

Simulation Methodology for Consideration of Injection System on Engine Noise Contribution

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ABSTRACT

The target of the investigation is the particular influence of a fuel injection system and its components as a noise source in automotive engines. The applied methodology is demonstrated on an automotive Inline 4-cylinder Diesel engine using a common rail system.

This methodology is targeted as an extension of a typical standard acoustic simulation approach for combustion engines. Such approaches basically use multi-body dynamic simulation with interacting FEM based flexible structures, where the main excitation crank train, timing drive, valve train system and piston secondary motion are considered. Within the extended approach the noise excitation of the hydraulic and mechanical parts of the entire fuel system is calculated and subsequently considered within the multi-body dynamic simulation for acoustic evaluation of structural vibrations.

The injection system is divided into its three main subsystems, the injector, the fuel pump and the common rail, and stepwise each of them is analyzed as a separate noise source. All three components are modeled as subsystems by 1D hydraulic model and finally combined to the complete fuel injection system. Moving mechanical components of the fuel pump are considered as additional multi-body components and connected to the timing drive. Fuel pump housing and the rail are modeled as Finite Element structures and attached to the engine model.

Resulting transient loads are injector forces, pressure pulsation in fuel pump chambers and the common rail. Those

are applied as external loads to the timing drive model and the power unit structure.

The paper focuses on the modeling technique and presents the obtained results and a basic comparison with measurements.

INTRODUCTION

Rigorous legislative regulations demand significant reduction of required system resources and emissions regarding CO₂, fuel consumptions as well as noise. To meet these demands in combination with requirements for light and compact design and low costs, the complexity of power units is increased, which extends the importance of simulation in the engine design process. Higher system complexity, dependency and interaction of different effects and the requirement in understanding the contribution of even small changes to the overall behavior, results in more extended simulated systems to predict the influence of a specific component in system context. In addition the targeted components and sub-systems are getting more detailed.

One of the main challenges to bring NVH analysis of power units closer to reality is to simulate and consider all excitation sources, transfer paths and radiating structures, contributing to the target frequency range. The investigation of indirect noise generation via interaction of mechanical components and the direct noise generation via orifice (intake and exhaust system) are well established. Indirect noise generation focuses on the crank train; valve and timing drive and for some years also on the transmission and partly auxiliaries (see [Fig. 1](#)).

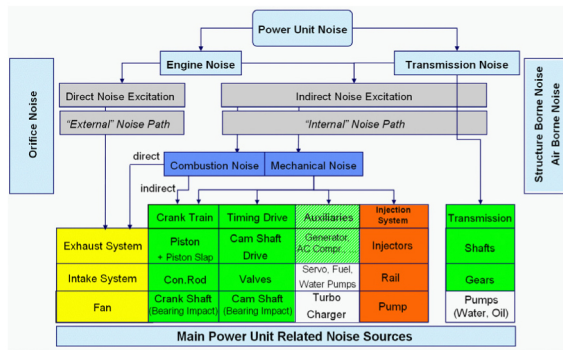


Figure 1. Power Unit Related Noise Sources

There is potential for improvement in representation of the fan, auxiliary parts as for example pumps and charging system, and the entire injection system.

The effect from injection systems is mostly considered as additional forces on cam shafts in the case of unit pumps (e.g. from measurements) or similar simplified approaches. The accuracy of such loads is often rather low. The effects of common rail systems are typically neglected, although they can generate significant loads due to high pressure waves inside the rail, which can excite the cylinder head cover. Also high frequency content in forces of injectors and the common rail pump itself can have valuable contribution to overall power unit NVH [1].

The presented solution procedure extends the state of the art numerical NVH simulation methods by consideration of the effect from the entire fuel injection system (FIS) on engine vibration and noise. It is based on combining different tools, developed by AVL.

As a basic engine model a passenger car 1.9 liter Inline 4-cylinder Diesel engine with a modern common rail system is used and basic validation is performed with some of the available measurements.

DEVELOPED WORKFLOW

Multi-body dynamic (MBS) software AVL EXCITE Power Unit (PU) [2] is used as the primary tool for the presented NVH simulations. This model includes the flexible power unit structure and the crank train interaction. The complete model of valve train driven by timing belt is modeled within the EXCITE module Timing Drive (TD), which can be coupled to the power unit in an offline modus, by applying resultant loads or online in sense of a co-simulation [3].

To improve this approach, the components of the fuel injection system are modeled, hydraulic and mechanical interaction is calculated using EXCITE TD and HYDSIM and considered as additional excitation sources (see Fig. 2).

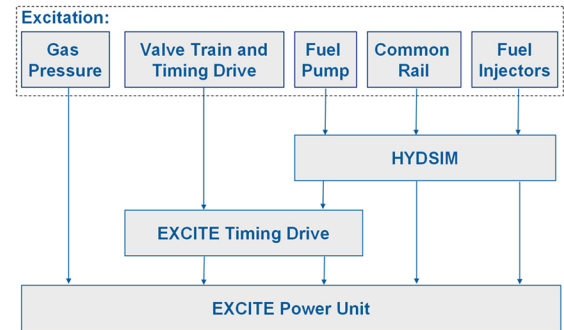


Figure 2. Developed workflow to consider FIS excitation in NVH simulation

The injection system consists of three main subsystems, the injector, the fuel pump and the common rail.

Analysis of the FIS is separated into the hydraulic excitation and the additional interaction of mechanical parts inside the fuel pump.

HYDRAULIC EXCITATION

The hydraulic part of the FIS is calculated separately with a 1-D hydraulic simulation approach. Mechanical elements of the FIS are considered inside the hydraulic model to cover the interaction and the effect on resultant excitation loads correctly.

Results are the injector dynamic forces, hydraulic excitation of the fuel pump and the pressure pulsation within the common rail. The pump loads are applied as external excitation in an intermediate step onto a separate mechanical model of the fuel pump. The other loads are directly applied onto the structural model of the power unit within EXCITE PU, as shown by Fig. 2.

MECHANICAL EXCITATION

In addition to the hydraulic model a structural model of the moving mechanical parts of the fuel pump is set-up and integrated into the timing drive model.

Pressure pulsation in high pressure pump chambers, derived from previous hydraulic simulation, is used as external excitation inside the pump model. Resulting pump bearing and chamber forces are applied again as excitation to the power unit model.

EXCITE PU and TD are offline coupled for the current investigation, but the created model is also capable for the co-simulation.

FUEL INJECTION SYSTEM

For the present paper AVL HYDSIM is used for simulation of the hydraulics inside the FIS. It is a program for the dynamic analysis of hydraulic and hydro-mechanical systems based on the theory of fluid dynamics and vibration of multi-body systems.

The program is applied in a variety of fields concerned with dynamic analysis of hydraulic and mechanical systems. One of the main application areas is the simulation of fuel injection systems. Primarily, the program has been developed for the simulation of diesel injection.

Three independent simulation models of the main sub-systems are generated, which are the injector, the high-pressure pump and a simplified model of the common-rail. Afterwards these sub-systems are combined to the entire FIS.

A fixed set of input parameters is associated with each element. They may be geometry, flow characteristics, solid or fluid properties. The main outputs are pressure and rate for hydraulic elements and coordinate, velocity and/or acceleration for mechanical elements.

INJECTOR

The investigated injector is a BOSCH 2nd generation injector model. The simulation model contains various hydraulic, mechanical and hydro-mechanical elements (see Fig. 3). For a better overview the elements are joined into groups according to their type and functionality. A group of elements are marked with a green line that shows the simplified functionality of the common-rail with task to keep the acquired supply pressure. Volume type elements are responsible for pressure generation and line type elements are responsible for flow dynamic simulation. In front of them is a high pressure pump represented only as boundary pressure source. A group of elements are marked with a red line that represents the solenoid actuator with valve seat. The main element is solenoid armature (7) actuated by a magnetic force. Magnetic force is a function of the actuation amperage and armature lift. The rest of the model is a standard CR injector with its nozzle (14) and control volume (2) sides.

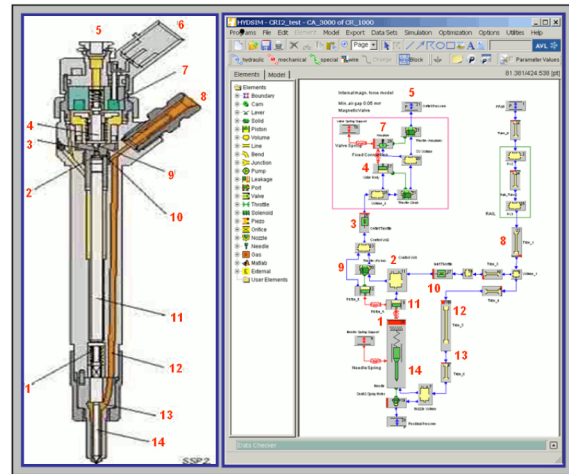


Figure 3. Injector model

The injection process is initiated by energizing the solenoid valve by the ECU. As a result, the outlet throttle opens. Fuel flows through the control volume towards the solenoid volume, and as a result the pressure in the control volume drops. The pressure difference between the top and bottom sides of the needle pushes the needle up, at the same time opening the injection nozzle. After some time the needle reaches the stable open position resulting in the optimum injection of fuel into the cylinder. When the solenoid valve is deactivated by the ECU, the spring in the solenoid valve closes the outlet throttle in the injector. As a result, the pressure in the control volume increases. The pressure on the top side of the control piston, together with the nozzle spring force, closes the nozzle and injection process ends.

The injector is primarily modeled in order to study its hydraulic characteristics like injection-rate, injection pressure, spray characteristics etc. But for the present investigation, the focus is on the calculation of all forces of the individual components which act on injector housing.

There are several possible force sources inside the injector and transfer paths to injector housing. Forces acting within the injector are calculated for one engine cycle and summed up to get resultant force acting on the injector base.

HIGH PRESSURE PUMP

A radial, 3-piston pump is used as the high-pressure pump for common-rail fuel pressure generation (see Fig. 4). The pump shaft is driven by the toothed distribution timing. Fuel pressure is generated independently of the injection process.

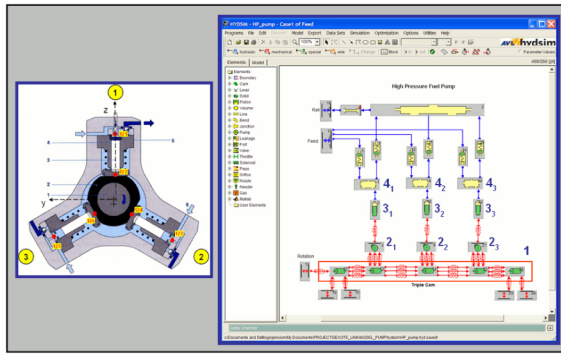


Figure 4. High Pressure Pump model

The high pressure is obtained from the action of three small plungers being arranged in radial position at an angular distance of 120°. The altering movement of them is assured by a triangular cam connected to the pump's shaft.

The pump does not require the phasing since the instant and time of injection are being entrusted to the control unit, which manages the opening of the injectors.

A hydraulic model of the high pressure fuel pump is driven by crankshaft angular velocity as boundary condition. The calculated 1D pressure in pump chambers is recalculated to forces acting both on chamber and pump shaft.

The hydraulic model is simplified to a shaft (1) with 3 cams (2), which push 3 plungers (3). Plungers generate pressure inside the pump chambers (4) (see Figure 4). These pressures act on volume walls and back to the plunger pressurized area. Forces are transferred to the pump housing via volume walls, and via the plunger and cams back to the pump shaft.

To get a more realistic model, which will include additional mechanical excitation, an equivalent fuel pump model is build up within an existing timing drive model. Using this model, also dynamic effects coming from crankshaft and timing drive are considered. In addition pressure in pump chambers is applied as load boundary condition acting on the pump plungers. The calculated rotor bearing forces are applied as additional excitation on the power unit model.

COMMON-RAIL

The fuel rail is mounted to the cylinder-head cover and distributes regulated high-pressure fuel equally to the fuel injectors.

At the same time, the pressure oscillations, generated due to the high-pressure pump delivery (1) and the injection of fuel (3), are damped by the rail volume (2). Even when large quantities of fuel are extracted, the fuel rail maintains a constant inner pressure. This ensures that injection pressure

remains constant from the instant the injector opens until the end of the injection event.

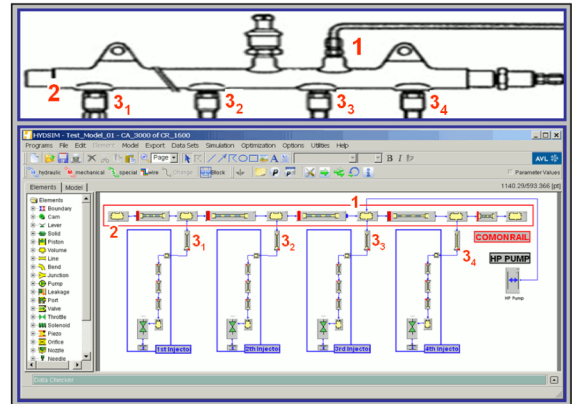


Figure 5. Common Rail Model

Two types of elements are used for modeling of the common-rail, volumes and pipes (see Fig. 5). Pipe elements are responsible to simulate propagation of shock waves through the rail and they are modeled with rigid walls. Volume elements are taken because they can calculate forces as a result of pressures on common-rail walls.

ENTIRE FIS

The sub-systems are combined to the entire fuel injection system (see Fig. 6).

Together with the timing drive model of the high pressure pump the resultant FIS loads are applied to the final power unit MBS model.

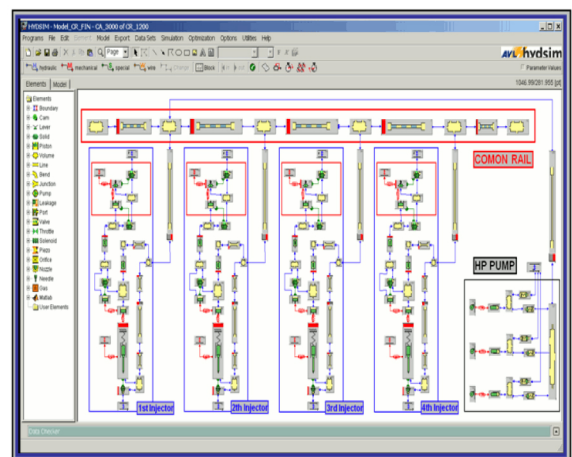


Figure 6. Entire FIS model