Noise reduction using Quarter Wave Tube

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Summary

A one-third octave frequency analysis of a vehicles tailpipe noise was performed. The principle of decibel addition is used to suggest an approach for reducing the overall sound pressure level. The sound pressure level of the vehicle was reduced through the use of Quarter Wave Tubes.

Introduction

A customer was having problems with the noise level of his vehicle. In particular, it was too loud during static tests where the vehicle was tested at 6000rpm. The customer had reported no issues with drive-by noise levels and in all other respects was happy with the existing exhaust system. Being a track vehicle, power, weight and durability were all important considerations.

Aims

Reduce the noise level of the vehicle without excessive weight increase or flow restrictions.

Objectives

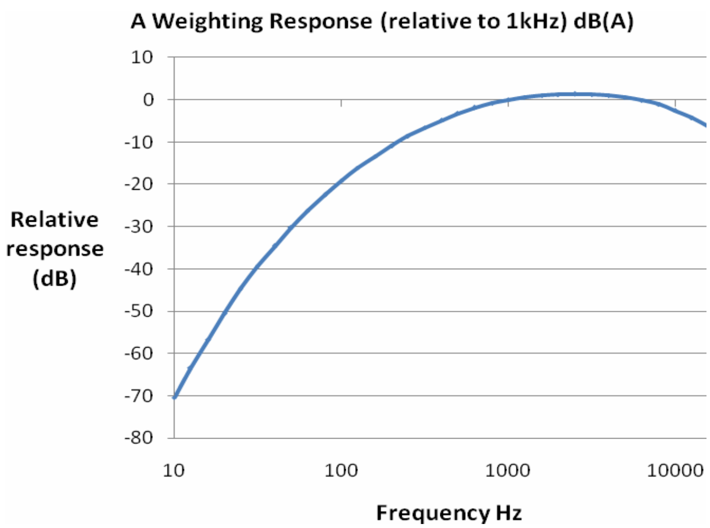
Reduce the noise level to less than 101dB(A) at 6000rpm

Theory

A-Weighting

Noise is made up of different frequencies. The human audible range is usually quoted as 20Hz to 20kHz. Frequencies in this range are perceived in different ways due to the sensitivity of the human ear. The most sensitive region for the human ear is 1 - 5kHz. Therefore, although two sources may have the same Sound Pressure Level (SPL) measured in dB, they may sound different to us if they have different frequency content. The A-weighting curve is used to take account of the sensitivity of the human ear and to produce a subjective noise level measured in dB(A). Sound levels in dB are attenuated by a specific amount for each frequency, e.g. an SPL of 80dB at 125Hz will be perceived as (80-16=) 64dB(A) by the receiver. The specific attenuation amounts are given below for the octave bands up to 8kHz.

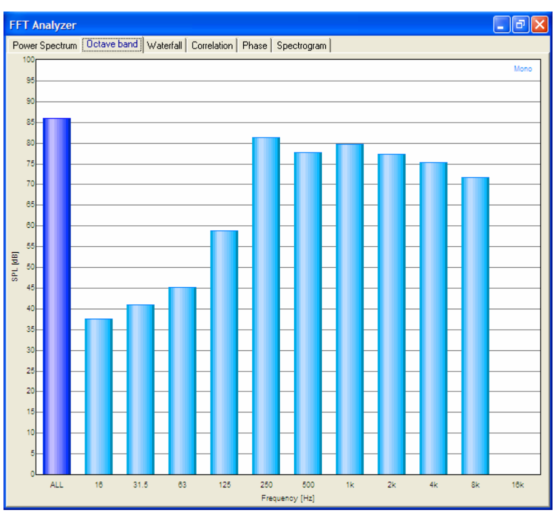
Frequency (Hz)	31.5	63	125	250	500	1k	2k	4k	8k
A-Weighting (dB)	-39	-26	-16	-9	-3	0	+1	+1	-1



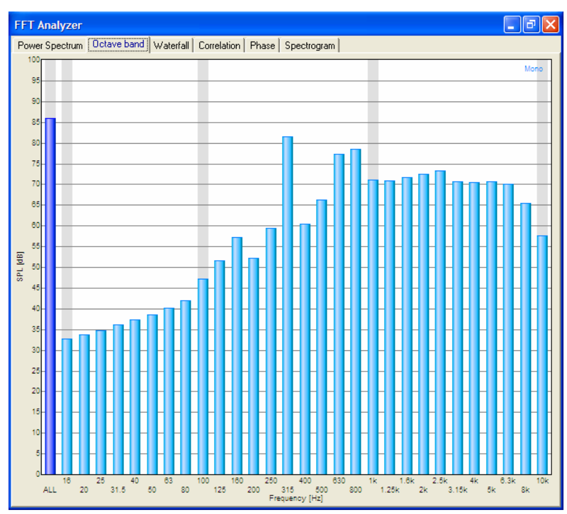
This report will use the subjective A-weighted results throughout, as defined by the test requirements.

Frequency Analysis Filters

Band pass filters are commonly used in frequency analysis in order to divide the frequency range into bands at which an SPL may be defined. Octave filters are band pass filters that have an upper frequency limit twice that of the lower frequency limit. When a noise is subject to frequency analysis using octave filters an octave band pressure level (BPL) reading can be obtained for each band and plotted as shown in the example on the left below. For a more detailed frequency analysis one third octave filters can be used, where the frequency range covered by an octave filter is divided into three parts. The same noise is shown with one third octave analysis on the right below.



Octave Bands

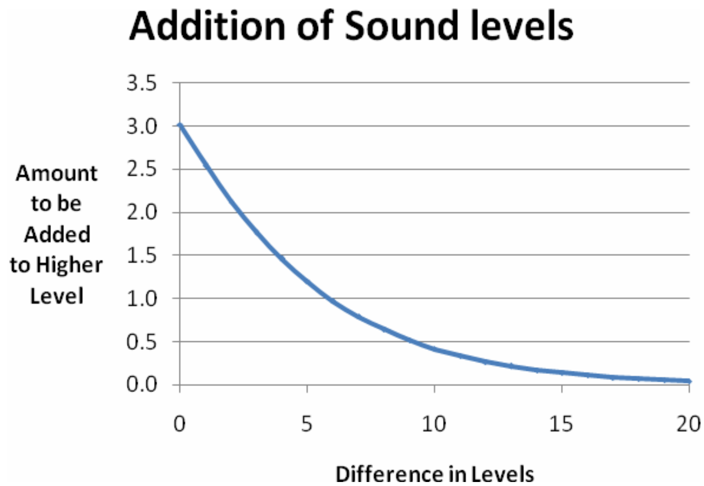


1/3rd Octave Bands

Addition of sound pressure levels

The figure below shows how sound levels are affected when they are added.

Difference between noise levels dB	Amount to add to higher level
0	3.0
1	2.5
2	2.1
3	1.8
4	1.5
5	1.2
6	1.0
7	0.8
8	0.6
9	0.5
10	0.4
11	0.3
12	0.3
13	0.2
14	0.2
15	0.1
16	0.1
17	0.1
18	0.1
19	0.1



For example two sound sources; one at 78dB and one at 83dB have a difference of 5dB, which relates to an addition of 1.2dB. Therefore the overall SPL of these two sources would be (83+1.2=) 84.2dB.

Addition of one third octave band pressure levels

The decibel addition principal applies to the individual frequency band pressure levels in the frequency analysis of a noise. For a specific noise that has undergone one third octave frequency analysis, the overall SPL can be obtained by 'adding' the individual one third octave band pressure levels, following the decibel addition rule, where

$$SPL = 10Log\left(\sum_{i=1}^{n} 10^{\frac{BPL_i}{10}}\right)dB$$

Method

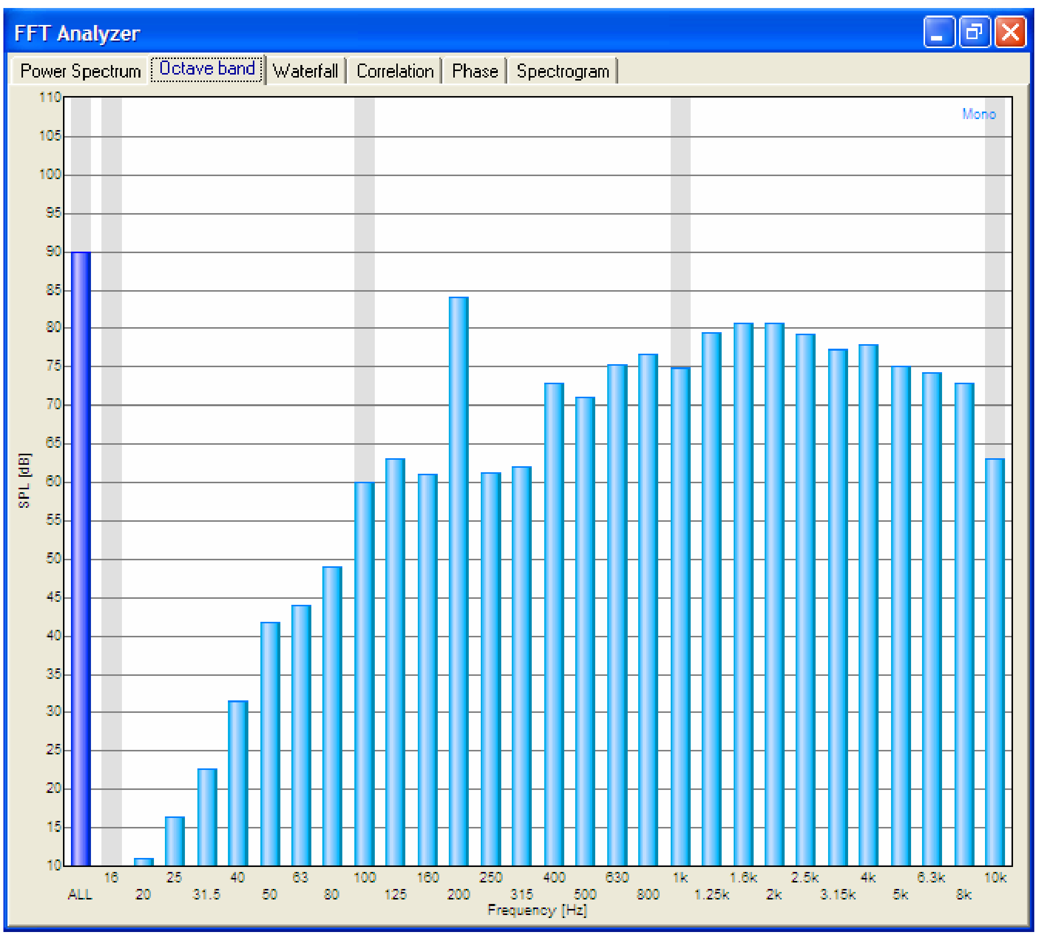
Equipment and set-up

A CEL-254 Sound level meter was used to record the overall SPL in dB(A) for each test. This also acted as the microphone input to the frequency analysis software. The software was used to indicate the relative levels of the different frequency bands however it should be noted that the dB levels shown in the software screenshots do not relate to the actual levels recorded by the sound level meter. This was because the microphone input had not been fully calibrated. The software was installed on an Acer Travelmate C300 laptop computer with an Intel 1.6GHz processor and 512MB RAM. The microphone was placed 0.5m away from the nearside tailpipe outlet in the horizontal plane at an angle of 45 degrees to the exhaust flow.

Initial Measurements

The first stage of the development process was to perform an initial analysis on the existing exhaust system in order to identify the characteristics of the noise that might be contributing to the excessive levels.

A one third octave analysis was performed on the vehicle with the engine speed held briefly at 6000rpm. The results are shown below.



1/3rd Octave Analysis of original system at 6000rpm

The results show a distinct peak at the 200Hz band. This relates to the 2^{nd} harmonic of the engine rotation frequency at 6000rpm. The 2^{nd} Harmonic is stronger than the others because there are two firing events per revolution. This dominant firing frequency is typical of naturally aspirated engines with tuned exhaust manifolds and straight through systems, where the even firing pulses are transmitted, with very little interruption, to the end of the system.

Application of Theory

The decibel addition rule shows that if the higher frequency BPLs were reduced but the 200Hz BPL remained unchanged, there would be little difference in the overall SPL. Therefore in order to reduce the overall SPL, it is necessary to maintain or reduce the BPL of the higher frequency bands while also significantly reducing the BPL of the 200Hz band. As size and weight are key criteria for this application, it would not be suitable to simply introduce bigger silencers with more absorption material, a typical approach to noise attenuation. Redirecting the flow within the existing silencers may help to break up the dominant frequency; however this is likely to result in a reduced volume available for absorption material. Experience has shown that this can have a negative effect by reducing the generally high level of broad-band attenuation that the material provides. It was therefore decided to attempt to maintain the volume of absorption material of the existing system in order to maintain the low BPLs for the higher frequencies. Further to this it would be necessary to specifically target the 200Hz frequency to reduce the BPL, with the aim of reducing the overall SPL.

The selected method for targeting the specific frequency was to use a Quarter Wave Tube (QWT). This device is essentially a side-branch attached to the exhaust system that has an overall length equal to a quarter of the wavelength of the specific frequency in question. The theory suggests that a sound wave entering the side branch will travel to the end of the tube where it is reflected back to the branch opening. By the time the wave has travelled a quarter wavelength down the tube and a quarter wavelength back again, the wave will be a total of half a wavelength (or 180 degrees) out of phase. In simple terms, the wave approaching from the exhaust system and the wave coming back from the QWT will cancel each other. In reality, a complete cancelling of the waves would not be possible but it should be possible to employ this technique to reduce the BPL at 200Hz.

An initial calculation was performed to obtain a value for the wavelength of the 200Hz frequency.

$$\gamma = \frac{c}{f}$$

Where $\gamma =$ Wavelength (m), c = Speed of Sound (ms^{-1}), f = Frequency (Hz).

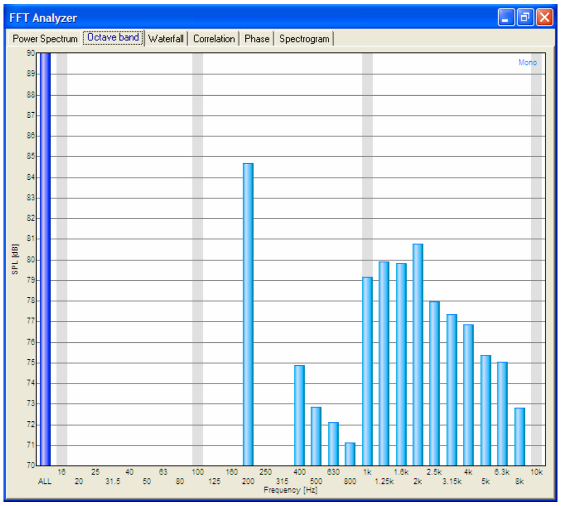
From this, the length of the required QWT could be determined. Note that the speed of sound is dependent upon gas temperature, an exact value for which was not known during the initial stages of the development. Therefore the QWT length determined was used as a starting point for physical testing.

Physical Testing

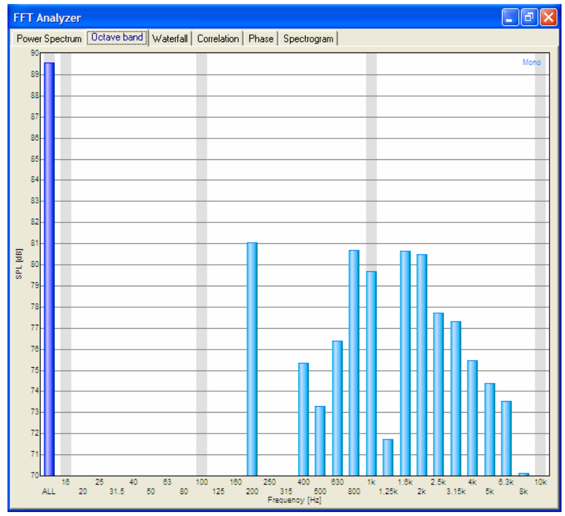
The next stage involved the production of two adjustable length QWTs that would fit into the system just before the silencers. Through a process of testing, data capture and analysis it was possible to tune the lengths of the QWTs so that they were most effective at the 200Hz band. This resulted in an overall SPL below the target on the test setup. Once the theory had been proven, a final set of silencers with incorporated adjustable QWTs were produced. These were fitted to the vehicle and "tuned" to the correct length.

Results

The one third octave analysis before and after are shown below. Note the vertical scale is zoomed to the area of interest.



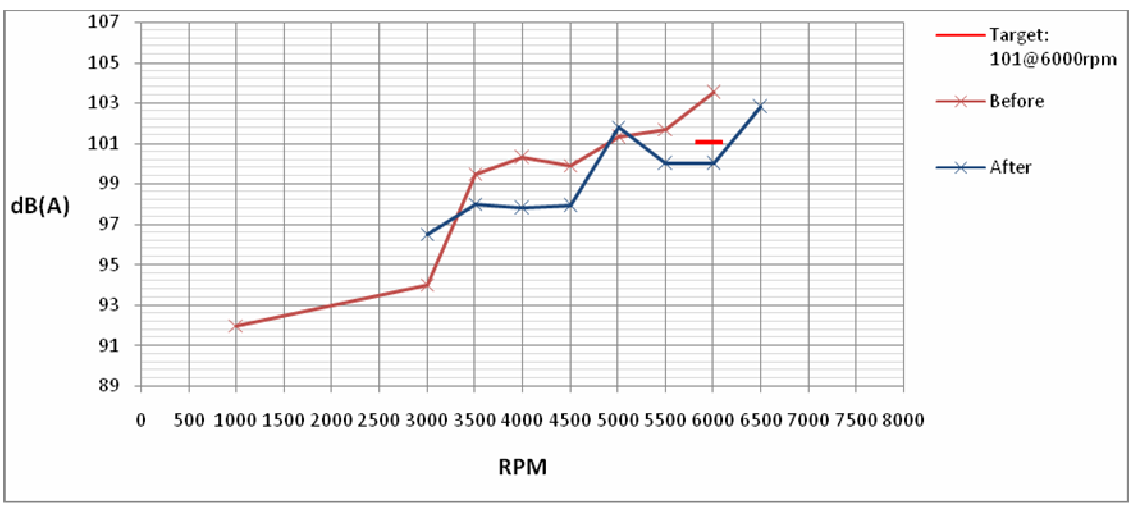
Before



After

The results show that there was a significant reduction in the 200Hz frequency band and that the higher frequency bands were not increased

The noise levels measured with the sound level meter are shown below.



Noise Level Comparison

Discussion

The basis of this work was the theoretical method for determining the overall SPL of a noise source based on the individual one-third octave BPLs. The results show that the reduction in the key BPL is also seen as a reduction in the measured SPL, as suggested by the theory. The final results met the objective of reducing the sound level of the vehicle to below 101dB(A) at 6000rpm suggesting that this approach was appropriate in this respect. Furthermore, the nature of the Quarter Wave Tube was such that it did not cause any restriction to the flow of exhaust gasses and was a relatively lightweight, compact solution.

Further research to investigate the effects of positioning and alternative geometry may have led to increased effectiveness of the system, however the time constraints of the project did not allow this.

Conclusions

Frequency analysis software was used to identify the structure of the vehicle tailpipe noise. Quarter Wave Tubes were used to attenuate the Band Pressure Level of an identified peak at 200Hz. The overall Sound Pressure Level of the vehicle was reduced to below the target 101dB(A) at 6000rpm, without significant weight increase or flow restriction.