

NVH of Electric Vehicles with Range Extender

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ABSTRACT

Intensive R&D is currently performed worldwide on hybrid and electric vehicles. For full electric vehicles the driving range is limited by the capacity of currently available batteries. If such a vehicle shall increase its driving range some range extending backup system should be available. Such a Range Extender is a small system of combustion engine and electric generator which produces the required electricity for charging the batteries in time.

Since the acoustic response of an electric motor driving the vehicle and of a combustion engine as part of a Range Extender is very different by nature an extensive acoustic tuning of the Range Extender is necessary to meet the requirements of exterior vehicle noise and passenger comfort.

This paper describes the NVH (noise, vibration & harshness) development work of a range extender within the AVL approach of an electrically driven passenger car with range extender. This work started with an acoustic front loading in the concept and design stage and was continued with intensive testing during combustion and engine development followed by the acoustic integration into the electric vehicle.

INTRODUCTION

The environmental situation requiring a sustainable reduction of CO₂ emissions and the repeating request for Zero Emission within cities lead to automotive powertrains with an increasing degree of electrification [1]. A German study in 2004 revealed that 70 % of the daily driving distances do not exceed 50 km. Such distances can be covered well by pure electric vehicles. However, the less frequently required longer driving distances can be enabled by an additional Range Extender (RE). Thus the AVL system approach for an electric vehicle (EV) focuses on a drive train layout for pure

electric propulsion optimized for the demands of city driving and equipped with a Range Extender module. Such a Range Extender represents a highly integrated auxiliary energy source with an excellent level of energy density and production costs compared to battery systems for an equivalent driving range [2].

The main specifications of the vehicle selected for this AVL demonstration project are given in Table 1. The basic vehicle arrangement with the electric traction motor in the vehicle front part replacing the conventional internal combustion engine and with the range extender unit beneath the trunk is shown in Fig. 1.

Table 1. Basic specifications of electric vehicle with Range Extender [3]

VEHICLE SPECIFICATIONS	
Standard small car (BMW Mini) converted to a pure electric vehicle	
Performance	
Maximum Speed [km/h]	130
Pure Electric Range [km]	~ 50
Acceleration [0 - 60 km/h in sec]	6
Occupants	4 (payload equal to conventional Mini)
Powertrain	
Electric Motor	1 central engine: 45 kW @ 1875 rpm (peak 75 kW at 3000 rpm)
HV Battery	Li-Ion Packs
Range Extender	18 kW IC engine, 15 kW generator
Weight	
Weight (kg)	< 1300

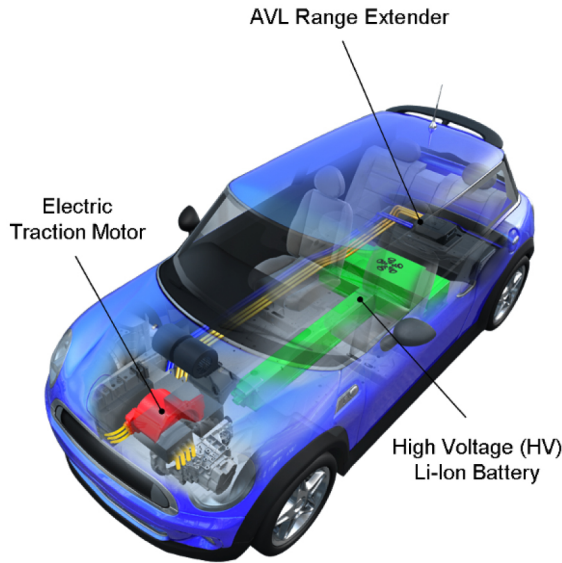


Fig. 1. Basic vehicle arrangement

Regarding the Range Extender, the major development priorities are

- Low noise and vibration (good NVH)
- Compact package
- Low weight
- Low system costs
- High system efficiency

These criteria were applied for the selection of the internal combustion (IC) engine to be used with the Range Extender. [Table 2](#) gives an overview of the assessment of the different ICE concept variants for the Range Extender.

(See [Table 2](#) after last section of paper)

The decision was made for the single rotary engine due to the advantages in packaging (very compact unit fitting excellently to the cylindrical shape of the electric generator), weight and NVH (low vibration excitation at main engine orders, small noise radiating surface). The drawback of lower efficiency (and also higher HC raw emissions) can be minimized by the RE specific operation limited to a few stationary speed/load points.

Table 3. Main specifications of Range Extender

Combustion Engine	Rotary engine (single rotor)
Displacement	254 ccm
Engine Speed	5000 rpm
Specific Fuel Consumption	260 gr/kWh
Generator Starter Machine	Permanent magnet synchronous machine
Electric Output Performance	15 kW at 320 - 420 V
Cooling System	Integr. single-loop cooling system
Control System	Integr. AVL rapid prototyping ECU
Communication	CAN bus
System Box Dim. (L x H x W)	490 mm x 400 mm x 980 mm
Noise Emission (Sound Pressure)	65 dBA (1m average level)
System Weight (ICE + Generator)	65 kg (29 kg)
Performance Potential (with single piston)	15 kW → 36 kW (= 240 %)
Interfaces RE to Vehicle	HV and 12 V connections, CAN bus, fuel supply, cooling, elastic mounts

The main specifications of the Range Extender are summarized in [Table 3](#) including a sound pressure target of 65 dBA at 1m distance. The concept to meet the acoustic target for the RE and to provide a good vehicle NVH is described in the next chapter.

ACOUSTIC CONCEPT OF RANGE EXTENDER

The initial intention was to provide a Range Extender module having all functions within the Range Extender box and using the RE box as an acoustic enclosure minimizing the interfaces to the vehicle to those of the electric power, electronic control as well as fuel and coolant supply. This means that the intake system and the exhaust system of the internal combustion engine of the RE core unit are within the RE box as illustrated in [Fig. 2](#). Therefore, the RE box needs an air inlet and an air/exhaust outlet. The incoming air is split into the intake air of the IC engine and cooling air ventilating the RE box. In the outlet section of the RE box, the exhaust gas is mixed with the box cooling air (for dilution and cooling down) and blown out.

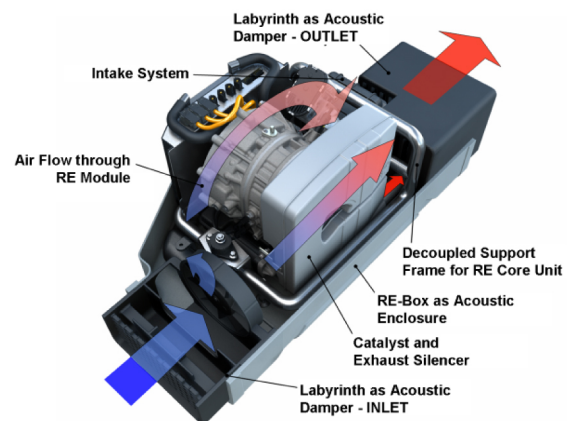


Fig. 2. Scheme of Range Extender module

Since the RE box works as an acoustic enclosure, the inlet and outlet sections have to be designed as acoustic labyrinths with high sound attenuation for low sound pressure levels outside the box. The main noise contributions inside the RE box are intake and exhaust orifice noise, surface noise from the intake and exhaust system, surface noise from the IC engine and generator unit and fan noise from the box ventilating fan.

Besides the control of airborne noise transfer through the RE box, the control of vibration transfer to the RE-box and to the vehicle body is of paramount importance. For this purpose, a decoupling system as shown in [Fig. 3](#) was applied. The core structure of the RE unit is the central support frame. This frame carries the RE core unit with the generator and IC engine via three elastic mounts and also the RE box via four elastic mounts. In addition, the frame carries the exhaust system (consisting of the catalyst and exhaust silencer), however, not decoupled via rigid brackets. Therefore, the support frame is installed in the vehicle in a decoupled way via four rubber mounts. The complete system includes some further decoupling and elastic sealing as mentioned in [Fig. 3](#) in order to avoid any disturbing vibration transfer to the RE box.

(See [Figure 3](#) after last section of paper)

A further key element of the acoustic concept is the internal combustion engine in terms of a rotary piston engine as shown in [Fig. 4](#). Regarding acoustics, this type of engine is characterized by low vibration excitation in the main engine orders due to 100 % balancing and low surface noise due to its compact design and small outer surface.

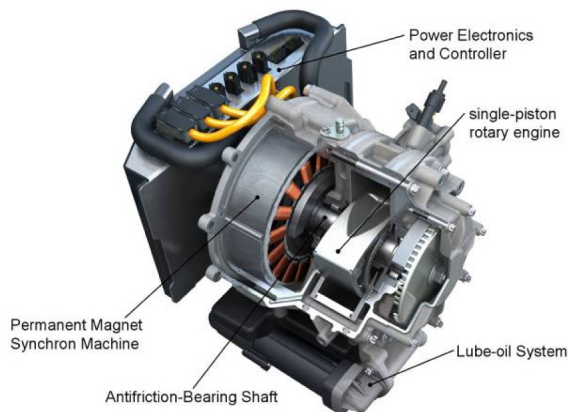


Fig. 4. RE core unit with generator (PM synchronous machine) and rotary piston engine

Thus, the acoustic concept can be summarized as follows:

- Rotary piston engine (for low noise and vibration)
- Acoustic encapsulation of RE with complete intake and exhaust system by RE box with two acoustic labyrinths (for low noise radiation from RE module)
- Enhanced decoupling system (for low vibration transfers to RE box and to the vehicle)

(See [Figure 5](#) after last section of paper)

NVH DEVELOPMENT AND RESULTS OF RE

The acoustic performance of the RE box labyrinths was considered as one of the key elements for low overall airborne noise emission of the Range Extender. Therefore, the acoustic development of the labyrinths was started with first tests already in an early stage when the generator and IC engine were not yet available as test parts. For this purpose, the labyrinths were made by rapid prototyping and installed in a RE dummy box. The airborne noise excitation was applied via loudspeakers in the box using airborne noise records from a similar rotary engine and synthesized orifice noise (first 5 orders) with estimated levels. As illustrated in [Fig. 5](#), the sound attenuation of the acoustic labyrinths reaches nearly 30 dB in the overall noise level.

The first results of exhaust muffler orifice noise measured under real operation of the rotary piston engine on the test bed are shown [Fig. 6](#). The orifice noise levels of the highest engine orders (mainly first and second order) are higher than the levels estimated for the loudspeaker tests of [Fig. 5](#) for both intake and exhaust orifice. In addition, the results of [Fig. 6](#) reveal that the exhaust orifice noise levels are approx. 10 dB higher than that of the intake orifice.