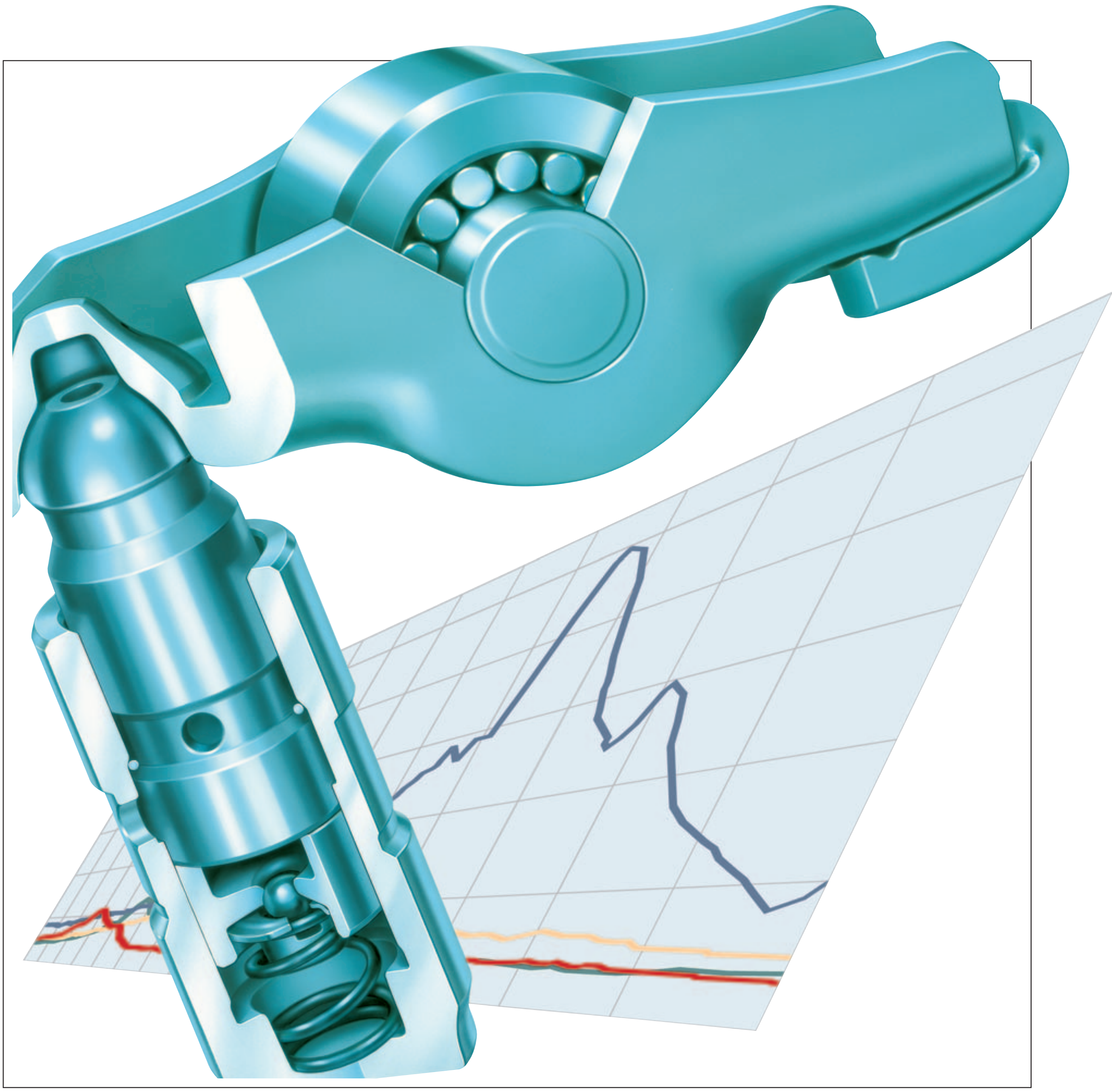

Testing

Valvetrain Systems for Combustion Engines

Publication VVV

This publication has been produced with a great deal of care, and all data have been checked for accuracy.
However, no liability can be assumed for any incorrect or incomplete data.

⚠ Product pictures and drawings in this publication are for illustration only and are not intended as an engineering design guide.

Applications must be developed only in accordance with the technical information, dimension tables, and dimension drawings contained in this publication.

Due to constant development of the product range, we reserve the right to make modifications.

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Investigations and Components

Velocities

Oil aeration

Dynamic behavior

Torsional vibrations

Acceleration

Ball stroke

Pressures

Roller slip

Rotation

Torque

Forces

Wear

Misfire

Friction

Rattling

Fatigue load

Displacement

New test methods

Elementary investigations

Switching process

Functional tests

Durability

Bucket tappets

Switchable tappets

Crosshead tappets

Roller tappets

Rocker arms

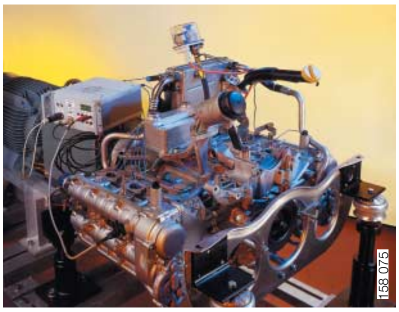
Finger followers

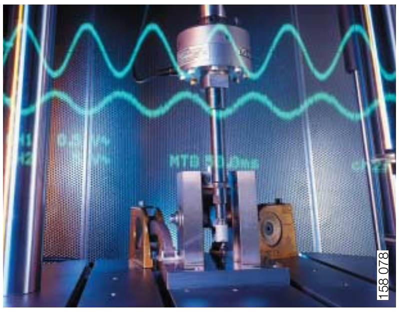
Hydraulic chain tensioners

Check valves

Pivot elements

Special designs





Testing Overview

Product development cycle times are continuously being reduced as the automotive industry attempts to develop new products faster and cheaper. An integral part of the product development cycle is design verification and production validation testing. As a result, a great deal of emphasis is placed on reducing development testing time.

At INA Corporation, testing is taken very seriously and has evolved over time. Cumbersome endurance tests that used to be conducted for thousands of hours have been reduced while still verifying component function and durability. This has been made possible through increased sophistication, improved analytical and predictive methods, automated testing and a better understanding of the application environment.

The proper facilities are key to meeting this challenge. As such, INA has assembled a collection of facilities in North America and Europe. Testing has long been a part of the parent company in Germany and more recently in Fort Mill, South Carolina. The addition of the Troy, Michigan, Technical Center in 2003 has increased testing capabilities even further. These capabilities include fixture, engine, and vehicle evaluation facilities. When completed, the Troy facility will provide both fixture and fired engine testing.

A variety of tests can be set up in these facilities. Abnormal conditions can be generated to test components under less-than-perfect operation. As an example, testing with various levels of oil aeration can be simulated to determine the effect on lash adjuster performance. The extremes of temperature, vibration and humidity can be controlled for additional product validation. Combinations of temperature, vibration and operating speeds can be used to stress parts during key-life testing. Testing is also used to validate a variety of analytical models. These predictive tools include hydraulic modeling, computational fluid dynamics, finite element stress models, kinematic models and complete dynamic motion models.

Test Cabin and Test Evaluation

Roller Test Stand

Test Stand Selection

An important part of generating an acceptable test plan is the selection of the test methods. In its product life cycle, a passenger car is expected to operate over a distance comparable to six times around the earth. In addition, it must operate under a wide range of environmental conditions from desert heat to the below-freezing temperatures of cold climates. This requires validation testing to be performed under equally demanding conditions. This can be accomplished by using a variety of facilities. Tests can be conducted in any or all of the following:

- Special test stands to simulate the component environment
- Motored cylinder heads or engines
- Firing engines, with and without dynamometer loading
- Vehicles on test tracks or on chassis dynamometers

Any one of these test strategies can be employed in a facility having the environmental controls to test at the extremes of temperature and humidity. The following aspects play an important role in selecting the right test stand for the intended task:

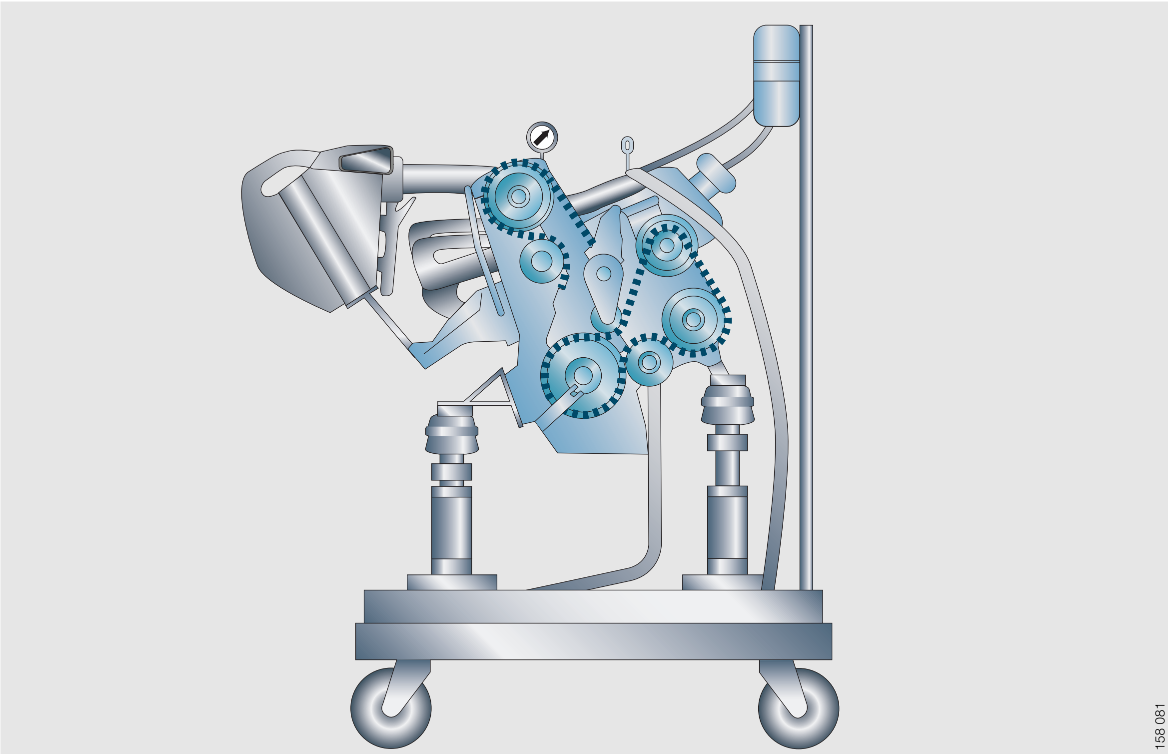
- Purpose of test
- Cost constraints and required effort (time, manpower, resources, etc.)
- Availability of test hardware (e.g. of prototype engines, vehicles, etc.)
- Accessibility for required instrumentation
- Accuracy required

To obtain meaningful results, all of the relevant boundary conditions must be maintained and/or generated. For the valvetrain product line these conditions include the normal environmental requirements and the following:

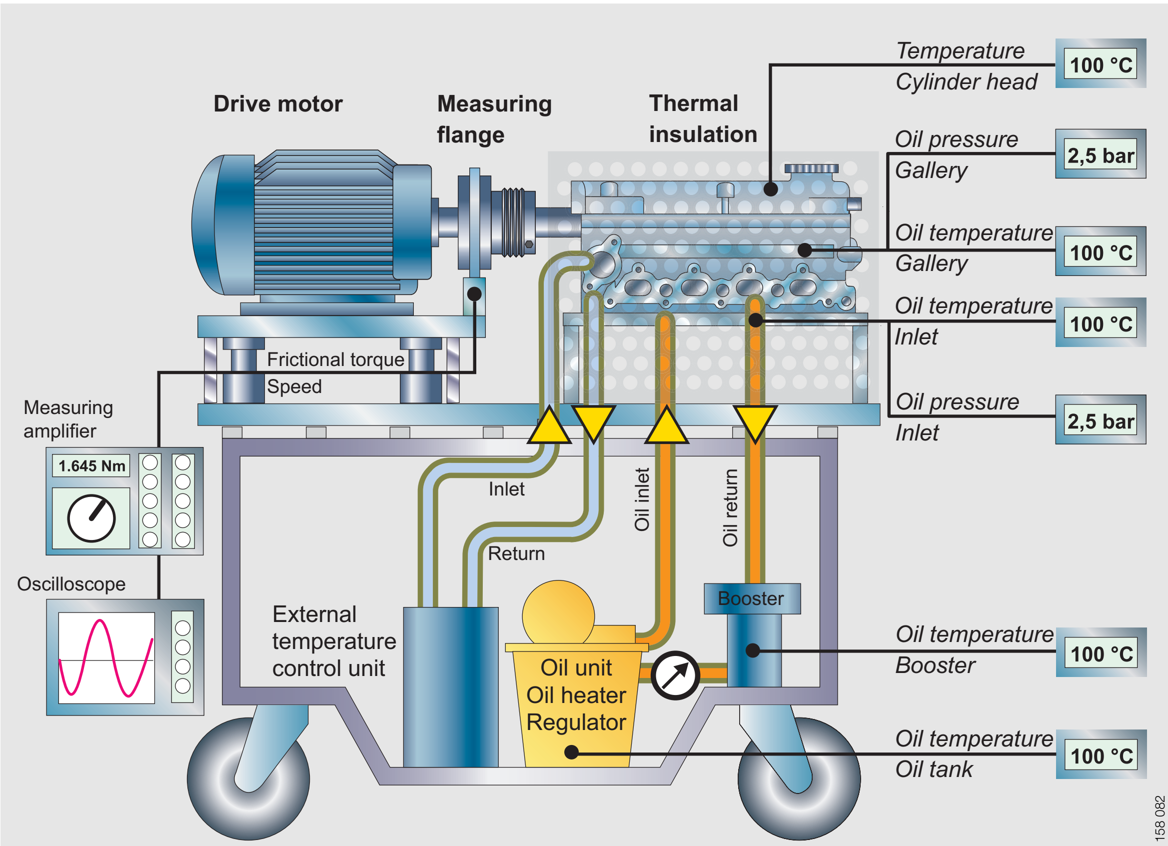
- Lubrication (oil type, pressure profiles, aeration, temperature, etc.)
- Material (material matching, heat treatment, etc.)
- Geometry (roughness, tolerances, limit samples, etc.)
- Loads (force profiles, vibration, torque, speed fluctuations, etc.)

INA's many years of experience are beneficial in the selection or design of the right test stand and specification of the correct test conditions.

Test Stand Configuration with Fired Engine



Test Stand Configuration for Friction Testing



Test Types

A variety of tests are required to design, develop and validate a new product concept or new application of an existing concept.

These tests are conducted at various stages in the product development cycle. They include, but are not limited to, the following:

- Fatigue Tests
- Dynamic Performance Tests
- Functional Tests
- Misfire Tests
- Switching Tests
- Dynamic Valve Train Simulation
- Special Investigations
- Timing Chain Drive Tests
- Wear Tests

Each of these test types will be described briefly in the following sections. This overview is intended to give the reader an idea about INA's capabilities, it is not intended to be exhaustive in nature.

Fatigue Tests I

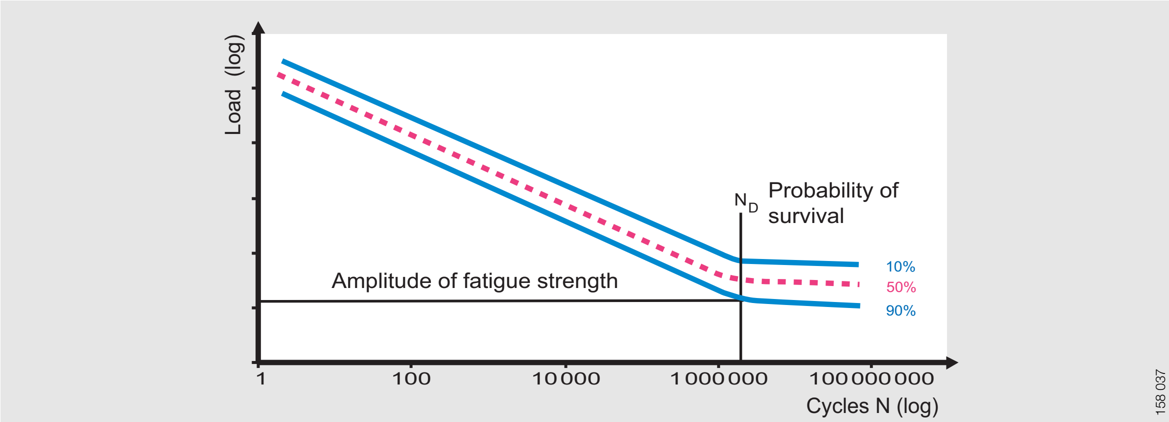
Fatigue tests are necessary to determine the sustainable dynamic loads on a particular valvetrain component.
Through these tests, a variety of questions can be answered, such as:

- Where are the weaknesses in the design?
- Is there a correlation with the FEA model?
- If there are competing designs, which one is less susceptible to fatigue?

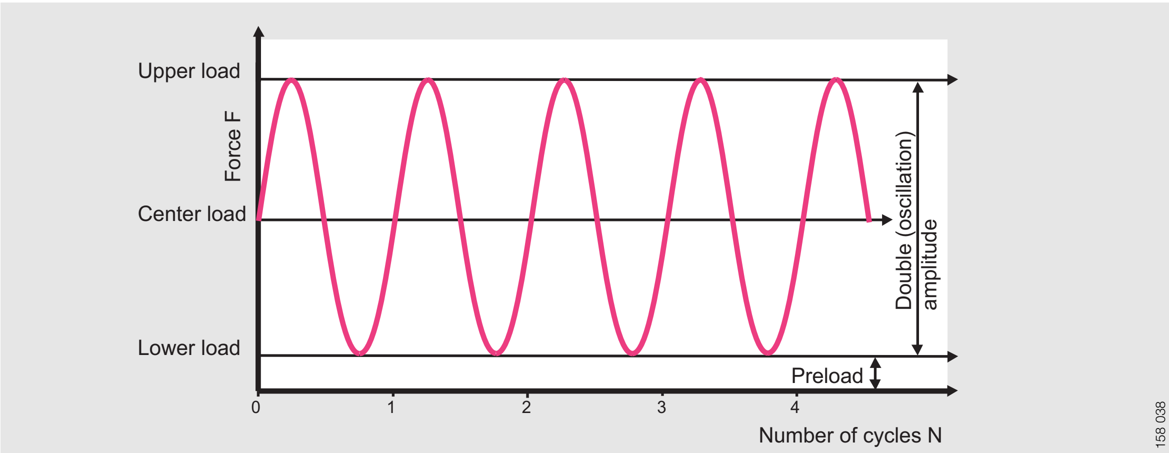
In one form of the test, the component is positioned in a fixture so that critical load conditions can be simulated. Hydro or resonance pulse generators are used to apply load to the component. Due to the high potential test frequency (up to 190 Hz), resonance pulse generators reduce test time.

Fatigue Tests I

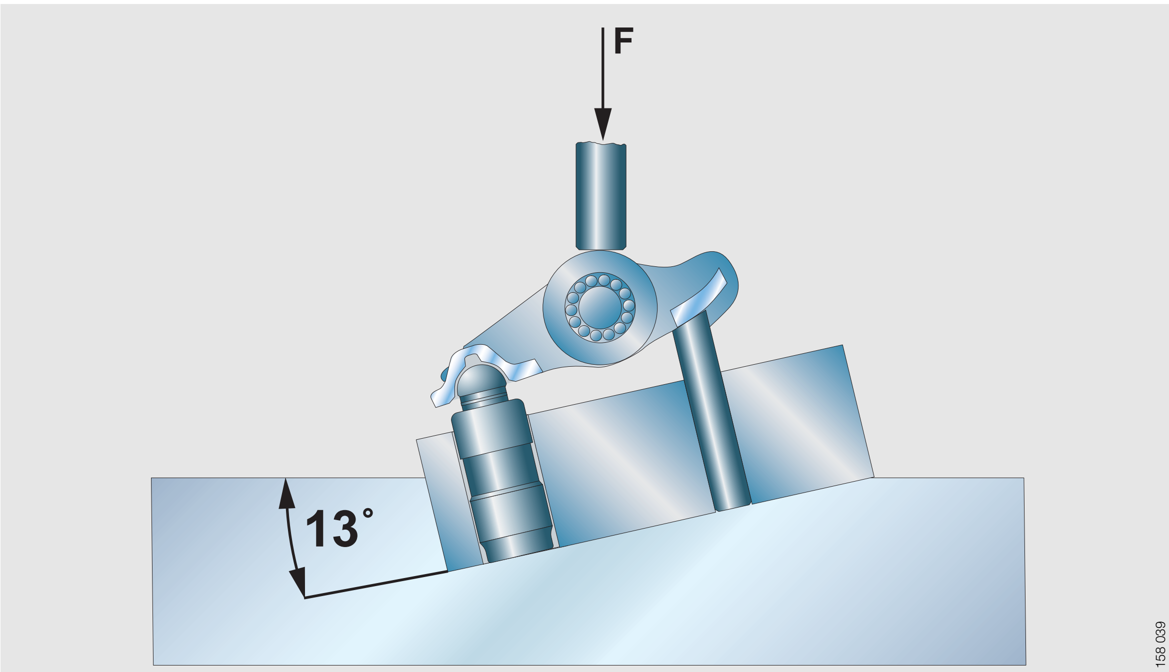
Fatigue Load Versus Life Relationship



Test Load Profile



Test Fixture with Critical Load Situation



Fatigue Tests II

The staircase method is used to test a random sample of 30 parts. If a steel part reaches four million cycles for a particular load level, it is regarded as having withstood the load, and the load is increased one level for the next sample. If a sample is damaged before reaching four million cycles, load is decreased by one level for the next sample.

The resulting staircase sequence allows statistical evaluations to be performed in order to correlate the failure probability with particular loads.

The following characteristic values are used for the evaluation:

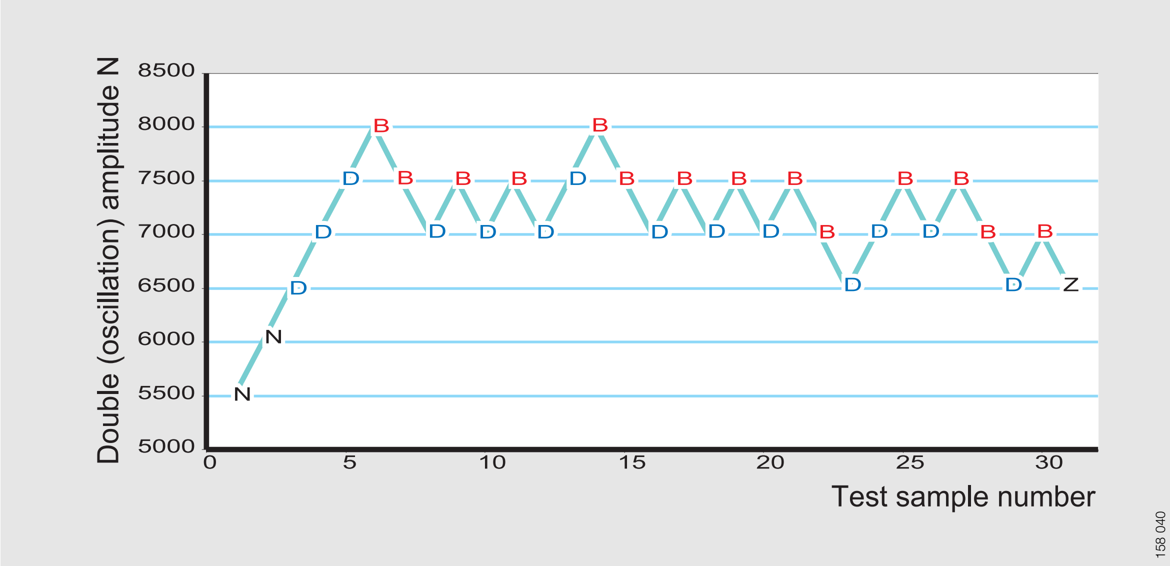
- Mean value (50% failure probability)
- 1% failure probability
- Standard deviation (measure for dispersion)

Safety factor:

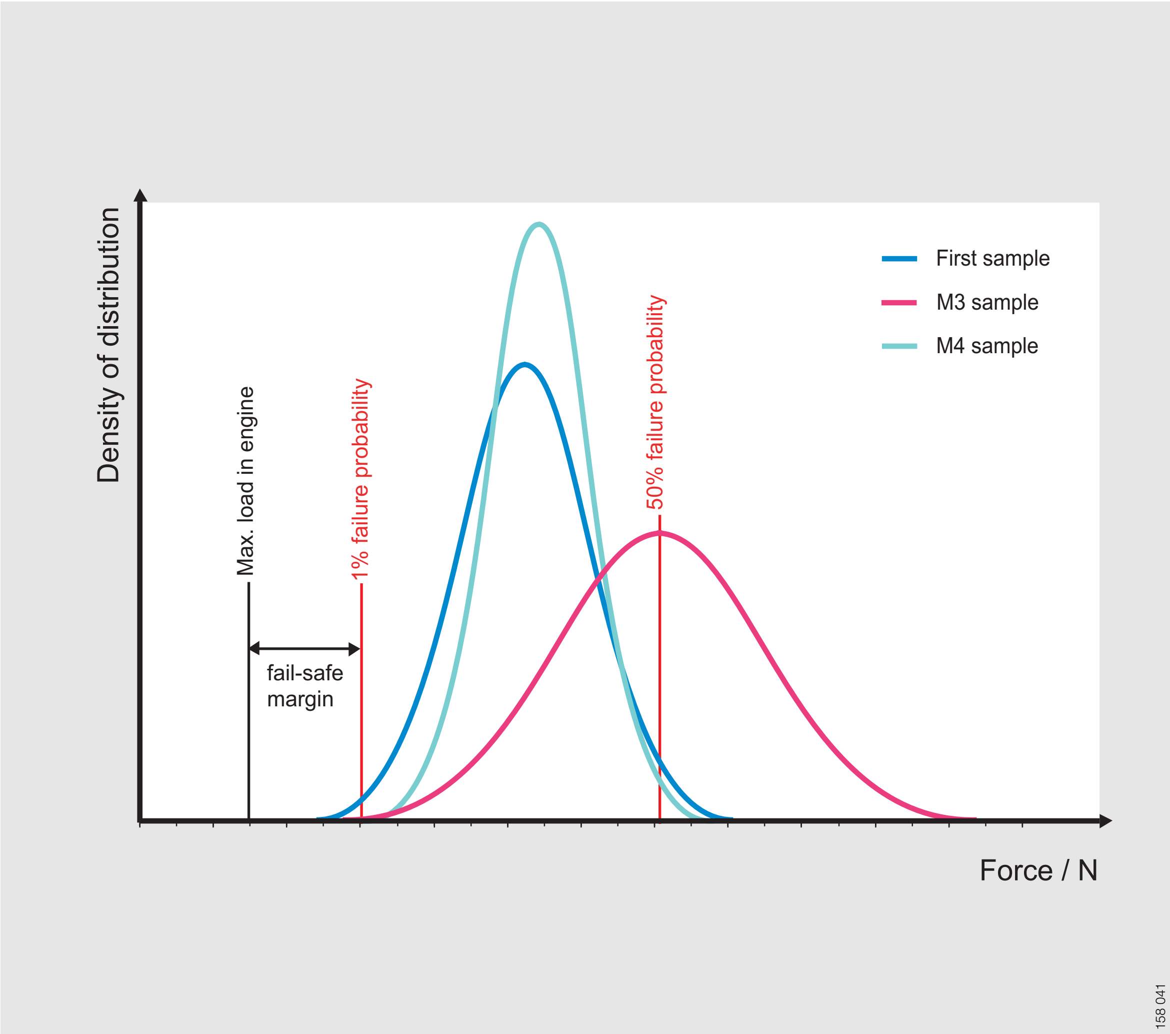
Ratio of 1% failure probability with respect to the maximum load.

Fatigue Tests II

Typical Staircase Sequence



Statistical Evaluation – Failure Prediction



Dynamic Performance Tests I

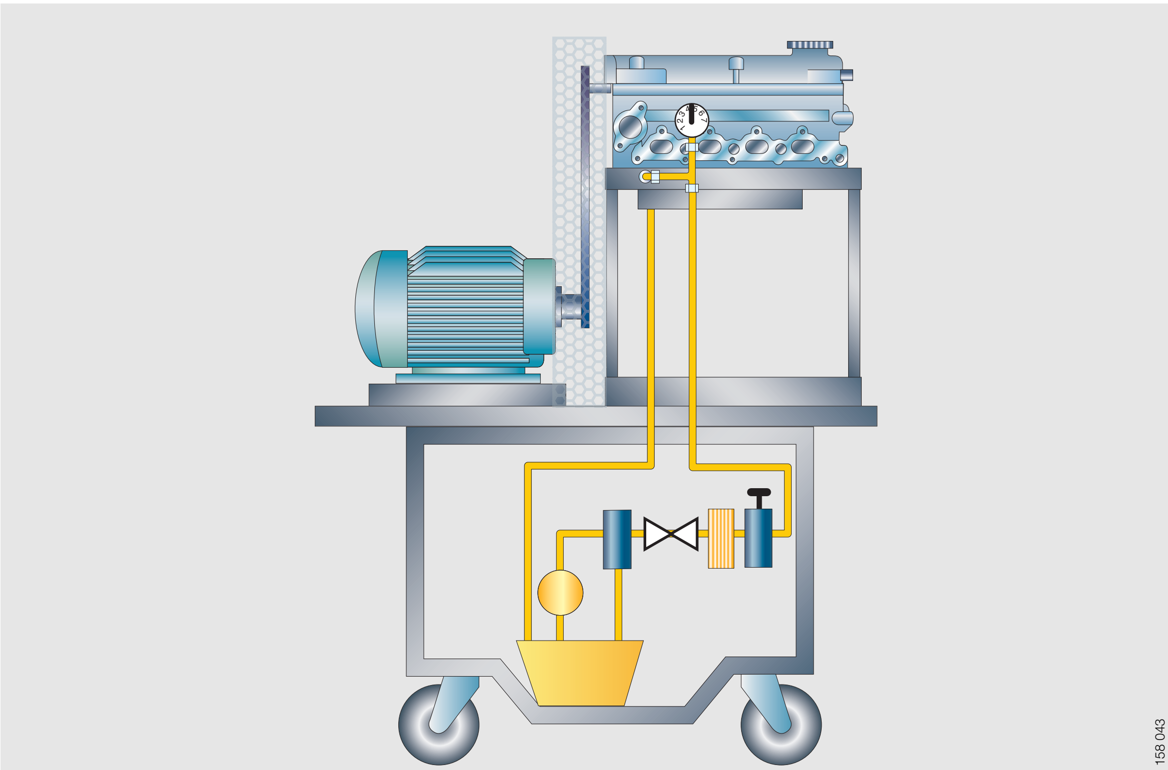
In **dynamic testing performed on a motored valve train**, parameters such as displacement and velocity are measured with a sampling frequency of up to 750 kHz.

This enables the functional reliability of a valvetrain to be assessed, even under extremely unfavorable operating conditions. The aim is to determine extremely high loads, such as acceleration peaks up to 2500 g, evaluate these and reduce them if possible by taking appropriate actions.

Motored cylinder heads have proven to be nearly ideal in terms of measuring. The most important advantages include low costs and easy access to the parts. In rare cases, the effects to be investigated are too complex, and measurements must be made in a fired engine.

Dynamic Performance Tests I

Design of a Motored Cylinder Head Test Stand



Dynamic Performance Tests II

Important parameters that are measured directly include:

Standard:

- Valve motion (stroke, several mm; velocity < 10 m/s)
- Oil pressure, oil temperature, speed
- Oil aeration

Special cases:

- Pressure in hydraulic element
- Hydraulic element leakdown
- Forces on the valve stem, rocker arm, valve spring, finger follower, etc.
- Check valve ball motion
- Rotational oscillation of camshaft

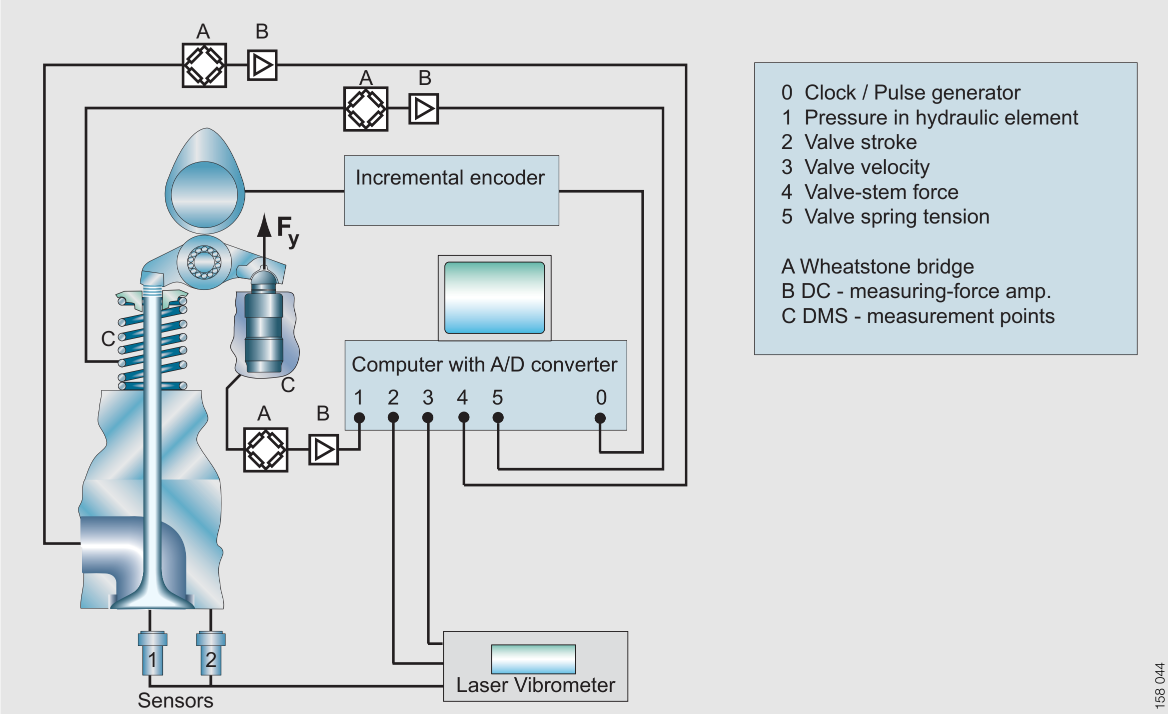
The following parameters are determined from the measurement data:

- Opening lift loss
  (stroke loss when valve is opened, several 1/100 mm)
- Total lift loss
  (stroke loss when valve is closed, several 1/100 mm)
- Valve closing velocity
  (velocity of the valve during closing, chance of valve failure, noise generation)
- Dynamic behavior of the valve timing gear
  (oscillations, resonance, contact loss)

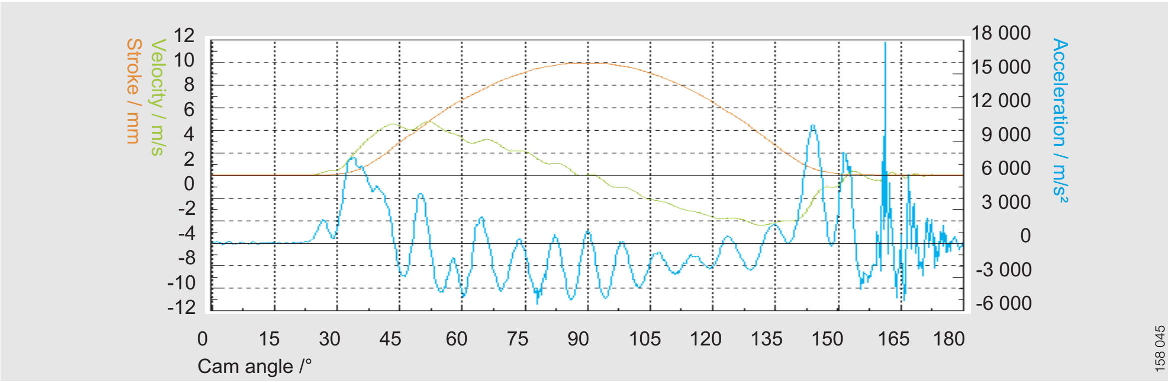
The following parameters are calculated using the measurement data:

- Contact forces
  (loads on valvetrain parts, up to 5 000 N)
- Hertzian pressure
  (wear, life)

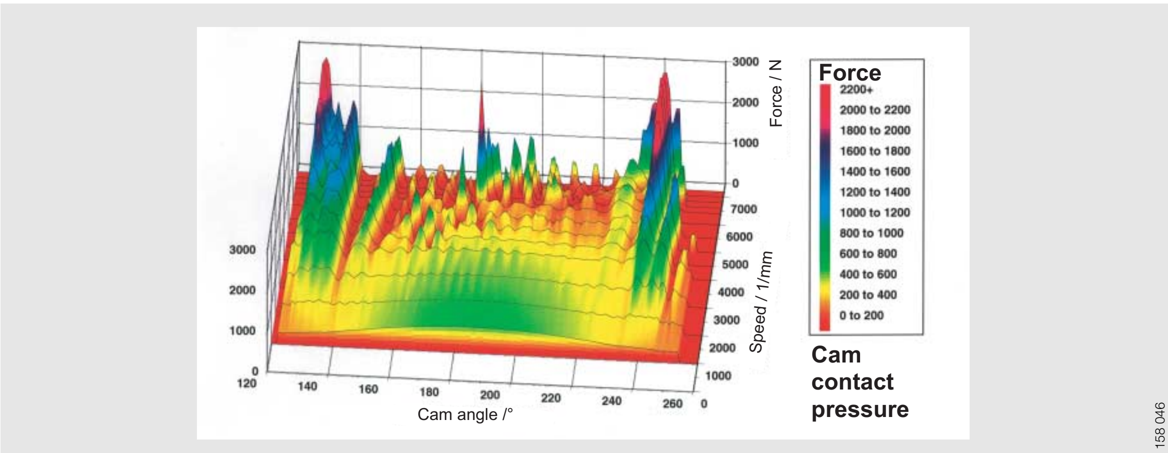
Design of Dynamic Test Stand



Stroke – Velocity – Acceleration



Evaluation of Force Map



Functional Tests I

Functional testing is performed to investigate the function of hydraulic elements under engine boundary conditions.

In order for the hydraulic adjustment elements to function properly, air must be minimized in the high pressure chamber. Excessive air leads to increased valve closing velocities (chance of valve failure at high speeds) and is audible as a rattling noise.

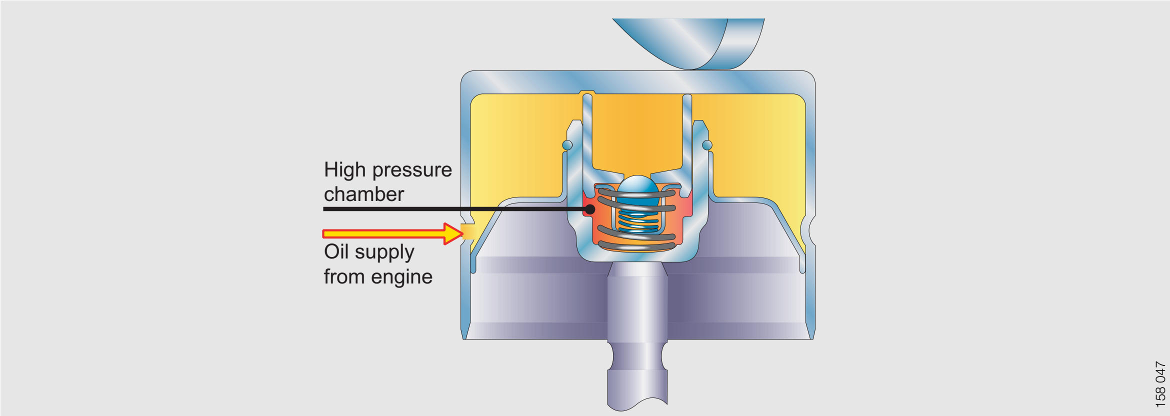
The functional reliability of the engine depends on the following:

- Installation
  (location, tilt, slope, connection to the oil supply, etc.)
- Oil supply
  (oil channels draining during idle, oil pressure increase after engine startup, deaeration potential in the oil passages, oil aeration, oil pressure, oil grade, viscosity (depending on temp.), etc.)

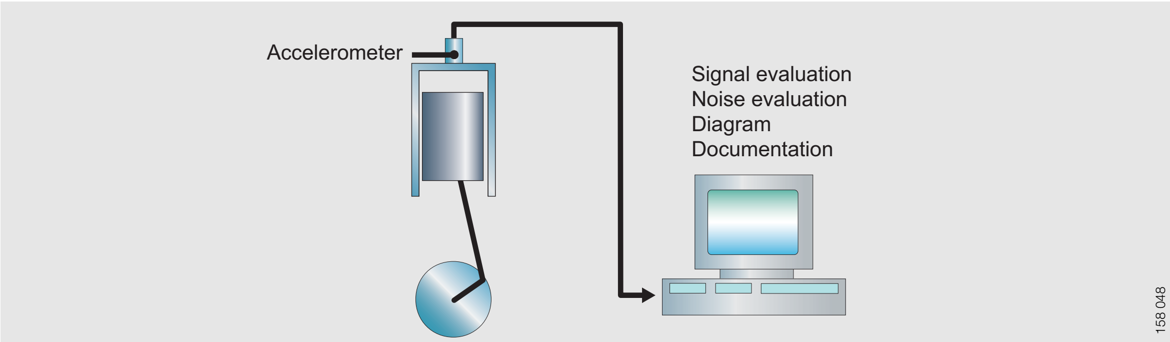
The only way to test these effects is by using original fired engines. An accelerometer to measure the structure-borne noise is used to evaluate the function. Computers are used to separate the valvetrain related noise and evaluate the information.

Functional Tests I

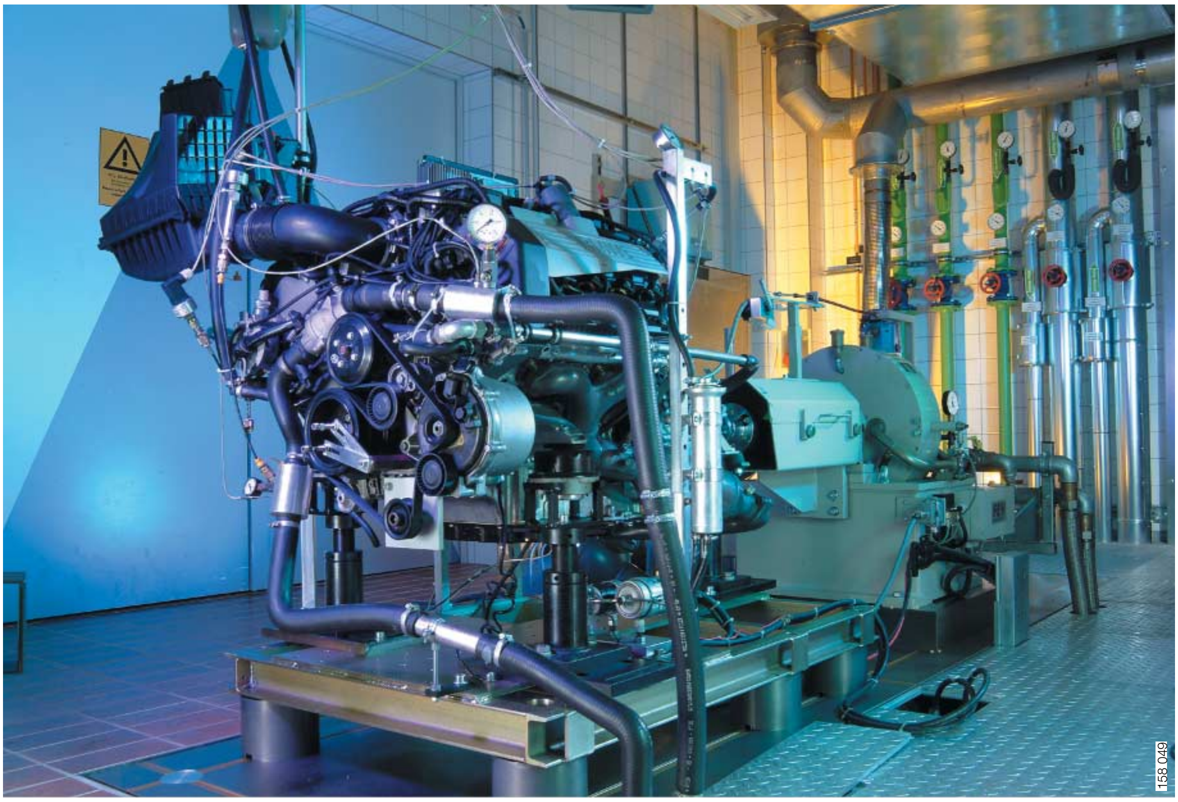
High Pressure Chamber



Vibration Measurement Principle



Test Stand

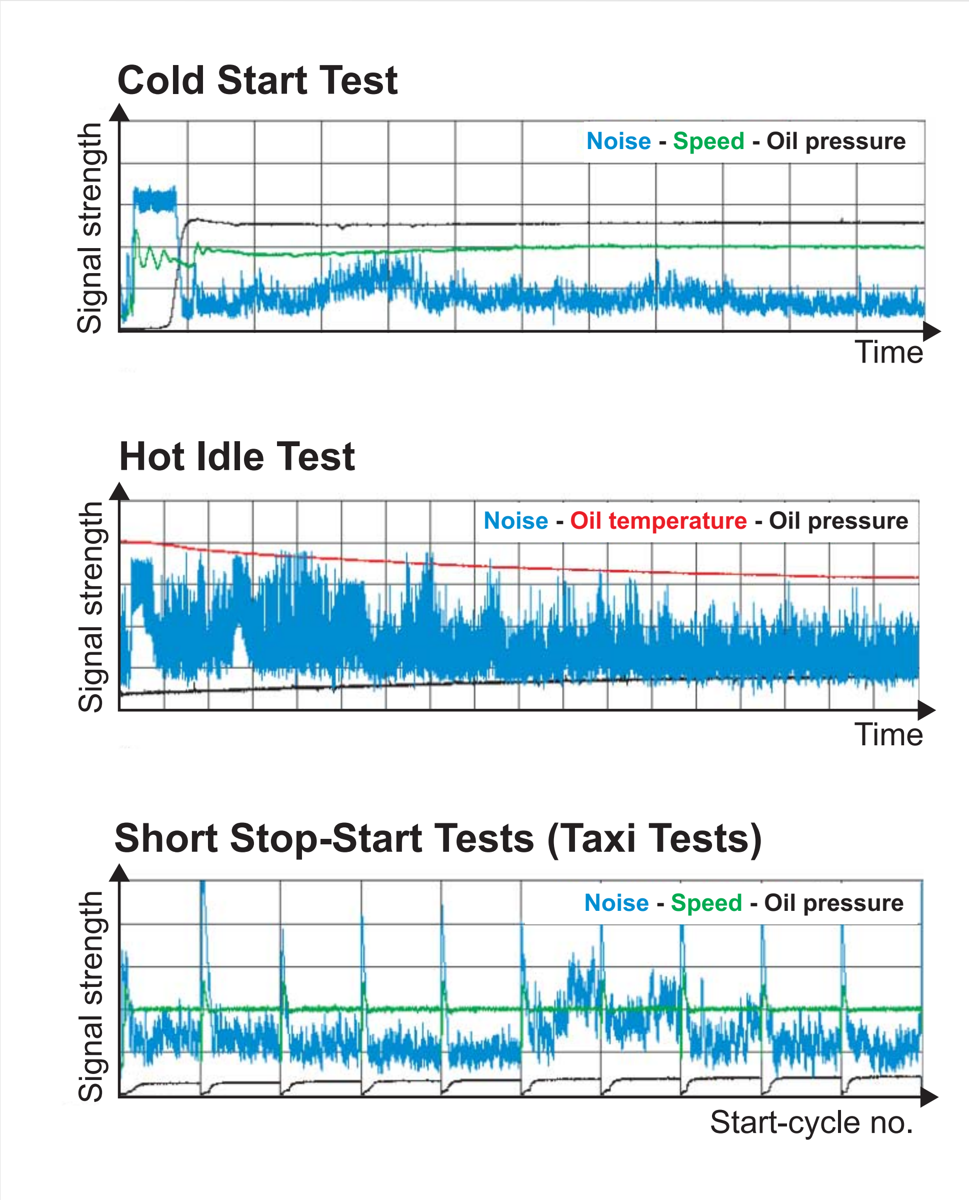


Functional Tests II

Standard tests are used to simulate the critical operating conditions in the engine:

- Cold start down to –40 °C ambient
  (drained oil supply, delayed oil pressure increase, thick oil, high oil pressure, etc.)
- Hot idle test
  30 min. operation at idle speed after sustained operation at high engine speeds and associated temperatures
  (thin oil, low oil pressure, oil aeration, sharp drop, etc.)
- 40 short stop-start tests (taxi tests)
  (draining of oil passage, leakdown of the hydraulic elements in the three minute downtime phase, air transport to the hydraulic elements during startup, only brief test run of 10 sec)
- Temperature-cycle tests
  (temperature variations up to 50 °C max. lead to draining effects due to the heat expansion of oil and air in the oil supply)

Typical Results of Standard Functional Tests



Misfire Tests I

Misfire tests are performed to investigate the effects of hydraulic lash adjusters (HLAs) on combustion in cold engines during transient temperature conditions.

If a generally cold engine is driven hard immediately after startup, the hot exhaust gases (800 °C) heat up the exhaust valve very quickly. The valve elongation due to heat expansion causes the valve to open a few microns when the HLA is not able to leak down fast enough. The delayed leakdown is due to the fact that the engine oil is still very cold and thus very thick. The oil must pass through a leakage gap only a few microns wide. If the engine is then brought to an idle, the partially open valve can result in misfire, which in extreme cases can result in an engine stall.

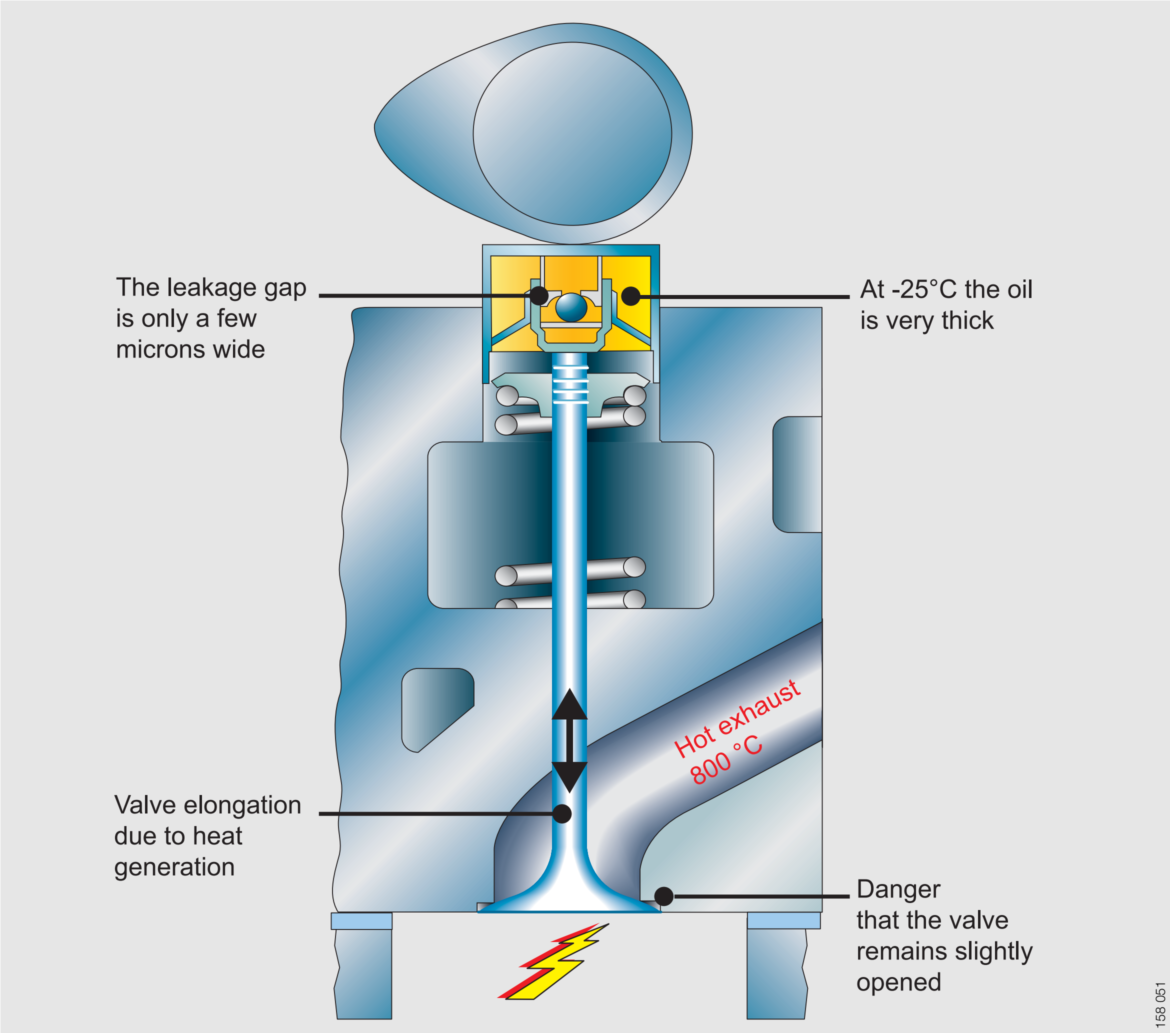
An increase in the size of the leakage gap is only possible to a limited extent because the resulting leakdown rate is too high when thin (hot) oil is present.

Special designs can be used to correct this.
These include:

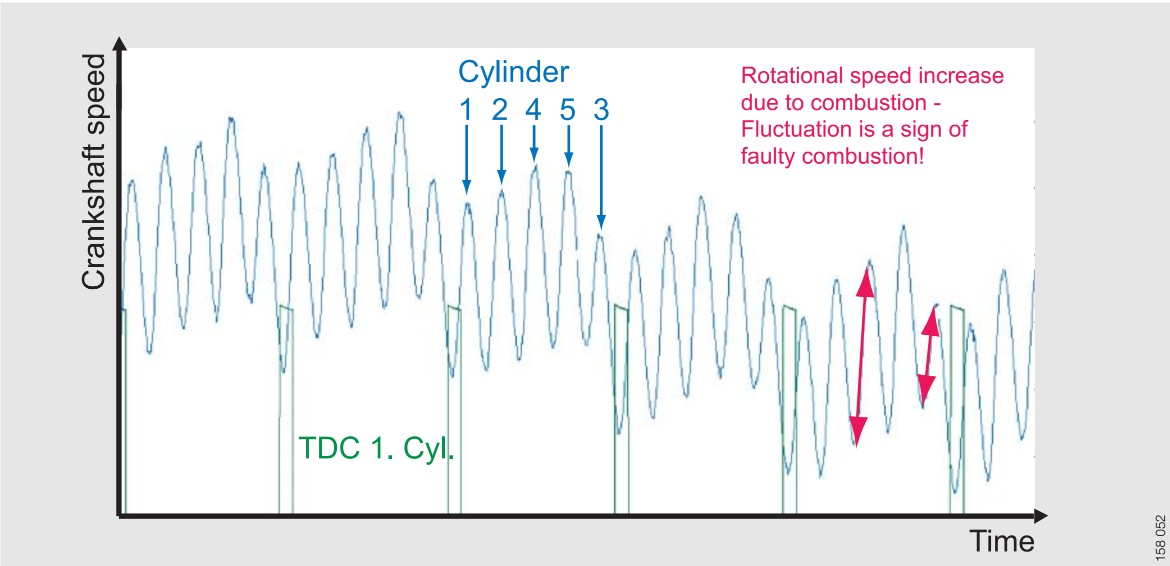
- Thermal HLAs
- Graded tappets
- Free-ball HLAs
- Pinball HLAs

Misfire Tests I

Schematic Diagram of Thermal Effect



Monitoring the Combustion Cycles



Misfire Tests II

In the U.S. and Europe, on-board diagnostics (OBD) are required by law. The emission-related components must be continuously monitored. The malfunction indicator lamp (MIL) and fault codes set in the engine control computer indicate the presence of emission related problems.

If the same reoccurring emission problem is found in 5% of the vehicles of the same type, production must be corrected at the expense of the responsible manufacturer.

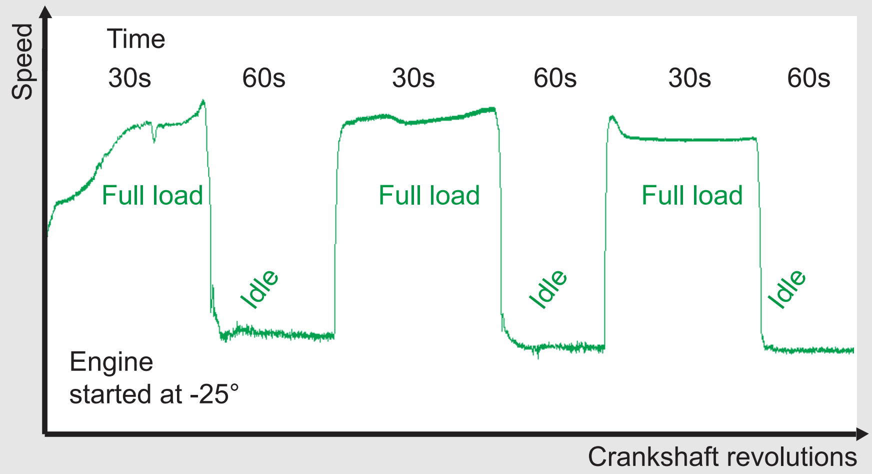
Compared to what the driver can perceive, the electronic monitoring of misfire is very precise, and malfunctions can be detected long before the driver notices them. Tests can be conducted to determine whether the hydraulic lash adjusters are causing misfire events.

Various procedures are used to monitor the engine:

- Crankshaft speed variations are measured, the ionization current in the exhaust gases is measured, etc.

To determine what safeguards exist that ensure that misfires detection is not activated, tests are performed on vehicles having the manufacturers' diagnostic systems. Here, misfire detection signals are compared with the current limiting values.

Test Cycle with Vehicle



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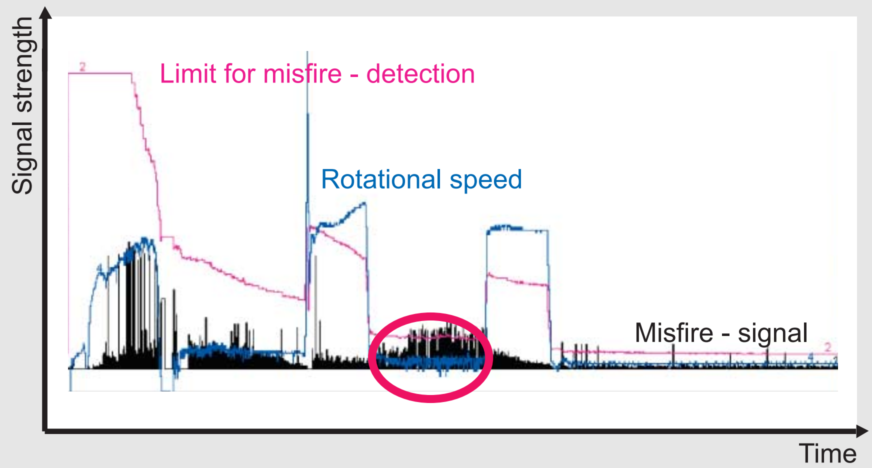
Test with Misfire



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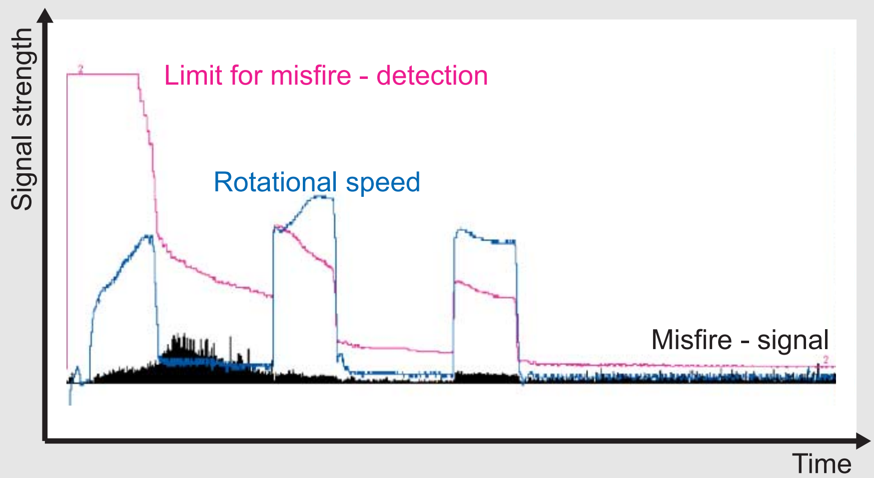
Test without Misfire



158 055

Switching Tests I

Switching tests are performed to investigate the behavior of switchable valvetrain components.

Performance of combustion engines can be further optimized when switchable valvetrain components are used. These components include bucket tappets, pivot elements, roller lifters and roller finger followers. They enable switching between two different cam contours (valve lifts), which in turn allows the cylinder charge or the thermodynamic effect to be improved. Switching elements have mechanical locking pins controlled by oil pressure.

Two variations exist depending on the engine design:

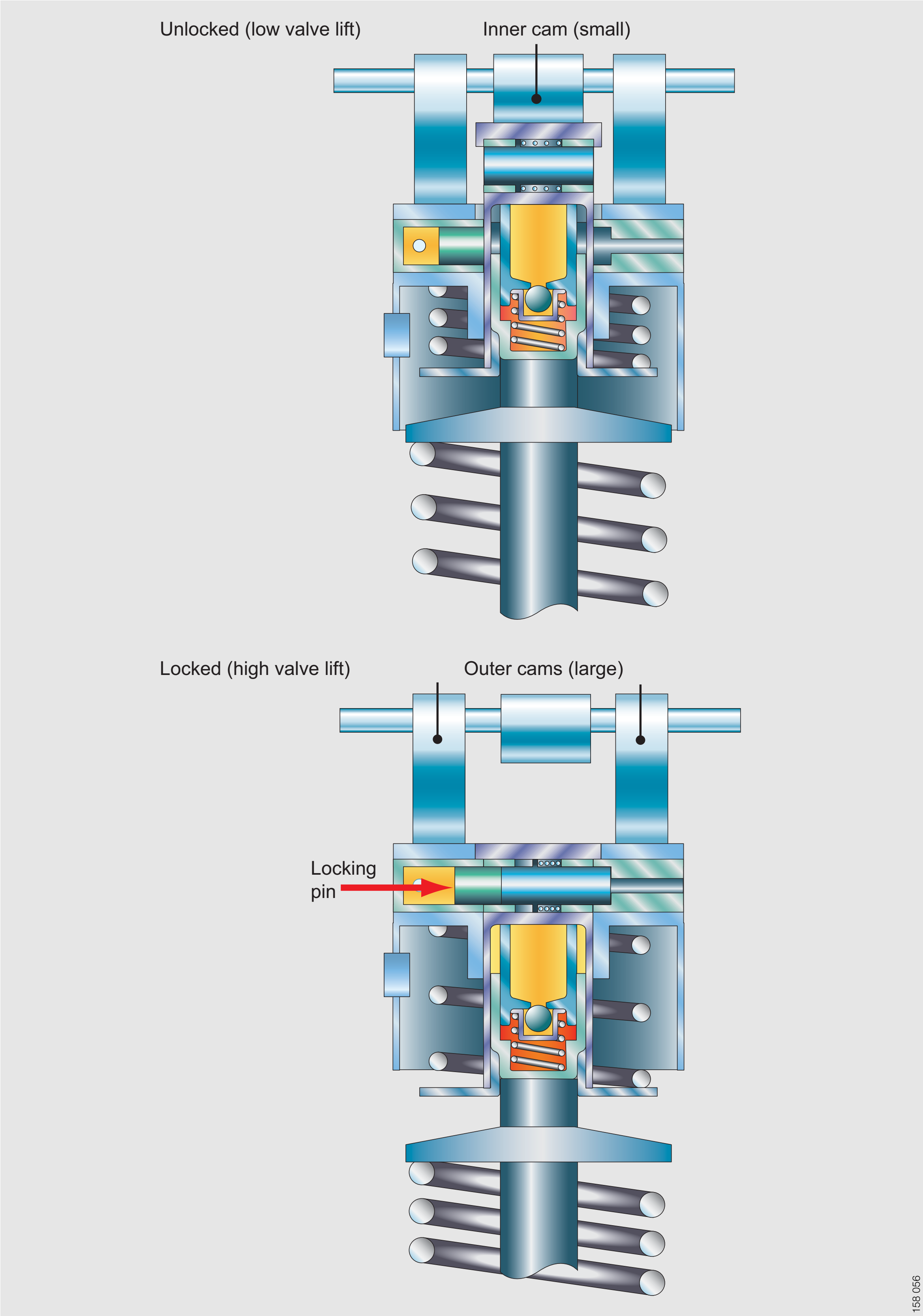
- Locked with pressure
- Unlocked with a pressure signal

Applications of switchable technology

- Switching ability between two different valve lift curves
  – Low lift provides improved low end torque
  – High lift provides increased peak power
- Switch between regular lift and no lift lobes
  – No lift can be used to deactivate cylinders for improved fuel economy

Switching Tests I

Switching



Switching Tests II

A switching event must not exceed 20 milliseconds in length and approximately 2.5 million switches must be performed during the life of the engine. Only one faulty switch event is permitted in 10,000 consecutive switch cycles. Testing is performed on complete engines that are driven by electric motors. The advantage here is that in the absence of combustion, sensors can be used directly on the valves.

For automatic test stand operation, it is necessary to develop the appropriate control systems. Measuring and evaluation units must accommodate the continuously changing test conditions set up by the automatic control system. In hundreds of test hours with millions of switch events, the switching reliability is determined and the timing of the oil pressure control is optimized.

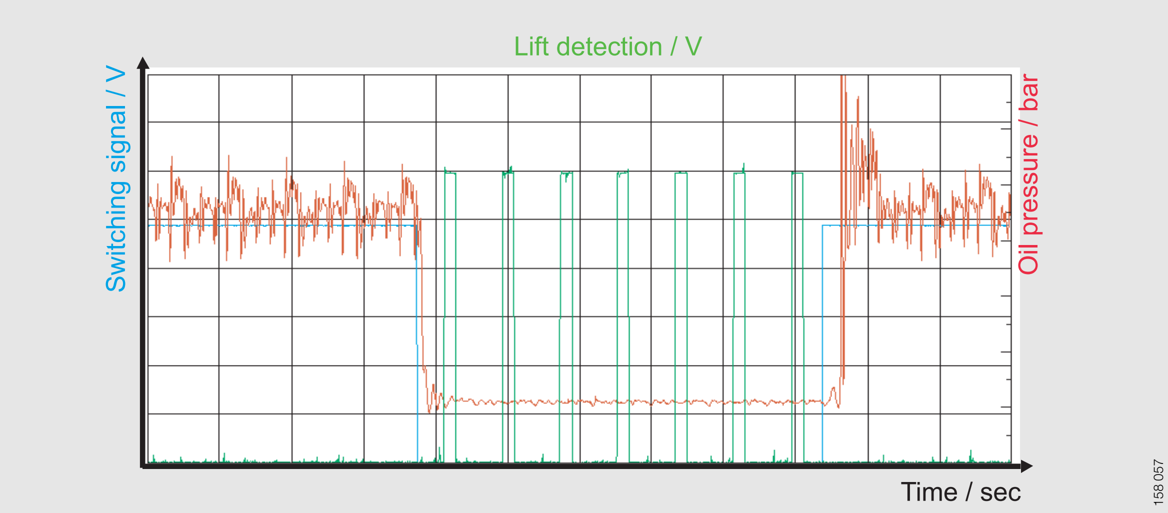
Maps are prepared to describe the effects of the following items on switching behavior:

- Trigger signal position
- Oil viscosity
- Wear
- Oil aeration

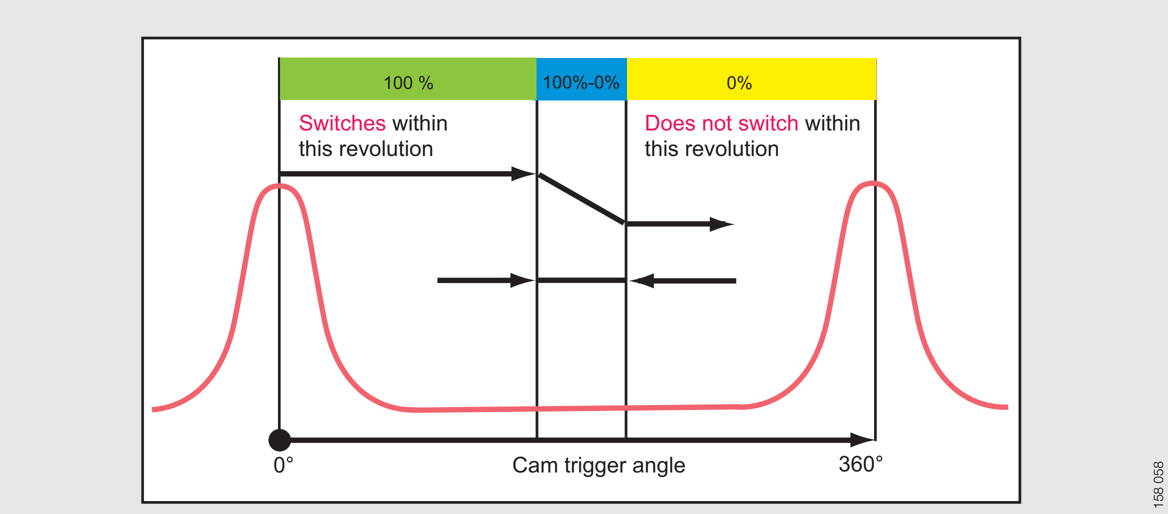
The values obtained are used for the solenoid control mapping in the engine control computer.

Switching Tests II

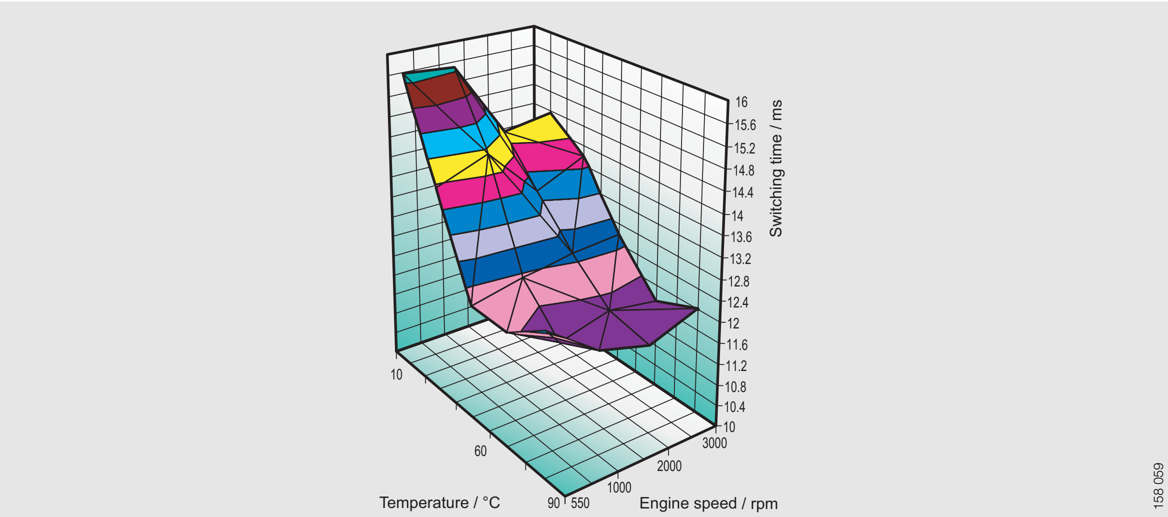
Signals Measured during Switching Event



Influence of the Trigger Signal Position



Map of Switching Times for Various Temperatures and Speeds



Dynamic Valve Train Simulation I

The benefit of multi-body **dynamic simulations** within the product development process is that testing time and costs can be reduced.

If the focus of a simulation is on the function of a single component like the switchable tappet shown at right (cf. Figures 1–3), the dynamic simulation carried out with a single valvetrain model yields the requested results. If the focus is on the overall behavior, including the interactions between the valve components and the influence of chain drives and camshaft-phasing units, it is necessary to simulate the complete valvetrain and connected systems (cf. Fig. 4).

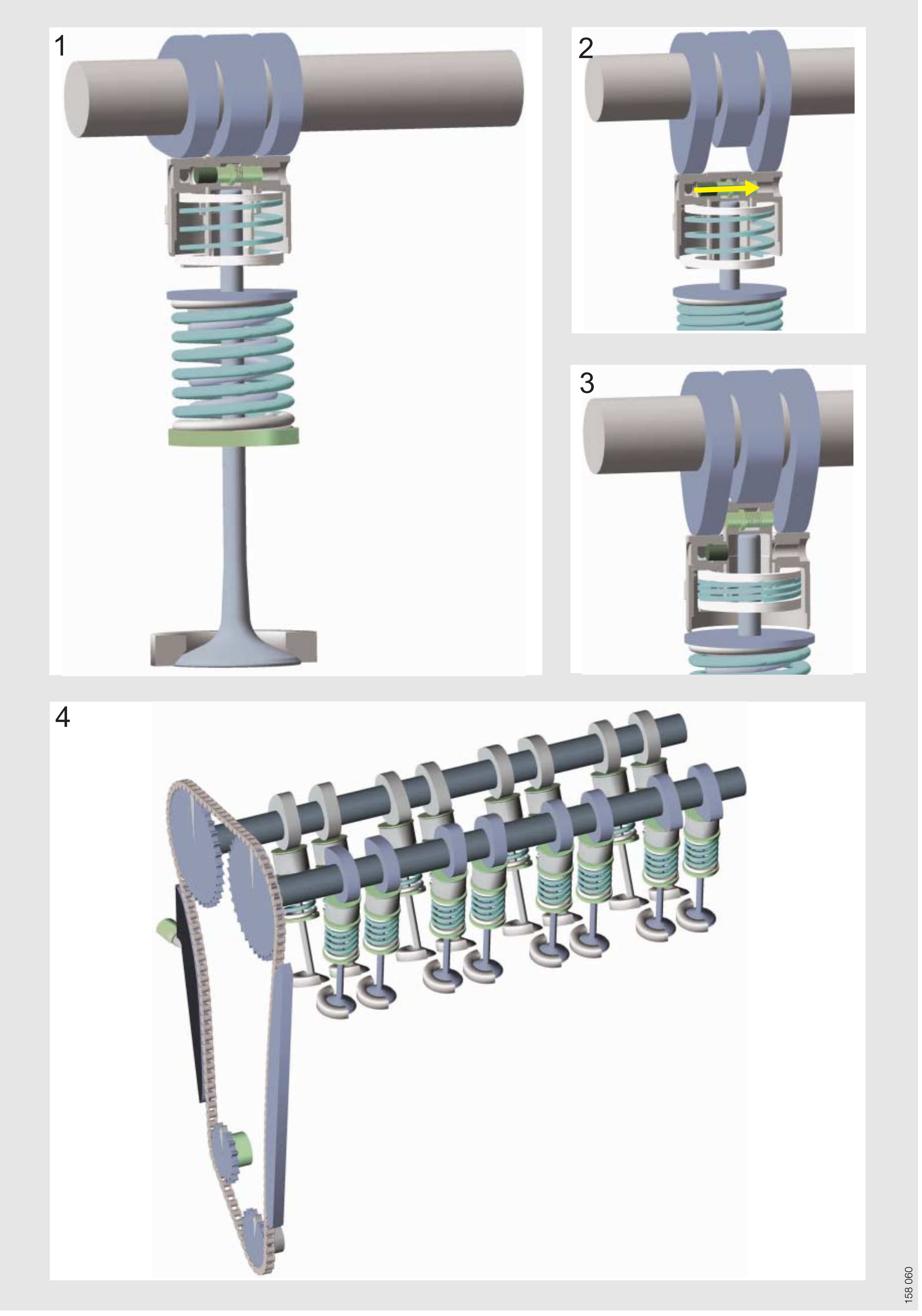
For further refinement of the simulation we can include flexible bodies, which also enable the facility to analyze the fatigue behavior of the components.

Features of switchable tappet, hydraulic:

- Switching facility between two different valve lift curves
  – valve or cylinder deactivation
- In valve or cylinder deactivation:
  – valve remains closed or
  – is opened to its full valve lift
- For cam profile switching there is:
  – low/medium valve lift or
  – high valve lift
- Advantages of valve or cylinder deactivation:
  – improved emission behavior
  – reduced fuel consumption
- Advantage of valve lift switching:
  – significantly improved torque curve (low end torque)
  – significantly increased engine power

Dynamic Valve Train Simulation I

Simulation Models



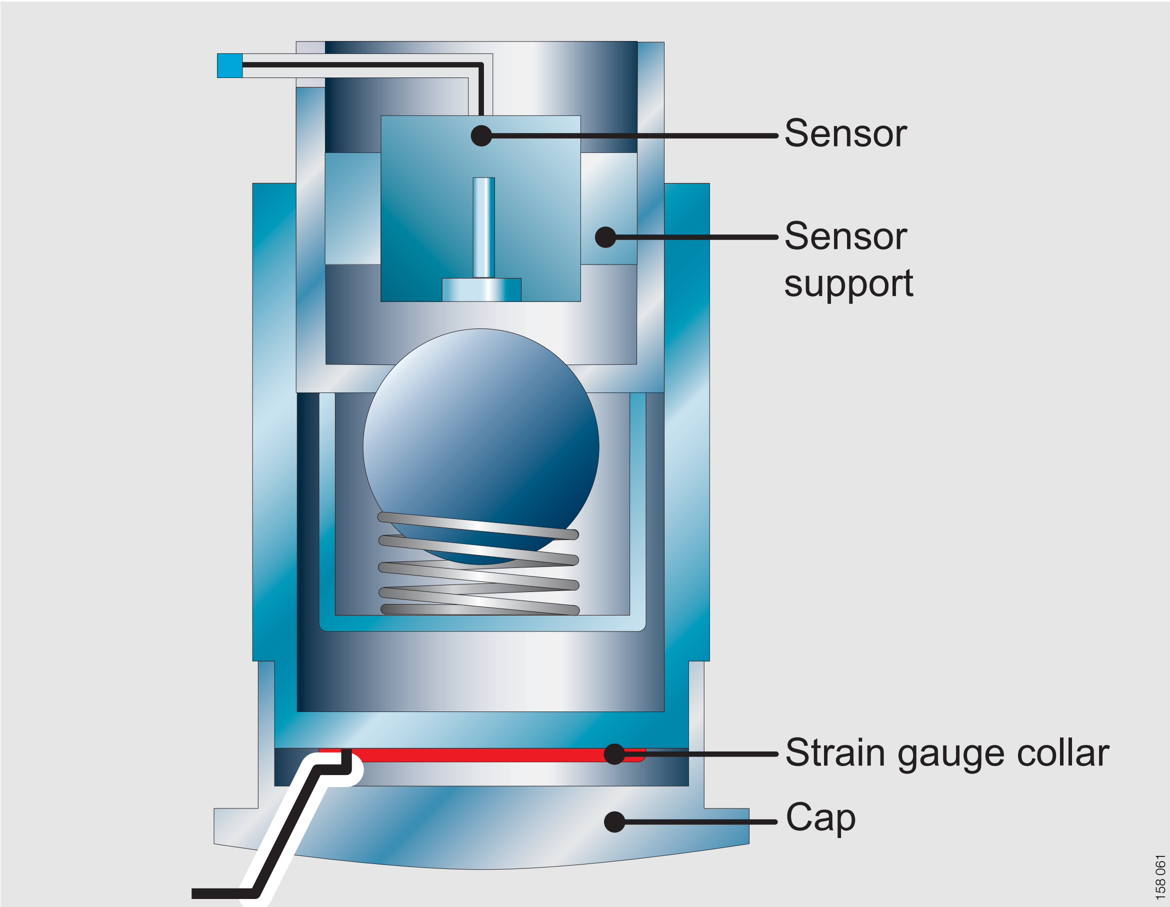
Dynamic Valve Train Simulation II

An example of a complex measurement task for model correlation is the determination of the highly dynamic motion of the ball in the check valve in a hydraulic lash adjuster. The ball size (3 to 4 mm dia.) together with its relatively small motion range (max. lift < 0.5 mm) presents challenging requirements for the metrological investigations performed.

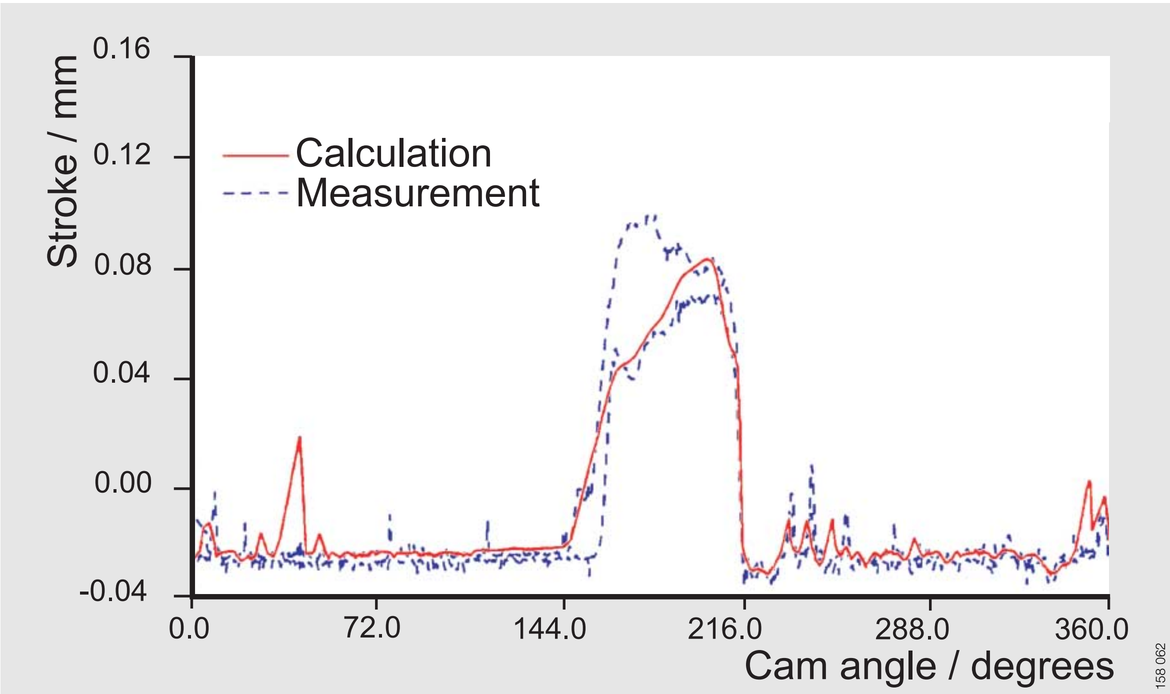
The figure at the right shows the capacitive sensor used and also illustrates how pressure is measured in the high pressure chamber using a strain gauge.

The ball movement is particularly sensitive to a wide variety of effects due to its very small mass (0.1 g) and the extremely low forces. This is why two check ball opening events are never the same even in the case of apparently identical conditions. For this reason, the profiles for the largest and smallest opening event from a series of measurements are used to compare calculations with actual measurements. Calculation results are between these two measurements.

Instrumented Hydraulic Element



Comparison of Ball Stroke Measurement and Calculation



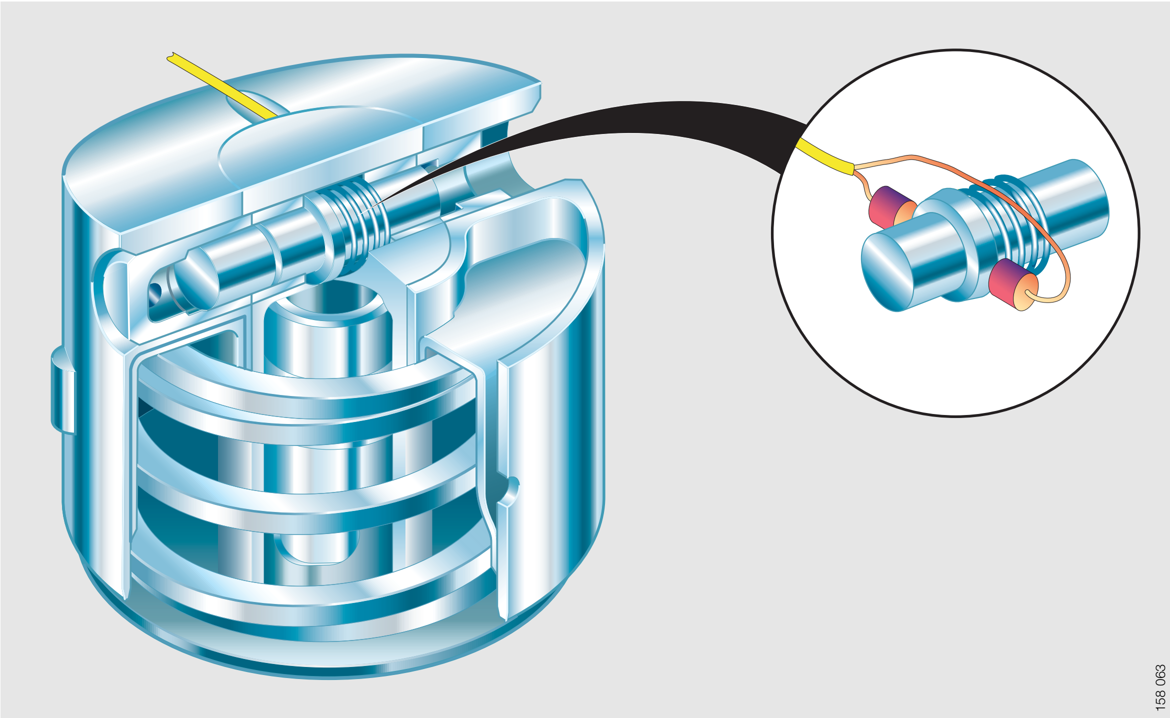
Special Investigations I

The purpose of **special investigations** is to provide new information regarding the function or load conditions of valvetrain components. They allow INA to verify theories that have been proposed and provide better answers to customer questions.

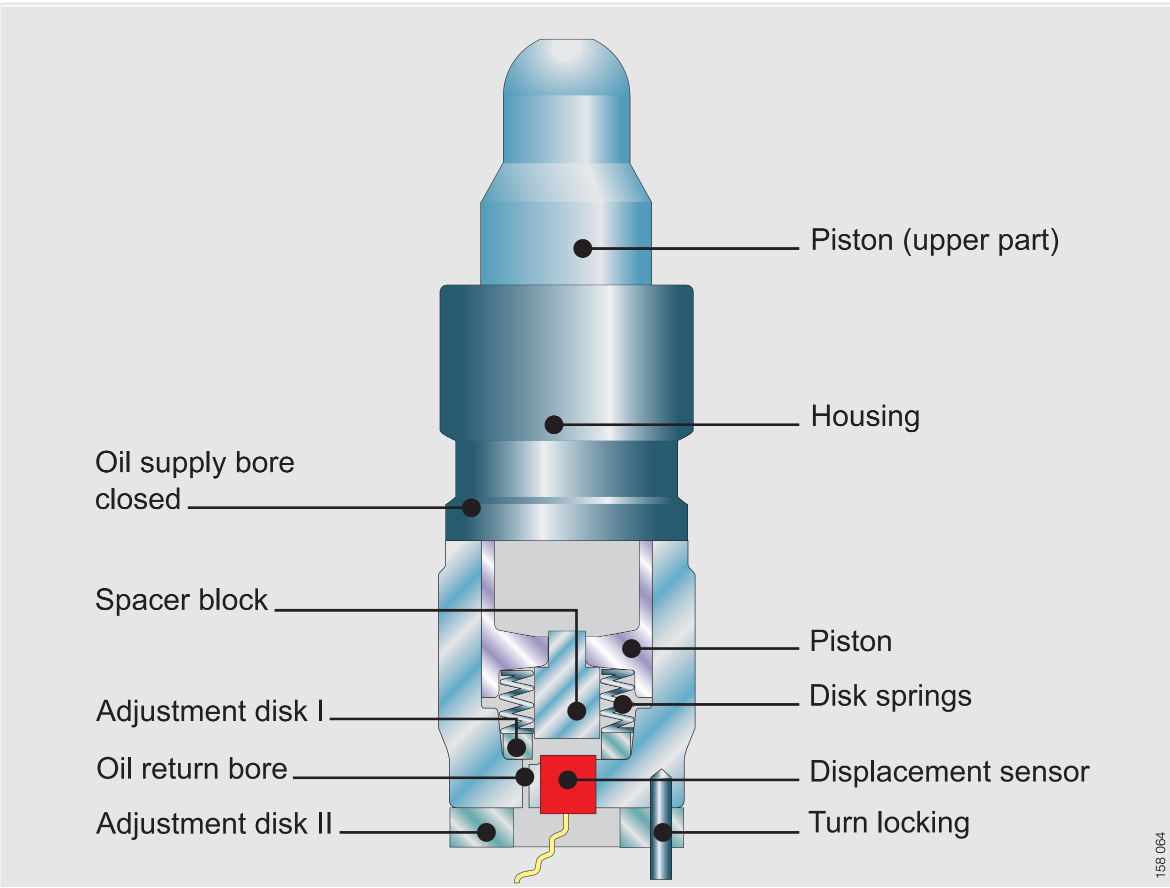
Although special investigations are very interesting, they are also time consuming and costly, because there are no standards to fall back on. In some cases, new sensors, and measuring and evaluating procedures must first be developed.

If there are critical time constraints, experienced internal engineers are assigned to develop the new technology. In less time sensitive cases, the development of new measuring techniques is often assigned as part of student master's degree programs. In these cases though, results are not available for several months.

Measurement of Locking Pin Motion



Changes of Installation Dimensions under Fired Operation



Special Investigations II

Some of the special investigations that have been performed include the following:

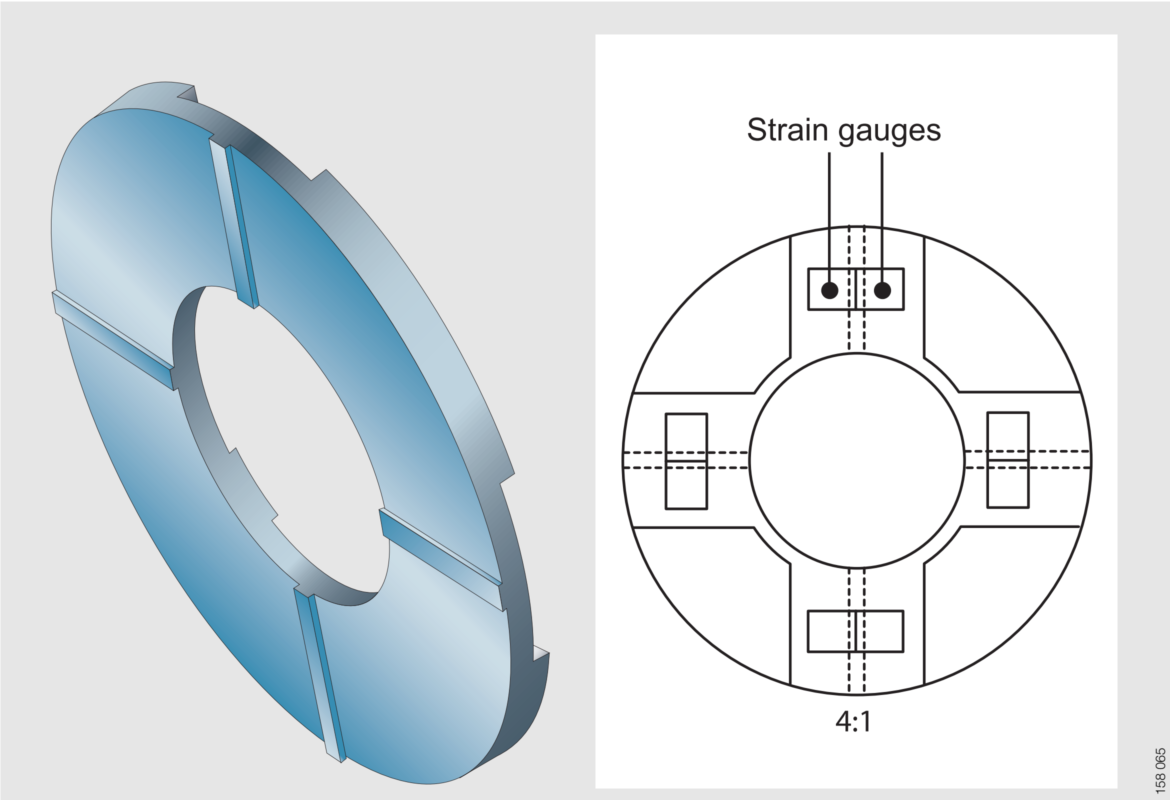
- Measurement of the rotation of hydraulic bucket tappets (TSTH)
- Quantification of oil aeration in the TSTH reservoir
- Measurement of TSTH ball opening behavior
- Measurement of the pressure within a high pressure chamber of a hydraulic lash adjuster (HLA)
- Measurement of valvetrain friction with roller bearing and plain bearing supports
- Measurement of rotational speed of rocker arm rollers

Over time, many special investigations have evolved into standard tests or measurements.

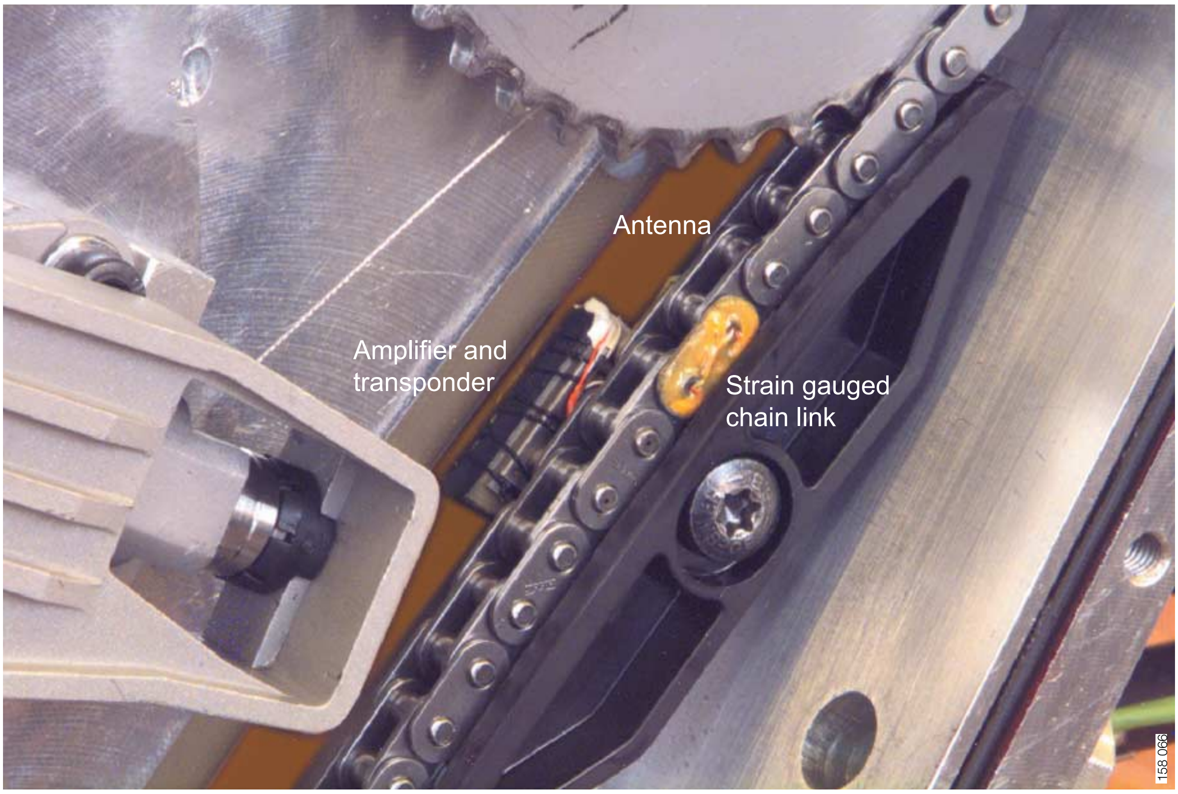
These investigations have contributed greatly to improving the reliability of our products in the engine.

Special Investigations II

Force Measurement Disk



Telemetry



Timing Chain Drive Tests I

In addition to valvetrain components, INA is also a supplier of camshaft drive components. As previously noted in the model correlation section (pages 30–31), camshaft drives can often affect the valvetrain components as well. For this reason, INA is actively involved in camshaft drive testing.

Timing chain drive tests are performed to optimize the design of the camshaft drive.

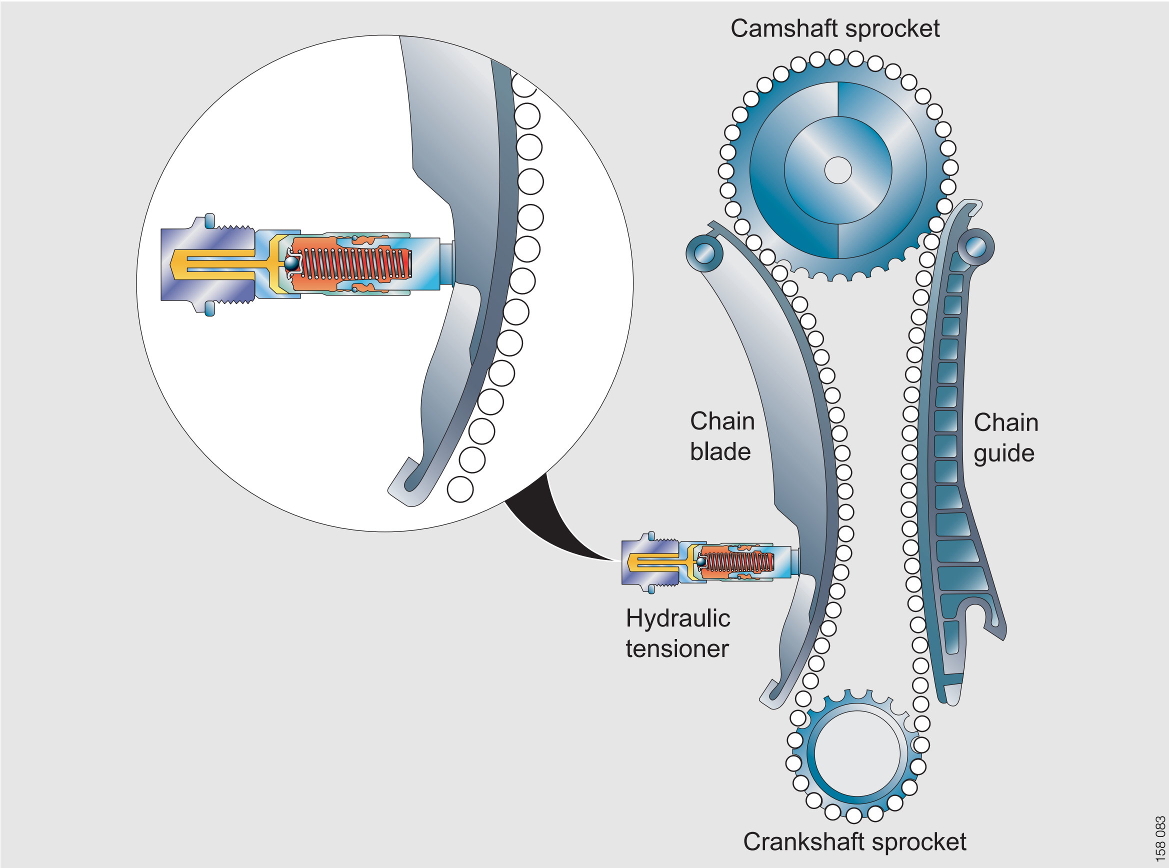
In modern combustion engines, camshafts, balancing shafts, fuel injection pumps and other devices are often driven by chain drives. Due to thermal elongation and wear, a means of compensation must be available in the form of a chain tension system. The system should also do its part in making load as evenly distributed as possible. To do this, an appropriate adjustment (spring-dampener) must be found.

The drive components (crankshaft, camshaft(s), sprockets, chain, tensioner, etc.) form a complex oscillating system. System oscillation can be initiated by alternating shaft torque, irregular crankshaft rotations and internal influencing mechanisms. Due to the broad bandwidth excitation, resonances often occur. In the case of resonance, unacceptable part loads or torsional oscillations in the drive can result.

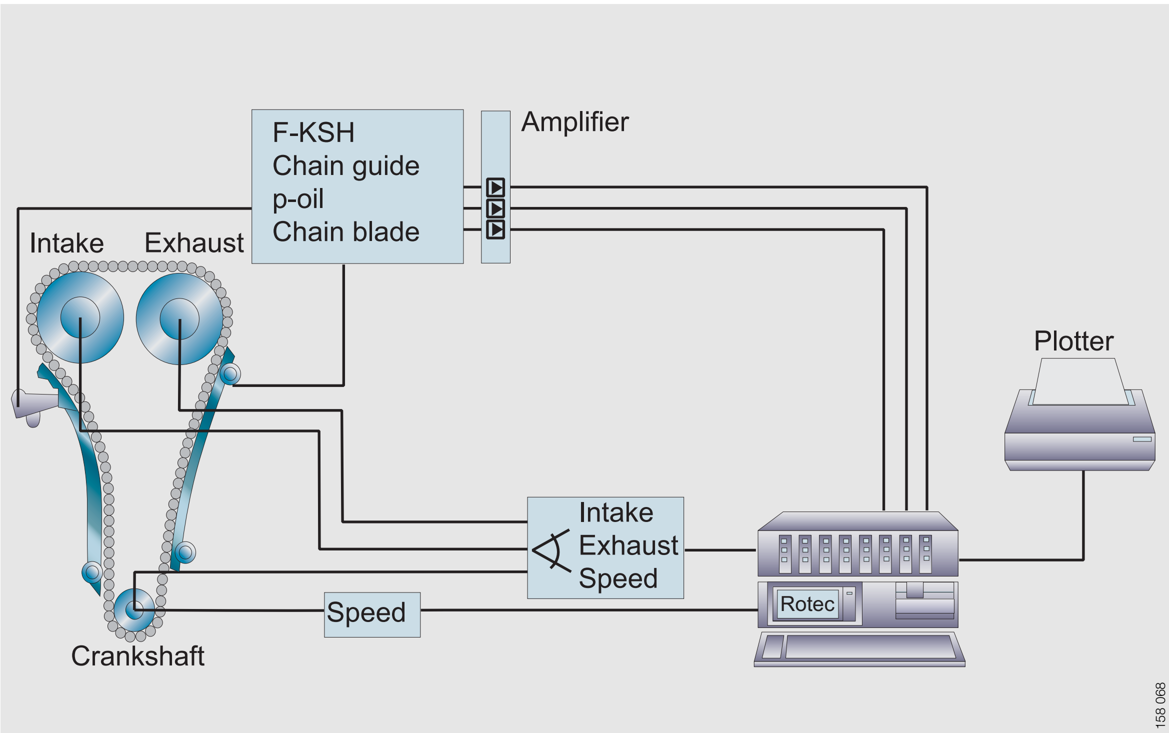
Measurements are generally made with specially matched or specially developed sensors in the chain drive under investigation. The fired engine is run on a dynamometer to include the irregular camshaft rotation changes under load.

Timing Chain Drive Tests I

Camshaft Primary Drive



Camshaft Measurement Configuration



Timing Chain Drive Tests II

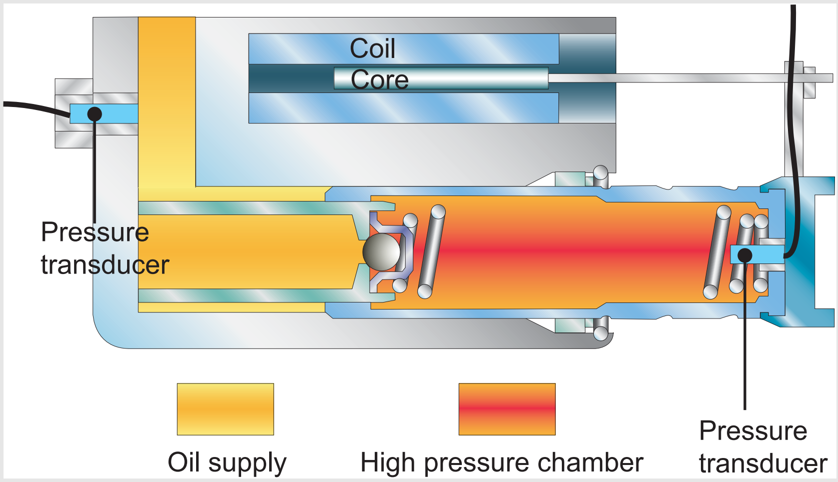
The following are measured in chain drives:

- Forces/tensioner strokes
- Torsional oscillations of the relevant shafts
- Oil pressure (tensioner supply, high-pressure chamber)
- Reaction forces on the chain guides

After these parameters have been evaluated, behavior can be assessed reliably, and necessary optimizations can be made.

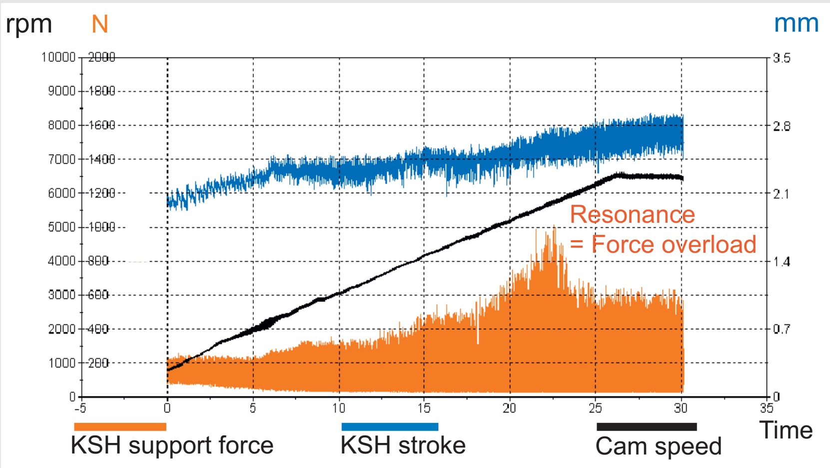
Timing Chain Drive Tests II

Measured Variables on the Tensioner



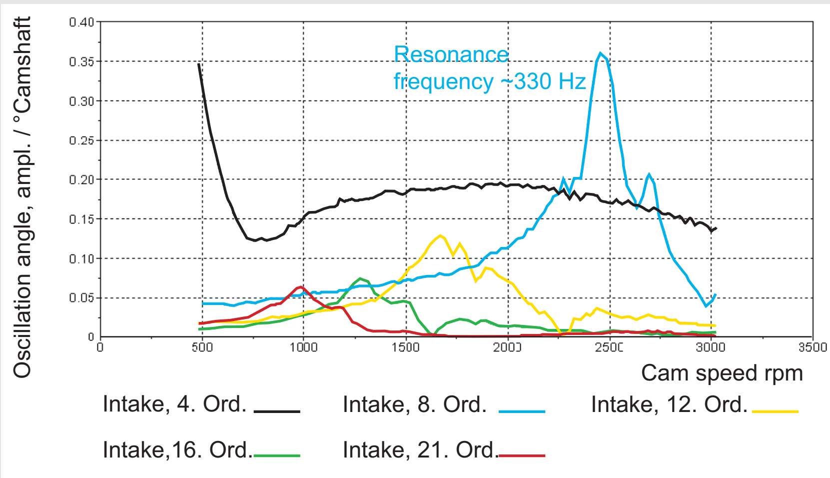
158 069

Speed Ramp in Time Domain



158 070

Speed Ramp in Frequency Domain



158 071

Wear Tests

Wear tests are conducted to verify the resistance of parts against material abrasion.

Metal pieces sliding against each other under mixed friction conditions produce abrasive and adhesive wear processes. Both of these wear mechanisms as well as fatigue wear, which leads to surface pitting, often cause the sliding contact partners to fail completely. Wear can also result from several types of corrosion.

Parameters that have an effect on wear include:

- Materials
  (material pairing, heat treatment, coating, etc.)
- Contact geometry
  (macro/microgeometry, geometric accuracy, roughness, supporting surface, etc.)
- Load
  (forces, moments, Hertzian pressure, etc.)
- Kinematic design
  (relative speed, hydrodynamic speed, contact pressure, etc.)
- Lubrication
  (oil, viscosity, quantity, additives, contamination, aging, etc.)

Worn HLA Ball Head before Optimization

HLA Ball Head after Optimization

Summary

As you can see, INA has world class testing capabilities to complement any product development program. Of course, a highly skilled staff of professionals is required to bring it all together. INA has that with ample resources available in Germany and a growing staff in North America.

Working jointly with you, the customer, sound solutions can be obtained for your product optimizations.

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