

NVH-Challenges of Air Supply Subsystems for Automotive Fuel Cell Applications

Jochen Sang and Massimo Venturi

NuCellSys GmbH

Ralf Bocksch

Daimler AG

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ABSTRACT

Fuel cells convert a fuel together with oxygen in a highly efficient electrochemical reaction to electricity and water. Automotive fuel cell systems mainly use compressed onboard stored hydrogen as fuel. Oxygen from ambient air is fed to the cathode of the fuel cell stack by an air supply subsystem.

For its current and next generation air supply subsystem NuCellSys has employed screw type compressor technology, which in the automotive area initially was developed for supercharged internal combustion (IC) engines.

As NVH expectations to fuel cell vehicles differ very much from IC-engine driven vehicles, specific efforts have to be taken to address the intense noise and vibration profile of the screw compressor.

This paper describes different counter measures which have been implemented into the NuCellSys next generation air supply subsystem. These counter measures shall firstly minimize the generated noise at the source and secondly attenuate the transferred air and structure-borne noise aiming to meet today's NVH expectations to a fuel cell vehicle.

INTRODUCTION

As the electrochemical reaction in the fuel cell stack in principle does not generate any noise the main NVH sources in a fuel cell powered automobile are the auxiliary equipment of the vehicle and the air & hydrogen supply subsystems for the fuel cell.

Fuel cell systems are expected to operate much quieter than combustion engines. Noise emissions of the fuel cell system affecting annoyance and comfort of vehicle users or bystanders must be avoided to get public acceptance for this propulsion technology.

This paper focuses on the specific NVH-challenges of the air supply subsystem, which is required to feed the ambient air to the cathode of the fuel cell stack. Core components of this subsystem are an air compressor (or an air pump) and an electric motor to drive it. As in many automotive fuel cell applications NuCellSys has employed automotive proven screw type compressor technology for its next generation air supply subsystem.

The screw compressor technology provides several advantages, e.g. high compression ratios and minor back pressure dependency, but its very intense tonal noise and vibration profile requires extensive effort to significantly reduce the noise level emitted from the air supply subsystem and meet today's customer expectations to fuel cell vehicles.

AIR SUPPLY SUBSYSTEM NVH CONCEPT

The next generation air supply system contains as core components the screw compressor and the corresponding electric auxiliary motor to drive it. Based on the power and torque spread in the compressor timing gear it is advantageous to join the drive shaft of the motor via a flexible coupling with the male rotor of the compressor. Based on this the 1st order frequency of the next generation air supply system is defined as the speed of the auxiliary drive which is equivalent to the speed of the coupling and the male compressor rotor.

ANALYSIS OF THE MAIN NOISE AND VIBRATION SOURCES

Imbalance of Rotating Parts

As the speed range of the auxiliary drive is 1,200 rpm (idle) to 19,800 rpm (peak load) the 1st order frequency can vary in the range of 20 – 330 Hz as a function of the motor speed. Any vibrations with the frequency of the 1st order can be traced back to imbalances of either the rotor of the auxiliary drive, the coupling or the male compressor rotor.

The screw compressor contains two rotors which revolute with different speeds. The rotors are synchronized by the compressor timing gear. In the case of the next generation air supply system the female rotor rotates with $3/5^{\text{th}}$ of the speed of the male rotor, so any vibrations with the frequency of the 0.6^{th} order can be traced back to an imbalance of the female compressor rotor. The 0.6^{th} order is varying from 12 – 198 Hz in the given speed range.

Pressure Level and Peaks of the Compression Process

Among different types of air pumps a machine having an internal compression is defined as compressor. Screw compressors apply the internal compression by engagement of their rotor lobes [Ref. 1].

The screw compressor employed in the next generation air supply system has a lobe ratio of 3:5 which means that the male rotor consists of three lobes whereas the female rotor consists of five lobes. Both rotors together create three compression chambers per revolution of the male rotor.

Each rotor lobe creates a dilatorily pressure pulsation when passing the suction or discharge port of the compressor. The pulsation on the suction side is mainly caused by the high speed of the lobes passing the edges of the suction port and sealing off the compression chambers. On the discharge side an additional effect of expansion has to be considered when the compressed air of a lobe chamber is released via the control edges of the discharge port into the discharge manifold.

In the case of the next generation air supply system the male rotor creates three pressure peaks per revolution whereas the female rotor creates five pulsations per revolution. Based on the inverse speed ratio between both rotors this results in one common order which is the 3^{rd} order of the auxiliary drive speed. In the given speed range the 3^{rd} order is varying from 60 – 990 Hz.

Timing Gear Mesh Vibration

The screw compressor applied in the next generation air supply system has a self lubricated timing gear. As the male rotor is driven the timing gear is reducing the speed for the female rotor with a ratio of 30 : 50. The related teeth meshing sound is of the 30^{th} order and varies in the range of 600 – 9,900 Hz as a function of the motor speed.

Electromagnetically Generated Noise and Vibration

The fundamental electromechanical concept of the auxiliary drive can have significant influence on the emitted noise of the air supply system. Influenced by the number of pole pairs discontinuities of the motor torque over the rotor revolution have to be taken into consideration. Torque ripples can be transmitted via the coupling to the compressor which due to relative

movement of the timing gears in the magnitude of the backlash can generate a chattering noise. As the applied auxiliary drive topology proposes a six pole rotor and a 12-tooth stator a noise emission of the 12^{th} order (240 – 3,960 Hz) and its multiples have to be taken into account.

The pole pairs of the rotor generate electromagnetic forces in radial direction which can result in an elastic deformation of the motor housing. These forces oscillate with two times of the rotational frequency [Ref.4].. Therefore for the applied six pole rotor these forces oscillate with the 3^{rd} order (60 – 990 Hz).

The frequency of the power electronics circuits of the auxiliary drive can be another NVH source. As the PWM-frequency in this specific application is set to 16 kHz and this is mainly above the human range of audibility this area is not discussed here.

Flow Noise

Pressure pulsations due to high velocity of the process air can be another source of noise. To avoid issues with flow noise the gas velocity should be limited to 30 m/s. Further the design of tubes, pipes, interfaces and manifolds must not generate tearing edges.

ANALYSIS OF THE MAIN NOISE AND VIBRATION TRANSFER PATHS

Air-borne Noise

All noise and vibration being generated in the core components of the air supply module can be emitted by the housings and be transferred via the air to the vehicle body, the driver and passengers of the vehicle and to the environment.

Pressure pulsations in the suction line can be emitted via the walls of the intake manifold to the environmental air. They can be further transferred via the process air towards the flow to the intake system and the air intake filter.

Discharge side pressure pulsations can be emitted by the outlet manifold to the environmental air. Further transmission via the process air in the tubes to the intercooler, the humidifier and the fuel cell stack has to be considered where the pulsations can be emitted by the housings to the surrounding air.

Structure-borne Noise

Structure-borne noise of the core components can be transferred via rigid joints to fastening elements, fixtures, tubes and manifolds to other process components (e.g. intercooler, humidifier, stack) and the vehicle body. All these parts can emit the noise and transfer it either via the air or via structure elements to the vehicle body, the driver and passengers of the vehicle and to the environment.

NEXT GENERATION CATHODE SIDE NVH CONCEPT AND DEFINITION OF COUNTER MEASURES

Key acceleration measurements show, that the 1st order frequency of the air supply system core components can be significant in the vehicle if greater imbalance of the rotating parts exists. Therefore mass of the rotating parts needs to be reduced and required balancing quality grade specified and controlled.

In general the applied maximum cathode system pressure level must not exceed levels absolutely required for the operation of the fuel cell stack. With respect to the system pressure level over the projected drive cycle the internal compression ratio of the screw compressor has to be optimized to generally reduce the noise level.

Key acoustic measurements show, that the 3rd order and its multiples are very significant in the suction line. As optimization potential of suction port of the screw compressor is limited an air intake muffler upstream of the compressor can be applied to an air supply system to attenuate the noise being transferred by the process air to the air intake system. Packaging and design of the subsystem have in all cases to consider that the undamped part of the connecting manifolds must be reduced to a minimum to limit the emitted air-borne noise.

Further the acoustic key tests show that as well on the discharge port of the screw compressor the 3rd order and its multiples are extremely significant. The reduction of the pressure peaks, generated on the discharge port is mandatory. Further the housing of the screw compressor has to be optimized for maximum rigidity to reduce the emitted body noise.

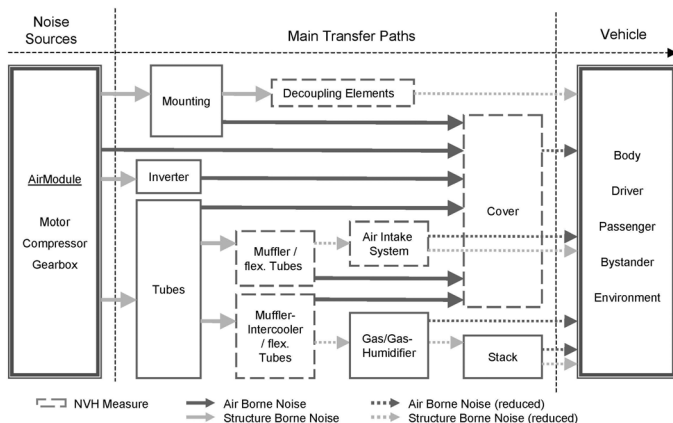


Figure 1: Next Generation Cathode Side NVH Concept

As still very high noise levels at the compressor discharge port have to be expected a muffler downstream of the compressor can be applied to the air supply system to attenuate the noise being transferred to subsequent components by the process air. To minimize the required packaging space this muffler is integrated into the intercooler.

To insulate the air supply module from the vehicle and to minimize the transfer of structure-borne noise to the vehicle body specific decoupling elements are developed to absorb structure-borne noise and to protect the air supply module from road generated shocks and vibrations.

To reduce the radiated air-borne noise the air supply system is hermetically encapsulated by a cover designed in foam / hard shell method.

DESIGN OF NVH COUNTER MEASURES

NVH COUNTER MEASURES AT THE SOURCE

In a first step mass and moment of inertia of the rotating parts had to be reduced. For the screw compressor the concept of hollowed male rotor lobes was applied. Light alloys were employed for the design of the compressor rotors, the coupling and components of the rotor of the auxiliary drive. For all rotating parts the balance quality grade of G2.5 [Ref.5] was specified.

The geometry of the compressor discharge port was optimized to meet the highest compression efficiency with respect to the fuel cell system pressure level over the projected drive cycle. Following design optimizations employed in existing automotive applications of screw compressors and roots blowers different options to dilute the discharge pressure peak were discussed. In specific slanted discharge angle, hole type pre outlets and slot type pre outlets were taken into consideration.

Key tests have shown that in combination with the applied pressure level of this specific application a double slot type pre outlet port is the most suitable trade off to dilute the discharge pressure peak without negative impact on the compression efficiency.

Comparative NVH tests with a number of screw compressors have shown that a cast discharge port geometry has significant influence on the acoustic finger print of each compressor due to casting tolerances. Derived from these results the entire discharge port geometry was specified to be machined aiming to normalize the acoustic behaviour of the screw compressor in production.

For evaluation of the influence of the torque ripple generated by the auxiliary drive the cogging torque, average torque and torque ripple at max load were analyzed for the given motor topology. The simulations indicated that the torque was oscillating with about $\pm 20\%$ and the frequency of the 12th order (240 – 3,960 Hz).

To reduce the torque oscillation skewing of rotor or stator can be considered. Arguments of producibility proposed to not skew the stator. So the skewing angle was applied by dividing the rotor into three segments each having a certain angular offset to the previous one.