Measurement and Characterisation of Faults in the Intake System of a Turbocharged Engine Using a Directional Acoustic Probe

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ABSTRACT

Engine intake system leaks are a primary reason behind unsatisfactory operational and emission characteristics of turbocharged engines. In faulty conditions, the intake mass flow sensed by the mass flow sensor does not reach the combustion chamber, resulting in a less than required air fuel mass ratio. This may result in increased emissions along with unsatisfactory performance of exhaust gas recirculation system. In the present work, an acoustic sniffer system has been developed which identifies the presence and location of leaks in the intake system. The acoustic sniffer system uses a directional acoustic probe which records acoustic signatures of the leaks and positively identifies their presence. The sound pressure level data obtained from the acoustic probe is converted into frequency domain by FFT. Frequencies corresponding to the leaks are then identified in different octave bands. Experimental work on a four stroke 4.3 litre diesel engine demonstrates that the sniffer could be used to identify and quantify the leaks in the engine system. The system performs satisfactorily on a variety of leaks created in the intake system. It has also been found that sound pressure levels and frequency bands corresponding to different leaks could be used to estimate the amount of gas leaked from the system. This acoustics based system provides a simple and yet reliable method for leak diagnosis in engine intake system.

Key words: Engine diagnostics, Intake leak, Acoustic sniffer

1. INTRODUCTION

The current emission regulations have forced automotive manufacturers to extensively research and develop systems for detection and early diagnosis of engine faults which may cause tailpipe emissions to go beyond the required standards. In an engine system there can be a number of faults that can develop during the life time of the engine. An early diagnosis of any fault can only be achieved by monitoring the automotive data readily available. The available data can then be used to characterise the onset of a particular fault. In a typical turbocharged engine system the operating pressures and temperatures vary over a wide range and cyclic nature and difficult conditions of operation sometimes result in leakage at a various joints and components in the intake system. The leak can also occur because of incorrect installation and poor workmanship.

Leaks in the air intake system are a major cause of concern [1, 2] because this particular kind of fault can be difficult to detect. Under a range of operating conditions of the turbocharged engine, the turbocharger waste gate will inherently try to counteract the fault and maintain the manifold boost pressure at a pre-determined level. Consequently, depending on the magnitude of the air leak, the fault may be imperceptible to the driver.

The engine management system (EMS) assumes that all of the air, which passes the airflow meter will subsequently enter the combustion chamber and injects fuel according that air mass. If leaks are present in the intake system then the overall air–fuel ratio will be lower than that assumed by the EMS. This may lead to an increase in the levels of carbon monoxide, unburned hydrocarbons and particulate matter being released into the atmosphere, especially at full load conditions. Depending on the location of the leak within the intake system and the method of control used, the exhaust gas recirculation process may also be affected leading to an increase in NOx emissions. Several studies [3, 4, 5, 6] have been reported in the past to develop a diagnostic model for leak in the intake system. All the above require fairly complex data acquisition and processing system to be able to detect intake system leaks.

Acoustic methods have been used with success to develop diagnostic tools for combustion behaviour as well as vibration of the engine. On the other hand a number of successful attempts have been made to detect the leaks in the high-pressure piping systems using acoustic methods. In the present study therefore an attempt has been to design and develop and acoustic sniffer for detection of leaks in the intake system of a turbocharged engine. Further the developed system been modified to identify, locate and quantify the leaks present in a turbocharged Diesel Engine.

2. DESIGN AND DEVELOPEMNT OF ACOUSTIC SNIFFER

Detecting a pressure leak in the turbo system from its acoustic emission is hindered by the high background noise content of the engine and other engine ancillary systems. The most common methods of acoustic monitoring have typically employed a pressure transducer which is sensitive to pressure changes caused by noise emission from the system being measured. Due to their design features, these probes have a non directional polar directivity pattern, which means they are equally sensitive to sound waves coming from any direction, which exception to those arriving from the back (180 °) as these are affected by the presence of the probe physical structure (7). Since these acoustic probes are able to pick up sound from any incoming direction, the diagnostic signal will invariably be merged with unwanted background noise from the engine and the acoustic effects of the enclosure, making the extraction of appropriate diagnostic signals very challenging.

Nevertheless, in this work, the potential locations for leaks are known in advance which may help in terms of locating the probes around the expected area of higher acoustic output for the diagnostic signal. In a turbo system, pressure leaks may occur in the discharge side of the compressor because of high delivery pressure particularly if the parts are not properly joined together. Furthermore, due to the high rate of gas flow in the leak site, the acoustic behaviour corresponding to leak flow will invariably be in the high frequency range.

The approach presented here takes advantage of this knowledge to design a system based on an acoustic probe with a highly directional polar directivity pattern, henceforth referred to as an acoustic 'sniffer'. A comparison of the benefits afforded by this type of probe over a conventional omni-directional pressure probe is also undertaken.

The acoustic probe employed is based on the principles of gradient microphones first described by Olson [7] and shown in Figure 1. The probe consists of a long tube (about 60 cm) with many slots on the side through which sound waves can enter. At the end of the tube, a microphone diaphragm exhibiting a uni-directional (hyper-cardioid) polar pattern captures any sound waves travelling inside the tube. Sound arriving from the front of the probe, at or near a 0 degree direction (on axis), travels through the tube and reaches the diaphragm unimpeded. Sound waves arriving from any other angle that deviates from 0 degrees (off axis) undergoes different travel paths to the diaphragm related to the distance between each entering slot and the diaphragm. A thin wire mesh cladding the inside of the tube prevents the sound-wave from escaping through the slots once it enters the tube. Since off axis sound waves enter the tube at various points, these will arrive at the diaphragm with a series of phase shifts. This *destructive interference* reduces their vectorial addition at the diaphragm thereby greatly reducing the level of off-axis sounds. The on axis sound is thus captured at much higher amplitude which gives the probe a highly directional sensitivity characteristic.

This interference behaviour is limited in frequency by the physical dimensions of the probe. The directivity index (gain of on-axis over off-axis incidence) varies from about 1 dB at λ/4 to around 14dB where the length of the tube is about 8λ, where λ is the wavelength. At high frequencies the diameter of the tube becomes comparable to the sound wavelength and part of the wave gets reflected by it effectively reducing the sensitivity of the probe. This effect can be seen in Figures 4 and 5 where there is a marked drop in level above 18 kHz. In order to identify the leak, the probe is moved around with the on-axis direction pointing towards the potential sites for leaks. When a given rise in level is detected in a given range of frequencies a leak is flagged – hence the name 'sniffer'.

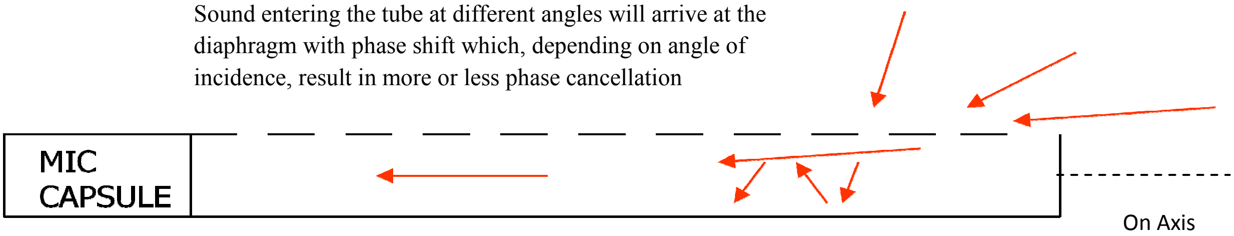

Figure 1 - Line Interference Acoustic Probe

3. EXPERIMENTAL SETUP

The experimental engine test bed consists of a four stroke 4.3 litre turbocharged diesel engine as shown in Figure 2. This test bed is well equipped with suitable instrumentation for the measurement of engine performance as well as emission. The available instruments include air mass flow meter, inlet manifold pressure, fuel consumption, turbocharger speed sensor, compressor inlet and out let pressure sensor and a number of additional pressure and temperature sensors.

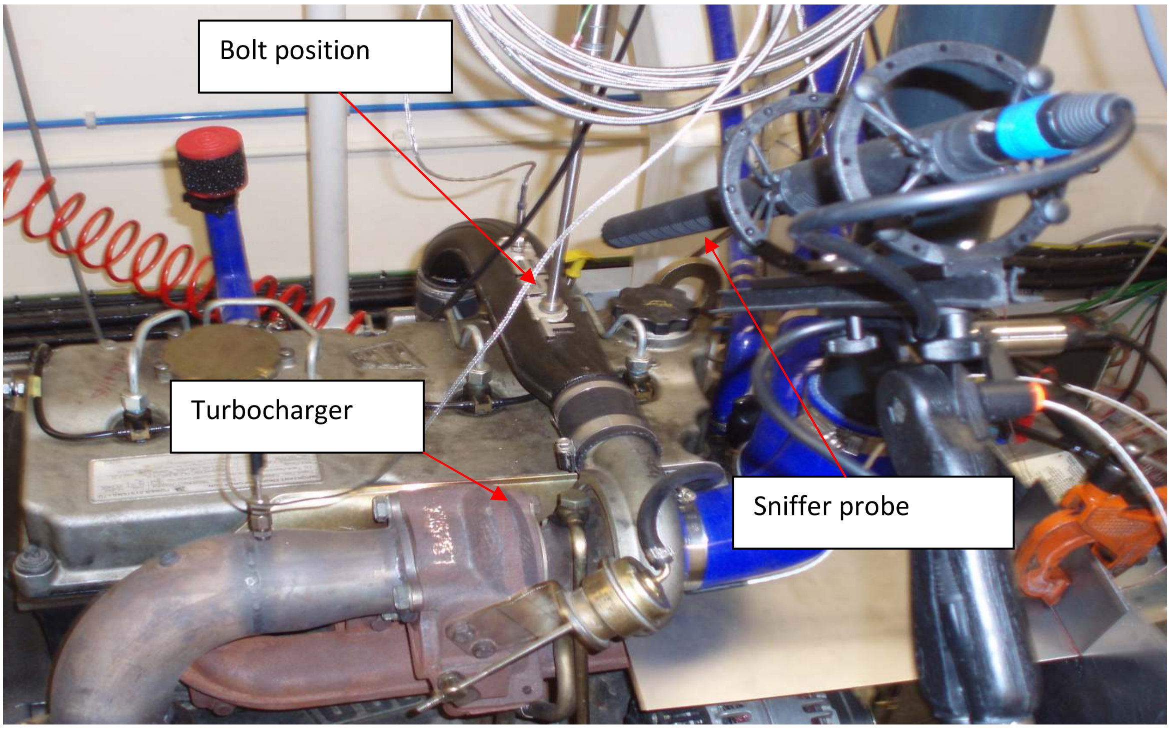

Figure 2 – Picture of experimental set-up

In the present investigation experiments were conducted for four different leakage conditions. These include no leak condition as well as leak through 3mm and5 mm diameter holes. The leaks were created by drilling the holes on a bolt. As shown Figure 2 and Figure **3**, the bolt is mounted on the immediate downstream of the turbocharger.

Figure 3 - Leak hole location on the outlet of turbocharger compressor

In the present investigations the engine was run at two different speeds and at three load conditions. For each of the above conditions, sound pressure levels were recorded using the 'sniffer' pointing towards the known leak location.

Once captured by the 'sniffer', the audio signal is converted to digital using an ADC sampling at 44.1 kHz, 16 bit. Given, that the acoustic leak activity is mostly evident in the 8 kHz to 16 kHz octave bands, this sampling rate is just sufficient to characterize it. Nevertheless, further tests are being undertaken where a higher sampling rate is employed to investigate acoustic effects at higher frequencies.

Once acquired, the data is converted into frequency domain using the Fast Fourier transform. In most cases presented in this paper, the data set converted is 2^{13} samples long, which at the sampling rate equates to approximately 18ms. Since the acoustic signature of the leak is periodic and of high frequency, the choice of data set length is considered adequate. The continuous and octave band magnitude spectra are presented for the analysis and detection of leak (see Figures 4 – 6).

4. RESULTS AND DISCUSSION

In the following, the characteristics of acoustic signals as obtained from various operating conditions of the engine have been analysed and the effect of various leak characteristics on the magnitude of acquired data have been characterised.

Figure 4(a) shows the sound spectrum at an engine speed of 1000 RPM under no leak (or 'leak free') condition. In the figure there is an apparent drop in level towards the higher frequency range. This is due to two aspects: the overall engine noise level is understandably concentrated below frequencies 10000Hz; the transfer function of the acoustic probe is less sensitive to very high frequencies as described in the previous section. The data also shows that increasing engine load increases the amplitude marginally between 7000Hz and 18 kHz. The levels present in each octave band are shown in Figure 4(b). The data indicates that amplitude increases consistently with load in each octave band. Another interesting feature in the data is the significant difference of 55dB in level between the low frequencies predominant in engine noise and the higher frequencies where the leak acoustic signature is likely to exist. This demonstrates the challenge posed to the detection system if a leak is to be detected under engine running conditions.

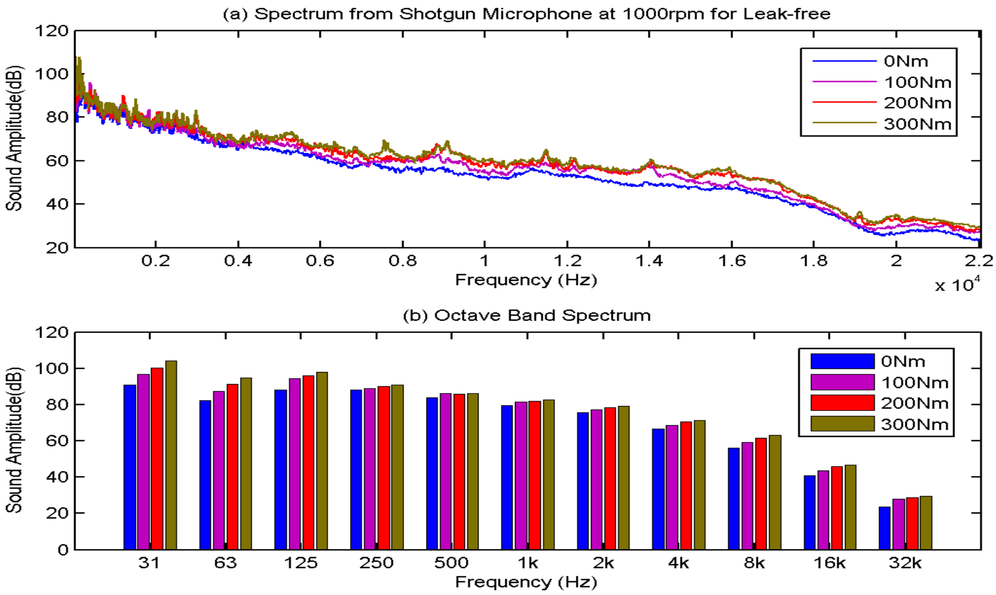

Figure 4 - Spectrum of the sound for leak free condition at an engine speed of 1000 RPM. a)Continuous spectra; b)Octave band spectra.

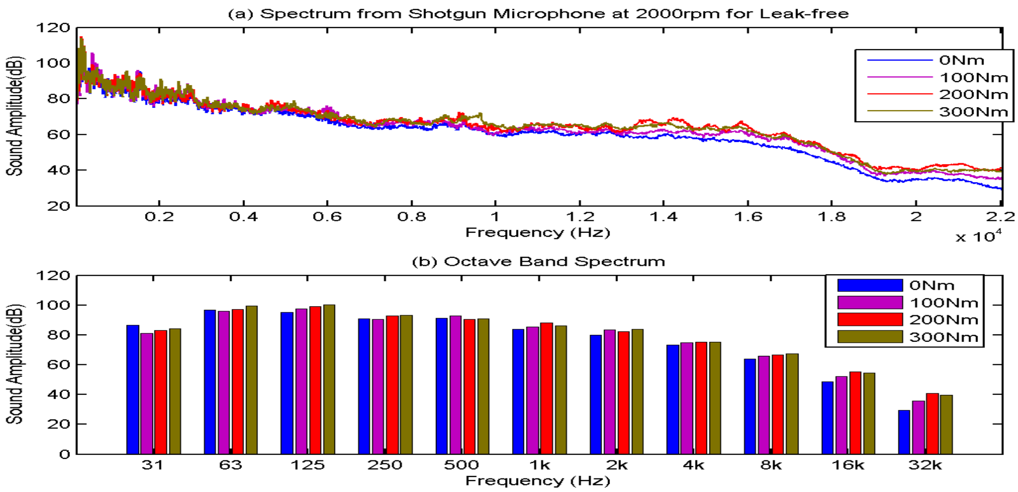

Figure 5 - Spectrum of the sound for leak free condition at an engine speed of 2000 RPM

Figure 5(a) shows the sound spectrum at an engine speed of 2000 RPM also under 'leak free' conditions. The observations of this data are generally similar to those found in Figure 4(a). The load increase leads to an increase in acoustic output in the high frequency octave bands (8 kHz to 16 kHz). There is no marked difference in the mid frequency ranges. However Figure 4(b) shows a steady increase of levels in the low frequency bands (31Hz to 250Hz) related to engine load that is not evident in Figure 5(b). This suggests that at higher engine speeds (2000 rpm) the engine noise characteristics related to engine load do not change as markedly as for lower engine speeds (1000 rpm). This may be due to the higher content of acoustic activity from the engine effectively masking the acoustic effects from engine load.

In Figure 6 (a) comparison of spectrum obtained for leak free as well as two progressively larger leaks, namely 3 mm and 5 mm, is shown. Figure 6(a) shows that there is no particular trend evident in the low frequency range. That is, the introduction of turbo charger leaks does not seem to affect the low frequency acoustic signature of the engine/turbo system. However, it is quite clear that in the high frequency range, namely at 4 kHz, 8 kHz and 16 kHz, the acoustic levels increase with the size of the leak. It can therefore be concluded that the high frequency amplitude levels can be expected to rise if a leak develops and this alteration of acoustic signature may be used to detect it.

The data shown in Figure 6 (a) corresponds to no engine load conditions. Figure 6(b) shows a similar trend at the same engine speed but at a higher load. The sound level difference in the high frequencies increases further in the presence of leaks. At even higher loads of 200Nm and 300Nm (figures 6 (c) and (d)) the difference between sound levels is progressively increased in the higher frequency bands. This is a trend that has been observed for engine speeds and engine loads over a wide range of operating conditions.

Up to this point, the work presented clearly shows that it is possible to detect the presence of a leak in a turbo-charged engine under running conditions using the acoustic signature of the leak. This is evident mainly in rising level of acoustic activity in the 4 to 16 kHz octave frequency bands. Figure 7 shows a comparison between the proposed 'sniffer' and a conventional acoustic probe with no specific directional sensitivity – an omni-directional polar directivity pattern. The graphs show the difference obtained in the 4k, 8k and 16k Hz frequency bands between a 'leak free' condition and each of the leaks tested (indicated in the legend on the top left graph) for an engine speed of 200rpm and two engine load conditions (200Nm and 300Nm). Results are shown for the conventional acoustic probe in Figure 7(a) and for the 'sniffer' in Figure 7(b). It is evident that both types of probes detect a rise in activity levels as the leak increases. However, it is clear that the differences in level between leak free and leak condition are emphasised by the 'sniffer' when compared to the conventional probe. This is due to the fact that the 'sniffer' is a highly directional probe which has been pointed at the known leak location. Its acoustic design, by definition, rejects off-axis sound from the nearby engine and focuses on the location of the leak. A conventional probe is not capable of such off-axis noise rejection and as such the 'sniffer' will perform better when attempting to locate the leak by moving the probe around the potential location. This kind of process is much more difficult if a non-directional conventional probe is used.

5. ONLINE IMPLEMENTATION

A system was developed to alert when a potential leak has been detected. An online implementation process is based on an adaptive threshold scheme.

A reference data is taken at about 1 meter away from the engine. The threshold is set to be the value 0.5dB higher than the sound level that was obtained from the reference data. The 0.5dB level difference takes into account the sound level increase when the probe is closer to the engine during the detection process. The probe then hovers over the potential leak locations whilst engine is running. The data acquired is continuously compared with the reference data – the process described in *experimental setup* is used where the data set size is 8192 data points long, sampled at 44.1KHz, 16 bit. If the difference in amplitude between the two data sets is beyond the threshold then a leak is flagged. The weighting extracted from the average magnitude difference in the high frequency range may be used to characterize the size of the leak. Figure 8 shows typical outputs from the system developed during reference measurement and leak conditions. The top graph shows the reference data while the middle and the bottom graph shows the 3 mm and 5mm leaks respectively. The red bar chart shows that the sound level exceeds the threshold and indicates a possible leak. In addition, the bottom bar chart has higher amplitudes than that of the middle bar chart. This shows that the leak degree is larger.

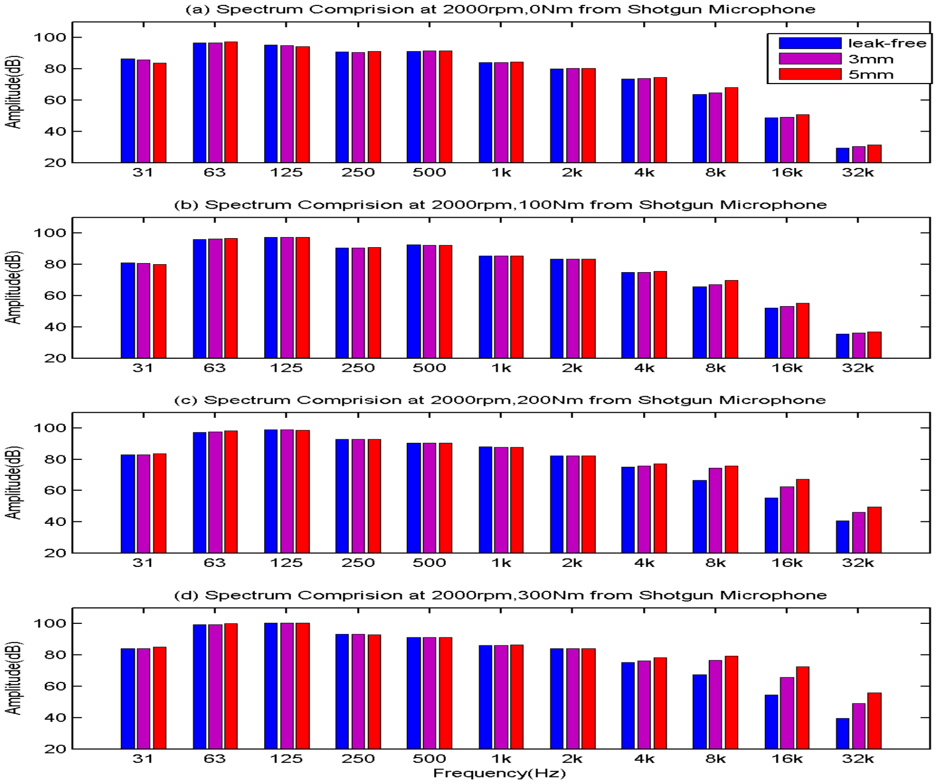

Figure 6 – Spectrum comparison of the sound for leak free as well as with leak conditions at an engine speed of 2000 RPM with the probe

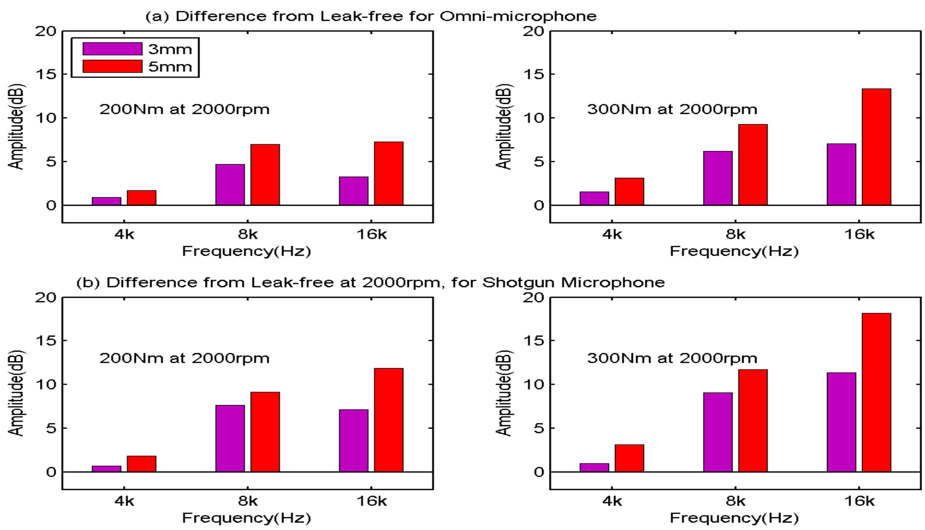

Figure 7 – Sound pressure level differences compared between a conventional 'omni-directional' acoustic probe and the 'sniffer'.

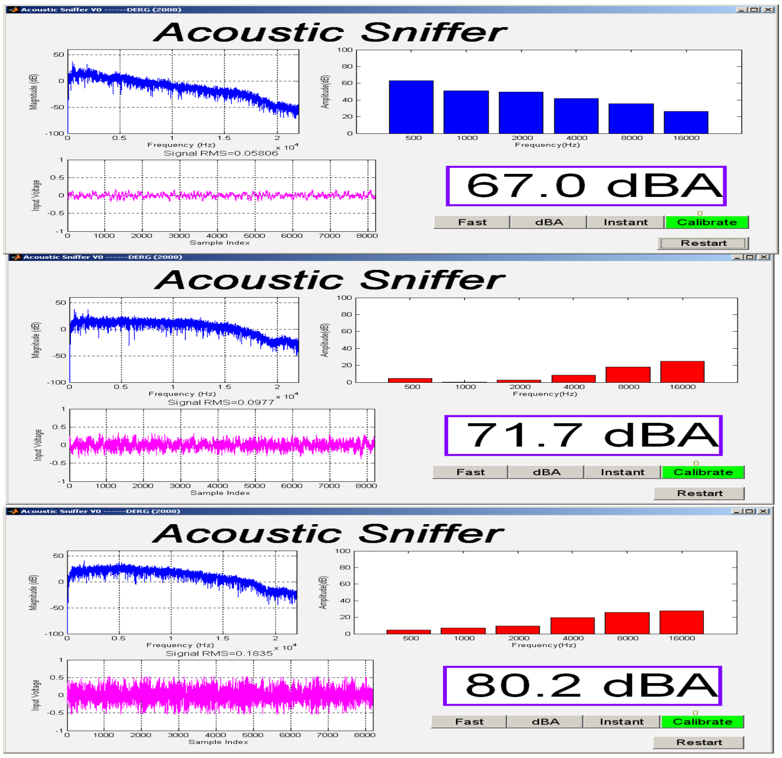

Figure 8 – Output from the system developed.

6. CONCLUSIONS

This investigation has clearly established that leaks in the engine intake system can be detected with the use of a directional probe. It has been shown that most common turbocharger leaks have an acoustic signature detectable in the high frequency range mainly between 8kHz and 16kHz.

Conventional, non-directional acoustic probes are also useful to detect this kind of leak but they are less efficient at detecting the exact location of the leak due to their omni-directional polar directivity patterns. It has been demonstrated that an acoustic ‘sniffer’ based on a highly direction gradient probe is able to detect the presence of a leak and indicate its location by rejecting sound waves impinging at an angle to the probe and emphasizing those that arrive from an on-axis direction.

The presence of a leak as well as its characterization in terms of size may be performed using octave band acoustic levels acquired by the probe.

It has further been observed that engine speed and engine load both have an influence in the differential amplitude caused by the presence of a leak.

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