# Acoustic Diagnosis of Driving Belt Physical Condition in Enclosures

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**ABSTRACT**

Timing belt transmission is a key subsystem of international combustion engines. Faults in such belt systems lead to power loss, increased emissions and, in case of failure, may even cause severe damage to the whole engine. Hitherto, the physical condition of the belt has been assessed manually, which is both inconvenient and inaccurate. It is well known that driving belts emit noise according to parametrical conditions such as speed of rotation, tension, structural integrity, etc. The analysis of belt behaviour and subsequent diagnosis of potential failure should preferably be carried out using non contact methods and, as such, acoustic diagnostic stands out as a promising method. One added problem in the diagnosis process is the noise generated by the engine and the acoustic behaviour of the enclosure where the measurement is taking place. This study investigates new approaches to measuring and analysing the acoustic emission from a belt at different conditions inside an enclosure. Techniques employing a combination of microphones in directional near-field and omni-directional elsewhere are used in order to obtain a better signal. Transfer function measurement techniques are applied in order to separate belt noise from engine noise and the acoustic response of the enclosure. The method allows the extraction of useful diagnostic information about the condition of the belt and indicates areas for further research.

## 1    INTRODUCTION

The assessment of belt condition in engines is problematic. Most available diagnostic methods use visual inspection of the belt which has to be done with the engine switched off and is prone to failure. Some diagnostic methods are available which use non-contact measures but are expensive to implement and prohibitive in a commercial application [1]. Acoustic diagnosis, as a non-contact method for measuring the condition of physical systems, has been demonstrated [2-4] to produce very promising monitoring results. However, associated problems arise due to the corruption of the diagnostic signal by unwanted background noise, acoustic emission from other parts of the system under test or through the interaction of the source and the acoustic effect of the enclosure housing it. The problem is often exacerbated if the diagnostic signal is weak compared to corruption signals.

This paper presents a preliminary study on a method to detect a loss of tension in an ancillary belt for a diesel engine. The loss of tension can be a common symptom of belt wear deterioration over time. A two-microphone method is investigated to develop a novel detection approach. A highly directional acoustic sensor (interference tube microphone) is used to capture the acoustic signal directly from the belt whereas a pressure sensitive sensor (omni-directional microphone) is used to capture the overall acoustic emission of the engine and the room effects. The signals from these two microphones are combined so that the

acoustic radiations from the engines are suppressed and those from the belt are enhanced for condition monitoring.

The paper is organised into 5 sections. In section 2, the theoretical basis of belt acoustics is reviewed to pave the way for experimental study and data analysis. In section 3, the facility and the engine used for the measurements is described and the method used to acquire the measurement signals is explained. In section 4, an analysis and discussion of the collected data is performed. Time domain statistical descriptors are established. A further analysis using power spectra demonstrates that it is possible to establish the effects of changing tension on the belt. A deconvolution method that extracts the belt diagnostic signal from the engine and room signal is discussed. Conclusion of the work is presented in Section 5.

## 2 THEORY

It has been shown [reference] that the section of the belt spanning between two pulleys undergoes transverse vibration which is related to its modes of resonance. This can be modelled as a string fixed at both ends of length L, mass per unit length μ and under tension T, as shown in Figure 1.
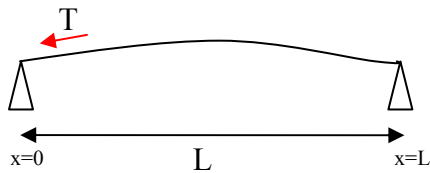


Figure 1 – Modes of Vibration on a string fixed at both ends.

For a simply supported case at the string ends where no damping is included the mode-shapes on the string take the form of sin (ωt) where f=ω/2π is the resonant frequency of the system. A detailed study of such system can be found at [5]. For a given length L, f is dependent on the tension and μ:

$$f = \frac{1}{2L}\sqrt{\frac{T}{\mu}} \tag{1}$$

Acoustically, the radiation of the vibrating string itself is not very efficient, as the coupling to the medium is weak. For a belt of given width and depth, this coupling would increase as the radiation impedance increase for the larger object. However, in the most common systems, the vibration of the string is transmitted mechanically to the fixed structure which also vibrates. If the fixed ends are part of a larger structure, coupling to air increases and there is potential of more efficient radiation. As such, noise radiation from belt systems is likely to occur not only from the belt itself but also from the structure (pulleys and bearing housing) where it is mounted. In cases where the vibration passed to the structure is very high, the string system is highly damped and the mode-shapes take the mathematical form of hyperbolic sin. For the cases studied here, equation 1 is an adequate approximation.

The transverse excitation of a belt system is likely to arise from slip and friction while it runs on the pulleys. Connell and Rorrer [6] presented a detailed study of V-ribbed belt noise where it is shown that radial slip (as the belt moves into the pulley grooves) and tangential slip of the belt relative to the pulley lead to friction-induced vibration. This causes perturbation on the normal belt movement which may then drive the belt into resonant modes responsible for noise emission. Three distinct noise generation regimes are evident from

Connell et al. study: span vibration (50–500 Hz), stick–slip (800–3500 Hz), and harmonic oscillation (4400–5600 Hz).

## 3  ACOUSTIC MEASUREMENTS

### 3.1  Engine and Measurement Facility

A 4-cylinder diesel engine, detailed in Table 1, was employed to realise the acoustic tests. The engine was connected to an eddy current dynamometer which was rated to be able to handle an engine of a maximum power of 210KW and a maximum torque of 501Nm. The test cell holding the dynamometer has a ventilation system to maintain room temperature and an exhaust extraction system.

The belt under analysis is driven from the crankshaft and is part of the engine ancillary system that drives the alternator and the oil pump. Figure 2 shows a picture of the belt system under study.
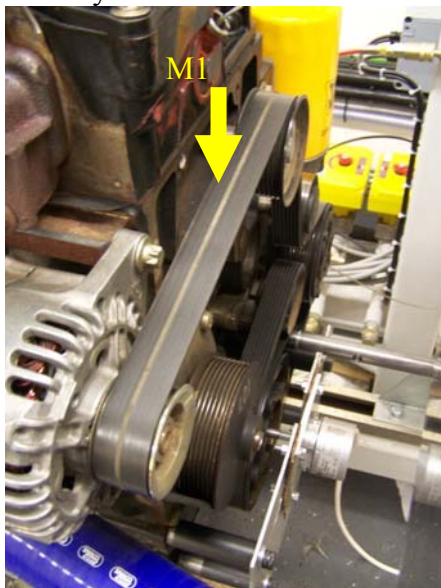


Figure 2 - Engine belt system and microphone M1 position. M1 has a very directional polar pattern
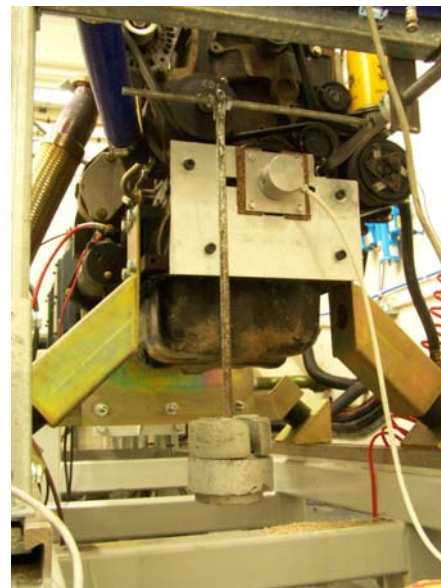


Figure 3 – Belt tensioner system

The tension on the belt was maintained by a spring loaded pulley. The tension was altered by a mechanism that applies a torsional load in an anti-clockwise direction onto the spring loaded pulley, as shown in Figure 2. This reduces the tension by reducing the load that the spring applies onto the belt. To apply the load onto the pulley the mechanism uses a lever arm that has a load of 5kg at a distance of 235mm from the pivot, which reduces the tension load of the spring by 11.5Nm.

Table 1 - **Engine Specification**

| Engine Type | 4 Stroke Diesel |
|---|---|
| Capacity | 4399cm$^3$ |
| Bore | 103mm |
| Stroke | 132 |
| Injection | Direct Injection with Rotary Mechanical Pump |
| Compression Ratio | 18.3 |
| Number of Cylinders | 4 |

Eight tests (shown on Table 2) were conducted to study the acoustic characteristics of the belt. Two speeds and two loads were applied to the engine with the dynamometer controlling the speed of the engine and the accelerator pedal controlling the torque output. Two belt

tension cases were tested. The first case, hereby called *high tension,* corresponds to the engine running without the tension adjustment mechanism. The second case, called *low tension,* was run with the tension reduction system applied.

Table 2 - **Engine Test Sets**

| Engine Speed (rpm) | Engine Torque (Nm) | Belt Tension Setting |
|---|---|---|
| 1000 | 100 | High Tension |
| 1000 | 380 | High Tension |
| 2000 | 100 | High Tension |
| 2000 | 380 | High Tension |
| 1000 | 100 | Low Tension |
| 1000 | 380 | Low Tension |
| 2000 | 100 | Low Tension |
| 2000 | 380 | Low Tension |

### 3.2 Measurement System

The acoustic measurement was performed using two condenser type microphones of specific polar pick up patterns as shown in 6.1. Microphone 1 has a highly directional pick up pattern which is able to reject most sound arriving from the sides or back whilst capturing sound waves arriving on axis to the microphone. This microphone was placed in the *near field* of the belt, as indicated in Figure 2, pointing towards the centre area of the moving belt at 90mm from it. This is a point of maximum displacement for odd order transverse modes which are believed to be those most likely to radiate noise. Furthermore, the directional properties of the microphone will focus on the noise radiation in the surrounding area of the belt, including the 2 uppermost pulleys, as likely sources of useful diagnostic data for faults developing in the belt.  Microphone 2 was placed in the *far-field*, 330mm away from the left pulley and to the side of the engine. This microphone has an omni-directional polar response and as such is able to capture the acoustic radiation from the whole engine and reflected energy from the enclosure. Detailed magnitude frequency responses for the microphones used can be found at Appendix 6.1 for reference.

The acquisition of acoustic data was carried out using a 4 channel digital audio recorder which was able to supply the necessary voltage to polarise the microphones. Data was acquired at a sampling rate of 48kHz and 16 bits. 8 sets of 60 second long samples were recorded. This data was later transferred to a computer for further analysis in Matlab.

### 4 ANALYSIS AND DISCUSSION OF RESULTS

### 4.1 Time domain statistical parameters

Three common statistical parameters: RMS, Skewness and Kurtosis are calculated firstly to study the signal differences measured for different belt cases, operating conditions and microphone placement. Figure 4 shows the results of the statistical parameters obtained in the time domain. RMS values from the microphones, a measure of the strength of noise amplitude for overall engine acoustics, increases with load and speed, which is consistent with that of engine noise expected to increase with engine load and speed. As expected there are some differences in RMS values between the two microphones. However, the difference amplitude varies with different operating conditions. Importantly, RMS from the belt microphone shows little difference between the low tension and high tension. This shows that it is not possible to extract a significant difference between belt conditions with the RMS values alone.
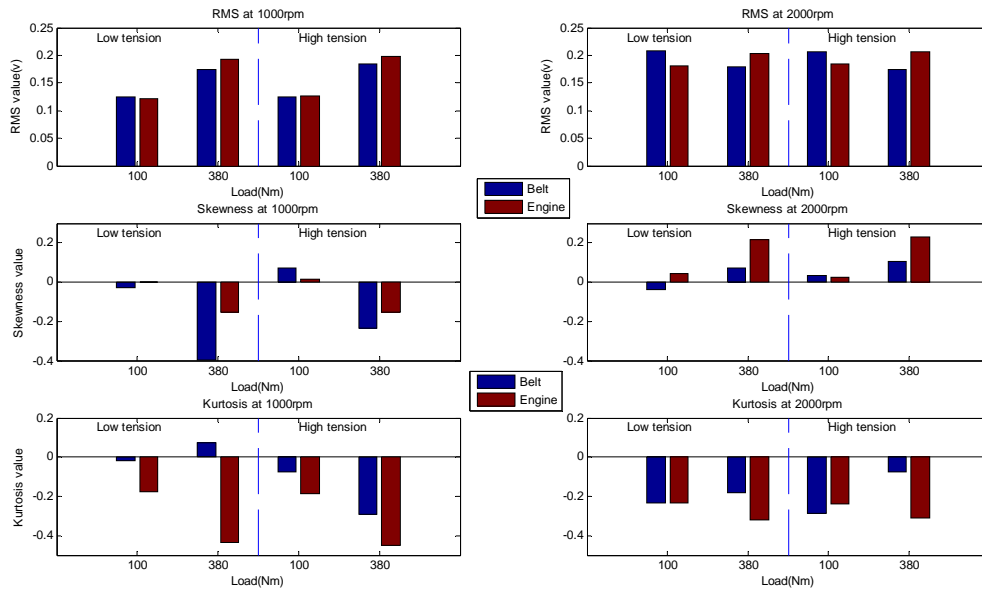
Figure 4 – RMS, Skewness and Kurtosis for signals acquired.

In contrast, the higher order statistics: Kurtosis and Skewness, measures of signal structures in the time domain, show a noticeable difference between the low tension and high tension from acoustic signals measured close to the belt. Especially, Kurtosis values of belt measurement show significant difference between the two tension conditions whereas the Kurtosis values of the engine measurement remain identical. This means that it is possible to detect belt faulty conditions from the Kurtosis difference.

## 4.2   Spectrum Analysis

To highlight the differences found in the time domain, spectrum analysis is applied to the acoustic signals. All spectra plots shown were determined using the average of 11 FFT carried over a full length signal of 60 second duration. Each window segment has been normalised to a magnitude of 1 and windowed using a hanning function prior to the calculation of the FFT. In addition, because no significant differences between different belt tension cases in the high frequency ranges have been found, the spectrum is only presented in the low frequency range from 0 to 120Hz. This is inline with previous results [6,7] that suggest belt noise at frequencies in the range 0 to 100Hz.

Figure 5 shows the power spectra of the signal acquired with microphone 2 (overall engine and enclosure microphone) for the 8 cases tested. The frequency axis range has been set to 120Hz where most of the relevant information is contained. The spectral peaks clearly show the engine fire frequency:

$$ff = \frac{k\,n}{2 \times 60}\,(Hz)$$

(2)

Where $k$ is the number of cylinders and $n$ is the engine speed in rpm.

As is clear from Figure 5, the spectrum evolves for different operating conditions, showing that the measured acoustics reflects the engine behaviour consistently. However, the engine acoustic signals obtained across the two belt tension cases are nearly identical. This suggests that the acoustic effects generated by the changing tension on the belt can not be

separated by the far-field measurement because of the strong reverberation in the enclosure and interferences from different engine noises sources.
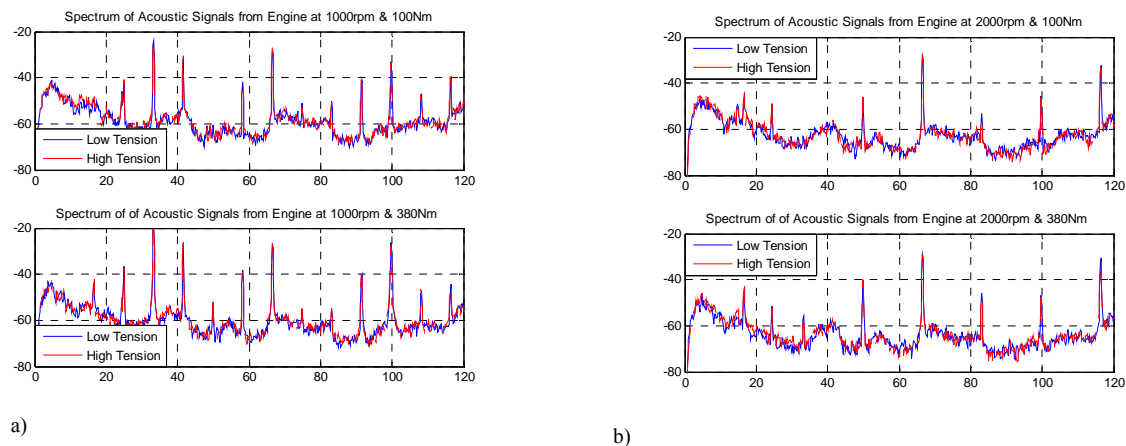


a)

b)

Figure 5 – Spectral data for acoustic signal from engine at different test cases. a) Speed of engine 1000rpm
b) Speed of engine 2000rpm

Figure 6 shows the acoustic signals acquired in the near-field of the belt mechanism using the directional microphone. The same features regarding the engine cycle are obvious, compared with that in Figure 5. However, and in contrast with the previous data, there is a clear difference between the two belt tension cases.

At low speed, 1000rpm, there is a clear indication that the first resonance of the belt in the low tension case is around 55Hz. At high tension this resonance appears to move up to around 105Hz. At higher engine speed, Figure 6b, the low tension resonance appears to move from around 62Hz to 110Hz. It is important to note that the 3$^{rd}$ harmonic of the engine fire frequency is around 100Hz which makes the extraction of belt diagnostic information difficult at these frequencies.
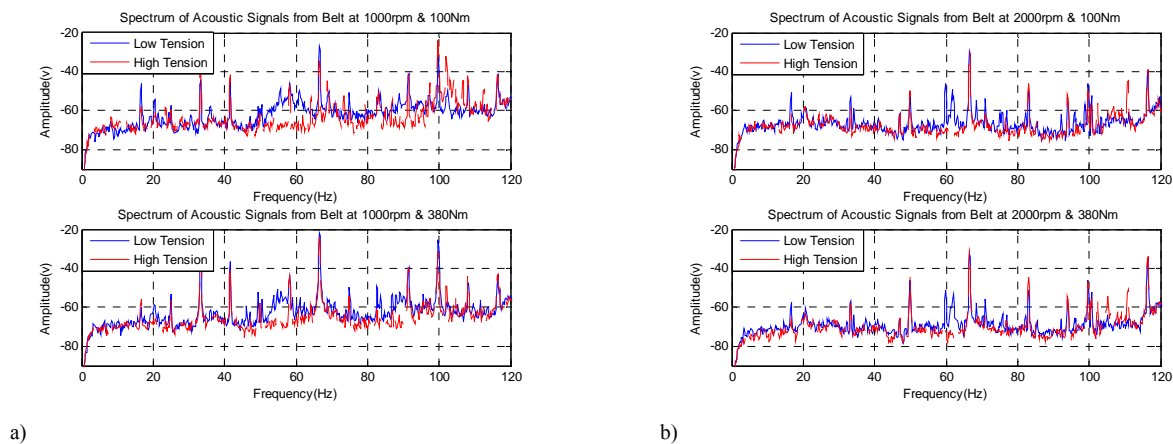


a)

b)

Figure 6 - Spectral data for acoustic signal from belt at different test cases. a) Speed of engine 1000rpm;
b) Speed of engine 2000rpm

## 4.3   Room and Engine 'deconvolution'

It is evident that the data collected at microphone 1 placed closed to the belt also contains the acoustic radiation of the engine. This hinders adequate diagnosis of belt faults as it is difficult to extract differences generated from changing the belt tension, especially when there is conflicting information such as that discussed in the previous section.

In order to separate the acoustic emission from the engine from that of the belt, a deconvolution technique was attempted [8]. This was obtained by multiplying the complex signal captured in the near field by the inverse of the one in the far field. The resulting data is shown in Figure 7. In this way the acoustic components such as fire frequency and its harmonics can be suppressed significantly and the resultant spectrum thus contains mainly the acoustic emissions from the belt.
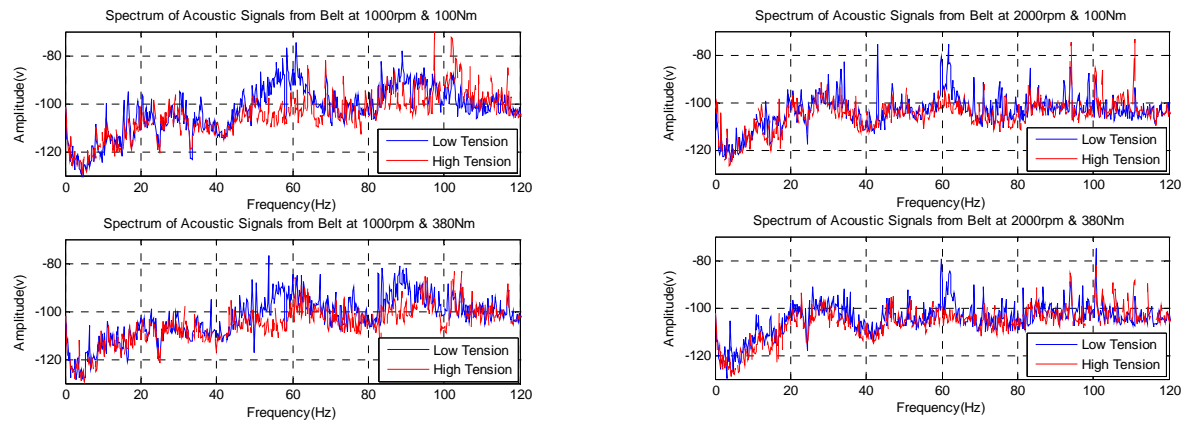


Figure 7 - Spectral data for acoustic signal from belt deconvolved from engine and enclosure shown at different test cases. a) Speed of engine 1000rpm; b) Speed of engine 2000rpm

The differences observed between the two tension cases are now clearer. At high tension, a number of spectral peaks are more evident. However, corruption from engine noise is still evident. It is therefore early to make any clear distinctions between the cases and use this as a diagnosis method. Nevertheless, the technique appears promising and further studies are now being carried out that employ a spatial average of the far-field at various enclosure positions that may improve the separation between the data.

## 5    CONCLUSION

A measurement of belt noise under healthy and faulty conditions was performed to find acoustic features for belt condition monitoring . The results presented show that the effects of variation on belt tension are only evident when measured very close to the belt. The frequency range where the most evident differences are found is below 120Hz, suggesting that most of the noise in the data acquired stems from span vibration as found by Connell et al. [6]. Within this range, a noticeable difference is clear at around 60Hz (resonant frequency for belt at low tension) and around 100Hz (resonant frequency for belt at high tension).

Another important result from this investigation is that the acoustic coupling of belt vibration to air is weak. This results in very low radiation levels which are difficult to capture, especially near a very noisy complex source such as the engine. It is likely that the belt vibration is transmitted strongly to the pulleys, where mechanical vibration may be strong and produce a louder acoustic signal. It is possible that the measurement technique proposed here, employing a highly directional microphone, has actually worked against this by rejecting sound from the pulleys which was slightly off axis. Different microphone positions may lead to an improvement of the near field data.

In conclusion, the method presented is promising and provides initial diagnostic data for fault detection as a drop of belt tension. Necessarily, the method requires improvement and further working areas have been indicated.

The authors have now initiated work that looks into the vibration modes of the belt and its coupling to the pulleys. More reliable deconvolution techniques using a time synchronous

average of the engine emissions are also being applied to achieve better results. Further work is also being carried out on identifying more efficient sources of faulty belt noise that may be mechanically coupled to the belt but perform better as radiators.

## 6  APPENDIX

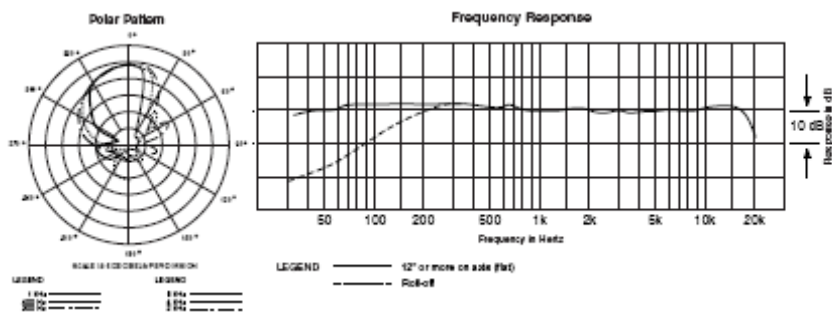### 6.1  Microphone Technical Data

#### 6.1.1  Microphone 1



Figure 8 – Directional and Frequency responses for Audio Technica 4071a
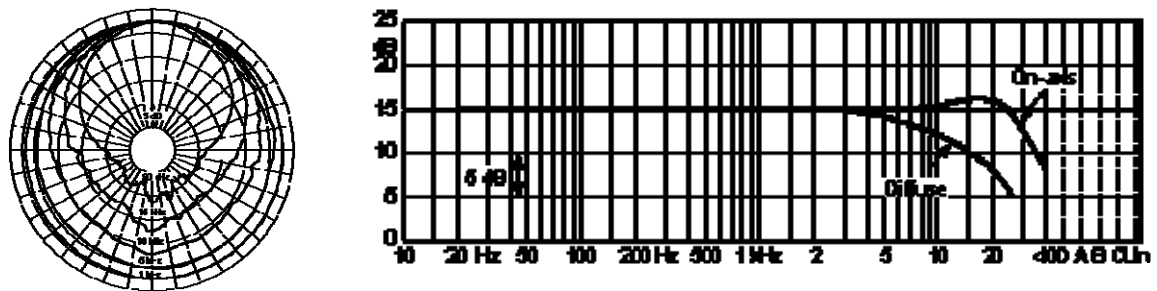
#### 6.1.2  Microphone 2



Figure 9 - Directional and Frequency responses for 4006-TL

## 6.2    Sound Level Measurements in Engine Enclosure

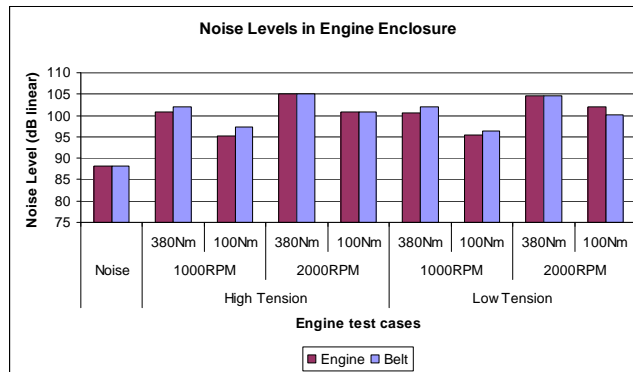**Noise Levels in Engine Enclosure**

Figure 10 – Noise levels measured in enclosure with engine running under the different test conditions. Results indicated correspond to the linear average of values in the range 16Hz-16KHz. The background noise levels with the ancillary equipment of the facility running are indicated in the first 2 bars.
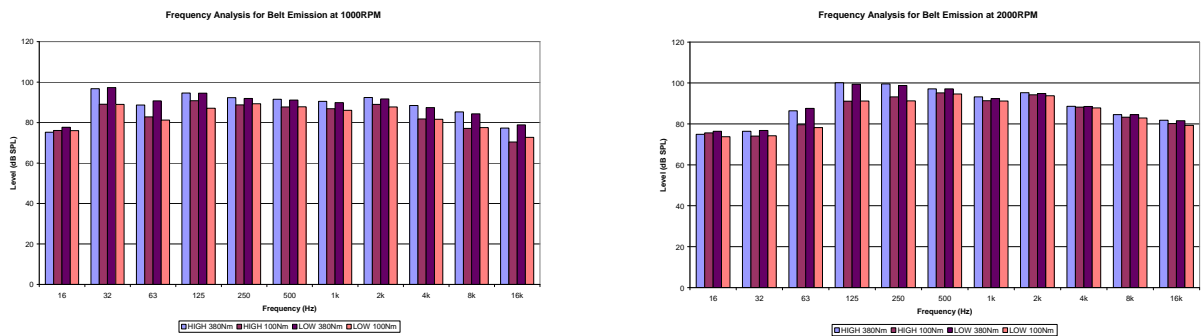
Figure 11 – Levels for Belt acoustic emission with engine running at 1000rpm and 2000rpm. The different tension and torque cases are presented.
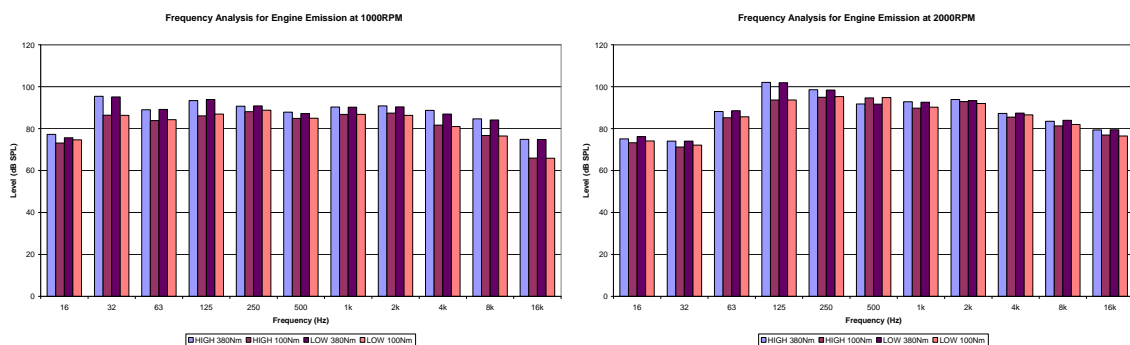
Figure 12 – Levels for Engine acoustic emission with engine running at 1000rpm and 2000rpm. The different tension and torque cases are presented.

## 7 REFERENCES

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