Prediction and measurement of air intake noise in a turbocharged petrol engine during surge events

PREDICTION AND MEASUREMENT OF AIR INTAKE SYSTEM NOISE IN A TURBOCHARGED PETROL ENGINE DURING SURGE EVENTS

Ajith V Pai Department of Aeronautical and Automotive Engineering, Loughborough University
S J Walsh Department of Aeronautical and Automotive Engineering, Loughborough University
Dan J. O'Boy Department of Aeronautical and Automotive Engineering, Loughborough University
Rui Chen Department of Aeronautical and Automotive Engineering, Loughborough University

1 INTRODUCTION

Turbochargers are introduced in petrol engines to facilitate downsizing and hence to reduce emissions and fuel consumption. 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 lab test conditions and may be different from the dynamic intake system during engine operation. The aim of the paper is to outline the methods used by the authors to predict and measure the noise generation. The static pressures predicted on various locations of intake system, such as upstream and downstream of the compressor, are processed in order to obtain the sound pressure level in both the frequency and the time domains. An experimental turbocharger rig is designed in order to verify the intake system dynamics during compressor surge and to further analyse and understand the noise generation mechanism.

2 BACKGROUND

2.1 Literature review

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 along with other goals such as higher overall efficiency, low fuel consumption and lower emission of 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 engines[1].

One of the methods to downsize the engine is to use turbocharger in the intake system. It has been stated in literature[2] that that turbocharged engine with the same torque output of that of a non-turbocharged engine produces high sound pressure level. The rise 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.

2.2 Turbocharger noise types

Turbocharger noise types are classified as in the fig.1 into constant tone type, 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 to 4.5 kHz[3,8,9] caused due to rotor eccentricities and blade geometry. Generally these types of noises are clearly identifiable from the background noise and can be detected using a test 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. Blow noise is mainly caused by high air flow rate and low turbocharger speeds. This type of noise is of broad band nature[3 8 9] and the frequency range is 1500-3000Hz. 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, turbocharger rig or on a vehicle at chassis dynamometer.

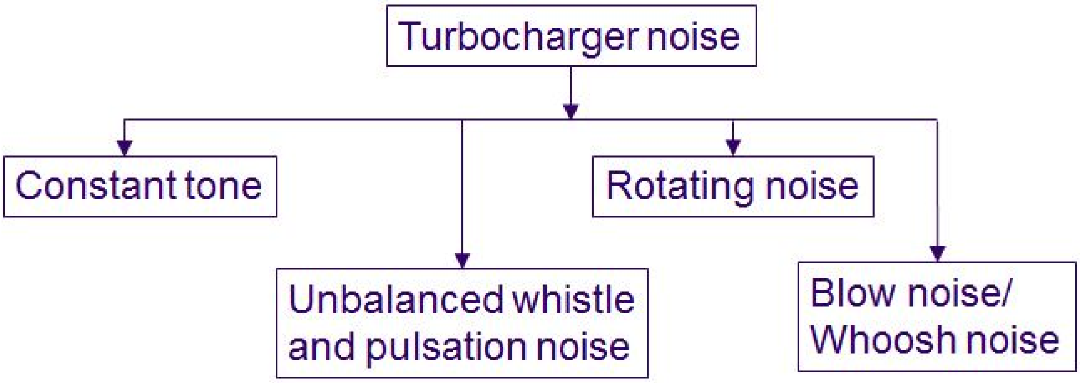

Fig. 1 Types of turbocharger noise

2.3 Methods to reduce turbocharger noise

Some methods are described in literature to reduce the noise caused due to turbocharger operation which can be classified as solution at source and at the transfer path. Solution at source includes 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 at transfer path is by using broad band resonator consisting of Herschel Quincke tube by Trochon[4]. Experiments with different length of branches were tried and different transmission losses were analysed. Stoffels et al. [2] used resonator very close to the turbocharger compressor outlet to filter out the noise at a certain frequency range.

3 SOLUTION METHODOLOGY

3.1 Background

Surge noise is observed in turbocharged petrol engine during throttle tip-in tip-out manoeuvre. The phenomena is assumed to be due to the operation of 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: stable operating zones (centrally placed), surge zone and the choking zone[5]. When the mass flow through the compressor is reduced at a constant pressure ratio, a point arises when the local flow reversal happens at boundary layers. This will result in low efficiency of the compressor. If the flow rate is further reduced, complete reversal of flow occurs and 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 and near surge zone operation of the compressor. A typical turbocharger map as described above is based on measurement on a static test bench. However, when the turbocharger is integrated to the intake system the map could shift and surge margin can be reduced. This is due to the dynamic operating condition of the engine. One of the aims of the project is to predict the occurrence of surge in given engine and to find the precise mechanism of noise generation. Three routes are defined to achieve the aim : to do experiment on a turbocharged petrol car in chassis dynamometer, to predict the surge occurence using one dimensional engine simulation code and experiment on a newly built compressor rig.

3.2 Engine simulation

A commercial one dimensional engine code is used for simulating the turbocharged petrol engine performance. Navier-Stokes equation is solved in the flow model involving the conservation of continuity, momentum and energy equations and applied to the laminar and turbulent flow[6,7]. The objective of this simulation is to predict the occurrence of higher pressure fluctuations during the defined manoeuvre and compare to the normal working of engine and also other properties such as a mass flow rate and temperature. The simulated properties are a good indication of the noise generated in the engine intake system. A spark ignited, 4 cylinder, turbocharged, gasoline direct injection engine's model is used for the simulation. Turbocharger with intercooler to maintain the temperature of intake air is integrated. CRV with a changeable opening area against time is modeled and included. Sensor connections to monitor the static pressure at intake pipe before the air filter, the compressor, compressor outlet and throttle inlet, mass flow rate, speed of the engine, speed of the turbocharger shaft, opening area of the CRV and the throttle are integrated 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 provided as an input. The compressor map is looked up to derive the mass flow rate and the efficiency. The turbine and the compressor speed are calculated from the power produced/consumed by the turbine/compressor from the basic equations.

Surge condition is modeled 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 can be processed to lookup the mass flow and the pressure ratio. Other important parameters used in the simulation for the project 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 lower time step of the order of 0.4 micro second is used to obtain good results at higher frequencies. The throttle position, CRV position data and the engine speed are obtained from the actual experimental measurement on a turbocharged petrol engine car. 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 present engine model, the CRV profile is provided as an input. The opening time, closing time and hence the duration of opening is variable using the model. The CRV is set to open when the throttle valve is beginning to shut, i.e. engine speed begins to drop as given in the fig 2

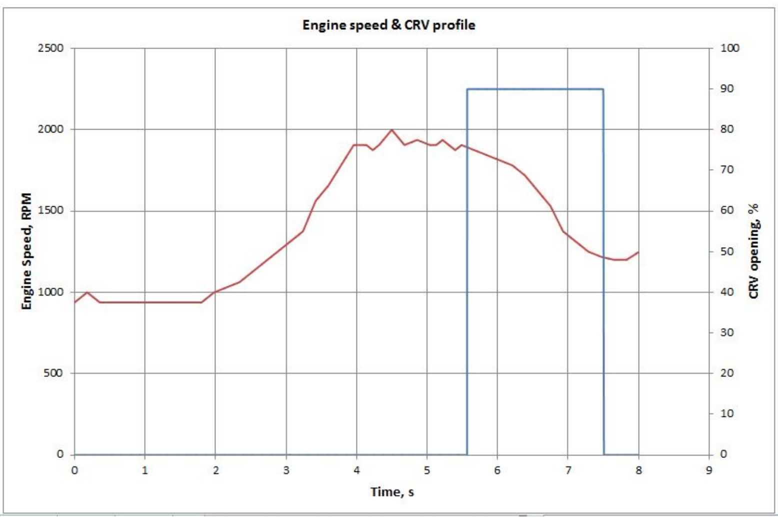

Fig. 2 Throttle and CRV profile

3.3 Test rig design

The main aim of the test rig is to simulate the pressure dynamics with in 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. Supercharger rig which simulates turbocharger flow condition and pressure fluctuations. A stand-alone supercharger rig is designed which comprises of a motor and a supercharger using the compressor map. 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. Combined supercharger and turbocharger rig which simulates turbocharger flow condition and pressure fluctuations. In this concept the outlet of the supercharger is used to drive the turbine blades. In this paper, the first concept is explained in detail.

Locations for sensors are chosen carefully based on the positions in the intake system where in surge occurrence can be sensed. The main parameters to be measured are the supercharger output flow, 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 test rig and hence to the automotive engine. The temperature recording can serve to indicate the pressure rise and also to do the necessary corrections in the compressor map.

The mechanical components comprises of intake system from a standard automotive, supercharger, throttle valve and the CRV. The throttle valve and the CRV are operated by electrical signals and are controlled using 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 need to be operated at an ideal temperature of 80 deg C, a lubrication system and a heat exchanger is used. The schematic representation of the rig is given in fig. 3.

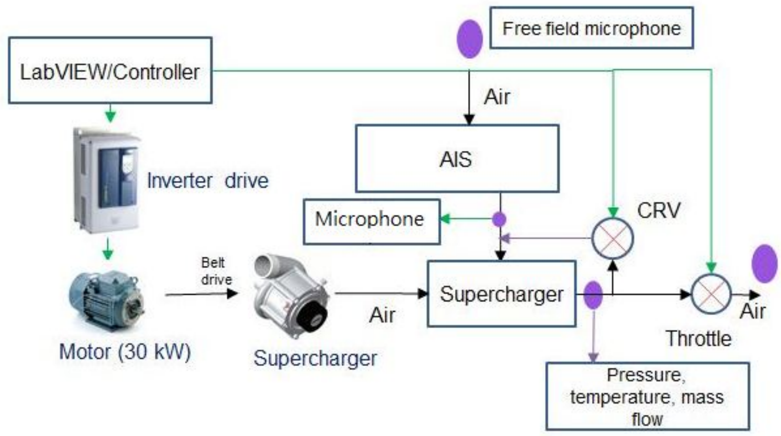

Fig.3 Schematic diagram of test rig

3.3.1 Design of supercharger rig components

Specifications of supercharger rig components are derived from the calculation and one dimensional code results. The calculated supercharger size was used to select the size and to obtain the compressor map from the manufacturer. In the simulation, throttle profile was given as a time based input. The supercharger shaft is driven using a motor model at a constant speed of 40000 rpm. The simulated results shown below (Fig. 4) represents the surge characteristics after the throttle is closed at a time of 16s.

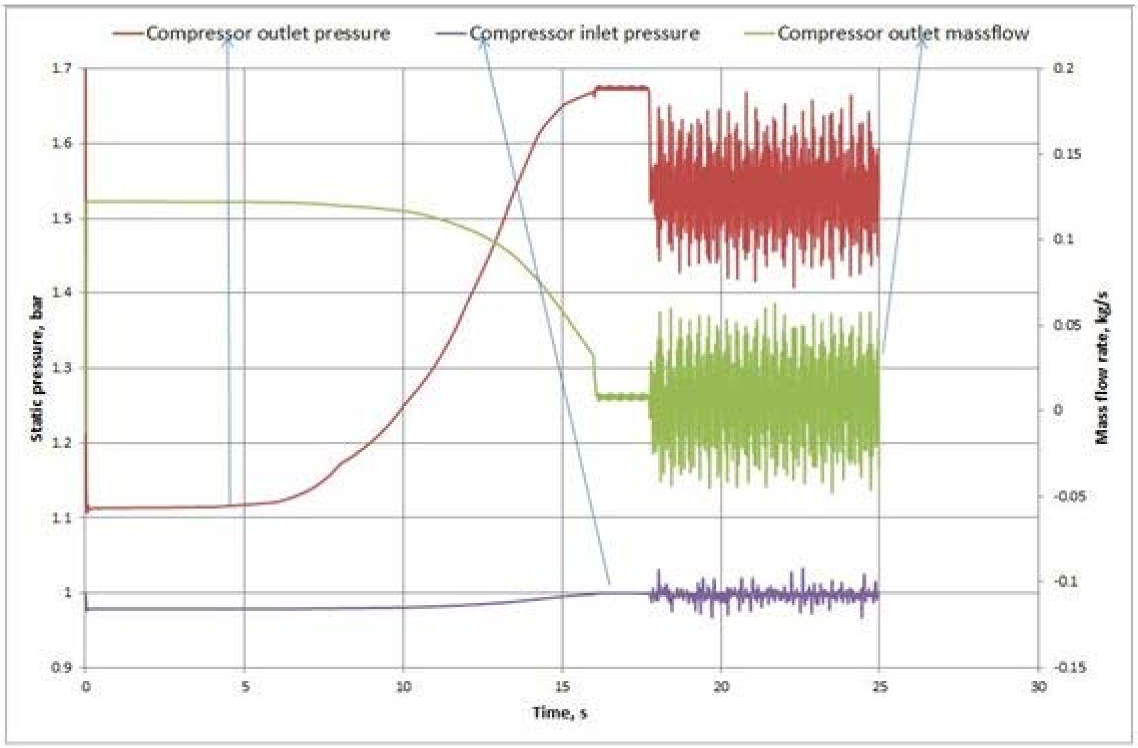

Fig.4 Simulated supercharger rig results under transient conditions

4 RESULTS OF ENGINE SIMULATION METHOD

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 experimental measurements. The compressor surge line is shifted to stable zone to predict extreme operating conditions of the turbocharger. The static pressure during the simulation is presented in fig. 5. Even though the compressor shaft speed curve across time is very smooth and the oscillations of the shaft in the zoomed in region of the curve shows +/-90 rpm, the pressure and the mass flow fluctuations are much higher during the throttle tip – in tip out manoeuvre. The pressure signal rise is almost parallel to the throttle profile and also engine speed rise. At the initial region of 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 is almost a 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 pressure and mass flow rate increases. The throttle is tipped out from 80% to 28% in the area 5.5 to 8 sec and the pressure and the mass flow amplitude reduces. However, the values are higher than and hence not equal to that of the 1 to 2 sec region. This is clearly due to high shaft speed and inertia of the turbocharging system. The mass flow rate through the CRV is given in fig. 6

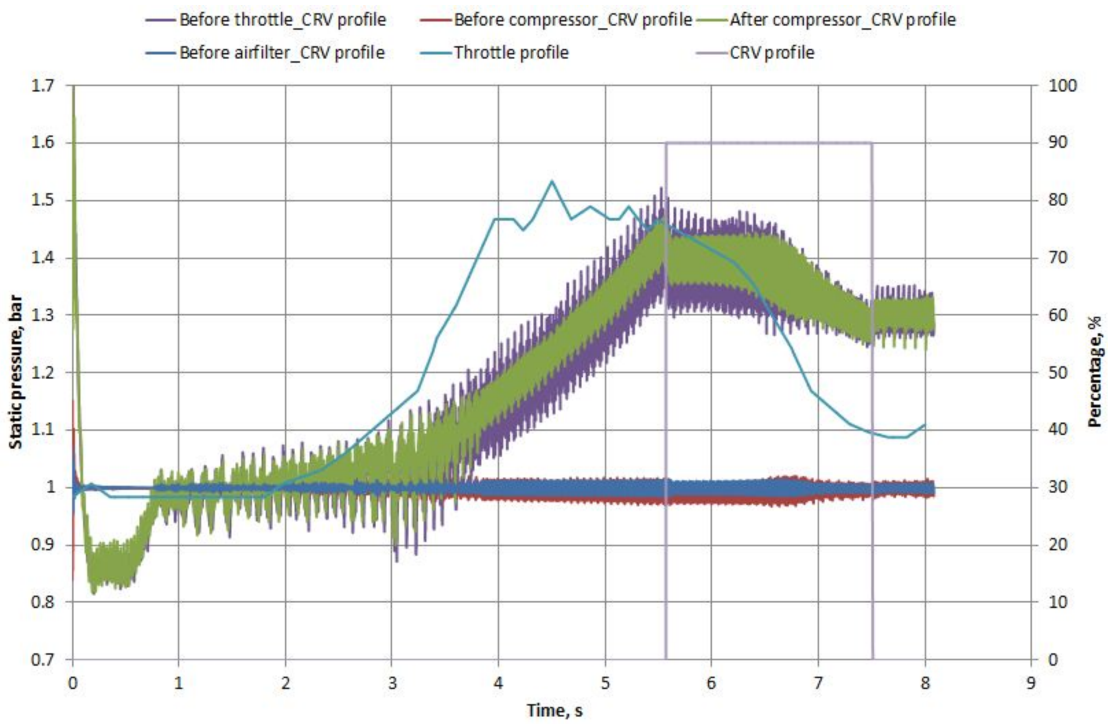

Fig. 5 Static pressure, throttle and CRV profiles

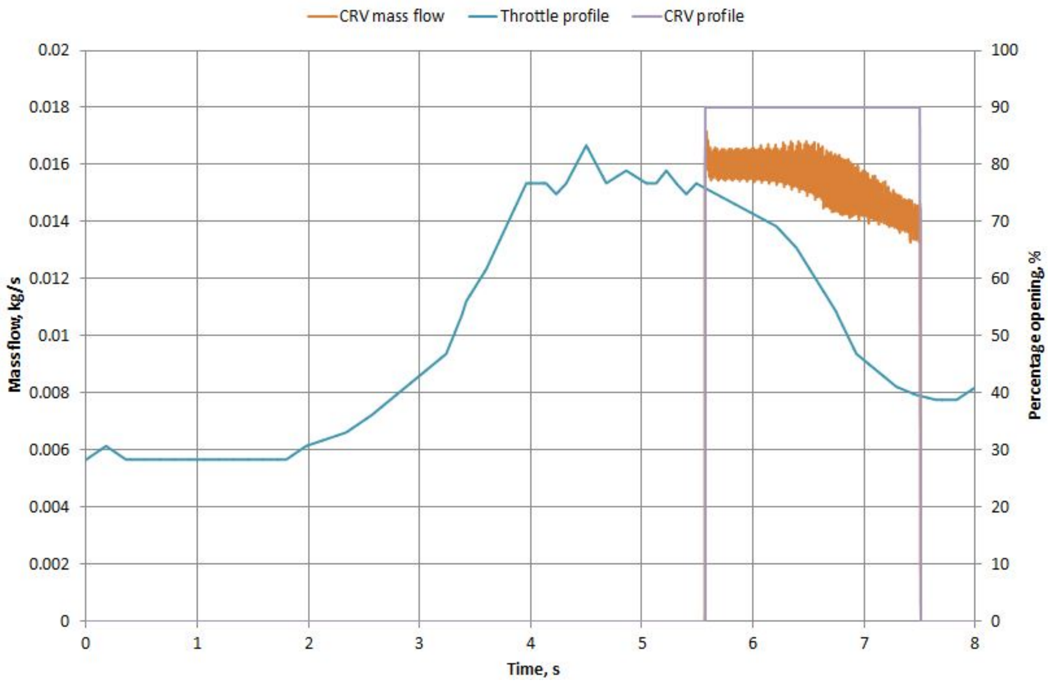

Fig. 6 Mass flow through the CRV

As the present study involves analysis of transient signals over a period of time, FFT may not be applied directly. Hence, Short time Fourier transform was used to analyse the pressure signals in the intake system. The analysis results are shown in fig 7 and fig 8. In the fig.7 the CRV is lifted and kept open at a particular instance to allow the transfer of high pressure air to the compressor inlet. In the fig.8 the CRV is kept closed. In the first case, the pressure rise at the compressor inlet is reduced and hence reducing the effect of surge. However, in the fig 8 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.

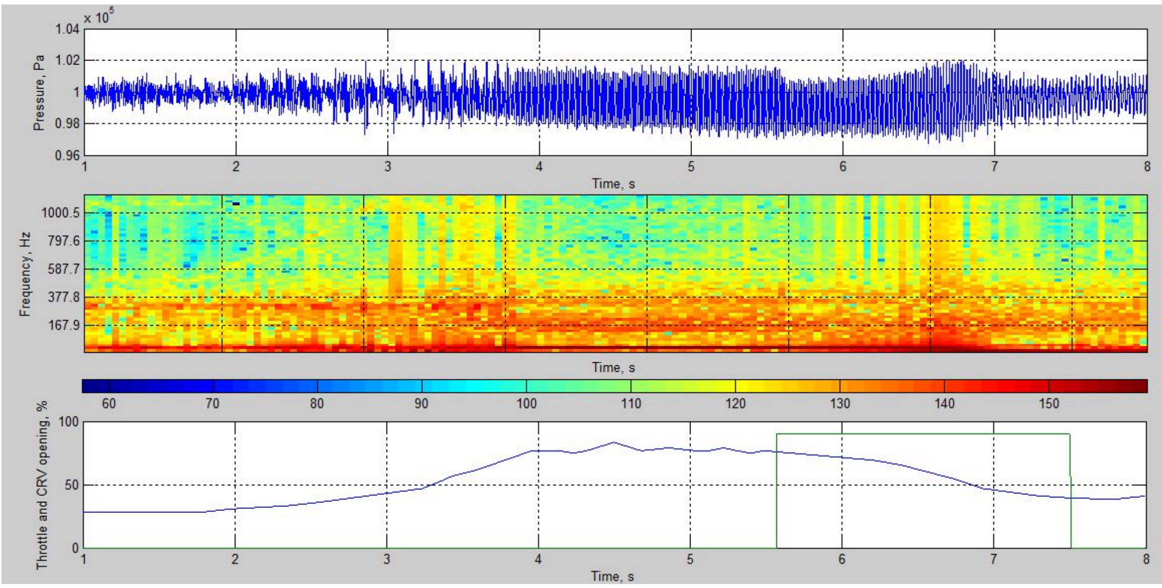

Fig. 7 STFT of static pressure at compressor inlet location (colour code shows sound pressure level in dB)

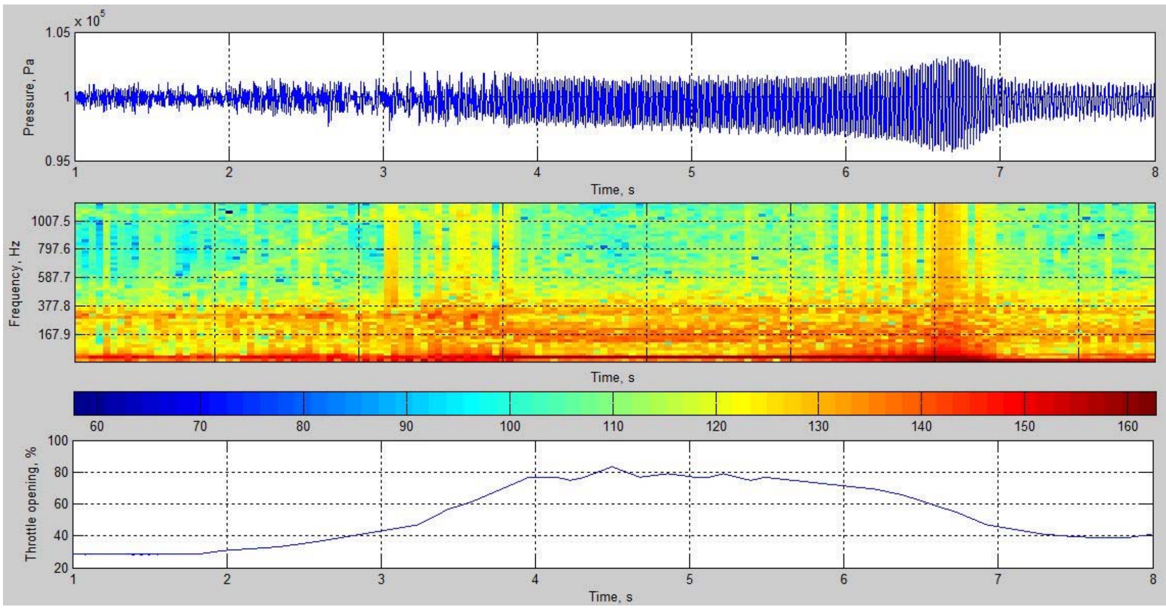

Fig. 8 STFT of static pressure at compressor inlet location (colour code shows sound pressure level in dB)

5 CONCLUSION

The importance of downsizing of engines is emphasized. Introduction of turbocharger is an important step to reduce the swept volume of engine. One of the challenges in introduction of turbocharger in an engine is the noise at the intake system. The various types of turbocharger noise are categorised and explained. Among these noise at the intake manifold during surge operation in a gasoline engine is focused in this paper. Some simulation and experimental methods used to determine the surge operation and to predict the pressure pulsations and noise is outlined. The solutions adapted to solve the noise problem are explained.

The test rig design is explained in detail. One dimensional modeling of the turbocharged engine is conducted and the results are presented. The influence of CRV opening on the noise characteristics in the intake system are explained by performing STFT of the predicted static pressure signals. The immediate step in the future is to complete the test rig build and to conduct experiments at turbocharger surge conditions and to identify the mechanism of noise generation in a given intake system.

6 REFERENCES

1. Prof. Rudi Kunze, “The environmental challenge for the automotive industry”, MSc in Automotive Systems Engineering Course Note, Loughborough University, 2004-05
2. Harald Stoffels and Markus Schroeer, Ford Werke AG, “NVH aspects of a downsized turbocharged gasoline powertrain with direct injection”, 2003-01-1664, SAE Technical Paper Series, Noise and Vibration Conference and Exhibition, traverse City, Michigan May 5-8, 2003
3. Charlie Teng and Steve Homco, Ford Motor Company, “Investigation of whoosh noise in automotive turbocharger” 2009-01-2053, SAE 2009
4. Eric P Trochon PSA Peugeot Citroen, “A new type of silencers for turbocharger noise control”, 2001-01-1436, SAE technical paper series, Proceedings of the 2001 Noise and Vibration Conference
5. N Watson and M S Janota, “Turbocharging the Internal Combustion Engine”, The Macmillan Press Ltd, 1993
6. Robert L Street, Gary Z Watters, John K Vennard, “Elementary Fluid Mechanics”, John Wiley & Sons, 1996
7. Engine performance application manual – GT Suite, Gamma Technologies 2010
8. P W Sachaberg, T Priede and R K Dutkiewicz, Energy Research Institute, University of Cape Town, “Effects of a rapid pressure rise on engine vibration and noise”, 900013, SAE Technical Paper Series, International Congress and Exposition, Detroit, Michigan, February 26 to March 2, 1990
9. Prof. Dr. –Ing Stefan Pischinger, RWTH Aachen, Dr.-Ing Harald Stoffels, Ford Werke GmbH, Dr.-Ing. Christoph Steffens, FEV Motorentechnik GmbH, Dipl.-Ing. Richard Aymanns, RWTH Aachen, Dipl.-Ing. Remi Stohr, FEV Motorentechnik GmbH, Dipl.-Ing. Martin Atzler, RWTH Aachen, “Acoustics development for exhaust gas turbochargers”, MTZ Worldwide 03/ March 2008, Vol 69