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Reducing Noise from an Oil Refinery Cat Cracker

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Abstract This paper concerns the noise from a Cat Cracker exhaust stack, used for the purpose of converting heavy oil into gasoline products. Following the upgrading of the Cat Cracker, there were persistent community complaints of an irregularly varying noise that sounded like an “overflying jet aircraft”. This paper describes a detailed study of the Cat Cracker noise involving: field tests on-plant and in the community; scale model tests in the laboratory; theoretical predictions using thin aerofoil unsteady aerodynamic theory; and a study of atmospheric propagation effects using the Parabolic Equation method.

The objective of the study was to i) identify methods of reducing the noise levels, and ii) establish the cause of the irregularity of the noise level in the community.

The laboratory tests used a ⅓ scale model to explore qualitatively the nature of any potential interaction between the two principal elements in the stack.

The study concluded that the cause of the noise was an interaction between the turbulent flow from a valve and a Multi-Holed Orifice (MHO) downstream of the valve. The irregular variations in the noise were predicted to be atmospheric effects.

Following the investigation the valve and the MHO were subsequently replaced by three MHO’s in series which gave a reduction in noise levels at the stack tip of up to 14dB. Noise measurements in the community demonstrated a similar level of noise reduction. In some weather conditions the Cat Cracker noise can still be heard, albeit at a much reduced level. Work is continuing to reduce the noise even further.

1. INTRODUCTION

This paper concerns the noise from the exhaust stack of a Cat Cracker. Following a major upgrade to the Cat Cracker, complaints had been received from the local community about a noise, which was likened to that from a jet aircraft. The noise was observed to rise and fall irregularly when the wind was blowing towards the community. The oil company had carried out a great deal of work to investigate the problem, and a new stack silencer had been installed. However, the problem had persisted. It was at this stage that ISVR Consulting was engaged to investigate the source of noise and identify means for its reduction.

A detailed study of the Cat Cracker noise involved: field tests on-plant and in the community; scale model tests in the laboratory; theoretical predictions using thin aerofoil unsteady aerodynamic theory; and a study of the atmospheric propagation effects using the Parabolic Equation method.

2. OUTLINE OF THE PROCESS

The Cat Cracker converts heavy oil into gasoline products within the Reactor by the distillation process. The exhaust gases discharge to atmosphere through a tall chimney. The process runs at 735oC. The reactor catalyst is fluidised at this temperature and spent catalyst is fed back to a Regenerator. There are 55 tonnes per minute of catalyst movement.

Air is blown through the regenerator and passes through 25 sets of cyclones, to remove process catalyst. The flue gases then pass through waste heat recovery units and valves, as shown in Figure 1. The volume of flue gas through the stack can be varied between 4800 and 6000m3/min.

The flue gas is normally controlled by Valve C, downstream of which is a Multi-Holed Orifice (MHO) which assists in controlling the velocity through the system to minimise erosion of the waste heat recovery units. Control can be maintained using Valve A but this is less efficient.

Two silencers are positioned downstream of the MHO plate. The stack discharges to atmosphere at an elevation of 89m. The process runs 24 hrs per day, 7 days per week. It is a steady process and not subject to sudden changes. Prior to December 2001 the cat cracker ran without complaints. At that time there was a single stack silencer to reduce a tonal problem. A new blower was installed during the upgrade to increase the air rate from approximately 3500 m3/min to 6000 m3/min. Following community complaints about the noise the stack was extensively altered and an additional silencer was fitted. Although this did reduce the noise, complaints persisted.

It had been observed that the noise problem mainly occurred when Valve C was in control and the problem could be reduced by switching control to Valve A.

3. FIELD SURVEY

Simultaneous recordings of the noise were taken on-site and in the community by recording continuously with Norsonics 121 data recorders in “audio” mode. Five recording systems were used: three were in the community, one recorded the noise at the stack tip and a fifth was at ground level in the refinery. Recordings were made continuously for about 5 hours as the Cat Cracker operation was varied from Valve A being in control, to Valve C being in control, and then the process was returned to Valve A being in control. During these tests some dynamic pressure measurements were taken in the stack, downstream of the MHO.

Previous work by the oil company suggested that most of the noise occurred at low frequencies so most of the noise measurements were low pass filtered with a cut-off frequency of 800Hz.

The overall conclusions of this noise survey were:

- The noise emitted at the stack tip was very stable, did not fluctuate over short time scales and was broadband and low frequency in character
- There were large fluctuations in the community noise levels and the magnitude of the fluctuations was greater at the location directly downwind of the stack (Figure 2).
- There was no correlation between the fluctuations at the three community positions, when the data was adjusted for the different source to receiver distances.
- The fluctuations in the community noise were due to propagation effects.
- The difference in overall, low-pass filtered noise level at the stack tip increased by 4dB from Valve A being in control to Valve C being in control.
- The ⅓ octave band sound pressure levels in the community were higher when Valve C was in control by up to 9dB.

From the in-stack measurements it was concluded that the overall in-stack sound pressure level was approximately 145dB and the spectrum was of the same shape as that for a bluff body in a uniform air-flow.

4. LABORATORY MODEL TESTS

Laboratory tests were carried out in the ISVR's reverberation chamber. A ⅓ scale model was constructed aimed at exploring the interaction between the turbulence produced by the valve impinging on the downstream MHO. Not all the controlling parameters could be scaled, however. The in-coming air entered through a 70mm diameter hole, which represented the vena contracta of the valve when Valve C was in control. Several designs of MHO plate were tested including the one fitted in the process. The use of multiple MHO's was also tested; as expected, lower noise levels were produced compared to the levels associated with a single MHO.

Figure 3 shows the differences in mid-frequency noise levels when the separation between the MHO and the valve was increased for a constant exhaust velocity.

5. THEORETICAL PREDICTIONS OF VALVE-MHO INTERACTION NOISE

A simple, first-order theory was developed to predict the noise produced by the interaction between isotropic turbulence and a downstream valve comprising a number of holes. The holes are assumed to be fitted with a 'neck' so that the noise is produced by the interaction of the turbulence with the leading edge of the neck.

The analysis assumes 'frozen' turbulence convected with velocity U (Taylor's hypothesis) with mean square turbulence velocity, u2, and length scale lx.

The final expression for the spectrum of sound power due to interaction with N holes is

$$\frac{dW}{d\omega} = \frac{N\pi^{\frac{3}{2}}\Gamma(5/6)}{2\Gamma(1/3)} \frac{\rho_0 L l_x U^2 \overline{u^2}}{c\omega} \left(1 + (\omega l_x / 2U)^2\right)^{-5/6} \quad (1)$$

For a fully turbulent free jet $\sqrt{\overline{u^2}} \approx 0.15U_1$, where U1 is the centre-line velocity and lx is roughly proportional to the convection distance X. Putting $1_x = aX$ and $U_1 = U$,

$$\frac{dW}{df} \approx 0.1 \frac{\alpha \rho_0 L X U_1^4(X)}{c\omega} \left(1 + (\omega l_x / 2U_1(X))^2\right)^{-5/6} \tag{2}$$

where an extra factor of π has been included to convert from radian/s to Hertz. For a fully developed, free jet, $a \approx 0.1$.

Prediction based on this model in terms of third octave sound power level gave trends that were consistent with measured data, although the absolute levels were over predicted by approximately 20dB.

6. THEORETICAL PREDICTIONS OF THE SOUND PROPAGATION USING A PARABOLIC EQUATION MODEL

The PE model considered both the steady state observed wind effect and the effect of atmospheric turbulence along the sound propagation path from the chimney stack to the observer. The turbulence model used here only accounts for typical turbulence fields produced naturally in the atmosphere, as the characteristics of the induced turbulence fields by the heat transfer activities of the refinery were unknown. Atmospheric turbulence is included in the PE model as small fluctuations of the acoustic refractive-index n, mathematically described as:

$$n = \overline{n} + \mu \tag{3}$$

Where $\bar{n}$ is the average value of the refractive-index and μ denotes the fluctuation representing the turbulence (with $\mu \ll \bar{n}$ and $\bar{\mu} = 0$). The mathematical function describing the turbulence has been built assuming that the fluctuating part of the refraction index μ(r,z) has an autocorrelation function defined by:

$$C(s) \equiv \langle \mu(R+s) \cdot \mu(R) \rangle \tag{4}$$

where < > denotes an ensemble average over many realizations of μ, R=(x,y,z) is a position vector and s represents some spatial separation distance in the r-z plane. It is assumed that for small-scale atmospheric turbulence, C(s) can be approximated by a Gaussian distribution.

$$C(s) = \mu_0^2 \cdot e^{-s^2/l^2} \tag{5}$$

Where μ_0 is the root-mean-square fluctuation of μ(r,z) and l is the correlation length (here assumed as 10^{-3} and 1m respectively). To obtain realizations of μ(r,z), the square-root of the wave number spectrum is calculated from the autocorrelation function C(s), then multiplied by a random phase function and finally computed using the inverse Fourier transform.

The PE model was run using 100 realizations of the fluctuating index of refraction for each frequency of interest. Figure 4 shows the predicted transmission loss for 63, 125, and 250 Hz. Subject to the caveat that the predictions are presented in single frequencies and that cannot be directly compared against the 1/3 octave band measurements, the predictions provide a useful indication of the effects of atmospheric turbulence for our particular site conditions. Fig. 4 shows that predicted transmission loss varies about 4 dB for 63 and 125 Hz, and about 10 dB in the 250Hz. These variation characteristics are very similar to those shown by the measured data in Figure 6, and suggest that atmospheric turbulence might be the cause of the existing roars at the receiver locations.

7. CONCLUSIONS AND THE PREFERRED NOISE CONTROL SOLUTION

The conclusions of the study were that the source of noise was due to turbulent interaction produced between Valve C and the MHO. This generated a steady noise at the stack tip. The effects of the wind and turbulence caused of the irregular fluctuations in the measured noise in the community.

Following the results of the investigation described above the existing MHO and Valve C were replaced by three MHO's in series. This arrangement is shown in Figure 5. Following these modifications a repeat survey was carried out. The results are given in Figure 6 and show a reduction in the stack tip noise of between 10 and 14dB. A similar level of reduction in the community noise is illustrated in Figure 7.

8. ACKNOWLEDGMENTS

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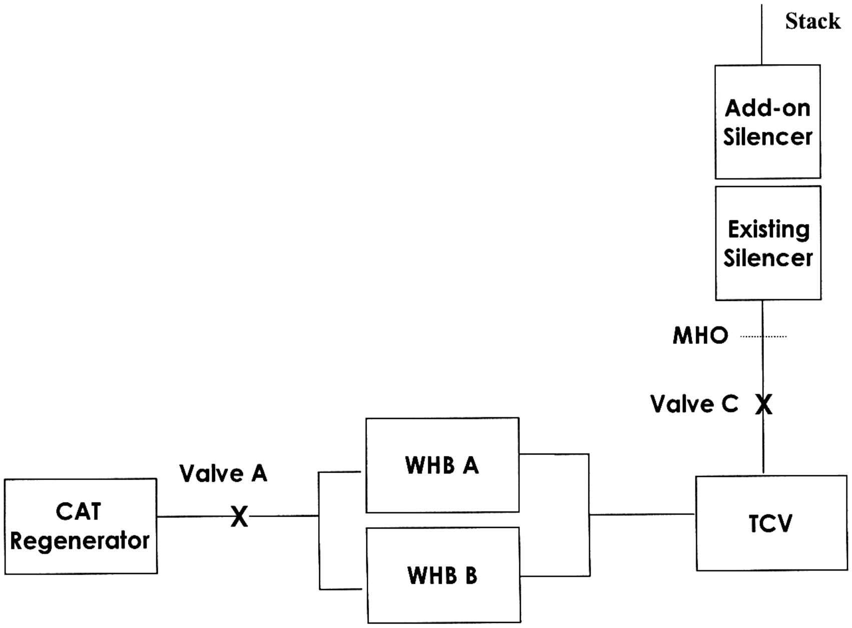

Figure 1: Schematic Diagram of the Process

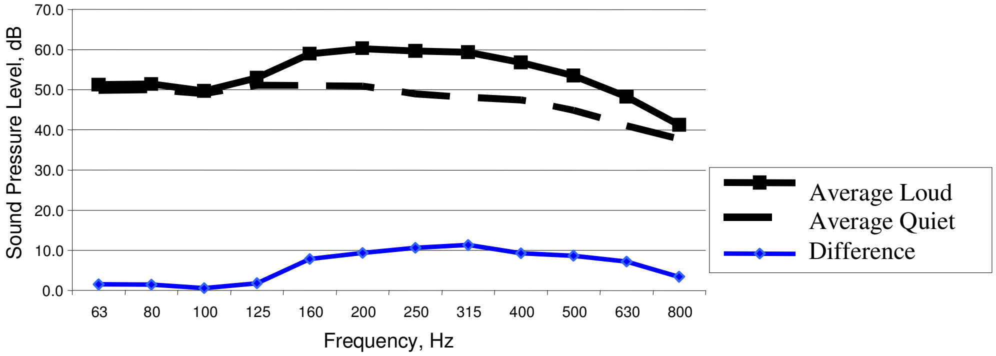

Figure 2: Noise Levels in the Community for Loud and Quiet Parts of the Fluctuations, and the Difference in Levels.

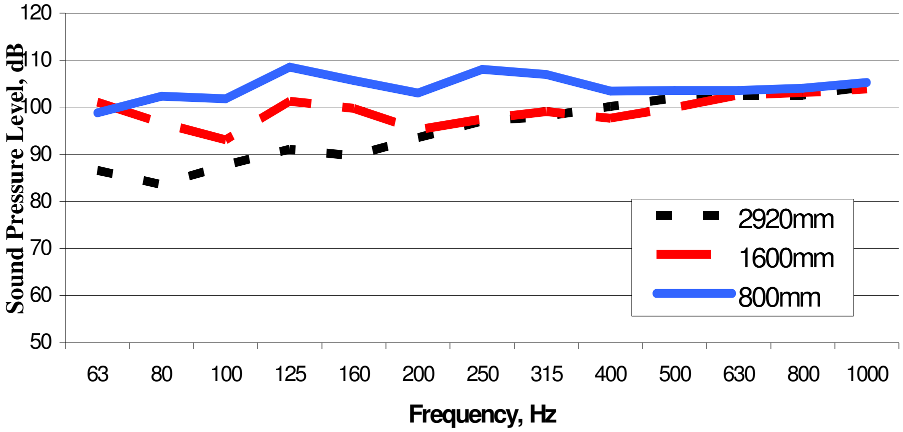

Figure 3: Effect of Separation between Valve and MHO (outlet velocity = 164m/s)

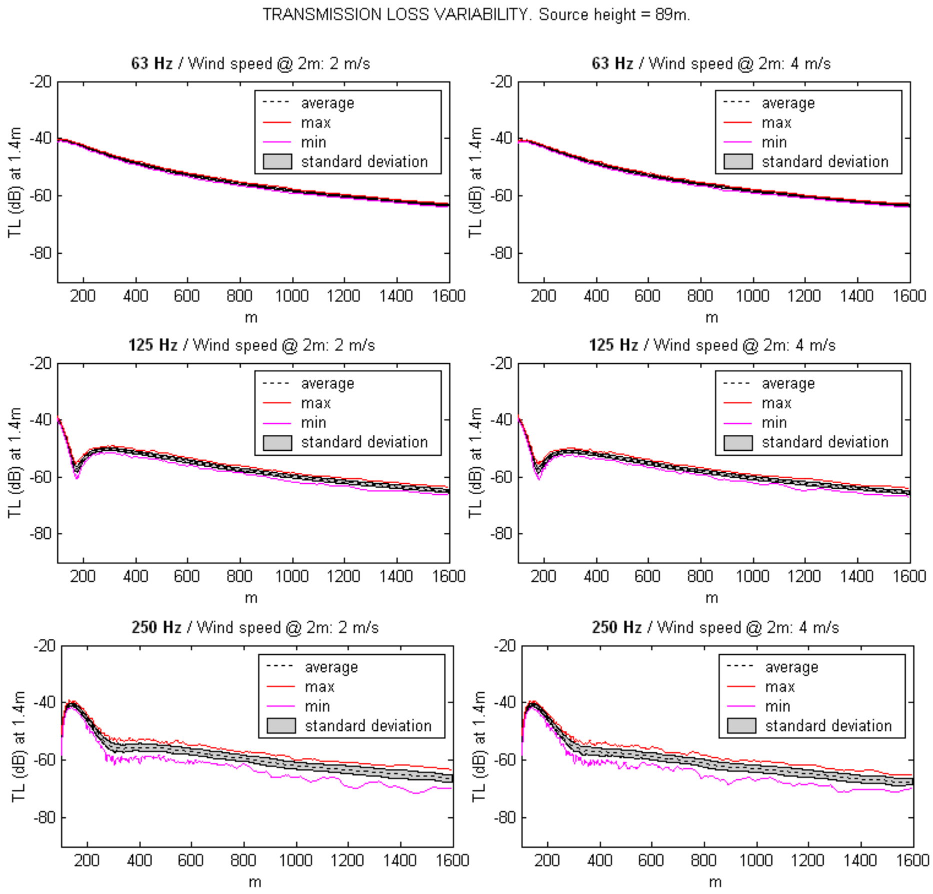

Figure 4: Transmission loss for 63, 125, 250 and 500 Hz. Obtained from 100 turbulence realizations implemented in a Parabolic Equation model.

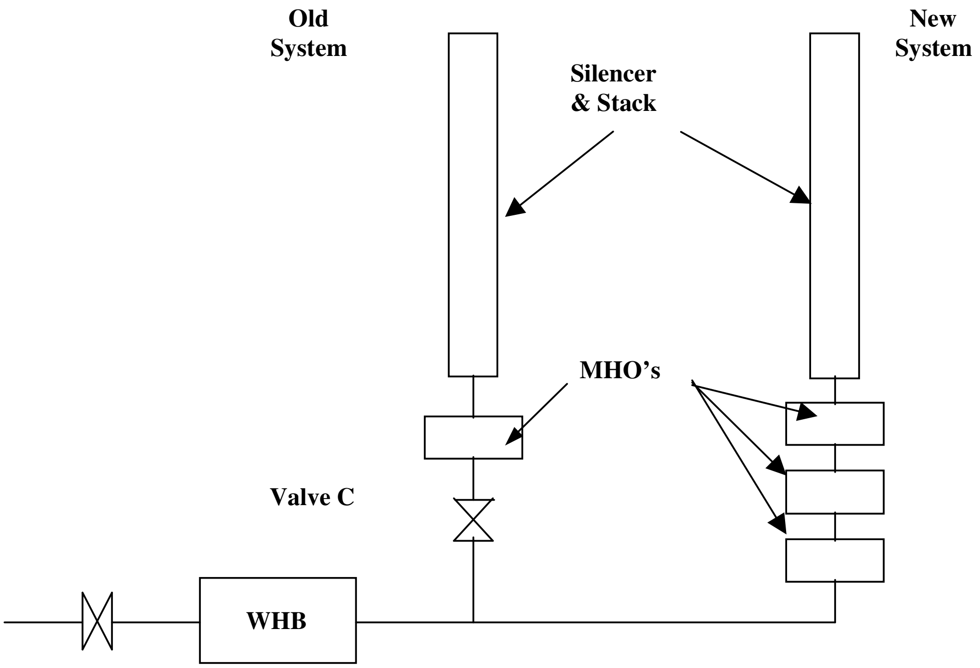

Figure 5: Process Changes to the Stack

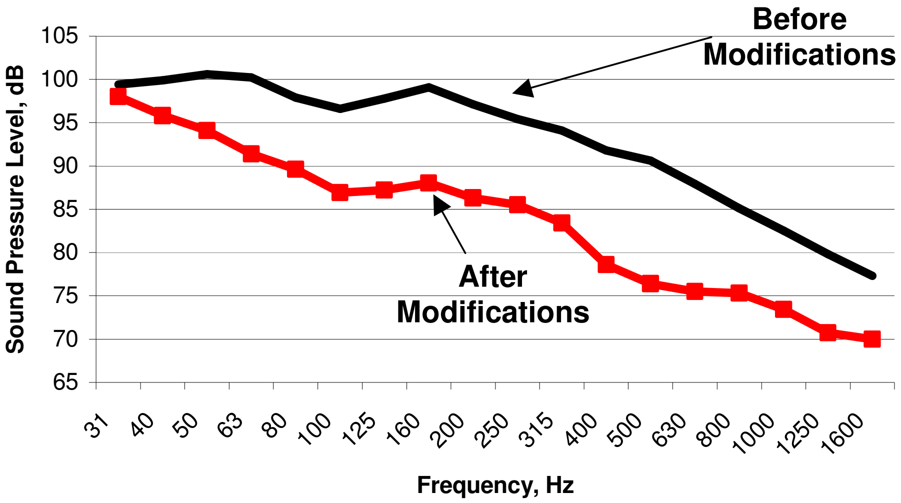

Figure 6: Sound Pressure Levels at the Stack Tip before and after the Modifications

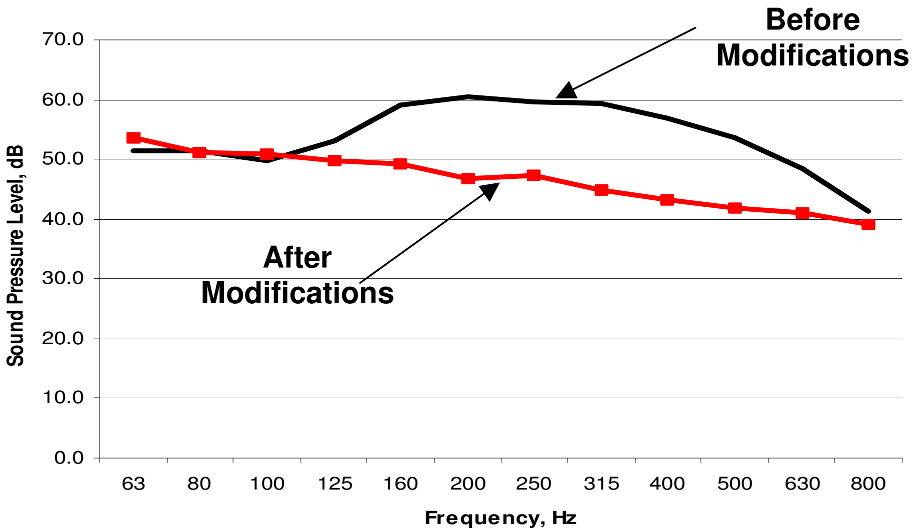

Figure 7: Sound Pressure Levels in the Community at "Loud" Part of Fluctuation