Variable Valve Drive

From the Concept to Series Approval

____ New vehicles are subject to ever more stringent limits in consumption cycles and emissions. At the same time, requirements in terms of engine performance, torque and smooth running at low engine speeds continue to rise. A key factor in resolving these conflicting objectives is played by the gas cycle. The development of an optimized, variable valve drive in particular shows potential.

By Andreas Eichenberg

The gas cycle and thus the design of the valve lift curve of a four-stroke engine are decisive for the fulfillment of the aforementioned requirements. Conventionally, the opening of gas exchange valves is designed for maximum engine performance. This definition, however, represents a compromise with regard to every other operating point in the engine control map. To achieve a better design in terms of the entire map, two or more valve lift curves tailored to the respective development focal points in the engine operating map are required. Porsche Engineering has therefore specialized in, among other things, the development and testing of trip cam systems that combine the advantages of different variable valve drive systems.

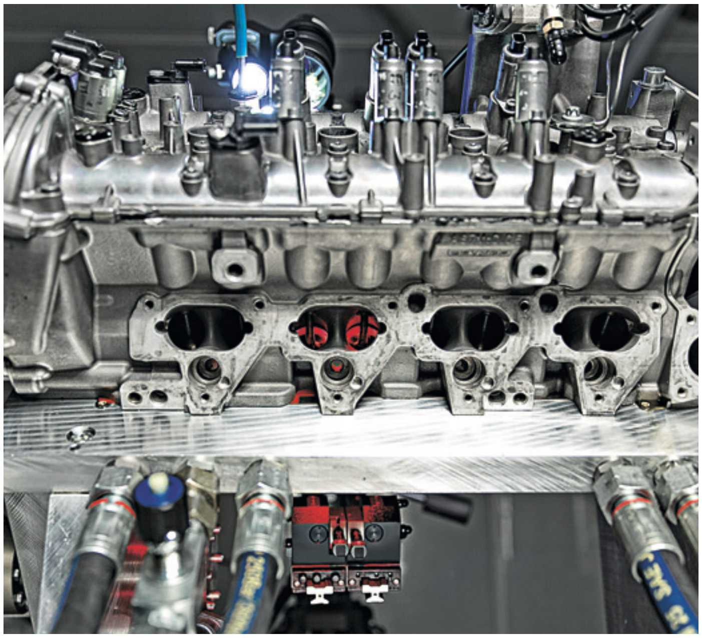
Valve drive systems in today's combustion engines are primarily focused on the transmission of the motion defined by the cam profile to the opening and closing gas exchange valve. The motion is mapped by various transmission elements. With these transmission elements, various principles are potentially in play. In current combustion engines, the most frequent elements are rocker arms with sliding or roller actuation. In the overall system, the valve spring provides a non-positive connection between the gas exchange valve and the rocker arm during the valve cycle. Taken together, these components are called the valve drive.

Valve drive development ranges from the concept, construction details, design and simulation to testing in the motored cylinder head and complete engine testing. By ensuring functionality at an early stage through simulations and on the mock-up test bench, development times for the engine as a whole can be kept to a minimum. Simulation-aided testing is increasingly common, and increasingly important in view of the rising complexity of variable, switchable valve drive systems.

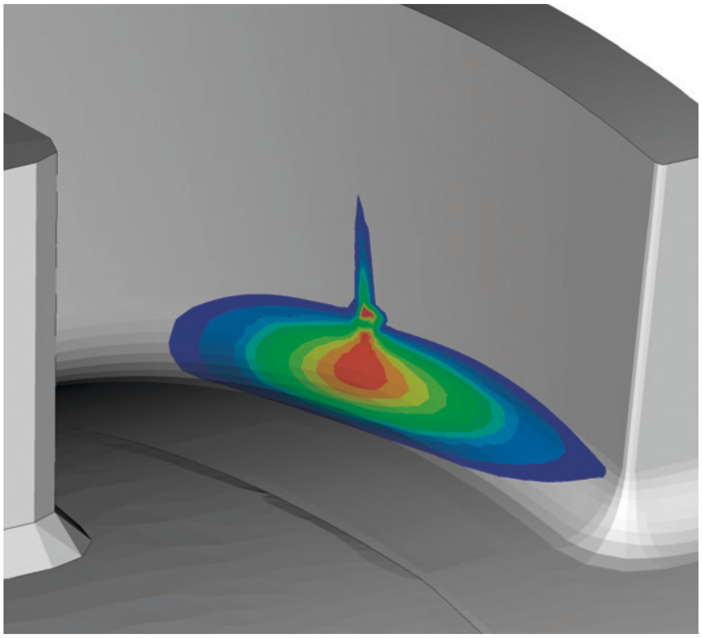
Different automobile manufacturers utilize variable valve drives. Trip cam systems are the most common type. Fully variable mechanical systems and hydraulically powered, mechanically switchable systems are also used. The diversity of different types of trip cam systems increases the complexity of the development, as do the requirements in terms of moving masses and shift speeds.

Effective and economical: trip cam systems

In spite of the variety of systems available on the market, the structure of a trip cam system is essentially always the same. A cam slide piece with multiple valve lift contours is pushed in a predefined groove—the shift guide—in the camshaft axis by a ram affixed to the cylinder head. This produces the axial sliding motion from the rotation of the camshaft. The ram is part of an electromagnetic actuator controlled by the engine control unit based on the engine control map. The cam slide piece is guided in the axial direction via an internal fundamental shaft.



Valve drive dynamics in the motored cylinder head



Result of structural calculation of shift guide parameters—service life

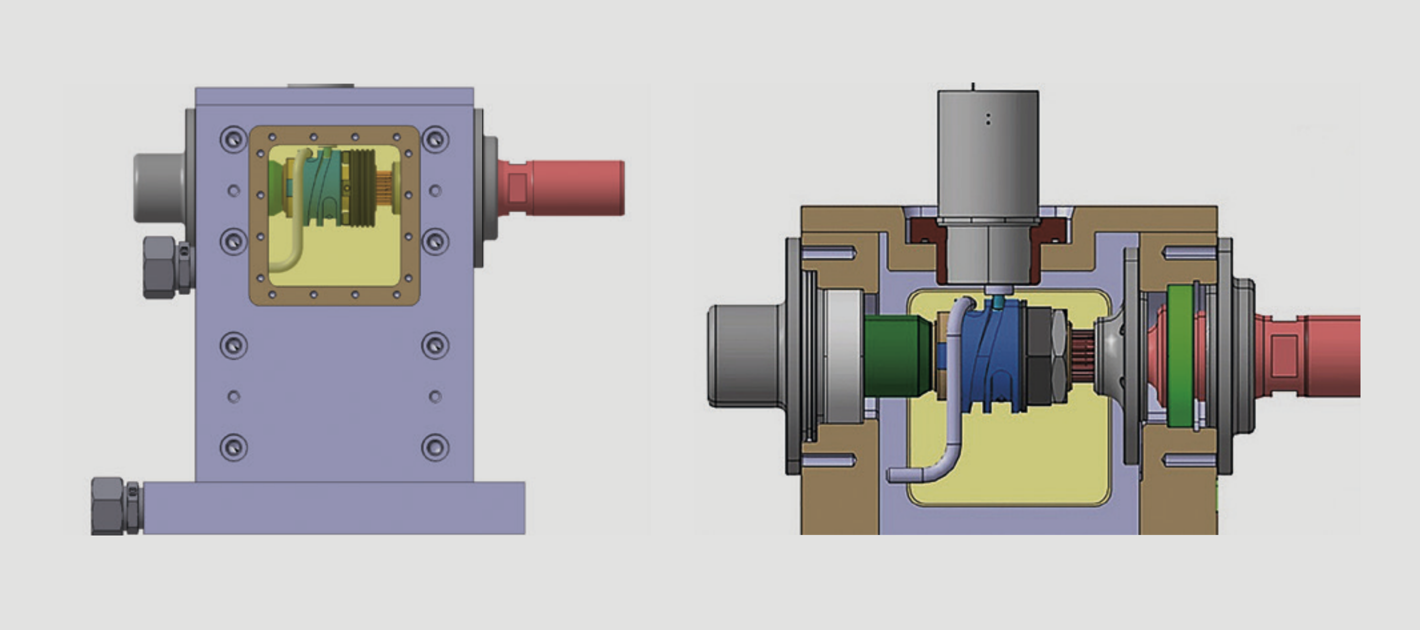
The advantages of this variable valve drive system are in the low impact on the dynamic opening and closing behavior of the gas exchange valves as well as in the low design and manufacturing complexity of the system. The dynamic properties of the valve drive depend on its moving mass. In trip cam systems, the moving mass is not increased due to the system. In contrast to other mechanically variable valve drive systems, a trip cam system has fewer components and their manufacture is simpler too, which directly impacts the overall complexity of the development.

Due to their design, trip cam systems present special challenges in the development process. Particularly noteworthy are the shift speed, the weight of the cam slide piece and the system tolerances that need to be mapped in the shift guide. Based on experience with conventional valve drive concepts, Porsche Engineering has established a modular process for the developers of such systems. The advantage: high flexibility and speed.

The foundation is the description of the requirements of the variable drive. In the concept phase, these requirements and conditions are implemented in a basic design. For a trip cam system, the primary issues are the bearing of the fundamental shaft and cam slide piece, the locking mechanism for the latter, the number of different cam profiles (which lead to two- or multi-level actuating mechanisms) and the design of the electromagnetic actuators. Apart from the design detailing, these points also influence the overall weight of the cam slide piece. As the heart of such a trip cam system, the shift guide is defined by the weight of the cam slide piece and the maximum attainable shift speed. The kinematic length of the shift guide is influenced by the position of the valve lift curves. Thus in the design phase, the displacement travel can be determined based on the disengaged base circle phases of the valve drive, and its course determined based on the acceleration.

In-house development: multibody simulation model

Based on Porsche Engineering's experience, a dynamic multibody simulation model (MBS model) was created. The model maps the dynamic influences on the displacement travel. These factors include the play between the actuator ram and shift guide as well as the rigidity of the bond between them, damping forces and the shift speeds. The results from the MBS model form the foundation for iterative modification of the acceleration profile of the shift guide. The focus here is on minimizing the load on the actuator ram and the shift guide in the form of Hertzian pressure and frictional forces in the actuator. Particular attention must be paid in this regard to the flank change within the shift guide during the ›



Set-up of the tribology test bench at Porsche Engineering

transition from acceleration to deceleration of the cam slide piece. The result of this iterative design process is a dynamically secured shift guide that is calculated to harmonize optimally with the framework conditions.

For the simulated loads, the shift guide parameters are adjusted in the CAD detailing. A particular focus here is on areas with low wall thicknesses, and optimal contact pattern distribution of the actuator ram on the guide flank. The shift guide parameters are confirmed in structural calculations using the finite-element method (FEM), among others. The structural calculations are also used in evaluating the contact conditions and material stresses. The areas with lower wall thicknesses are evaluated with regard to the changing loads using service life calculations. The detailed design generally concludes this theory-heavy development phase with a rapid-prototyping component as a visual sample.

Pre-testing ensures viability of materials and coatings

In pre-testing, individual components are examined. This is done at the earliest possible stage in the development process in order to allow the test results to be integrated into the development of the product without extraneous development cycles. The focus is on testing various material combinations and coating systems in the area of the material contact between the actuator ram and the guide flank. The pre-testing also includes an examination of the actuator switch time under the influence of various parameters. For example, the electromagnetic dead time and time-of-flight of the actuators for complete engine operation in the range from –20 °C to 120 °C with respect to the oil and component temperature is examined. The reproducibility of the lubrication conditions and the test conditions are critical here.

At Porsche Engineering, tribological tests are conducted on a test bench devised specifically for this purpose. The purpose of such tests is to examine the interaction of various surfaces in relative motion with regard to material characteristics and coating systems. The objective is to get a read on the viability of the selected tribological pairing in the shortest possible time.

The heart of the tribology test bench is the interchangeable slide piece on which the shift guide defined in the design phase is located. The interchangeable slide piece is driven by a splined fundamental shaft. In the shift guide, there is a permanent actuator ram mounted in an electromagnetic actuator. An oil injection nozzle within the test bench ensures ideal lubrication conditions. A housing shields the test chamber from the lubricating oil mist generated during operation.

The modular set-up of the test bench enables highly flexible use and rapid modifications of the components being tested. Pre-testing of trip cam systems may involve the examination of, for example, different DLC coatings (diamond-like carbon), changes to material pairings in the area of the shift guide and actuator ram, as well as various acceleration processes for the shift guide.

On the interchangeable slide piece, the shift guide takes the form of an endless groove. In conjunction with the actuator ram, the endless guide executes two opposing movements of the interchangeable slide piece per revolution. Thus with an appropriate shift speed, a large number of shift cycles can be carried out on the test bench in a short amount of time. The speed and mass of the interchangeable slide piece determine the loads on the actuator ram. The speed represents a compromise of the actuation frequency and thus the local heat input on the test components. Pre-testing concludes with an analysis of the run marks on the shift guide and actuator ram. The results are integrated directly into the development process—for instance component manufacturing.

Secure path to series production

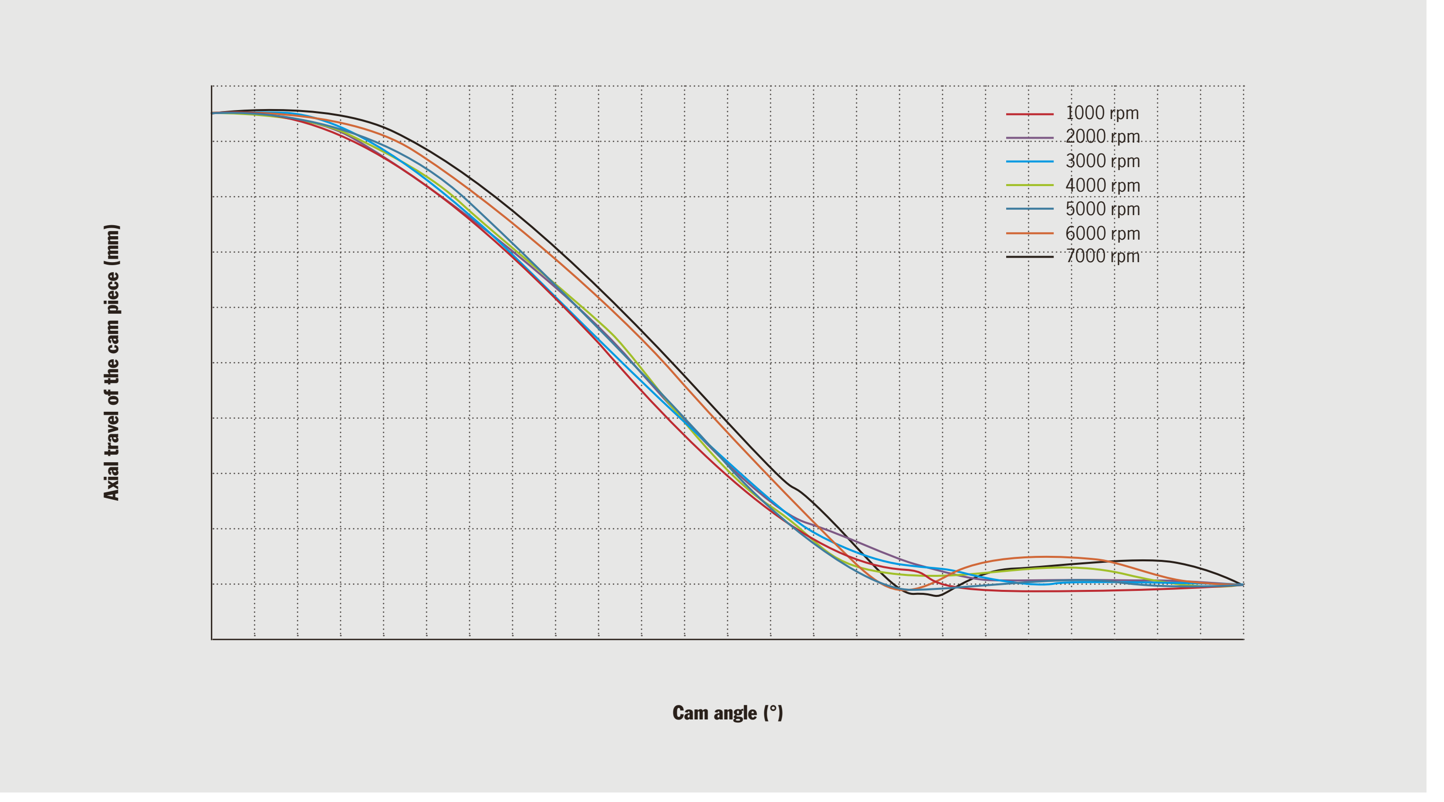
Due to the complexity and the requirements in terms of dimensional accuracy and surfaces of the components, production of the components of the trip cam system requires a high degree of precision. Porsche Engineering accompanies the implementation of such a system in the prototype phase, from heat treating and the individual processing steps to component measurement and quality control.

Functional and durability testing conclude the validation of the trip cam system. These tests are conducted under near-complete engine conditions on a cylinder head mock-up test bench. The test bench is a cylinder head with the original control assembly equipped with measuring technology. The drive power is supplied by a high-torque asynchronous machine. The connection between the electric machine and the stand-in crankshaft is provided by a torsionally stiff coupling with an integrated torque measurement flange that records the drive torques and thus the friction of the individual assemblies.

The focus of the testing of the trip cam system is on the functional dimensions of the displacement travel and the dynamic actuator ram forces. The displacement characteristic is measured using a magnetoresistive sensor and analyzed visually with the aid of a high-speed camera. To measure the actuator ram forces during the cam displacement, calibrated strain gauges are used in the area of the ram mount. The system records the measurement indicators for values from the camshaft angle to the maximum displacement speed. The dynamic effects in the measured values are analyzed to form a basis for the further development and approval of the trip cam system. The focus is on the initial contact of the actuator ram with the shift guide, the switching of the shift guide side from the acceleration flank to the deceleration flank of the cam slide piece and the movement of the latter towards its end position after its complete displacement travel.

Additional tests of torsional vibration and the displacement path of the cam slide piece depend on the selected bearing and valve drive concept. These measurements are generally required when negative influences on the dynamic opening and closing behavior of the gas exchange valves occur in complete engine operation. It remains important to prevent any ›

Interchangeable slide piece with endless guide



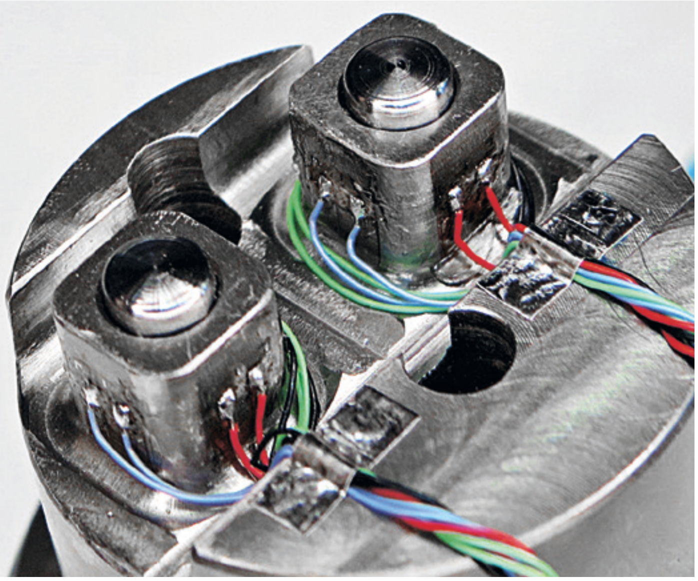
High-resolution measurement of the dynamic displacement travel

impact on the conventional valve motion by the trip cam system. To ensure proper functioning, the valve drive dynamics are tested on the cylinder head mock-up test bench or in the running complete engine. Functional testing ultimately concludes with a test of the rocker arm and mount element loads and measurement of the friction values of the variable valve drive system.

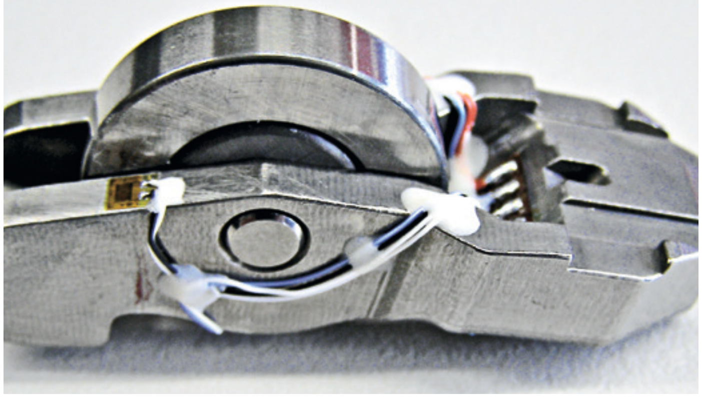
The trip cam system must demonstrate durability

After the functional validation, the trip cam system is subjected to endurance testing on the test bench. The testing of this subsystem is also conducted in the cylinder head in order to ensure efficient and rapid feedback for the complete engine development process. This involves automatic testing of realistic—e.g. highly dynamic—and synthetic speed profiles. The focus of synthetic speed profiles is to test a large number of shift cycles in a short amount of time on the test bench without neglecting realistic use conditions. The power supply to the actuators is triggered by a specially developed real-time operating system when the defined shift conditions occur. The emphasis here is on avoiding incorrect shifting. The intelligent shift logic developed for this is based on the recording of the axial and rotation angle-specific position of the cam slide piece. These measured values are recorded on the test bench by multiple sensors. The pilot control of the component-specific dead time and time-of-flight of the actuators is also mapped in the shift logic. This ensures that the actuator rams are only extended in the geometrically prescribed angle range.

During endurance testing, the running surfaces on the shift guide and actuator rams are regularly inspected. The history of the run marks is part of the comprehensive assessment



Strain gauge application: actuator ram force measurement



Strain gauge application: rocker arm load

following completion of the endurance shift testing. The data collected during the duration of endurance testing forms the foundation for the overall validation of the trip cam system. In such an endurance test, a variety of threshold states is tested in view of the desired target conditions. These threshold states relate to the component-specific dimensions and the functional conditions of the target system. Endurance testing is the foundation for the further functional development or approval of the trip cam system.

Summary

Early validation of subsystems of the combustion engine plays an increasingly important role in shortening the overall development duration. This requirement is reflected in the development process for trip cam systems. It is foreseeable that with the continuous development of variable valve drives, additional individual tasks will be added to the process. These include, for example, the prevention of incorrect shift states and the development of locking concepts. Porsche Engineering will continue to actively pursue and advance this trend towards multi-level development in these systems, both conceptually and in terms of design. ■