

Analytical and Developmental Techniques Utilized in the Structural Optimization of a New Lightweight Diesel Engine

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ABSTRACT

Jaguar Land Rover (JLR) has designed and developed a new inline 4 cylinder engine family, branded Ingenium. In addition to delivering improved emissions and fuel economy over the outgoing engine, another key aim from the outset of the program was to reduce the combustion noise.

This paper details the NVH development of the lead engine in this family, a 2.0 liter common rail turbo diesel. The task from the outset of this new program was to reduce the mass of the engine by 21.5 kg, whilst also improving the structural attenuation of the engine by 5 dB in comparison to the outgoing engine. Improving the structural attenuation by 5 dB was not only a key enabler in reducing combustion noise, but also helped to achieve a certified CO₂ performance of 99 g/km in the all-new Jaguar XE model, by allowing more scope for increasing cylinder pressure forcing without compromising NVH.

To achieve this structural attenuation target, an intensive program of CAE analysis, rig testing and full powertrain measurements in an Engine Noise Test Cell (ENTC) were undertaken on three progressive levels of prototype engines. Details are included of the key hardware changes that were implemented to deliver the target attenuation, as well as the correlation that was achieved between CAE, rig and full powertrain testing.

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INTRODUCTION

In order to achieve JLR's ambition of delivering class-leading levels of refinement, a range of engine level NVH targets were set at the outset of the program. Different metrics were chosen across the full operating window that a customer will experience, with the aim of avoiding a wide variety of different error states.

This paper focuses on the development process for meeting one of those targets, structural attenuation, which is critical for controlling combustion noise. Structural attenuation is defined as the cylinder pressure minus the combustion noise, in other words, an improved structural attenuation will result in lower combustion noise for a given cylinder pressure.

Combustion noise targets across the full speed/load range of the engine were cascaded from vehicle testing on the existing product; this was undertaken by sweeping parameters such as injection timing in order to reduce combustion noise to the point of inaudibility inside the car, whilst simultaneously measuring cylinder pressure. To achieve these levels of refinement a reduction of up to 8 dB was required at the worst speed/load points on the engine map, therefore it became clear that to deliver the targets would require a step change in the structural attenuation. By comparing the existing product to the

competitor spread, it was determined that a 5 dB improvement was realistic; the following paper describes the methodology for achieving this.

STRUCTURAL ATTENUATION METHODOLOGY

Various techniques have been proposed for determining the structural attenuation of an engine. During the development of this engine two different measurement techniques were compared, both of which aim to determine the structural attenuation from the measured cylinder pressure to four microphones at the standard 1m locations [1]. Both these techniques have advantages and disadvantages as described below.

Banger Rig

The "Banger Rig" at the Institute of Sound and Vibration Research (ISVR) calculates the structural attenuation of a non-running engine by utilizing a charged mixture of propane, air and oxygen [2]. This is repetitively ignited in one of the combustion chambers to provide a transfer function from that cylinder to the four microphones.

The main advantage of this technique is that it is carried out independently of any mechanical noise sources and therefore gives a true indication of the structural attenuation; this process can then be carried out for each cylinder to determine any differences through the engine. The main disadvantage is that the measurement takes place on a dedicated third party facility, which is only capable of running this specific test. With limited prototype hardware and a requirement to work on several NVH issues simultaneously, JLR were keen to compare Banger Rig results to the structural attenuation calculated from an algorithm generated from a running engine in a standard ENTIC.

Combustion Mechanical Breakdown (CMB)

The CMB technique that was utilized by JLR was similar to the multiple regression technique described by Hirano et al [3]. The engine is run at a series of steady speeds, with the load swept from 0 - 100 % at each point. Radiated noise, cylinder pressure and load are measured simultaneously, allowing the algorithm to determine the split between combustion noise and mechanical noise in each third octave band. Finally, the calculated structural attenuation is averaged across the speed range to give a single number for that engine build.

A comparison of the two test methods is shown in Figure 1. Whilst the results are very similar across the mid frequency range, there is an offset at higher frequency, with the CMB method showing an improved result (lower is better due to negative scale).

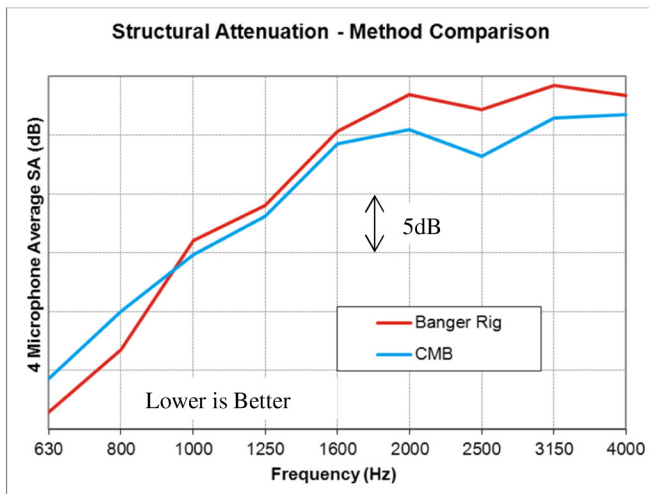


Figure 1. Comparison of Banger Rig and CMB methods for calculating structural attenuation.

The main reason for this offset is the engine oil damping, which is not present in the Banger Rig test. This damping has a significant effect on the panel modes of the sump, as measured on a previous engine, Figure 2. Despite this offset, the salient modes are clearly predicted by both methods, therefore the decision was taken to utilize the CMB method to develop engine hardware through developmental testing. Confidence in this technique was further increased by assessing engine-to-engine, test cell-to-test cell and calibration-to-calibration repeatability, with good repeatability experienced across these measurements.

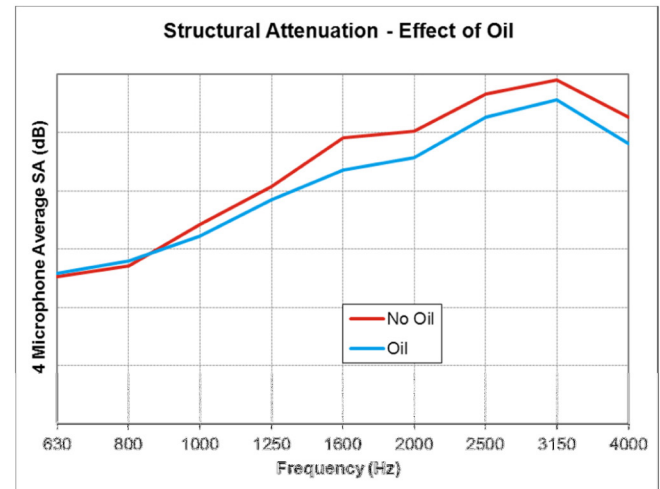


Figure 2. Improvement in Banger Rig attenuation that was achieved by filling the sump with oil.

CAE METHODOLOGY

Rather than wait until physical prototypes were available, a virtual simulation process was implemented using the finite element technique. In order to be effective, this virtual process was required to produce the same results as the physical test, with a degree of accuracy that would allow the results to be used to steer important design decisions with confidence. A virtual procedure was therefore developed and implemented that would replicate the Banger Rig test.

The virtual process that was implemented was based on the finite element software ABAQUS. A steady state forced response analysis was used to determine the response of the engine structure to a frequency domain input. The resultant surface vibration of the engine structure was then further processed to calculate a surface based radiated sound power and finally the structural attenuation. Figure 3 highlights the key steps in the CAE process:

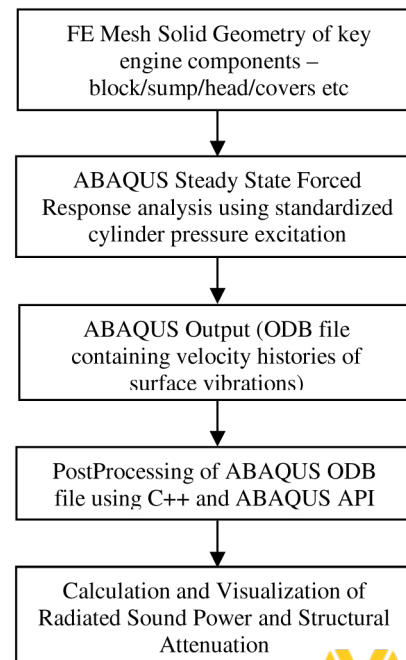


Figure 3. Key steps in the analysis process

The CAE process can be utilized to assess the response of either a fully dressed engine assembly, if details are available, or a subset of components considered major sources of radiated noise. For early design decisions the engine assembly analyzed was limited to the core components comprising of cylinder block, cylinder head, oil sump, front and rear covers, structural windage tray and the complete cranktrain (including damper and flywheel). The CAE model of the engine assembly for an early prototype is shown in [Figure 4](#).

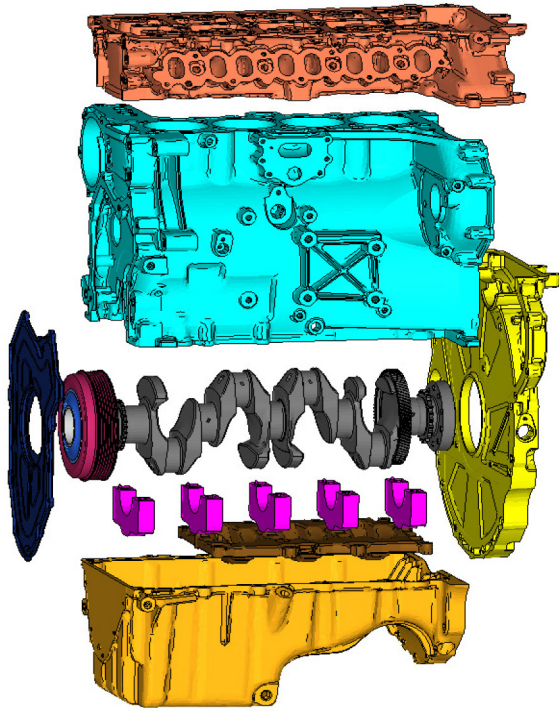


Figure 4. Core components analyzed in engine assembly

To facilitate easy model creation and subsequent speed of analysis the engine assembly was created using the *TIE constraints available within the ABAQUS software. This constraint rigidly connects the contacting surfaces between parts of the assembly. More detailed modeling of joints and interaction between components was considered and tested as part of the correlation of the CAE process, however, the improvements in accuracy resulting from these changes in modeling approach were considered too small in comparison to the increase in time associated with model creation.

However, given the importance of the dynamics of the crank system and the influence of this on the overall vibration of the system, the interaction between crankshaft and main bearings was considered in more detail. A standard technique of attaching crank journals and main bearings using rows of spring elements was employed such that the crank dynamics were predicted and at the same time direct forces and moments to the bearing panels were transferred appropriately.

In order to correctly model the effect of a transmission on the lower frequency modes of the assembly it was important to have some representation of the large mass and inertia attached to the rear of the

engine assembly. Again, in order to facilitate an acceptable analysis time a solution was adopted which provided a good balance between analysis set up, analysis run times and accuracy of prediction. The solution adopted was the use of an ABAQUS substructure to represent the transmission mass and stiffness.

As the purpose of the CAE process was to augment an existing test, the forcing applied to the model reflected the physical counterpart. The Banger Rig test, applies an explosive ‘firing’ event to a single cylinder, starting with the piston at Top Dead Centre (TDC). Similarly, the crankshaft system in the model was rotated such that the crankpin of the ‘fired’ cylinder was at TDC. A frequency dependent force was then applied to the crankpin and an equal and opposite force applied to the center of the cylinder on the flame face of the head. Since the piston remains at TDC throughout the load history no radial force was applied to the cylinder bore.

The effect of ‘firing’ each cylinder was analyzed by rotating the crankshaft such that each piston was at TDC and applying the same forcing accordingly. For correlation to a structural attenuation of a ‘running’ engine, an average was then taken for all cylinders.

The results from the ABAQUS forced response analysis are surface vibrations (velocity) throughout the frequency range excited. On their own the surface velocities are of limited value. In order to extract more meaning from these results and to again replicate the output of the physical Banger Rig test a further post-processing step was applied. This was achieved by utilizing the ABAQUS API supplied with the software and a C++ program written within JLR, which could read the nodal values of surface velocity and calculate a radiated sound power using a simple summation over the radiating surface.

$$SW = \sum eff.A.v^2.p.c$$

Where SW is the total sound power, eff radiation efficiency A area of a surface element, v nodal surface normal velocity, p density of the acoustic medium and c the speed of sound in the acoustic medium

The radiated sound power could then be plotted as a contoured value on the FE model giving a valuable indication of the areas of the structure which were radiating noise at frequencies throughout the spectrum. Together with the ability to visualize the power being radiated from the model the sound power could be integrated over the surfaces associated with each component in the assembly in order to generate a ‘source ranking’. This was later used to focus attention on design changes of those components responsible for the largest or dominant sound power.

In addition to being able to visualize the contoured radiated sound power from the surfaces of the FE model, these results could also be read back into the original ABAQUS results database to be overlaid with and animated using the forced response displaced shape. [Figure 5](#) shows a typical radiated sound output at a key response frequency.