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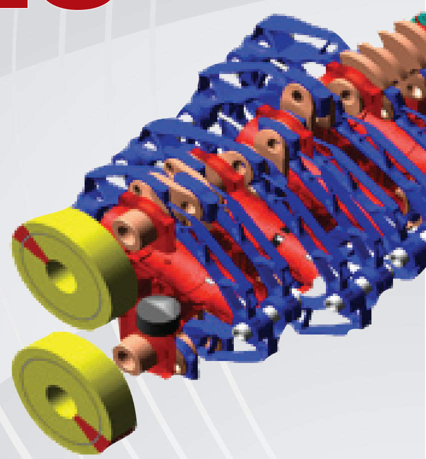
ACHATES POWER

Structural Dynamic Analysis of an Opposed-Piston Engine with Flexible Support



Abstract

Achates Power, Inc. is developing a lightweight, low-emissions and low fuel consumption two-stroke, opposed-piston diesel engine designed as a modular and scalable mechanism termed A40. Achates Power places heavy emphasis on modeling and simulation through state-of-the-art analytical tools and methods.

Within the structural dynamic analysis arena, the focus is on overall dynamics, such as torsional and bending vibrations, including torsional vibration damper (TVD) and flywheel layouts, as well as (hydrodynamic) bearing analysis. The emphasis is on identifying areas of conceptual, structural and dynamic improvement with regard to overall dimensions and weight. A hybrid approach is utilized, thus combining the advantages of multi-body simulation (MBS) and finite element analysis (FEA).

This paper specifically discusses the application of structural dynamic simulation based on MSC Adams software with regard to:

- The influence of the engine block support structure sensitivity on bearing loads: The A40 opposed piston engine has comparably small main bearing loads relative to the peak cylinder pressure (PCP) due to the partial cancellation of forces during the opposed motion of the reciprocating masses. This allows for aggressive weight optimization of the support structure while maintaining sufficient bearing support.
- The mitigation of gear resonances: The two crankshafts of the mechanism are timed by a set of gears. During testing, a gear resonance within the operating speed range was detected that induced a substantial load on the neighboring main bearings. A sensitivity study was performed to find the optimum solution for removing the resonance from the speed range.

Introduction

A world with finite supplies of petroleum and limits on carbon dioxide emissions demands fundamentally better engines with increased fuel efficiency. Compared to conventional engines currently on the market, opposed piston diesel engines have a thermodynamic advantage (no heat rejection into cylinder heads) and the potential for lower friction (no valve-train and low piston side loads) leading to substantially better fuel efficiency. A further advantage of this engine architecture is the decreased cost due to a lower parts count while maintaining ordinary manufacturing methods. Opposed-piston engines, besides their thermodynamic advantages, naturally have a weight advantage over conventional engine architectures due to being a two-stroke engine and due to the lower complexity of the engine mechanism. To further reduce weight, while maintaining adequate durability, advanced analysis methods are required that combine multi-body simulation (MBS), finite element analysis (FEA), optimization and fatigue analysis.

Adams-based FEV Engine has been used as the MBS software of choice to reduce the number of degrees of freedom (DOFs) of core components like the crankshaft and engine block while retaining nearly complete structural information. This approach allows for reasonable runtimes in order to explore a large range of operating conditions while maintaining full component interaction.

Model

In an opposed-piston engine, two facing pistons in a single cylinder come together at top dead center and move apart under combustion.

The opposed-piston A40 engine architecture incorporates an innovative mechanism to drive the pistons. The two pistons are being connected to two crankshafts via six connecting rods per cylinder with the intent to create a purely axial piston motion and ideally no piston side forces. The connecting rods are in permanent tension and thus, lead to main bearing reaction forces feeding into the block rather than the bearing cap. In addition, the nature of the A40 opposed piston motion leads to partial cancellation of the combustion forces. These two effects allow for a lightweight support structure. The two crankshafts are connected via a gear train and a single flywheel is mounted on the output shaft. Figure 1 illustrates one view of the A40 4-cylinder cranktrain model in the flexible support structure in addition to a rear view of the gear train. The mechanism may appear complex at first sight but, in actuality, it is composed of approximately half the number of components of a conventional engine.
The results demonstrated in this work will focus on a 4-cylinder version of the Achates Power A40 engine.

With the different levels of refinement offered in the Adams software, the cranktrain was moved from a purely kinematic component model with rigid components and constraint bearings into a fully flexible model supported

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by hydrodynamic bearings. The Adams software conveniently allows for replacing any component with its flexible representation and thus, increasing the accuracy of the analysis.

The software combines the advantages of a general purpose, open architecture MBS code with an engine component library. Hence, it provides "push button" implementation of engine-specific components like the connecting rods, pistons and many others. As a result, the requirement of this multi-crankshaft and multiple connecting rods-per-cylinder mechanism is adequately supported within Adams.

The timing gear module has been used to model the gear train dynamics including gear contact and backlash and thus, allowing for full component interaction in the mechanism. The gear stiffness and cold backlash have been determined experimentally and provided as input to the model. Based on the gear attachment locations, material combination and temperature, the backlash under the operating temperature has been calculated. As backlash and meshing errors can cause significant impulsive excitation of the whole mechanism, it is crucial to accurately model these parameters.

Approach

A hybrid approach of MBS and FEA has been chosen for the structural dynamic analysis of the A40 mechanism. The first step of this approach determines the modal-neutral file (MNF) of the crankshaft and block based on the Craig-Bampton method [1, 2]. The method allows the selection of a subset of DOFs that are preserved during the modal reduction that can be used as interface nodes in the MBS model. For example, placing such DOFs at the bearing locations allows for convenient monitoring of bearing deflections under various engine operating conditions. The advantage behind modal reduction is the greatly reduced number of DOFs, while maintaining near complete modal (inertia and stiffness tensor) information along with the modal stress.

As a second step, the component MNFs are imported into the Adams model in order to achieve the best possible representation of the structural stiffness of the mechanism. The third step involves setting the boundary conditions, like gas pressure traces, oil viscosity and temperature which can be easily accomplished within Adams. Lastly, the MBS analysis is performed to analyze various aspects of engine dynamics: torsional and bending vibrations, the effect of torsional vibration damper (TVD) and flywheel lay-outs, as well as bearing analysis. In this scenario, particular emphasis has been placed on identifying areas of structural and dynamic improvement that would result in a reduction of overall dimensions and weight.

At Achates Power, Inc., this hybrid approach is routinely used in all stages of development including sensitivity studies and root cause analyses. The approach is continuously being improved and refined in the area of component optimization and durability analysis. Additionally, the modal stresses and participation factors are superimposed and reverted into a stress tensor as basis for subsequent fatigue analysis (not described here).

Support Structure Sensitivity

In the A40 mechanism, the port timing is generated by the respective phasing of the exhaust and intake connecting rods. The two counter-rotating crankshafts are identically symmetric and in phase. Therefore, the combustion forces are partially cancelled. As previously cited, the reverse architecture leads to main bearing forces that react to the block/crankcase rather than to the main bearing caps. These two effects allow for a lightweight support structure in relation to the PCP achieved with the Achates Power A40 engine.

Early on in testing, it became apparent that the limitations for the structure's weight reduction would be determined by its capacity to support the crankshafts. The torsional and bending deflections of the crankshaft are a first indication for durability and noise and vibration harshness (NVH). The analysis started with a rigid block structure, which was subsequently replaced by a flexible representation.

The fully-coupled crankshaft bending results from incremental block refinements are shown in Figure 2.

As expected, the block representation has hardly any influence on the crank torsional behavior (not shown). However, the impact on the crank bending is significant. With the rigid block, a dominant 4th order excitation is observed with a resonance at 3,000 rpm. In comparison, the response of the flexible block shows all orders from one through four with the frequency content shifted. Despite the crank-bending amplitudes satisfying the Achates Power requirements, a higher block stiffness would further reduce crank-bending. Hence, the block stiffness was artificially increased by 20 percent to demonstrate the improvement (see Figure 2).

In addition to investigating the effect of the block stiffness, the method can also be used to guide the design toward local stiffness improvements while keeping the weight down.

Gear Resonance Mitigation

During the early A40 4-cylinder mechanism testing, a gear train noise/resonance was observed. Although this particular engine was only instrumented with two strain gage sensors, the measured gear train resonance has been qualitatively reproduced with the Adams/Engine model. The result is shown in Fig. 3.

The Adams model has subsequently been used to perform an extensive parameter study

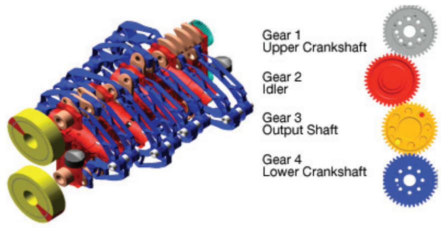

Figure 1: Adams/Engine Crank Train model with Flexible Components and Rear View

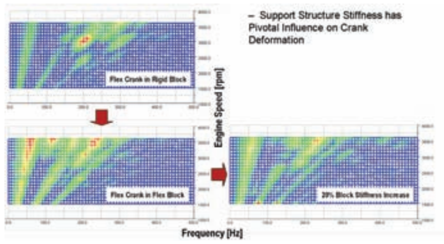

Figure 2: Support Structure Sensitivity, Influence on Crank Bending

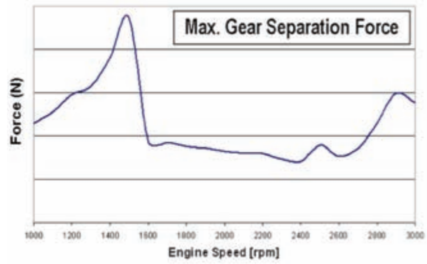

Figure 3: Maximum Gear Separation Force Over Engine Speed

to find the root cause and solutions to the observed gear resonance. From the many ideas of how to mitigate the gear resonance, only some selected results are presented here. The potential solutions are divided into three categories:

1. No or minor impact on the mechanism design
2. Medium impact on the mechanism design
3. Major impact on the mechanism design

The solutions in the first category include, among others, the reduction of gear backlash and flywheel inertia. From a tolerance and manufacturability standpoint, the backlash could be reduced to as low as 40 percent of the current design backlash leading to a bearing load reduction of only 20 percent which is deemed insufficient. The reduction of the flywheel inertia to 50 percent of its original value, or a complete removal of the flywheel (zero inertia), has very little if any impact on the resonance characteristics. Interestingly, the dynamic study shows that the engine could be run entirely without flywheel which would save 13.7 kg in the overall engine weight.

In the second category, two solutions involving architectural changes seem promising: moving the power-take-off to the lower crank or helical gears. The former approach shows the best results when combined with TVD and flywheel inertia tuning. This solution has been pursued in design but not yet in hardware. In addition, due to presence of gear separation under any given load situation and for NVH

Solutions from the third category would involve significant redesign and impact on engine package. For example, a single flywheel on the output shaft could be replaced with one flywheel on each of the crankshafts, using two large gears instead of the four gears, or moving the TVDs to the rear end of the crankshaft. Even though all of these modifications are holding some promise, the redesign effort is best incorporated into future engine designs.

Each of the graphs in Figure 4 show time domain data at 1,500 rpm resonance speed.

In order to account for even minor speed shifts, a full speed sweep has been run for each case. Figure 5 illustrates the results of the speed sweep as a shift of the resonance above the current speed limit of 2,800 rpm.

Correlation

Among other correlation efforts, the crank nose speed fluctuation has been measured with a crank angle encoder. The comparison between test and simulation is shown in Figure 6.

Two speeds are shown within Figure 6. One speed is below the gear resonance and the other is in the upper speed range of the engine (see also top of Figure 5). With the exception of a slight over-prediction of the 4th order contribution, the correlation between simulation and test at 1,200 rpm is already very good. However, at 2,800 rpm, the frequency and time correlation is excellent.

Summary and conclusion

The increasingly demanding emissions and fuel consumption requirements are not only a challenge for the performance prediction, but also for the structural dynamic aspects during the engine development process.

This paper outlines a suitable method for evaluating the structural viability of an engine architecture. Additionally, the potential for supporting structural improvement, root cause and solution analysis have been demonstrated with the Achates Power A40 architecture serving as the example. The simulation shows the importance of capturing the effects of a flexible support structure and integrating cranktrain and geartrain dynamics.

With the selected approach it is possible to evaluate the influence of the support structure and gear interaction effects under specific engine working conditions. This approach also allows for clear design recommendations based on the analytical results.

Most importantly, the analysis confirmed the structural integrity and sound design of the Achates Power, Inc. A-40 mechanism and permutations thereof. The Achates Power, Inc. A-40 is a viable mechanism and an effective means of power output for an opposed-piston engine. ■

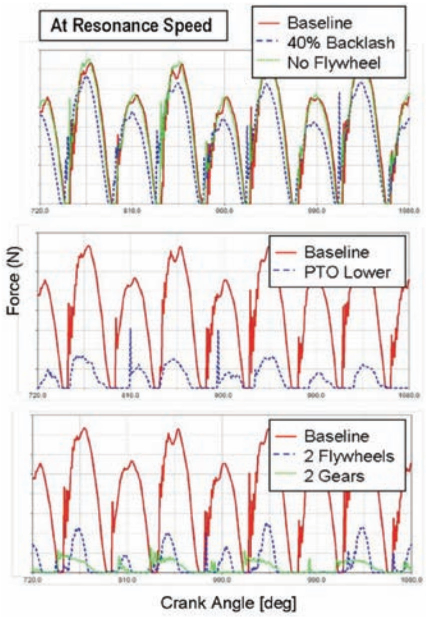

Figure 4: Selected Solutions of the Gear Resonance Mitigation Study

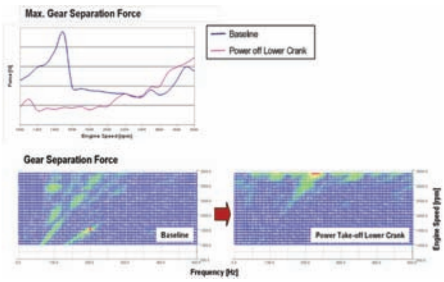

Figure 5: Solution for Gear Resonance: Power Take-off Moved to Lower Crankshaft

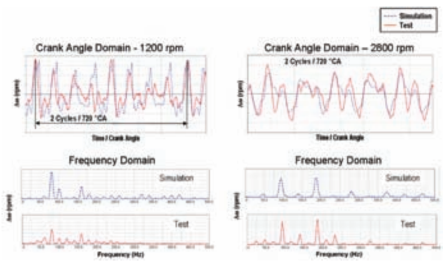

Figure 6: Correlation of Crank Nose Speed Fluctuation

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2. Adams/Flex Training Guide, Appendix D, Theoretical Background, www.mscsoftware.com

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Continued from page 21 (Innova Engineering) >>> unacceptable part performance and will likely necessitate a redesign.

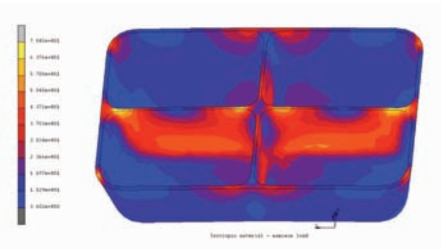

Figure 9: Isotropic Material Model

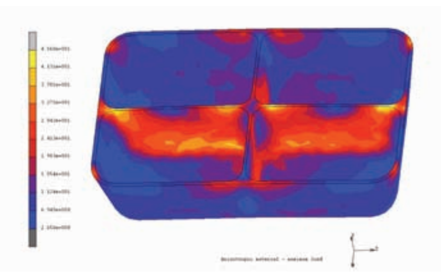

Figure 10: As-Molded (Anisotropic) Material Model

Now, let's rerun the job with all conditions identical, except this time we will consider the as molded material conditions, which is to say we will take into account the directionality of the glass fibers. Figure 10 shows us the results of the same loadcase using the anisotropic material model.

The difference in stress magnitude is quite dramatic. We now see a peak Von Mises stress of 45 Mpa, well under yield, and gives us a very different version of the structural performance of the part with this material.

Conclusions

In the case of this 30% glass filled material, using the standard isotropic material properties yields highly inaccurate results.

The predicted stress magnitudes differ by 55%, a substantial error. It is noteworthy to mention that this loadcase was displacement based, meaning the same fixed deflection was introduced to both parts as described earlier. If the analysis was load based, meaning the same force was applied to each part and the resulting deflection was allowed to vary, the effect would be more than 50% predicted deflection for the isotropic part instance.

Most materials have some flow directionality when molded, especially filled materials. If an accurate assessment of as molded behavior is expected, it is important to capture the flow induced orientation of the material. ■

About Innova Engineering:

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