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Air intake system noise in a turbocharged petrol engine during transient operation

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ABSTRACT

Engine downsizing is undertaken in the automotive industry in order to reduce the emissions and the fuel consumption of the vehicle. Turbocharging is one of the important methods to enable downsizing of the engine; however, increased noise is the side-effect of this introduction. The noise generation is assumed to be due to the operation of turbocharger very close to the surge zone of the compressor map. For example, the compressor map is typically measured under static laboratory test conditions and may be different in the dynamic environment of the intake system during engine operation. The aim of this paper is to outline the methods used by the authors to predict and measure the turbocharger noise generation and also to understand its fundamental mechanism. A naturally aspirated car is chosen to measure the noise generated at the intake system as a starting point. Analysis methods such as STFT for the acquired data measured are explained. This will form a basis for further analysis on a turbocharged car. A simulation methodology is outlined in order to predict the noise generation mechanism. The static pressures predicted on various locations of intake system, such as upstream and downstream of compressor, are processed to obtain estimates of the sound pressure in both the frequency and the time domains. A modular turbocharger rig is designed to study the intake system dynamics during compressor surge operation and to further understand the noise generation mechanism. The paper is concluded by listing the future work planned.
Keywords: Turbocharger, Noise, engine-simulation

1. INTRODUCTION

There is continuous effort in the automotive industry to downsize the engine, i.e. to increase the power to weight ratio of the engine or to increase the power to volume ratio. The major goal of downsizing is carried out along with other goals such as achieving higher overall efficiency, lower fuel consumption and lower emissions of the engine. Downsizing is achieved by increasing the power of engine for a given engine weight or by reducing the weight of engine for a given power. The weight to power ratio has approximately halved over the last 25 years for both petrol and diesel

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engines [1].

One of the methods employed to successfully downsize the engine is to use turbocharger in the intake system. It has been stated in the literature [2] that a turbocharged engine with the same torque output as that of a non-turbocharged engine produces higher sound pressure level. The increase in the noise level of a turbocharged engine in the speed range of 1500 to 2800 rpm is attributed to the boost pressure build-up and, hence, due to the turbocharging.

1.1 Turbocharger noise classification

Turbocharger noise can be classified, as shown in figure1, into constant tone noise, unbalanced whistle and pulsation noise, rotating noise and blow noise or whoosh noise. The constant tone noise is characterized by constant frequency noise which does not vary with the turbocharger shaft speed. In the case of pulsation noise, the frequency is of the order of 1.2 - 4.5 kHz [3,8,9] and is caused by the rotor eccentricities and blade geometry. Generally these types of noises are clearly identifiable from the background noise and can be measured using an experimental rig. The pressure difference between the suction and the compression side of the turbocharger causes the rotating noise. The rotational speed of the shaft and the number of blades involved influences the noise level and the frequency content. Blow noise is mainly caused by high air flow rate and low turbocharger speeds. This type of noise is of broadband nature [3,8,9] and the frequency range is 1.5-3 kHz. This paper focusses on the whoosh noise which is created during tip-in tip-out manoeuvres of the throttle. Noise due to turbocharger operation is normally measured on a powertrain dynamometer, a specially designed turbocharger rig or on an instrumented vehicle on a chassis dynamometer.

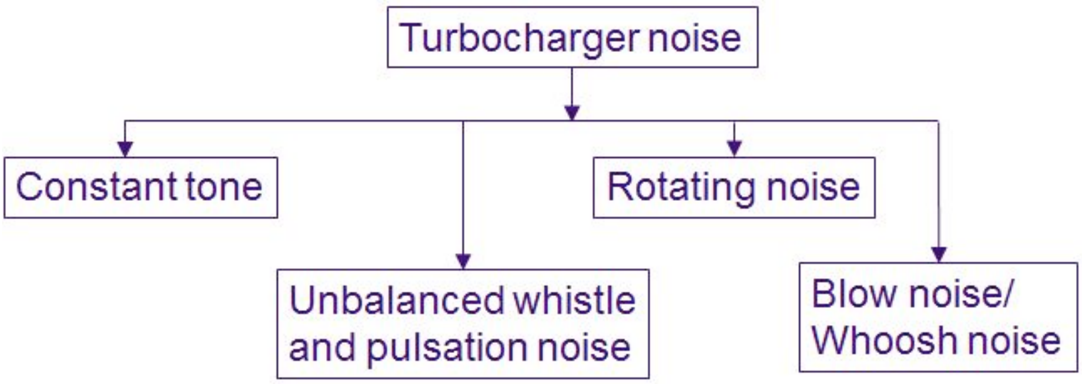

Figure 1 - Turbocharger noise classification

1.2 Methods to reduce turbocharger noise

Methods described in the literature to reduce the noise due to turbocharger operation can be classified as solution at source and/or the transfer path. Solution at source include changing the design of the components such as optimizing the shaft and bearing configuration, by using different sizes of compressor and by engine calibration. Solution on the transfer path methods include using broadband resonator consisting of Herschel Quincke tube by Trochon [4]. Stoffels and Schroeder [2] used a resonator very close to the turbocharger compressor outlet to filter out the noise in a given frequency range.

2. SOLUTION METHODOLOGY

2.1 Background

Whoosh or surge noise is observed in a turbocharged petrol engine during the throttle tip-in tip-out manoeuvre. The phenomena is assumed to be due to the operation of the turbocharger near to the surge zone and also due to the timing of the compressor recirculation valve (CRV) used in the system.

The compressor map of a turbocharger is divided into three zones: a) stable operating zone (centrally placed); b) surge zone; and c) choking zone [5]. When the mass flow through the compressor is reduced at a constant pressure ratio, a point arises when local flow reversal happens at the boundary layers. This will result in a low efficiency of the compressor. If the flow rate is further reduced, complete reversal of flow occurs and this will relieve the adverse pressure gradient until a new flow regime and pressure ratio is established. The compressor is then said to be in the surge operation.

This paper focusses on the surge zone and near surge zone operation of the compressor. A typical turbocharger map as described above is based upon measurements on a static test bench. However, when the turbocharger is integrated to the intake system of a vehicle, the map could shift and the surge margin can be reduced. This is due to the dynamic operating condition of the engine. One of the aims of this project is to predict the occurrence of surge in given engine design and to find the precise mechanism of noise generation. Three routes are defined in order to achieve the aim: (i) experiments on a turbocharged petrol engined car on a chassis dynamometer; (ii) prediction of the surge occurence using one dimensional engine simulation software; and (iii) experiments on a specially designed compressor rig.

2.2 Transient noise measurement on a naturally aspirated petrol engined vehicle

Initial experiments were conducted on a non-turbocharged petrol engined car on the chassis dynamometer at Loughborough University. Surface microphones are integrated to the intake duct to measure the noise during a transient tip-in and tip-out manoeuvre. The sound pressure level recorded at a post air filter location (figure 2) indicates a sudden increase in noise level during tip-in stage and a slow decrease in noise level during the tip-out stage. The short time Fourier transform of the measured sound pressure signal shows that much of the signal energy lies in the lower frequency range and thus does not indicate a characteristic whoosh noise.

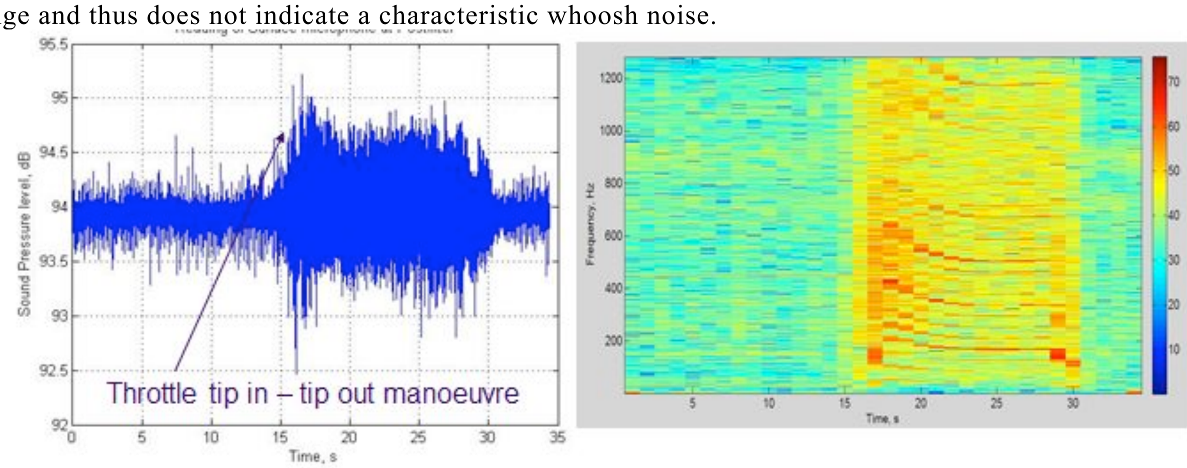

Figure 2 – Measured sound pressure in the intake system – post air filter location

2.3 Engine simulation

A commercial one-dimensional engine code is used to simulate the turbocharged petrol engine performance. Navier-Stokes equation is solved in the flow model and applied to the laminar and turbulent flow [6,7]. The objective of the simulation is to predict the occurrence of higher pressure fluctuations during the defined manoeuvre and to compare this with the normal working of engine. Other properties such as mass flow rate and temperature are also monitored. A spark-ignited, 4-cylinder, turbocharged, gasoline direct-injection engine's model is used for the simulation. A turbocharger with an intercooler to maintain the temperature of intake air is integrated in the model. A CRV with a changeable opening area is modeled and included. Sensor connections are included to monitor the static pressure at intake pipe before the air filter, before the compressor, at the compressor outlet and throttle inlet. Sensors to monitor the mass flow rate, the speed of the engine, the speed of the turbocharger shaft, the opening area of the CRV and the opening area of throttle are also incorporated to the model.

Turbine and compressor characteristic maps are used to define the turbocharger model. The friction and the inertia of the turbocharger shaft are given as an input. The compressor map is used to derive the mass flow rate and the efficiency. The turbine and the compressor speeds are calculated from the power produced or consumed by the turbine or compressor, respectively.

A Surge condition is modeled by using an advanced surge model with flow reversal. During the surge mode, flow reversal happens in the intake system and through the compressor. Extrapolation of the compressor map constant speed lines is used to achieve this feature. The extended constant speed lines are processed to look-up the mass flow and the pressure ratio. Other parameters used in the simulation are: the ‘cycles’ method for time control; an ‘explicit’ solution method for the flow; and an ‘explicit’ Range-Kutta solution method for the mechanical motion.

A short duration time step of the order of 0.4 micro second is used to obtain good results at higher frequencies. The throttle position, CRV position and the engine speed data are obtained from experimental measurements on a turbocharged petrol engine car undergoing the tip-in and tip-out manoeuvre. The CRV is opened and closed in a profile different to that of the throttle profile. In an engine, the CRV is typically opened using mechanical means by using differential pressure acting on a diaphragm. Hence, the timing of the CRV is highly dependent on the responsiveness of the mechanical valve to the pressure fluctuations in the intake system. In the simulated engine model, the CRV profile is provided as an input. The opening time, closing time and, hence, the duration of opening are variables in the model. For the current simulation, the CRV is set to open when the throttle valve is beginning to shut, i.e. when the engine speed begins to drop as illustrated in figure 3.

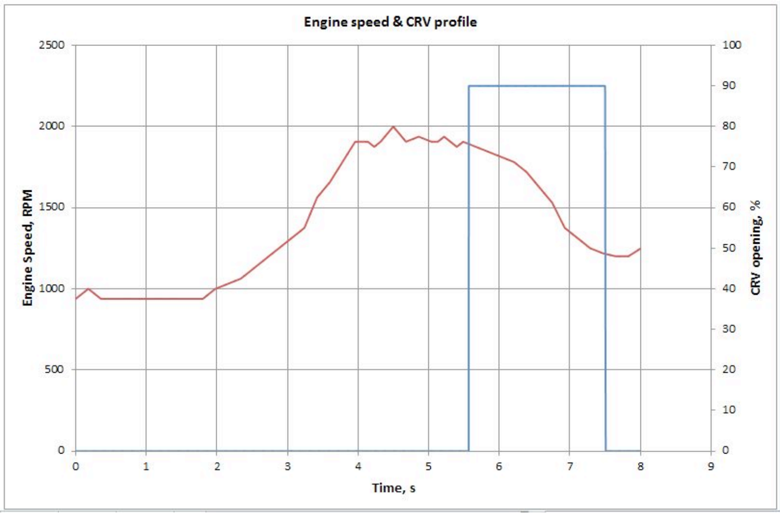

Figure 3 – Engine speed(red) and CRV opening % (blue)

2.4 Experimental test rig design

The aim of the test rig is to recreate the pressure dynamics within the intake system of an automotive engine under laboratory conditions. The test rig is designed to be of modular type and the intake system can be changed to conduct experiment on different types of induction system and turbochargers.

Two concepts of test rigs are proposed: 1. a supercharger rig which simulates turbocharger flow condition and pressure fluctuations. A stand-alone supercharger rig is designed which comprises a motor and a supercharger. The objective is to operate the motor and, hence, the supercharger in a way that the pressure and the flow conditions are similar to that in the automotive intake system. 2. A combined supercharger and turbocharger rig which simulates turbocharger flow conditions and pressure fluctuations. In this second concept the outlet of the supercharger is used to drive the turbine blades. The first concept is explained in detail in this paper.

The locations for the sensors are chosen carefully in the intake system in order to detect the surge occurence. The main parameters to be measured are the supercharger output flow, the pressure ratio across the supercharger and the compressor shaft speed. The static pressure measured on the intake duct wall and the flow along the duct are helpful to calibrate the simulation model with that of the experimental rig and, hence, with the actual vehicle. A temperature recording can serve to indicate the pressure rise and also to indicate the necessary corrections in the compressor map.

The mechanical components comprise of a standard automotive intake system, a supercharger, a throttle valve and the CRV. The throttle valve and the CRV are operated by electrical signals and are controlled using a DAQ (Data Acquisition) card and LabVIEW software. A predefined profile is used to define the throttle valve and CRV lift against time. As the supercharger needs to be operated at an ideal temperature of 80 C, a lubrication system and a heat exchanger is used. The schematic representation of the experimental rig is given in figure 4.

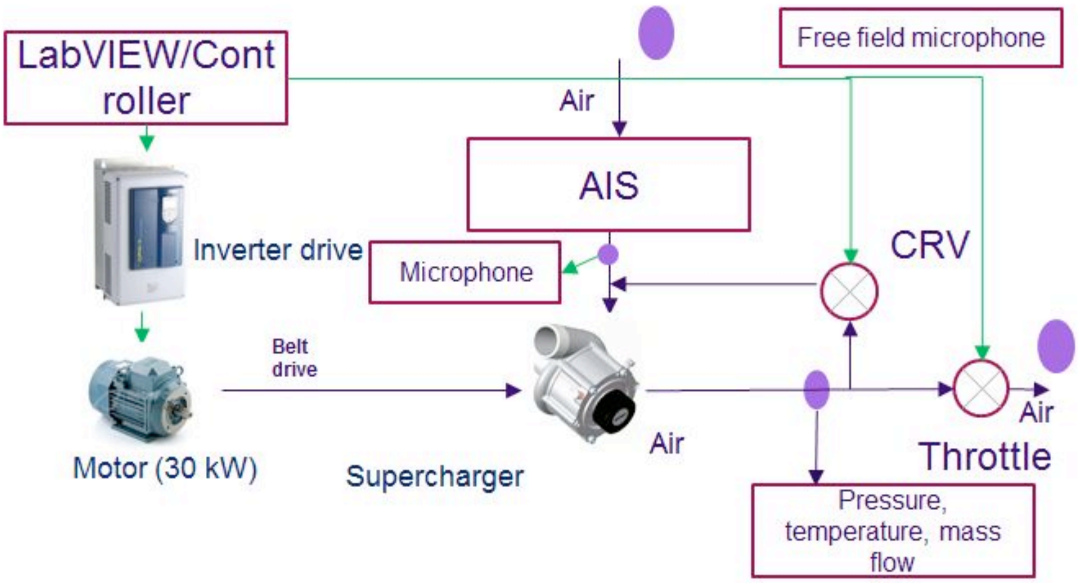

Figure 4 Schematic representation of test rig

The Specifications for the supercharger rig components are derived from theoretical calculations and the one-dimensional simulation code results. Calculation was used to select the supercharger size and to obtain the approximate compressor map from the manufacturer. The supercharger shaft is driven using a motor modelled at a constant speed of 40,000 rpm. The simulated results shown below (figure 5) represent the surge characteristics after the throttle is closed at around 16 seconds.

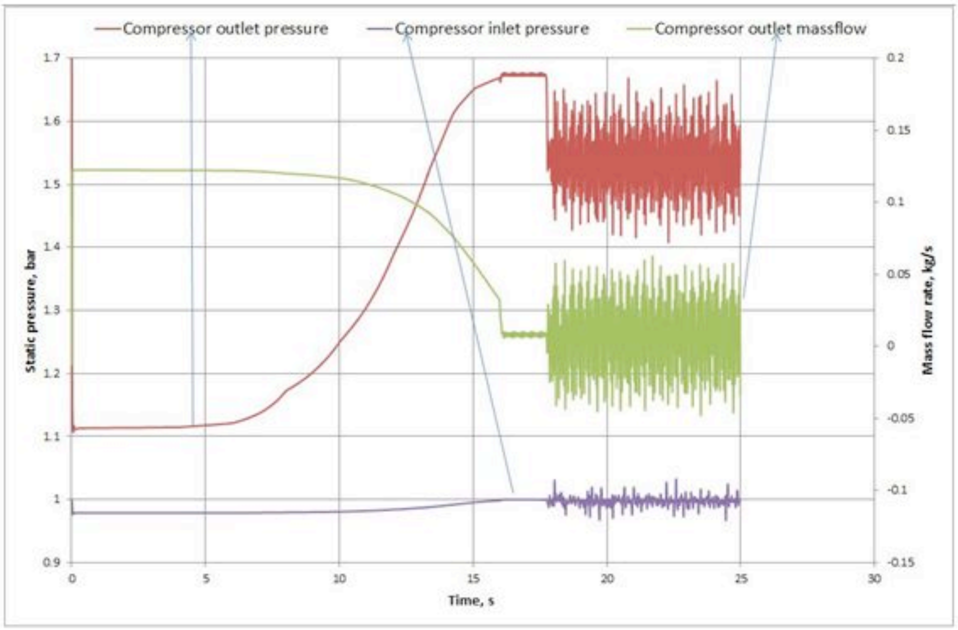

Figure 5 - Simulated compressor inlet pressure, outlet pressure and mass flow

3. RESULTS OF ENGINE SIMULATION

The objective of the simulation is to theoretically predict the occurrence of noise under surge conditions. The engine speed, throttle opening and CRV opening profile are as per the vehicle experimental measurements. The compressor surge line is artificially shifted in to the stable zone in order to predict extreme operating conditions of the turbocharger. The static pressure during the simulation is presented in figure 6. The before throttle and after compressor pressure signals rise is almost parallel to the throttle profile. In the initial region, from 0 to 1 sec., the entire simulation undergoes a transient phase. After settling down, in the region of 1 to 2 sec., the amplitude of the pressure remains almost constant value. Also the mass flow rate remains as a steady value in this zone. Initially, the throttle valve opening is maintained at a constant value of around 28% and then tipped in to around 80%. In this region, the amplitude of the pressure and the mass flow rate increases. The throttle is tipped-out from 80% to 28% in the region from 5.5 to 8 sec. and the pressure and the mass flow amplitude reduces. However, the values are higher than that of the 1 to 2 sec. region. This is due to high shaft speed and inertia of the turbocharging system. The mass flow rate through the CRV is illustrated in figure 7

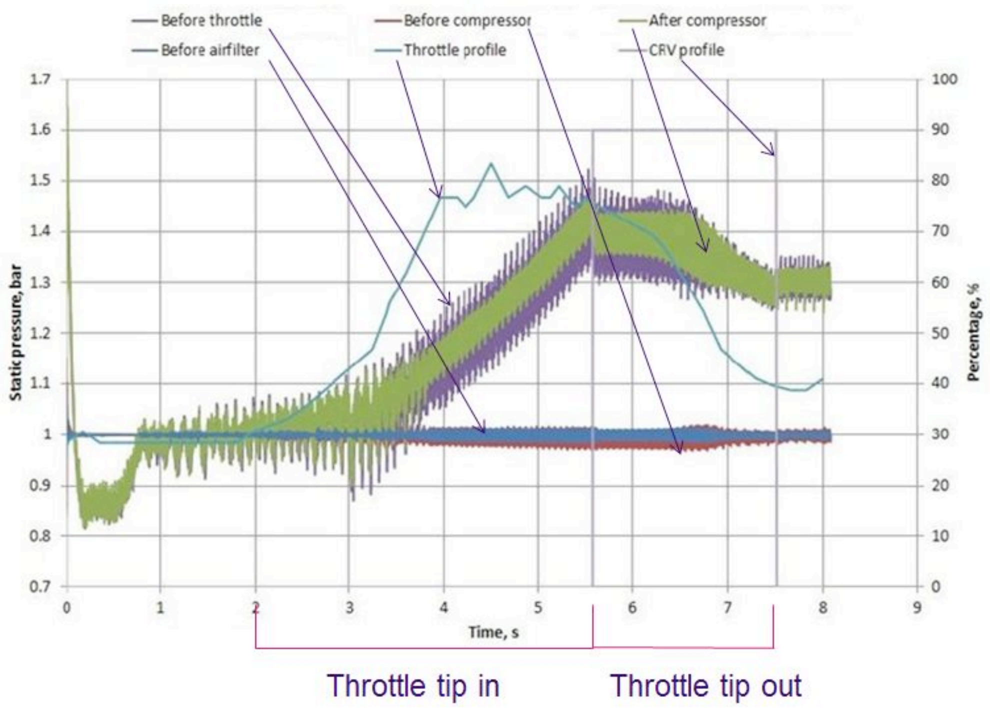

Figure 6 - Static pressure, throttle and CRV profiles

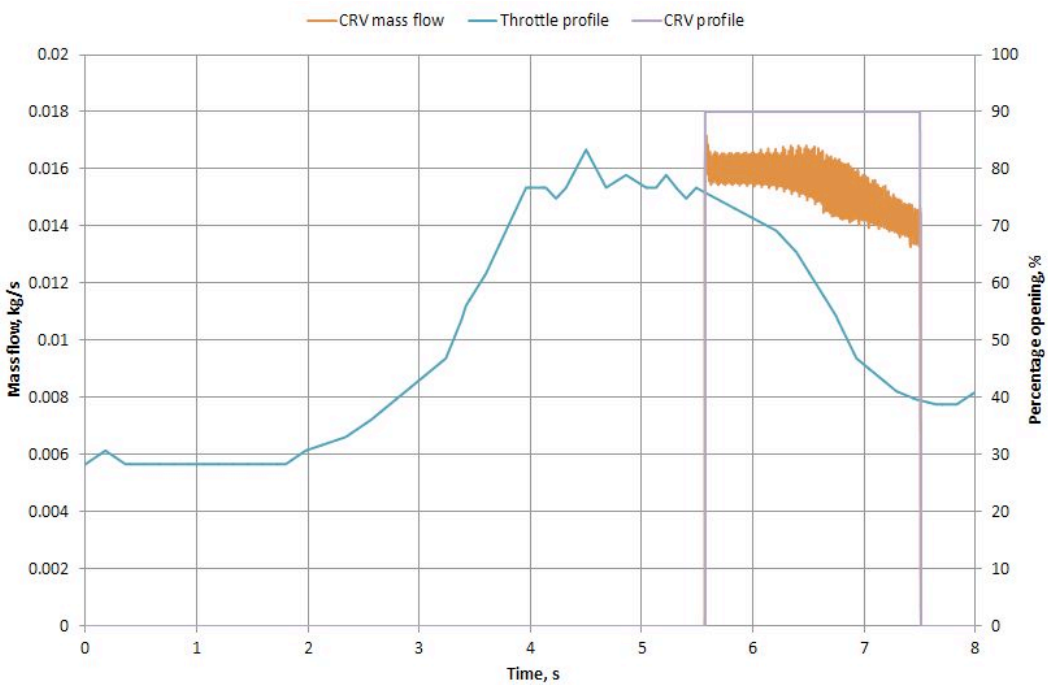

Figure 7 - Mass flow through the CRV

As the present study involves analysis of transient signals, the FFT may not be applied directly. Hence, the short time Fourier transform was used to analyse the pressure signals in the intake system. The analysis results are shown in figure 8 and figure 9. In figure 8 the CRV is lifted and kept open from 5.5-7.5 sec. to allow the transfer of high pressure air to the compressor inlet. In figure 9 the CRV is kept closed. In the first case, the pressure rise at the compressor inlet is reduced, hence, reducing the effect of surge. However, in the figure 9 pressure rise is continued as there is no recirculation of air. The results show that the noise level in the second case is higher than in the first case.

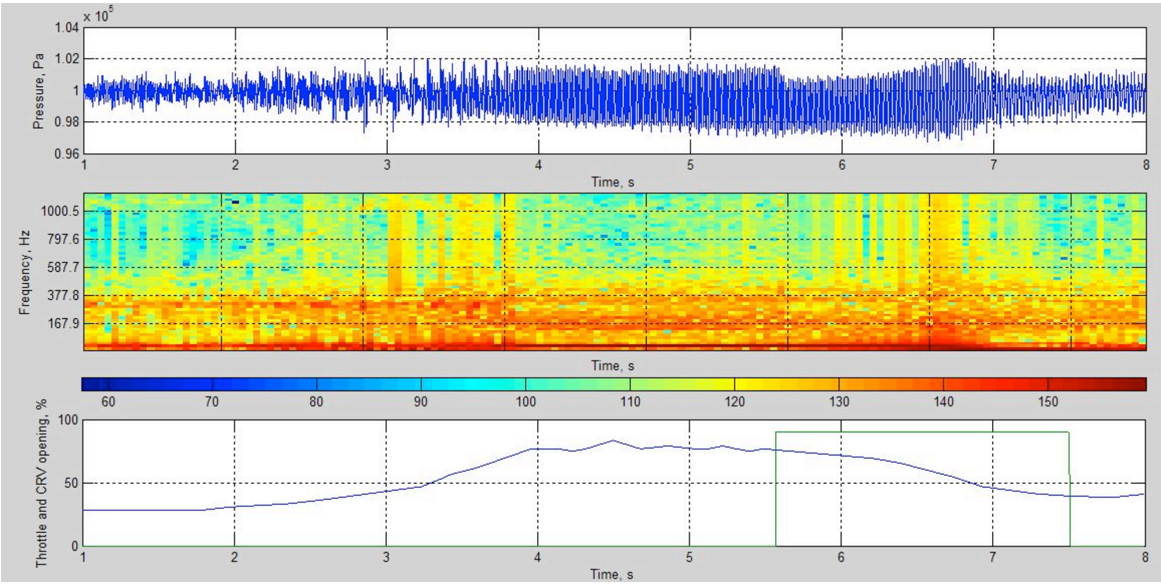

Figure 8 - STFT of static pressure at the compressor inlet location with CRV opening (colour code shows sound pressure level in dB)

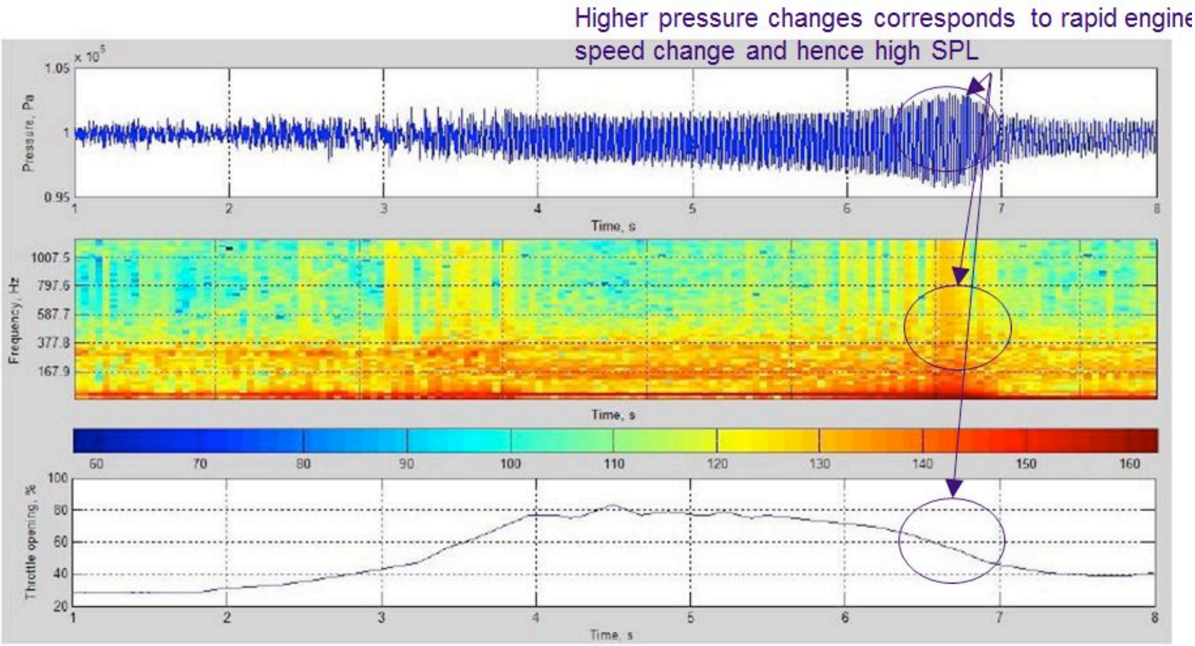

Figure 9 - STFT of static pressure at compressor inlet location with CRV permanently closed (colour code shows sound pressure level in dB)

4. CONCLUSIONS

One of the challenges with the introduction of turbocharger in an engine is the increased noise in the intake system. The various types of turbocharger noise are categorised and explained. In particular, whoosh noise at the intake manifold during surge operation in a gasoline engine is the focus in this paper. Simulation and experimental methods used to investigate the surge operation and to predict the resulting pressure pulsations and noise is outlined. The solutions adapted to solve the noise problem are explained. An experimental test rig design is explained in detail. One dimensional modeling of the turbocharged engine is conducted and results are presented. The influence of the CRV opening on the noise characteristics in the intake system are illustrated by performing a STFT of the predicted static pressure signals. The immediate step in the future is to complete the experimental-rig build and to conduct measurements during turbocharger surge conditions in order to identify the mechanism of noise generation in a given intake system.

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