GM Saves Money By Eliminating Engine Noise in Concept Phase

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Engineers in the General Motors Powertrain used multibody analysis to eliminate noise and vibration in the concept design phase of a new engine, saving considerable engineering and prototyping costs. The 3.5 liter V6 engine uses a finger-follower cam system that incorporates low friction rolling-element rocker arms anchored with a stationary hydraulic lash adjustor to automatically maintain correct valve lash. The engineers' challenge was to prevent socket hop – a phenomenon describing a momentary loss of contact between the rocker arm and lash adjuster that could generate noise and vibration.

The custom software programs traditionally used by General Motors in valve design weren't applicable here because they are 2D codes that can't predict socket hop and non-plane contact phenomenon. So the engineers developed a 3D dynamic model using commercial multibody analysis software to consider the interactions between the valve train and camshaft, producing a model capable of predicting the dynamic behavior at the socket. Their analysis showed that the initial concept design indeed suffered from socket hop. Instead, engineers were able to diagnosis the problem and recommended to redesign the valve spring to fix it at minimal cost during the concept phase.

The 3.5 liter Premium V6 (PV6) engine used in the Oldsmobile Intrigue is a four valve per cylinder, dual overhead cam design. The Premium V6 displaces 3473 cc or 211 cubic inches. Employing the latest in combustion technology, it delivers 215 hp at 5600 rpmand 230 foot-pounds of torque at 4400 rpm. By carefully balancing compression ratio, inlet tuning and camshaft profile, the engine provides an exceptionally wide powerband with 90% of the available torque on tap from 1600 rpm to 5600 rpm. The 9.3:1 compression ratio was optimized for regular fuel. A knock sensor protects the engine if substandard fuel is encountered. With 24 valves to open and close, fuel economy robbing friction becomes an issue. The Premium V6 solves this dilemma by incorporating low-friction rolling element rocker arms at the camshaft interface. Each end pivot rocker arm is anchored with a stationary hydraulic lash adjuster to automatically maintain correct valve lash. Induction hardened nodular iron cams are used instead of more costly steel cams because contact stresses at the cam lobe were kept low.

Importance of valve train

The valve train is one of the most complex and critical parts of any modern engine system. The valve lift characteristics contribute to engine efficiency and impact overall emissions. In addition valve train noise and vibrations can be significant contributors to the overall performance of the powertrain. General Motors is in the process of migrating many of its new engines to the finger follower design used in the PV6 in which an end pivot rocker arm translates rotation of the camshaft into linear valve motion. The lift of the cam is amplified by the rocker arm ratio of the finger follower. The finger follower has a socket at one end that is mated to a spherical head on the hydraulic lash adjuster – serving as the pivot point. Near the center of the finger follower, a roller shaft is attached with a needle bearing assembly – providing a rolling contact surface for the Cam surface. At the opposite end of the finger follower is the valve pallet, which contacts the top of the stem for an intake or exhaust valve. The valve pallet is radiused to prevent edge contact with the valve tip. This design inherently generates less noise than earlier direct acting valve trains, but it introduces several complex challenges. One is the task of ensuring that there is no loss in contact in the spherical socket connection between the rocker arm and hydraulic lash adjuster at high engine speeds. The seperation between the rocker arm and the adjuster would be likely to cause noise and vibration.

A 3D finger-follower valve train system with deformable rockers, camshafts, springs, and valves.

In the past, General Motors engineers relied upon homegrown programs to model the kinematics and dynamics of the valvetrain. These programs worked well on the plane motion of valvetrain but were lacking the capability to predict socket hop phenomenon because it is a three-dimensional phenomenon. The problem is that the 2D codes cannot predict lateral forces which have a major impact on socket hop. Another drawback is the lack of flexibility of the homegrown codes. Making simple geometric changes requires tedious calculation and entry of coordinates while more complicated design changes usually involve writing new code. There are also accuracy limitations inherent in this approach

that result from the assumptions made in the derivation, such as the relatively crude geometrical definition and the inability to consider nonlinear force systems and helical spring elements.

Use of commercial codes

To overcome these problems, General Motors engineers have recently begun using a commercial multibody dynamic code called LMS DADS from LMS International, Leuven, Belgium,because it provides the necessary special features such as a cam contact element, combustion force element and helical spring model. The software allows a 3D system to be modeled or imported from major CAD packages, such as CATIA, Pro/ENGINEER, and I-DEAS. Engineers are able to define joints, constraints, and forces on the system. Then, DADS automatically derives and solves the non-linear equations of motion and reports loads, positions, velocities, and accelerations at each time step of the simulation. Results are viewed in graphs and as photo-realistic 3D animations that enable engineers to visualize the flexible deformation of engine components in motion.

The complete DADS model of the PV6 engine included all three cylinders on the right bank and the associated parts. The complete model contained a total of 38 flexible bodies, including flexible camshafts, intake and exhaust valves, rocker arms, and helical valve springs. Each flexible body is comprised of multiple mode shapes to represent its flexibility. Figure 2 shows a closer view of the model with just one intake and exhaust valve shown. The deformation due to flexibility, which is normally too small to see with the naked eye, has been scaled for visualization purposes.

One feature of the simulation model was the application of combustion loads acting on the valve heads. Some other features provided by DADS for use in this model were a hydrodynamic oil film algorithm to calculate cam-bearing loads, and an algorithm for tracking the complex hydraulic fluid pressures as they dynamically pump through chambers inside the lash adjuster. Input to the simulation model was provided by a constant angular velocity at one end of the camshaft. The camshaft rotation was non-uniform due to the torsional flexibility of the camshaft and the influence of combustion loads being phased according to the firing order. Different operating engine speeds were used for simulation by changing the angular velocity.

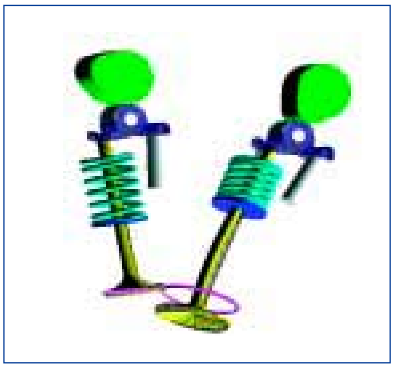
Modeling the cam

The cam surface is modeled using a series of 5th order spline functions that are fit to a table of points of lift versus cam angle. Cam contact force is a function of the stiffness and damping properties of the cam and follower. For each cam in the simulation, the spline-fitted surface is then used to determine penetration depth, velocity and sliding velocity between the cam and the follower. These values are then fed to a contact algorithm that generates and applies forces onto the cam and roller bodies based upon the stiffness and damping properties of the materials and their tangential friction properties. These calculations are performed simultaneously for all cams and updated at each time step during the simulation. This approach is capable of predicting valve float, since the cam and follower are allowed to separate and re-impact throughout the simulation. Figure 3 shows a model plot of cam contact. In the valve train, springs have important dynamic properties that affect system performance, especially at high speeds.

In addition to the contact modeling at the cam and follower, contact force elements are also used to model the interaction between the rocker pallet to valve tip, and between the valve head and the valve seat insert. A Hertzian contact model holds at each contact point by assuming the local deformation at the contact surface is sufficiently small. The Hertzian contact force is implicitly influenced by the radii of curvature of the two contact surfaces at the contact point. The surface radii of curvatures are computed by DADS during the simulation. The normal contact force is a function of Young's modulus, restitution coefficient and transition velocity, and the tangential contact force uses a friction coefficient or nonlinear function of friction vs. tangential velocity.

Modeling the spring

The inertial surging effects and resonances within the valve spring are also important factors to consider in the model, particularly if the spring vibrations are severe enough to result in coil-to-coil contact. The DADS software includes a sophisticated Helical Spring element that was used to account for these behaviors. First, a 3D finite element model of the spring is meshed and solved in the modal domain. The modeling procedure for the spring is similar to that used for standard flexible bodies, but has been automated for spring-generation and does not require

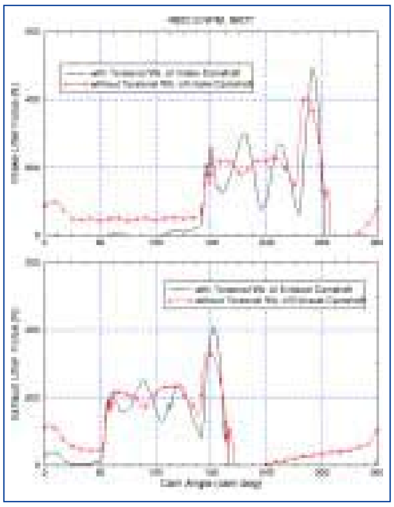


Valve train view of a single intake & exhaust pair – with deformation emphasized.

A cam contact model defined in the valve train system

3rd party FE tools. The spring modeler in DADS can handle general spring shapes like beehives, tapered springs, variable pitches, etc., and has features to account for ground ends. Behind the scenes it employs enhancements to allow geometrically nonlinear deformations. Normally flexible bodies are limited to linear elastic deformation, which is acceptable for bodies like the rocker arm, valve stem, and camshaft, but is not acceptable for a spring. Coil-to-coil contact is also accounted for by defining material contact properties as well as a description of the wire cross-section shape in polar coordinates. Once generated, this 3D spring model can be incorporated directly into the larger valvetrain simulation. However an optional modeling procedure is used which reduces the complex 3D model into a dynamically equivalent 1D spring model. The reduction process provided in DADS employs a quasi-static compression of the detailed 3D model to create the 1D model. The 1D spring is highly efficient and retains the necessary mass distribution to capture surge behavior, and also uses a series of nonlinear coil contact force relationships that emulate the more sophisticated contact algorithms found in the 3D model.

The model was used to investigate the performance of the valve train at four different engine speeds. Figure 3 shows the results of adjuster forces at 4800 and 6000 engine rpm (erpm) with flexible camshafts. The hydraulic adjuster force exhibits the typical skewed double-peak feature due to the fluctuation of the rocker-arm ratio. At 6000 erpm, in the coupled flexible camshaft system, the adjuster force is 65 N at 246o at intake side. In the finger-follower cam system, the motion of the adjuster changes the position of the follower pivot, which consequently affects the contact position between cam and follower. Socket jump occurs when the adjuster force along its translation axis drops to zero. This effect may lead to a loss of contact period at high speed and cause valve bouncing or impacts. The vibrations transmit to the head structure via the valve seat, spring seat and journal bearings. Understanding these results, GM engineers were able to make changes to the valve spring design that eliminated the socket jump problems. If the problem had not been discovered and solved at this phase of the design, it would have been detected after the testing of the first prototypes, when it would have been much more expensive to fix. The design changes saved large amounts of money and eliminated possible delays in the introduction of the engine while ensuring the performance of the final product. ■



Lifter adjuster forces comparison with rigid camshaft and flexible camshaft at 4800 and 6000 ERPM

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LMS INTERNATIONAL
Researchpark Z1, Interleuvenlaan 68
B-3001 Leuven [Belgium]
T +32 16 384 200 | F +32 16 384 350
info@lmsintl.com | www.lmsintl.com

Worldwide For the address of your local representative, please visit www.lmsintl.com/lmsworldwide

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