Simulation is Key in Design of Revolutionary BMW Valvetronic Engine

ENGINEERING INNOVATION

Multibody simulation played a key role in designing BMW's revolutionary new Valvetronic engine, the first series production engine to provide a mechanically infinitely variable valve lift, improving fuel economy 10% by eliminating the pressure loss of the throttle valve. The BMW Valvetronic engine is superior to state of the art GDI engines, since it offers equivalent fuel economy but is not limited by the need for special fuel quality. Designing the all-new valve train was the biggest challenge, because of the major impact that it has on power output, fuel economy and noise, vibration and harshness.

On this project BMW engineers used LMS DADS/Engine for multibody simulation to evaluate critical mechanical characteristics well before physical prototypes were built. In the early design stage, kinematics and dynamic models of the single valve train were used for the components layout and optimization. Later, a full-engine model was developed to evaluate effects that vary from cylinder to cylinder, which were especially important in this design because the valve train is used to control engine speed. "The very high quality standard of the Valvetronic engine design would not have been achieved without using multibody simulation." said Michael Allgeier, who works on computational methods in mechanics design.

The BMW Valvetronic Engine

BMW's Valvetronic engine represents a major breakthrough in automotive engineering by replacing the function of the throttle butterfly valve, which obstructs free ventilation of the engine, with an infinitely-variable valve lift. A lever is positioned between the camshaft and the intake valves, whose distance from the camshaft is controlled by an additional eccentric shaft operated by an electric motor. As the lever is repositioned, the cam contour translates into a larger or smaller valve lift motion depending on the engine load. This approach is analogous to the way that humans control their breathing, taking shorter, shallower breaths when they need less air rather than 'throttling' their air supply by closing their mouth or nasal passage. The elimination of the pressure drop caused by throttling in the new engine improves fuel economy by about 10% under normal driving conditions.

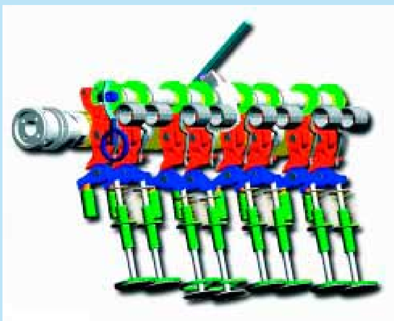
Another advantage is the nearly immediate response of the new engine when the gas pedal is depressed. This is attributable to the fact that load control now takes place directly in the combustion chamber rather than in the throttle, eliminating the need to fill the intake manifold between the throttle butterfly and the combustion chamber. The European 3 Series with the new engine achieves 40.9 miles per gallon (mpg) in the European test cycle, compared to about 36 mpg for the previous version of this vehicle. The 316ti also accelerates to 62 miles per hour (mph) in 10.9 seconds, 1.8 seconds faster than before. It has a top speed of 125 mph, 7 mph faster than the former model.

The kinematic design process

BMW began valve train development for the new engine by designing the valve train kinematics based on target values determined by the charge cycle requirements, which in turn are determined by the engine's power output and torque potential. At the same time, the design of the cylinder head had progressed to the point that the packaging envelope for the valve train could be fairly closely defined. Custom codes developed in-house that model valve train kinematics were used to define the cam contour.

A quasi-static examination was used to determine the speed and acceleration characteristics resulting from the cam contour yield forces and stresses. From the inertia forces at maximum engine speed, an initial valve spring design was obtained with the aim of preventing lift-off of the moved components. Engineers evaluated a number of different designs in an effort to develop a concept that met the design objectives and could be manufactured at a reasonable cost.

While the kinematic analysis is an essential first step in valve design, at high engine operating speeds the actual dynamic lift motion of the valves differs significantly from ideal kinematic behavior. This is due to factors such as the component flexibility, the hydraulic lash adjuster and valve spring surging characteristics that change according to engine speed and other conditions. As a result, kinematic analysis does not address critical dynamic performance characteristics such as vibration during the lift phase caused by valve spring oscillation. In addition, dynamic characteristics such as oil pressure, oil temperature and oil foaming play a major role in the dynamic performance



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of the valve train. In the past, valvetrain dynamic design relied primarily upon physical testing cycles in which hardware prototypes were constructed and tested, and the results were used to design additional prototypes. The problem with this approach is that building and testing prototypes is expensive and time-consuming. More recently, BMW has begun using multibody simulation to address the increasing requirements on refinement and complexity in valve train design. This process has been accelerated by co-development of multibody simulation packages that are specially designed to simplify the process of engine simulation.

Excellent correlation between Test and CAE

BMW selected LMS DADS dynamic simulation software because of its proven numerical stability, integration with finite element analysis for flexible body simulation and user-defined subroutines. LMS DADS/Engine is a compilation of special features that were built into DADS to meet the specific needs for valvetrain simulation such as a cam contact element, combustion force element, helical spring model and flexible bodies. Engineers define joints, constraints, and forces on the system. Then, DADS automatically solves the nonlinear 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.

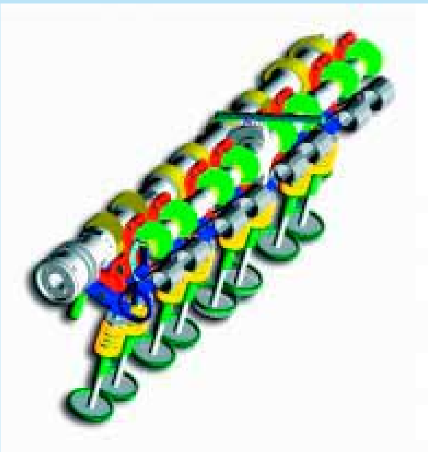
A recent joint development project between LMS's mechanical simulation experts and BMW and DaimlerChrysler engine designers resulted in the development of a new helical spring element that combines numerical efficiency, accurate modeling of coil clash and spring surging effects at high speeds. DADS flexible body methods, which combine FEA results with rigid body dynamics, were used to create the new spring model. Simulation results, using the new modeling element, were validated against experimental test data with excellent correlation.

The dynamic design process

Allgeier began the dynamic design process by creating a DADS model of a single valve. The initial iteration of his model used rigid body elements and a simplified spring stiffness to essentially duplicate the kinematic design model. Once the model had been validated, Allgeier enhanced it by adding finite element models of the components where it was desired to take flexibility into account and added the more sophisticated helical spring element co-developed with LMS.

Stiffness from finite element models was calculated for the valve head and finger follower and allocated to the relevant contact stiffness between the valve head and valve seat ring and between the valve stem and roller cam follower. Further contribution to the overall compliance comes from the valve train support in the cylinder head via the hydraulic lash adjusters and the camshaft bearings. Since stabilized cylinder head geometry was not available at this point in the design process, BMW engineers obtained experimental values from previous engines and used them for the initial dynamic simulation iterations.

Conversely, the multibody analysis yielded the valve train forces acting on moved components and the cylinder head structure, which were used in finalizing the cylinder head design. Later, finite element analysis of the cylinder head was used to provide more accurate stiffness values. The valve train's free mass effects were obtained from multibody simulation and used to balance the camshaft. The remaining mass effects after balancing were cascaded into the acoustic evaluation of the engine and the vibration-related design of other engine sub-assemblies. The final step in the simulation process was modeling the entire valvetrain in order to ensure matching between cylinders. This is important because with the engine controlled by intake valve position rather than a throttle, the valve lift position should be the same among all cylinders to ensure a smooth idle. "Multibody simulation has been one of the key technologies that enabled us to develop the revolutionary Valvetronic to its very high standard in the given time." Allgeier concluded. ■



3D animations enable engineers to visualize the flexible deformation of engine components in motion.

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