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INA cam shifting system

Prepared for the future

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Introduction

A major objective in the further development of internal combustion engines is the reduction of fuel consumption and CO_2 emissions. Future exhaust regulations will also require a further reduction of emissions.

The internal combustion engine will remain an important drive source for motor vehicles, even if there are currently a lot of activities in the direction of electric drives and fuel cells. The efficiency of the internal combustion engine must be continuously increased.

Important potential areas during the optimization of the engine are the reduction of the charge cycle work, the optimization of the charge motion, influencing the percentage of residual exhaust gases, especially under partial load, the control of the temperature at the start of the compression stroke and metering the mass of the fresh air. Variability in the valve train is required in order to implement these measures.

The implementation options available range from pure cam phase adjustment and partially-variable valve lift to fully-variable valve lift. The greater the degree of variability that is used, the greater the potential that can be achieved.

Figure 1 Partially-variable valve train components with electro-hydraulic actuation

For example, the combination of a variable camshaft phasing unit and a partially-variable valve train has proven advantageous. This paper concentrates mainly on partially-variable valve trains.

INA has been developing, amongst other things, partially-variable valve trains for over 20 years and looks back on over 10 years of volume production of the switchable tappet. INA was also involved in the development of the cam shifting system and has further developed the Audi Valve Lift System which is currently on the market. The aim of this publication is to show how it has been possible to achieve more functionality while maintaining the same design space conditions by means of an intelligent actuator concept.

State of the art

There are many different, partially-variable valve train concepts with different actuator systems and implementation levels of variability for finger-follower valve trains.

Figure 1 shows well-known electro-hydraulic systems. The switchable pivot element (picture on the left) enables valve/cylinder deactivation. The switchable roller finger follower (picture on the right) can be used to perform cam profile switching or valve/cylinder deactivation.

In addition, there is also the possibility of varying the lift directly on the camshaft using electro-mechanical actuators, as in the Audi Valve Lift System (AVS) (Figure 2) [1]. This two-stage switching system comprises a base shaft, one cam element per cylinder, the associated finger followers and pivot elements as well as two actuators per cam element. The cam element is fixed for co-rotation with the base shaft by means of axial splines but can be moved in an axial direction. The cam element is supported by the camshaft bearing located centrally between the valves. The cam element for both valves includes two sets of associated cams and the control grooves. In the current arrangement, the cam element is shifted on the base shaft in both axial directions using two S-shaped groove contours and two electrically controlled actuators (Figure 2).

Figure 2 Audi Valve Lift System [1]

Comparison between the cam shifting system and other familiar switching systems

A comparison of these different systems shows that electrically actuated cam shifting systems have a number of advantages.

Increased operational temperature range

Electro-hydraulically actuated systems have limitations in the low temperature range (Figure 3). Only one switching is permissible with oil pressure at oil temperatures below 20 °C. Switching is not permitted in the opposite direction less than 20 °C due to the high oil viscosity at low temperatures and the associated rapid increase in faulty switching. Unlimited operation is usually only ensured for an oil temperature of 20 °C and above. The cam shifting system operates without switching faults in a significantly larger operating range due to the electric actuator and the positively controlled switching (Figure 3). There is also further potential for extending the operating range.

No restrictions of valve lift curves

Another disadvantage of well-known components with lost motion elements (switchable tappets, switchable roller finger followers) is the restricted freedom for the design of the valve lift curves. For example, the switchable roller finger follower comprises a primary lever and a secondary lever. The lift on the primary lever is always applied, while the lift on the secondary lever can be blanked out by switching. The smaller lift must always be overlapped by the larger lift or the smaller lift must be completely outside the range of the large lift (Figure 4). The individual lifts cannot be realized if both curves intersect. A contact

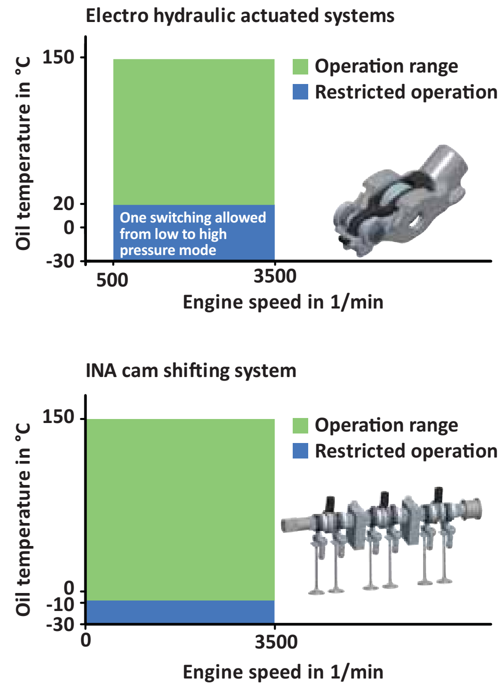

Figure 3 Comparison of operating ranges

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change from one cam to another would occur during the valve lift and the overlapped lift curve would be realized. The cam shifting system does not have this restriction. The lift curves can be selected freely.

No hydraulic system required for switching

The oil circuit and especially the oil pump must be appropriately dimensioned in electro-hydraulically actuated systems in order to ensure the required minimum oil pressure is maintained at all switching points. However, it is usually not possible to shift the camshaft phasing system and switching components simultaneously. The cam shifting system with electric actuation can be used at any time and is independent of the oil circuit.

Positively-controlled switching within one rotation of the camshaft

The cam shifting system is based on positive control during the switching operation, i.e. the cam element must be shifted after one rotation of the camshaft. It is possible that the switching operation may take longer than one rotation on hydraulically actuated systems, especially at low temperatures. Cyclical switching is, therefore, not possible at low temperatures. The cam shifting system enables cyclical switching within one rotation of the camshaft. Faulty switching, which occasionally occurs with hydraulically actuated systems, are prevented with the cam shifting system.

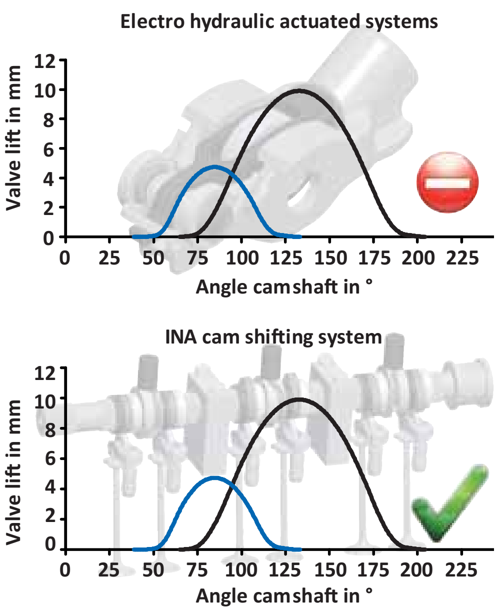

Figure 4 Restrictions for the design of the valve lift

Switching of individual cylinders is possible

Switching of individual cylinders on electro-hydraulically actuated systems is only possible with additional outlay. In this case, more switching valves must be installed and the design of the hydraulic oil circuit is more complex. The cam shifting system with its clear assignment of actuators per cylinder enables switching of individual cylinders without additional complexity. This allows further potential for fuel consumption savings during adaption of the engine control unit without incurring additional costs.

No additional valve lift variation

Locking mechanisms, which are based on pistons, show backlash in the lock due to tolerances. This backlash, which varies depending on the design, leads to a corresponding variation of the valve lift during the secondary lift. The cam shifting system has in comparison to switchable roller finger followers no additional valve lift variation.

Low moving mass/ mass moment of inertia

The switchable roller finger follower has a larger moving mass and a larger moment of inertia than the cam shifting system due to its design with two levers arranged in parallel. The basic roller finger follower design for the cam shifting system is only slightly modified compared with well-known standard finger followers. This allows the original valve springs to be maintained and higher friction in the valve train is prevented. The valve lift curves in the cam shifting system can be freely selected within the limits of accelerations which are possible in finger follower valve trains. Restrictions with switchable roller finger followers often occur due to the greater mass moment of inertia. The valve lift curve of switchable roller finger followers often has to be adapted in order to restrict the loads.

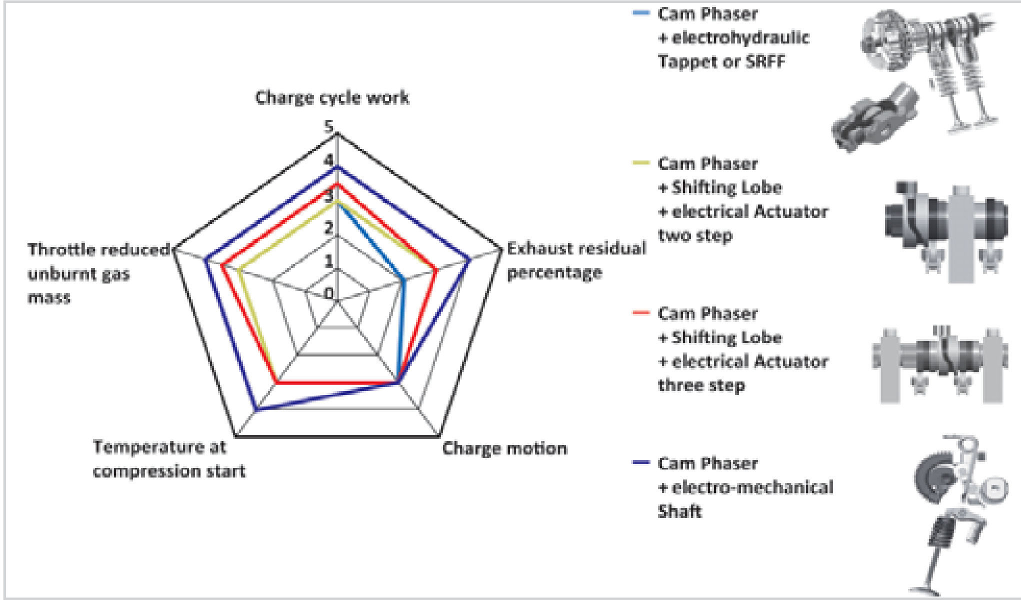

Figure 5 Comparison of the thermodynamic potential of different concepts

System flexibility for CPS, CDA and CAI/HCCI

Flexible systems with a greater degree of freedom are often required during development in order to test different concepts. Engine manufacturers continuously strive to use systems for volume production, which are flexible enough for several engine concepts. This eliminates significant costs and enables a reduction in the variety of components.

For example, there are different requirements when starting the engine (start with a small or large valve lift). These are realized on hydraulically actuated systems by using different locking mechanisms (unlocked or locked in a depressurized state) depending on the application.

This functionality is achieved on the cam shifting system simply by varying control of the actuators. The cam shifting system can be simply adapted for different requirements while maintaining the important functions without any technical disadvantages.

Motivation

In total, the described advantages of the cam shifting system result in the achievement of greater savings in fuel consumption compared with switchable roller finger followers.

The proposed three-stage valve lift variation in combination with an electric actuator comes closer to the performance of a fully-variable valve train, but has a more favorable cost-benefit ratio (Figure 5). This was the reason why INA further developed the three-stage cam shifting system.

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INA cam shifting system

Design and function

The objective for the INA cam shifting system is to implement a three-stage switching system without making significant changes to the basic idea, i.e. “shifting the cam element axially on a base shaft”. An additional INA requirement is that the cam shifting system should be adaptable for the largest possible range of engine architecture with different valve and cylinder spacing.

The core of the cam shifting system is the groove contour, in which the actuator pin meshes and the cam element for a cylinder is shifted axially on the base shaft. The design space available for the shift grooves for implementing the three switch-

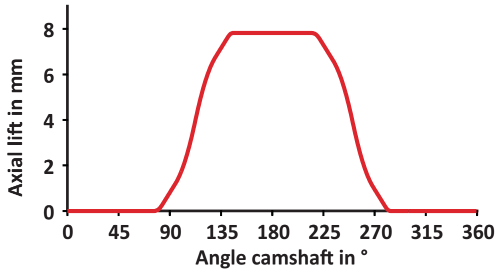

Figure 6 Axial lift of the cam element with the double S-groove

ing stages is significantly restricted with the existing valve and cylinder spacing. A design with two S-grooves (Figure 2) is, therefore, not possible. A double S-groove proved to be the most promising following an analysis of different groove configurations. This groove design generates motion in both shift directions in a base circle phase of approximately 210 degrees of camshaft rotation. In addition to both axial motions, an entry zone must also be set aside in the groove base for the actuator pin motion in this phase (approximately 70 degrees of camshaft rotation). This means there is effectively only approximately 70 degrees of camshaft rotation available for shifting the cam element axially. The double S-groove (Figure 6) was optimized with a simulation model. The contact forces on the actuator pin were kept at almost the same level as those on the S-groove used in volume production (Figure 2), although significantly less phase angle is available. Figure 6 shows an example of the axial lift of the cam element with the double S-groove.

The cam element bearing support has to be redefined for the three-stage cam shifting system.

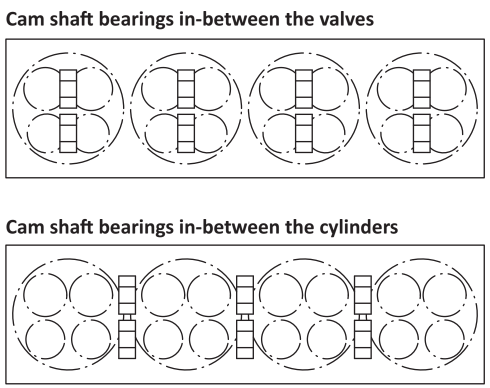

Figure 7 Different camshaft bearing supports

Where the bearing support is arranged between the valves (Figure 7), the bearing has insufficient width if there is narrow spacing between the valves. Therefore, an arrangement with the base shaft bearing support between the cylinders is the most promising approach here (Figure 7).

Figure 8 shows that the double S-groove must be positioned between the cams when an additional base shaft bearing support is located between the cylinders. This defines the camshaft design of the INA three-stage cam shifting system.

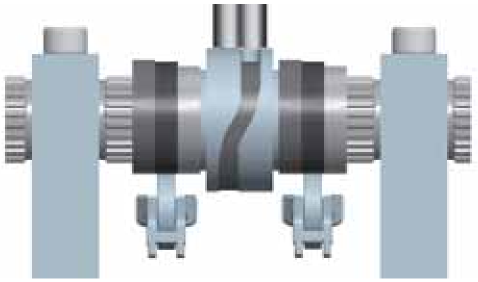

Figure 8 INA three-stage cam shifting system

The INA cam shifting system can also be a two-stage design (Figure 9). In this case, only a one-pin actuator is required per cylinder and the base shaft bearing support can be located between the valves.

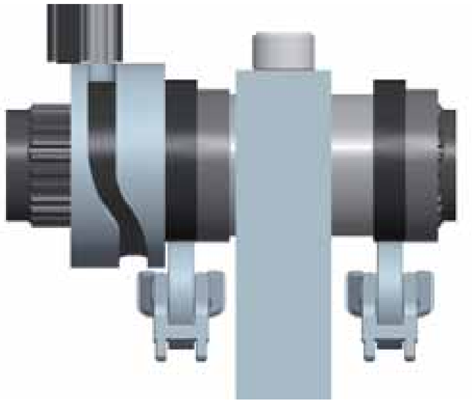

Figure 9 INA two-stage cam shifting system

The cam element is fixed for simultaneous rotation with the base shaft by means of axial splines allowing it to move in an axial direction. Cam profile switching means that the cam element is shifted axially by one cam width on the base shaft. If the cam element is not actuated, the detent (Fig-

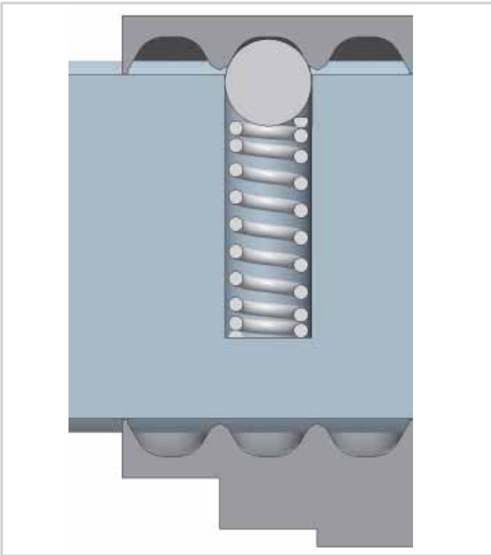

Figure 10 Three-stage detent

ure 10) fixes the cam element in the corresponding position on the base shaft. The detent has one spring-loaded ball per cylinder.

The three recesses for locking the cam element detent are assigned to the three cams (Figure 10).

An INA two-pin actuator acts on the double S-groove in order to switch between the three cam lifts. If the actuator is activated using a control signal from the engine control system, only one of the two actuator pins enters the first groove before the start of the cam base circle and shifts the cam element axially by means of the groove pitch during the base circle phase. The other pin cannot engage in a groove. It slides on the high circle surface of the sliding groove. The rotation of the camshaft and the pitch of the groove contour move the cam element axially by one cam width and the actuator pin is pushed out of the groove by a radial lead-out slope at the end of the groove contour and returns to its initial position. The second actuator pin produces a further shift of the cam element in the same direction, again with the first groove. If the cam element is now shifted in the opposing direction, the second actuator pin enters the second groove during the cam base circle phase. The cam element is shifted back by one cam width by the pitch of this groove. There is also a radial lead-out slope at the end of the second shift groove which moves the actuator pin back to its initial position (Figure 11).

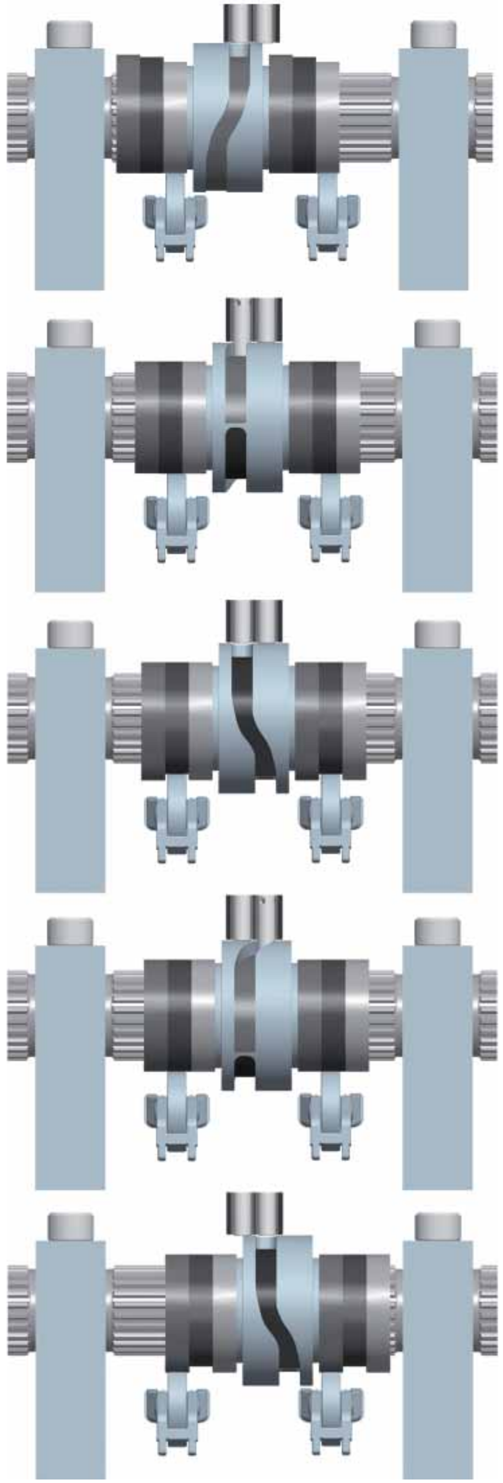

Figure 11 Function of the INA three-stage cam shifting system

Figure 12 INA finger follower system for cam shifting

The INA finger follower system (Figure 12) currently in volume production is also used for the three-stage cam shifting system. The optimized INA finger follower with a cam roller width of only 5.4 mm and a roller diameter of 21 mm has proved very reliable since the start of volume production in 2006.

INA multi-pin actuator

Concept

The required actuator functions were reanalyzed from scratch in order to meet the requirements for the new generation of cam shifting systems. The INA multi-pin actuator was developed from the strict implementation of the individual functions. The following points were included and implemented in the concept:

- The work performed when the pin is pushed into the actuator is stored
- This energy is selectively released in order to push the pin out of the actuator
- The pin stroke is reduced to the minimum distance required
- The insertion depth is increased to a maximum
- The design space is reduced to a minimum

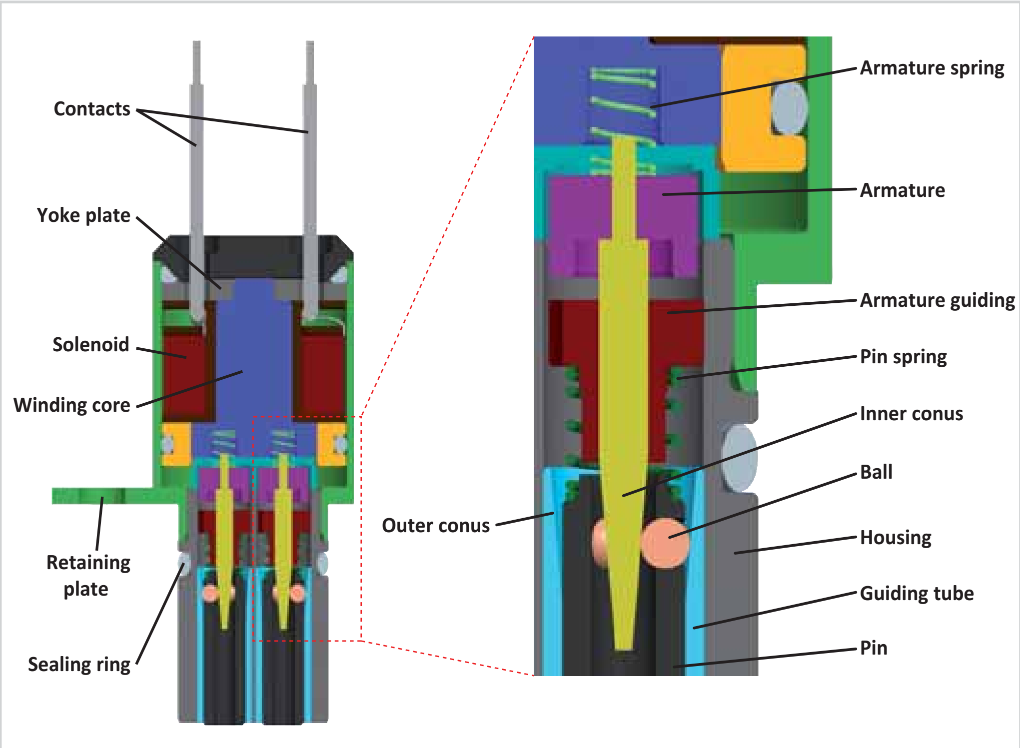

Figure 13 Basic design of the multi-pin actuator

Functions of the INA multi-pin actuator

Energy storage

In order to keep the design space of the actuator as small as possible, not all pins were provided with their own electric drives. Each individual pin obtains its drive energy from the motion, which is stored in the pin when it is pushed into the actuator. A spring stores this potential energy until it is released again by deactivating the clamping unit.

Reduction of the pin stroke by means of a stepless detent

Besides the maintenance of the storage function, the clamping unit has a further task. Positional and manufacturing tolerances result in imprecise positioning of the actuator to the cam shifting element. This is compensated by the stepless clamping unit. These tolerances are taken into account by an additional stroke in the series actuators, currently in use. In this design the permanent magnet draws the pin into the actuator. The additional distance covered during meshing of the pin, however has a negative effect on switching times. In order to prevent this, a stepless clamping unit was designed which ensures the shortest possible meshing distance irrespective of the tolerances.

This clamping unit comprises two conical friction surfaces, in which there are three ball-shaped locking elements located. The outer cone surface is firmly connected to the actuator housing, while the spring-loaded inner cone surface is connected to the armature and is pressed against the locking elements. The locking elements are positioned by holes in the pin offset at 120° intervals on the same height. The pin will move in the guide tube depending on the clearance between the balls and the bores.

When the pin is moved into the actuator (Figure 14), it pushes the balls in the guide tube in the direction of the inner cone until they touch the cone. The balls lift the inner cone against a spring force until they are between both cone surfaces. From this point onwards, the inner cone remains stationary in its position due to the equal angle in relation to the outer cone, although the pin continues to move the balls.

The inward motion of the pin ends when it leaves the radial lead-out slope in the cam element. If there is no longer contact between the pin and the cam element after the ramp, the pin spring tries to push the pin out of the actuator. The pin moves within the limits of the fit clearance between the hole and the ball and is then stopped by the balls (Figure 14). The balls remain stationary in their positions due to the self-locking action against the inner cone. The self-locking action is produced by the frictional force on the inner cone, which acts in the opposite direction of the lead-out and increases the clamping force. This means that the locking function is independent of the spring force which acts on the pin.

The coil is fed with a current to release the pin and the armature as well as the inner cone, which is connected to the armature, move upwards against the preload of the armature spring. This means the

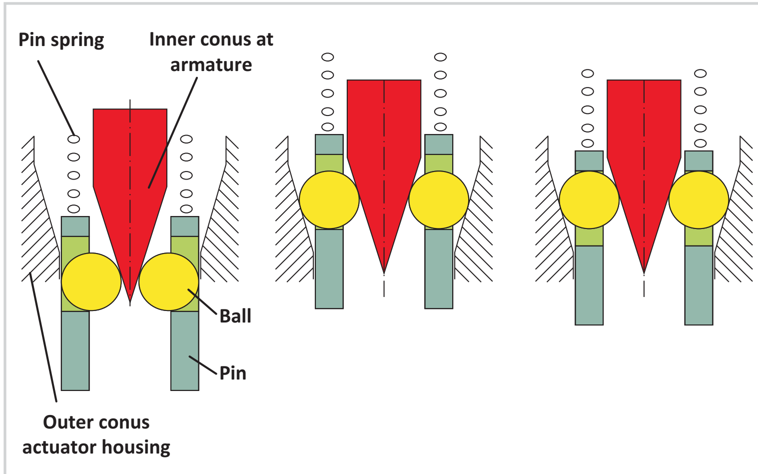

Figure 14 Clamping unit actuator (diagram: both balls are rotated in one plane)

clamping effect against the outer cone is cancelled and the pin is pushed into the groove by the pin spring.

Customer benefits of the INA cam shifting system

The INA cam shifting system provides engine developers with a flexible, high-performance and sustainable, variable valve train system for use in development and volume production.

The objective was to make the cam shifting system even more attractive by carrying out continuous development. The INA cam shifting system has the following advantages compared with well-known cam shifting solutions:

- Reduced design space requirements for the actuator
- Realizing a three-stage system in the design space of a two-stage system
- A halving of the number of actuator pins and grooves (two-stage system)
- A reduction in the design space requirement in the axial direction of the camshaft
- A reduction in friction by using a new detent

Application examples

The marked growth of knowledge in the areas of thermodynamics and the degree of freedom offered by the INA three- and two-stage cam shifting systems make the use of these systems very attractive in gasoline and diesel engines and in conjunction with new combustion methods [5]. Different thermodynamic concepts can be implemented by varying the design of valve lift curves.

Summary

The INA cam shifting system presented here is characterized by a number of advantages. The following must be mentioned especially here:

- Three-stage lift variability
- The freedom to design valve lift curves
- Switching can be performed irrespective of the oil pressure
- The use of an extended temperature range
- Switching of individual cylinders

Ultimately, these features make the INA system a flexible, high-performance and sustainable cam profile switching system. It can be simply matched to different requirements. By utilizing the new actuator concept, the solution presented here offers further advantages, which can improve the situation with regard to design space and reduce the complexity of the system. It has been possible through continuous development to provide a three-stage system in the design space of a two-stage system.

The INA three-stage cam shifting system is positioned between well-known two-stage electrohydraulically actuated systems and fully variable systems, while having a good cost-benefit ratio at the same time. With the system presented here, INA is providing engine developers with increased variability, which in conjunction with modern engine control systems can unlock further potential for reducing fuel consumption and emissions, especially in transient engine operation.

Abbreviations used

CPS	Cam Profile Switching
CDA	Cylinder Deactivation
CAI	Controlled Auto Ignition
HCCI	Homogenous Charge Compression Ignition
AVS	Audi Valve Lift System
EGR	Exhaust Gas Recirculation

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