting flow through a bypass around the MHOs caused a small reduction in sound power level above the MHO and above the TCV, but not in the TCV, as expected.
- Reducing the flow through the TCV produced a downwards frequency shift of the maximum level in the frequency spectrum.
- With the reduced flow through the TCV a narrowband analysis of the sound pressure in the TCV showed a prominent tone at 220 Hz. This corresponded to the frequency of a tonal problem that had occurred at this lower flow rate before the plant was upgraded in 1991.

4 CONCLUSIONS

- Laboratory tests have demonstrated the validity of the method of measuring the in-stack sound power levels based on the cross-spectrum of the pressures for the two probes.
- There was good agreement between laboratory estimates made of the in-duct sound power using this technique and that obtained by the method in ISO 3743.
- The accuracy of the method, when used in the laboratory, was demonstrated to be ± 3 dB.
- The upper frequency limitation of the method is set by the microphone/probe separation distance, which should be less than a quarter wavelength of the highest frequency of interest.
- The effect of temperature on the probe's frequency response is incorporated into the analysis.
- There was good repeatability for measurements taken in the field.
- Changing the air rate of the process gave predictable changes in the in-duct sound power estimates.
- A narrowband analysis of the noise in the TCV shows the presence of a tonal component at 220 Hz when the flow rate was reduced to pre-2001 levels. In 1991 the process caused tonal noise in the community at 210 Hz at this lower flow rate.

5 REFERENCES

[1] "Status Report on a New ASTM Standard Guide for Measuring Large Gas Turbine Inlet and Exhaust Duct Sound Pressure Levels" R. A. Putnam, Internoise 2005 Conference, Rio de Janeiro, August 2005.

[2] "Multi-mode sound transmission in ducts with flow", P. Joseph, C. L. Morfey and C. Lewis, Journal of Sound and Vibration 264, 2003, 523-544.

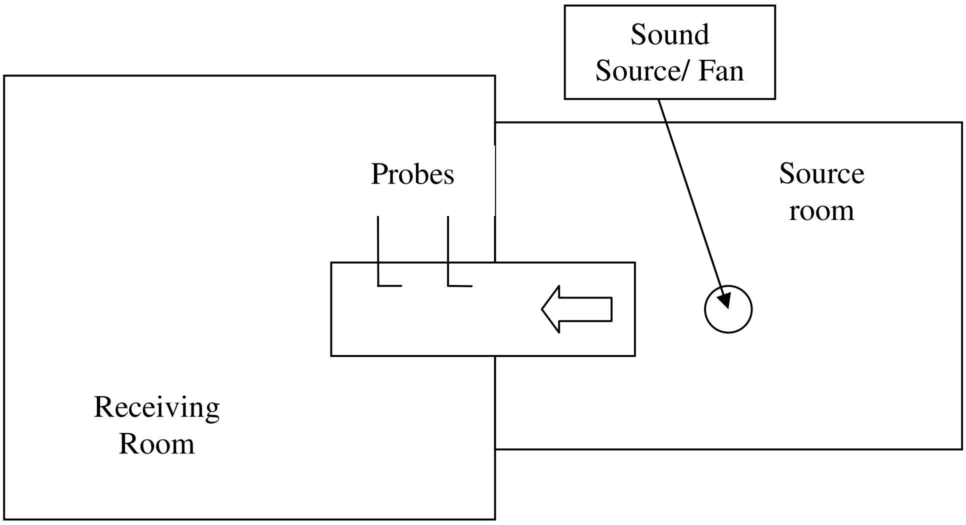

FIGURE 1: Schematic Diagram of the Laboratory Arrangement

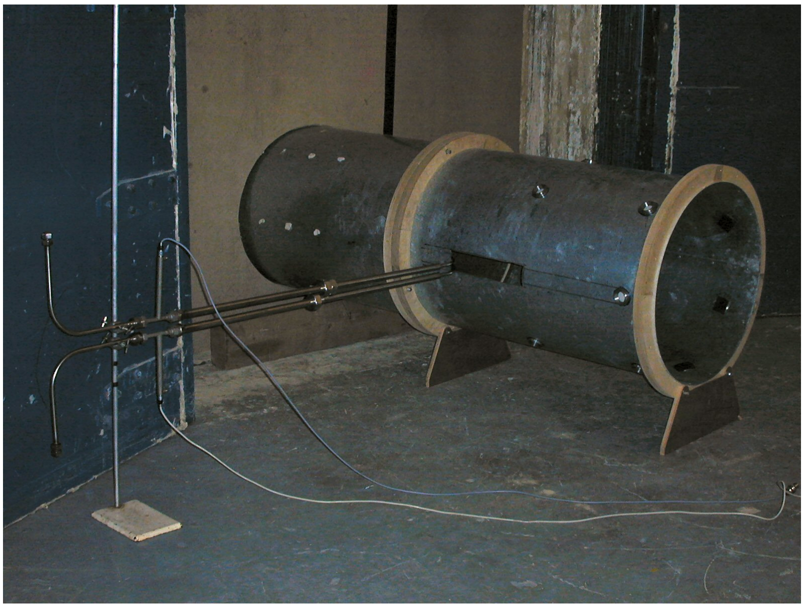

FIGURE 2: Arrangement in the Receiving Room

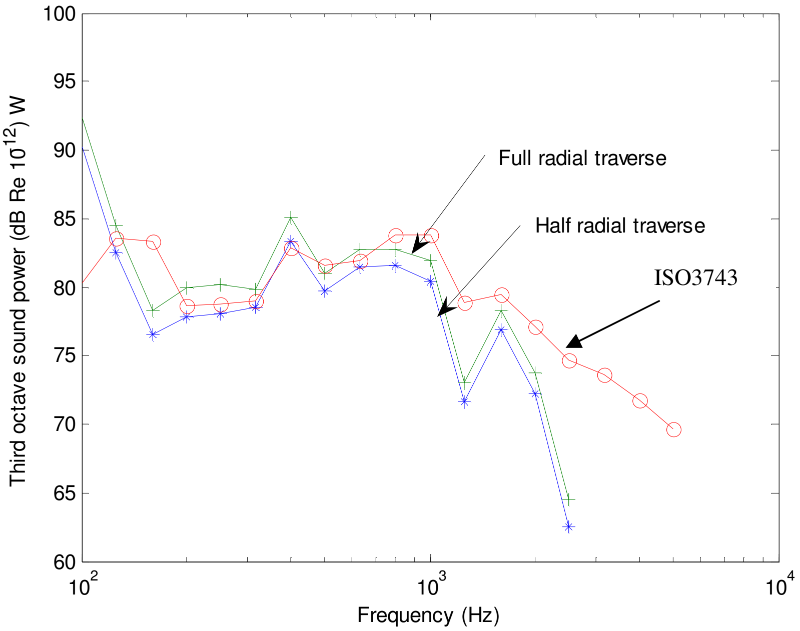

FIGURE 3: Comparison of Sound Power Levels obtained from a Complete Radial Traverse of the Duct (+), a Half Radial Traverse of the Duct (∗) and from ISO 3743 (O)

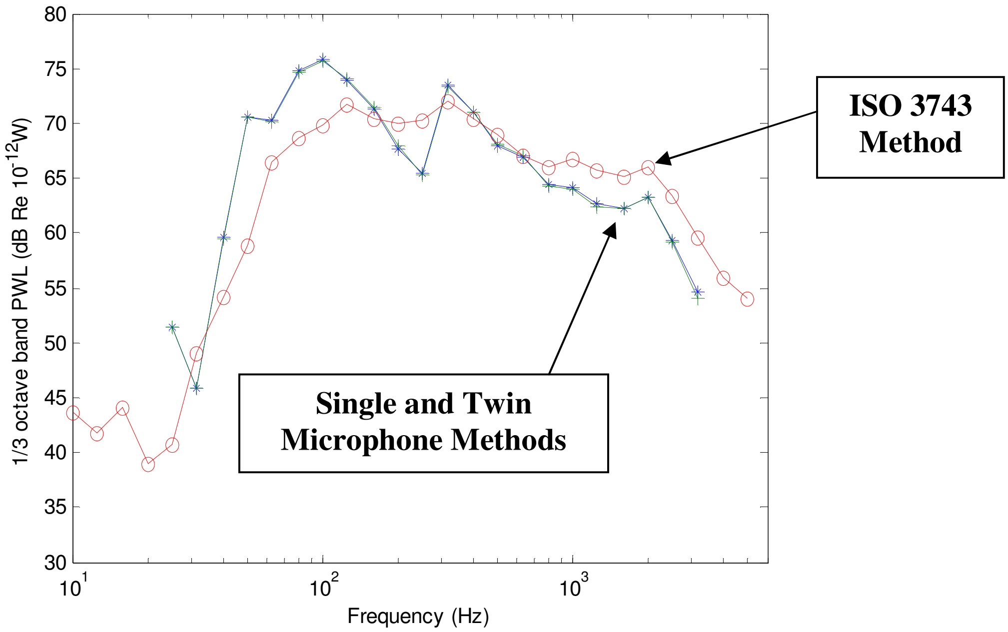

FIGURE 4: Comparison of Sound Power obtained from ISO 3743 and with the Probes: Microphones, separated axially by 3 cm: Loudspeaker only, No Flow

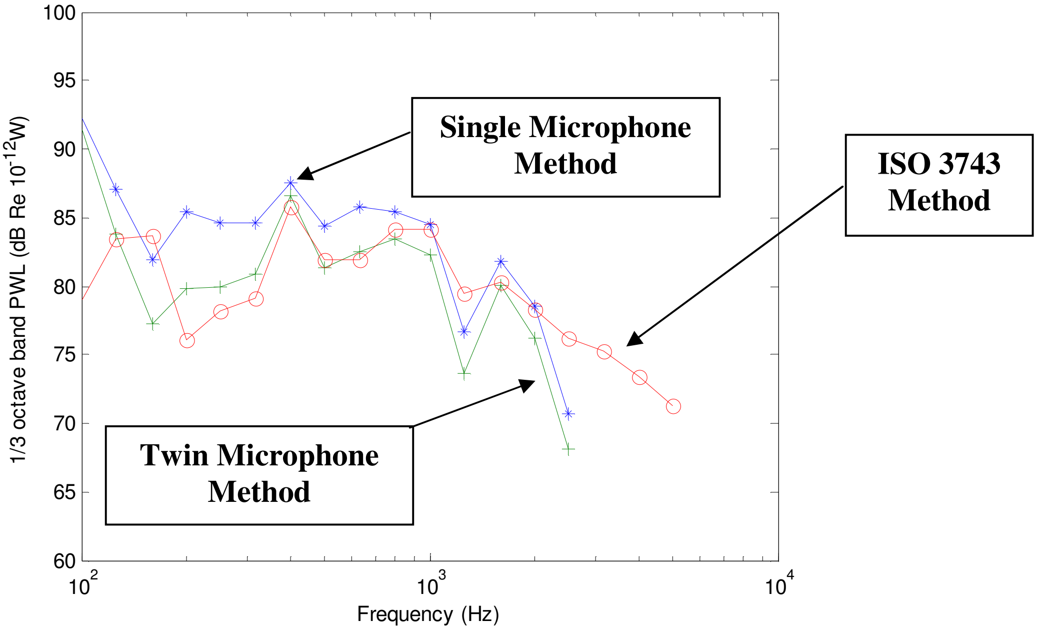

FIGURE 5: Comparison of Sound Power obtained from ISO3743 and from the Probes: Flow produced by Centrifugal Fan with Spoilers located at the end of the Fan

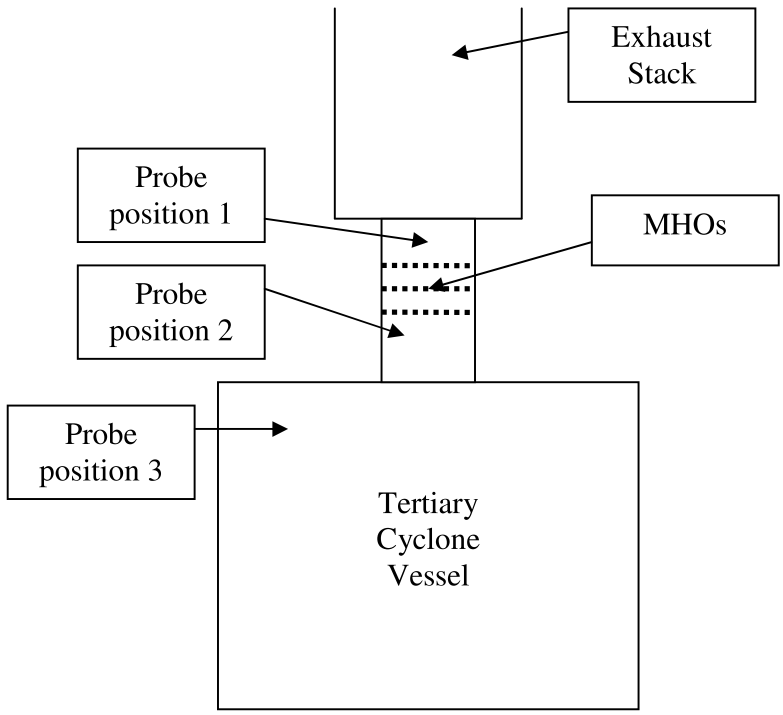

FIGURE 6: Measurement Positions in the Field

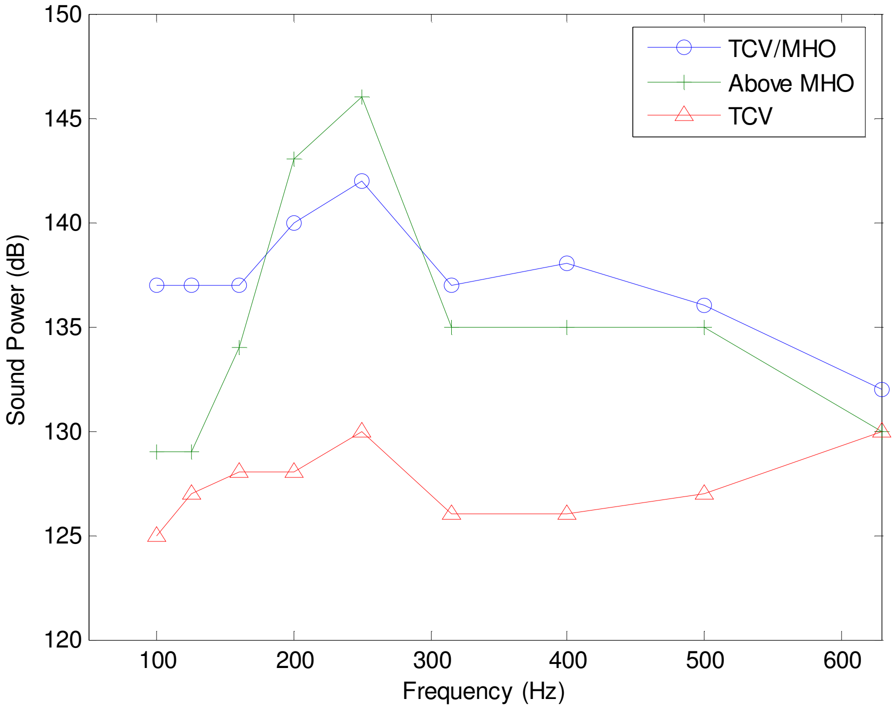

FIGURE 7: Comparison of Sound Power Levels in the Process

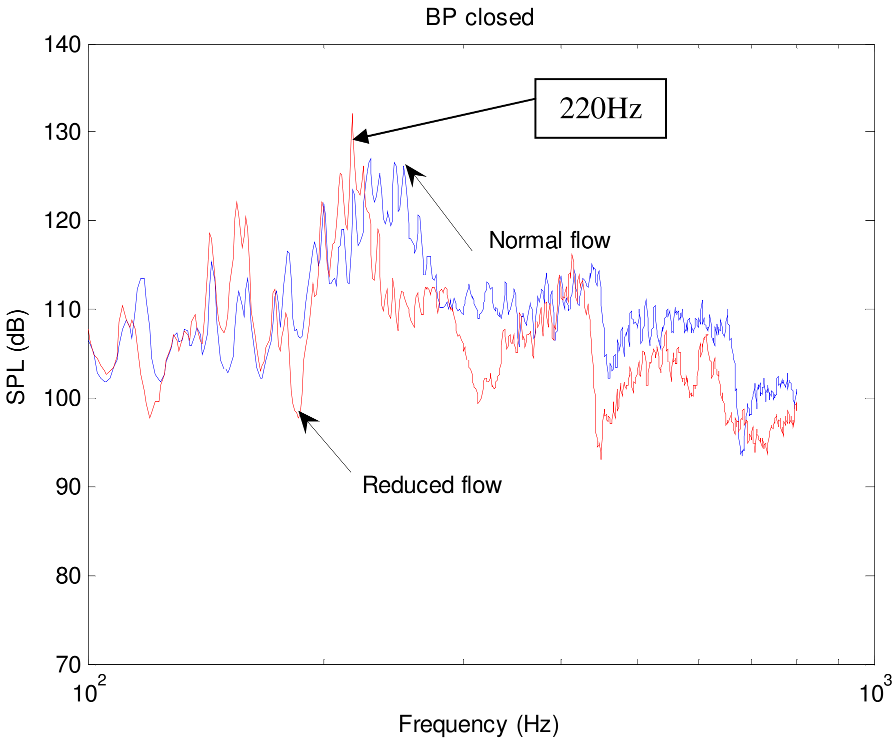

FIGURE 8: Narrow Band Sound Pressure Level Spectrum in TCV: With Normal and Reduced Flow