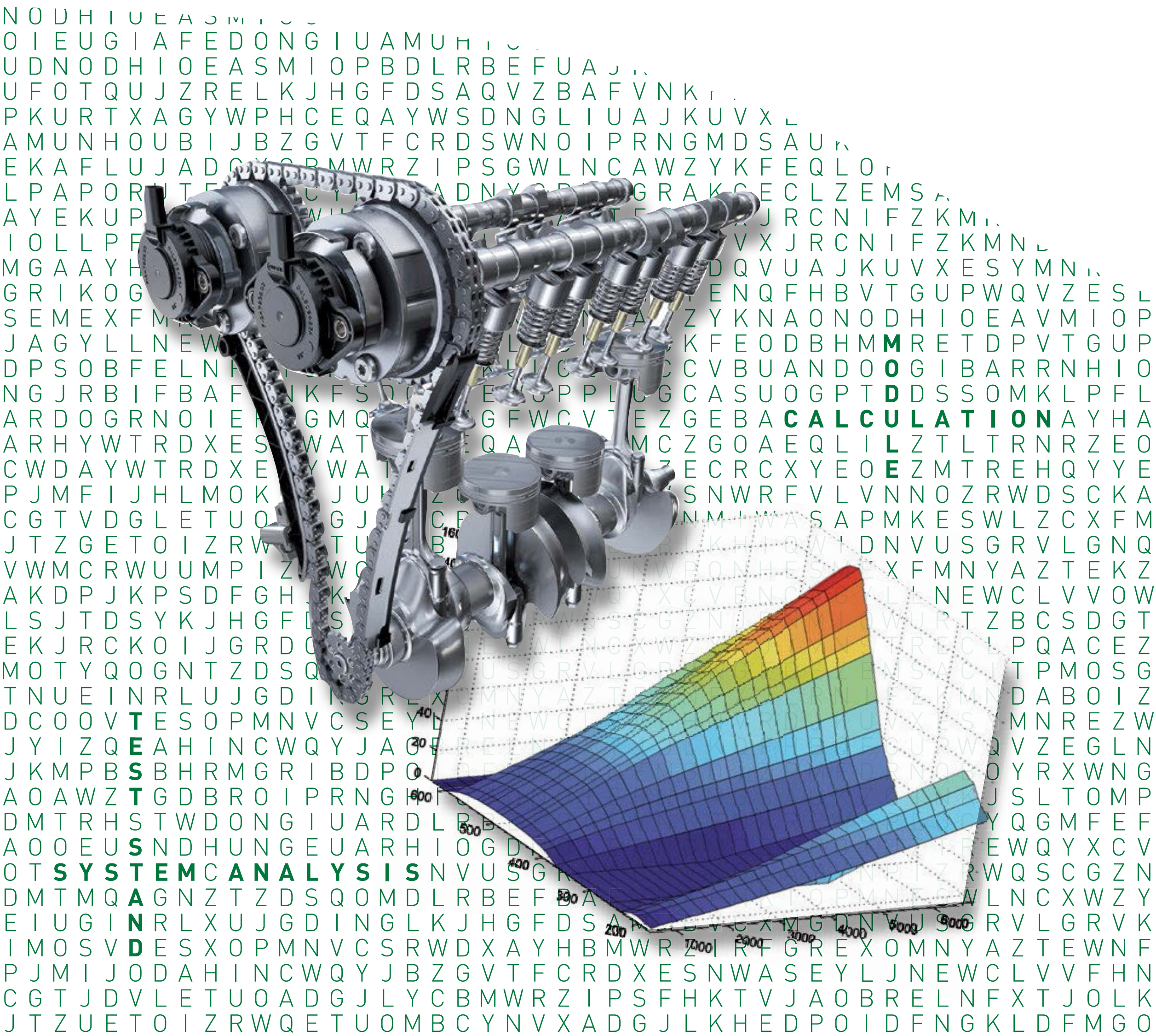

CALCULATION
MODULE
TEST STAND
SYSTEM ANALYSIS

Holistic Simulation

The future approach for calculating engine systems?

Dr. Christoph Brands

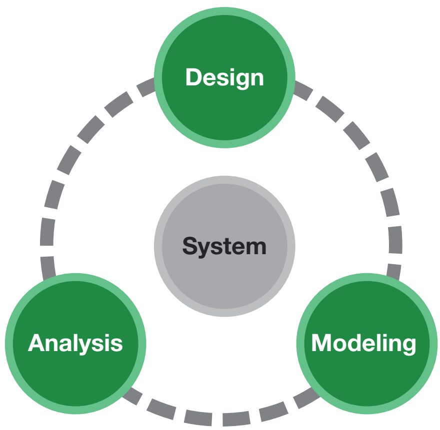
9

Introduction

Ever shorter development times, an increased range as well as continually more complexity and diversity of engine systems, are the megatrends driving the value-added chains in the automotive and supplier industry. To relieve some of the pressure exerted by these processes, virtual product development has become an essential component of design and engineering work. When incorporated in time, technical calculations can facilitate quick response in many different areas and thereby effectively shorten development cycles and times.

Very few technologies have made as great of an impact on product development processes as the move toward digitalizing process flows. In the process, the only aspects that have changed are the tools used and the procedures followed. The core development tasks for engineers remain the same. Figure 1 shows the main tasks associated with making technical calculations, which include:

– Analyzing and modeling the system
– Carrying out the steps involved in the analysis (i.e. the actual calculation exercises)
– Deriving design and concept proposals from the results obtained



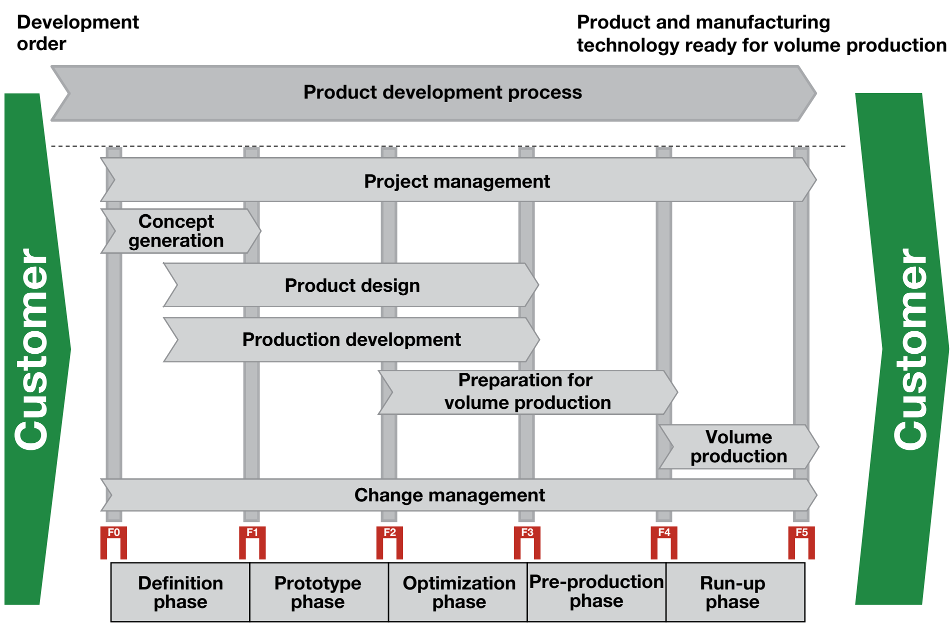


Figure 1 Tasks associated with carrying out technical calculations during the product development phase

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System Analysis and Modeling

Modeling always revolves around simplifying the properties and characteristics of the real, physical system. A simulation only provides results that relate to the model at hand and its performance limitations. Therefore, in order to ensure that the work carried out at this time can be transferred as required, steps must be taken to verify that the model (depending on the level of detail it incorporates) exhibits the right tendencies and leads to the correct quantitative results when used under defined system limits as performance parameters are varied in real time. This validation is typically realized by drawing comparisons with trial testing data. Different models with varying levels of detail can be created depending on the knowledge acquired about the real system. If the physical correlations of the real system are not known, a mathematical model can at least be made that provides corresponding results for changes to input parameters. In the most basic scenario, this takes the form of a regression of existing trial testing data (data-based modeling).

If the physical correlations are known, however, and sufficient, reliable input data is available, analytical approaches or complex physical models can be devised and solved numerically.

Unlike the realm of natural science, engineering involves simplifying matters and concepts on a daily basis. This abstraction or simplification is a key tool used to systematically approach complex systems. A good example of this is the pendulum as considered in the context of a point mass with respect to a thread that has no mass. When small angles are observed, $\sin(\Phi(t)) = \Phi(t)$ is then used by way of the Taylor approximation. Modelling also involves accepting the risk of incompleteness. To this end, when system analyses are carried out, all required effects must be identified and factored into the model so that technical and design-related questions can be answered. In order to safeguard reasonable calculation times with respect to numerical computability (stability), the model must also not be overloaded with performance data. After all, the right model must be processed using the right tool, depending on the question to explore.

One of the main tasks involved in technical calculation exercises is therefore to conduct an initial system analysis and create a model to establish a baseline. The next step is to check the plausibility of the external and internal input data available and to provide this data in a suitable format for the simulation as required. This includes geometric data from CAD systems as well as functional data such as plotted rigidity curves. Checking and verifying the input data is critical, since every result obtained directly correlates with the quality of the data itself. All process steps must be accompanied by a defined change management policy such that when geometric or other relevant data is changed, this is communicated appropriately.

External Influential Factors

As an integral part of the product development process, the technical calculation department must deal with and account for external influential factors as is required of all other participating departments. These factors can encompass the needs and preferences of specific markets and economic requirements as well as key technical aspects (Figure 2). The automotive industry is currently being pressed to design and build vehicles that offer ever better levels of efficiency.

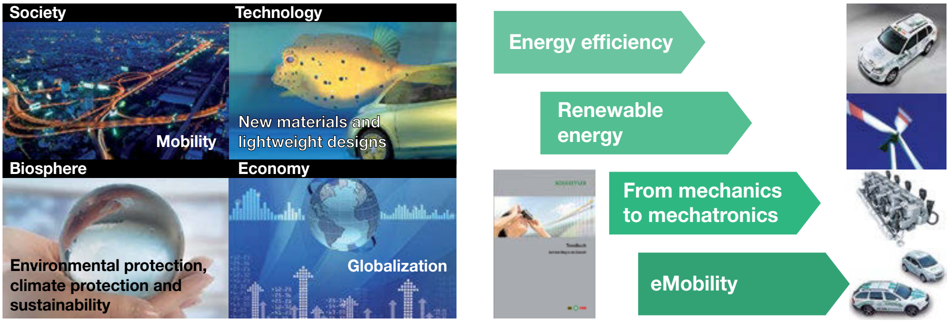

Figure 2 Trends in the automotive industry

Expressed in specific terms, this translates to such developments as:

- Optimizing engine output by making the air path variable in design (VT, VCT, ECP)
- Reducing mechanical loss by enhancing tribological systems
- Integrating lightweight materials
- Electrifying the powertrain

In addition to satisfying customers by offering more fuel-efficient passenger cars and meeting self-imposed obligations, complying with ever stricter CO_2 emission regulations further motivates the entire industry to design and engineer engines and vehicles that consume less fuel than their predecessor models.

It goes without saying technical calculation experts need to address these constraints by amassing new knowledge and devising methods that cater to this trend. Correctly evaluating internal engine measures requires a great deal of knowledge about thermodynamics, for example, and the increasing complexity of modern systems designed to enhance variable response characteristics need to be thoroughly understood to accurately integrate them in a simulation model. The same ap-

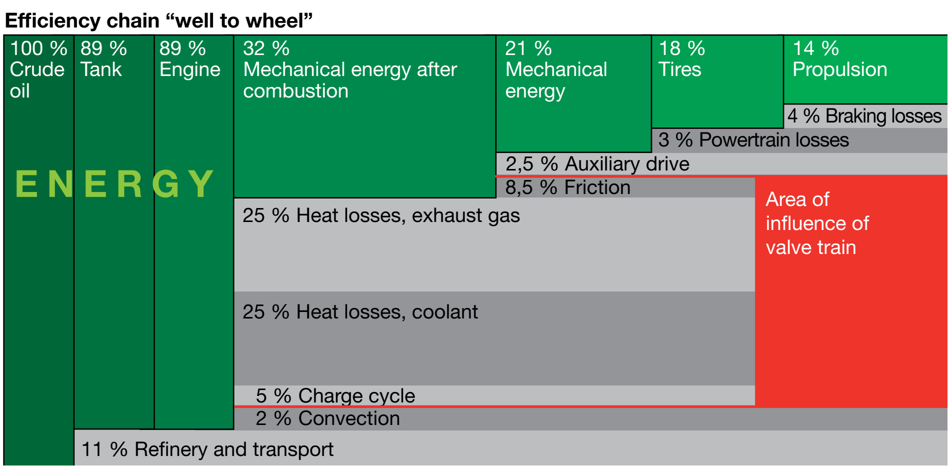

Figure 3 Energy lost from mining crude oil to operating a vehicle ("well to wheel")

plies to components and systems used to electrify or hybridize powertrains. In addition, methods must be devised to reliably predict the outcome of friction-reducing design measures. Figure 3 provides a starting point for achieving higher levels of efficiency. As various sources indicate that by 2020, up to 1.5 billion vehicles will be in use around the world, of which well over 90 percent will have an internal combustion engine, it pays to further optimize the internal combustion engine.

Not only have these trends in technology made a significant impact on the development work and technical calculations carried out by the automotive industry, but also the recent move toward globalization. In the process, basic engines (world engines) are now being assembled in large numbers and subsequently adapted to different vehicle classes by varying the levels of performance and equipment accordingly. This, in turn, necessitates highly robust methods when it comes to technical calculation, since any inherent design flaw has the potential to affect that many more units. The models used must also accurately represent each individual variant.

Globalization has likewise led to a change in production locations, which are now spread across multiple geographical regions that are served by a separate group of suppliers offering different material mixes. This brings with it the consequence that the development teams themselves are also distributed around the globe and must collaborate to resolve the intercultural, regional, and method-based problems that arise in this context.

If the full potential that technical calculation has to offer is to be leveraged, the practices that it entails must be integrated in the overall design process as early as possible, and all departments need to collaborate effectively on a daily basis. This applies to new developments and products in particular. Established components and systems require less commitment, since specifications and standard performance criteria are already in place and used around the world.

When new, highly sophisticated systems and hardware are designed, rapidly constructing simulation models around defined performance criteria is not an option, since this approach does not guarantee reliable, accurate results confirming that the function required operates within the target parameters assigned to it. Complex systems can sometimes take years to establish the right development environment including models and processes. The benefit, however, is that validated models and procedural approaches are created that are robust and can provide qualified answers to a wide range of questions in minimal time, including to ones that are asked on short notice. This, in turn, reduces outlay and underscores the true value of technical calculation.

Internal Influential Factors

The individual phases of the product development process (PDP) correlate with different technical questions and issues that pertain to aspects of manufacturing and product development and also have a noticeable effect on modeling. This effect becomes apparent as soon as a project is started, when reliable input data is frequently not available. At the same time, the manufacturer and suppliers are busy making a great deal of changes such that the initial priority is to limit efforts to investigating the primary effects that will point to the best possible concept to be adopted (design definition and finalization). When familiar components or systems are integrated, a lack of data can be temporarily substituted with values from existing databases. The results provided by the simulation must then be taken into account with this constraint in mind and replaced with qualified, realistic values later on. In addition to this time-

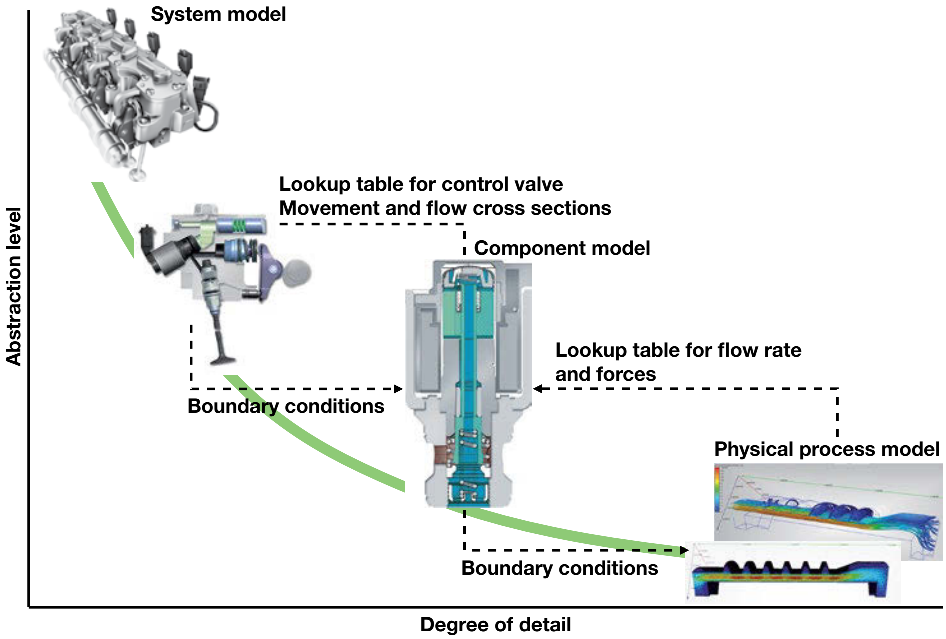

Figure 4 Modeling and system analysis

based component in the product development process, technical calculation work is also characterized by the experience that has already been gained with the system being developed.

For existing products, all recurring processes have usually been automated or at least defined in a specification (Figure 4). This is absolutely essential, especially in the case of global projects. After tools have been automated in line with technical calculation data, they can be handed over to the project engineers, who then make smaller calculations on their own and profit from expedited response times. When a finger follower is designed, for example, the question of rigidity becomes relevant. Schaeffler has fully automated this calculation and integrated it in its CAD system. Ninety-nine percent of the time, the system e-mails an automatically generated report to the project engineer at the click of a mouse just a few minutes after the start of the calculation.

The situation is different when new applications are developed, however, which are characterized by different levels of modeling detail as a result of the individual phases of the product development process and various questions fielded by specialists. Production planning personnel, for example, do not ask the same questions as the software department tasked with programming the functions for the engine control unit. Constructing a complete model that can answer all of these questions is usually too complex, requires too much calculation time, and is sometimes not even possible. Models are therefore constructed to target a specific question pertaining to a certain technical aspect and do not map an overall scenario.

One example of a scenario in which many different questions are asked throughout the product development process involves the multiphysics simulation model for the quick-acting valve used in the fully variable UniAir valve train (Figure 5).

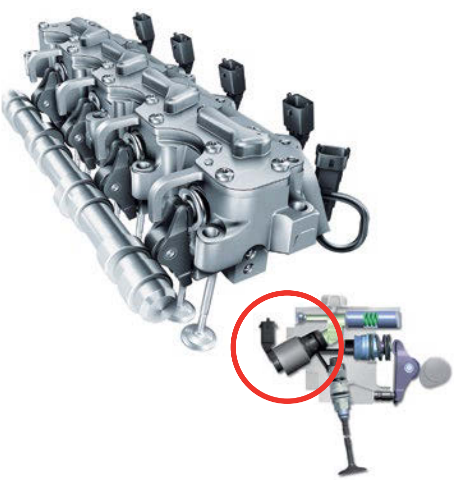

Figure 5 UniAir system

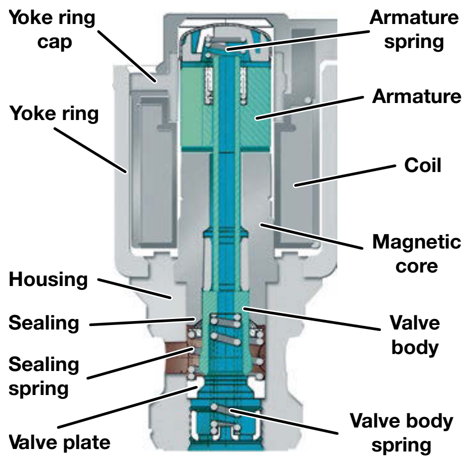

Figure 6 Quick-acting switching valve

The UniAir system comprises a camshaft-controlled actuator with an integrated, quick-acting hydraulic valve and corresponding valve timing software [1]. The switching valve is a de-energized, open 2/2-way switching valve by design that displaces a valve body relative to the valve seat to open and close the connection linking the high and intermediate pressure chambers.

To bring the quick-acting valve into the development environment (Figure 6), a multiphysics simulation model was created that maps and correlates all mechanical, hydraulic, magnetic, and electrical design as-

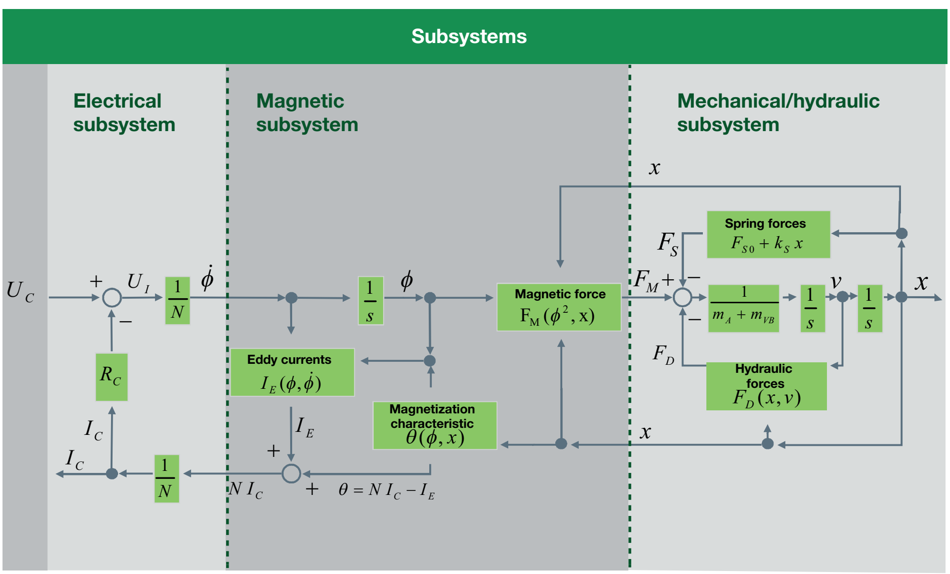

Figure 7 Physical interactions with the quick-acting switching valve

pects. Figure 7 shows the coil current. After an initial current is introduced, the maximum rated voltage is applied to produce a magnetic flux while generating the coil current and magnetic force required to close the valve. When the maximum current is reached, the closing time is characterized by a bend in the current signal ("V shape") as a result of an actuation triggered in the presence of a constant pulse width modulation (PWM) of between 0 and 12 V. During the hold phase, an electrical current lower than the one observed in the peak phase ensures that the closed position of the valve is reliably held. Although the energy consumed at this time continues to be high, it is in line with operating requirements [2].

The valve is opened when the coil is reverse connected to the Z diode, which causes the magnetic force to quickly deplete and triggers a fast opening movement. The opening time is detected by short-circuiting the magnetic coil so that the remaining magnetism produces a current coincidental with the motion pattern of the current signal via the magnetic-mechanical coupling. Raising and overshooting the anchor as a magnetically active component, however, means that the exact opening time can only be determined using higher outlay than that for the closing time.

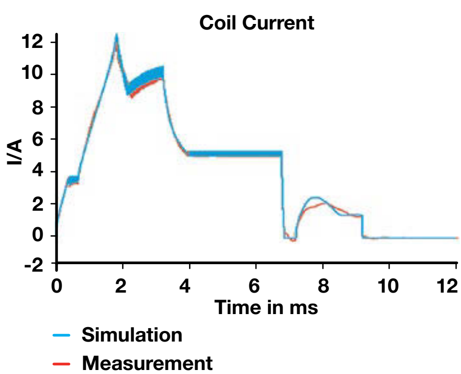

Figure 8 Comparison of measurement and simulation results

When all required correlations are taken into account, a high level of conformity between the results of the measurement and the simulation is achieved (Figure 8). This, in turn, makes it possible to use the model to quantify the influence of a leakage gap variation on the operative function, for example. Questions of this nature are typically fielded by production planning experts, since the size of the gap can lead to varying costs.

The model does not lend itself to answering questions fielded by the software developers responsible for realizing the functions for the control unit. Instead, a model with real-time capability is required whose simulation time corresponds with the time spent in the real world, much as is the case in a flight simulator.

Analysis

After system analysis and modeling have been carried out, the actual analysis work takes place. In the most basic of scenarios, calculations are run using an appropriate software application. This step can also involve model verification or a sensitivity analysis, however, which can retroactively affect the initial modeling. The objective of this verification of unknown or new models is to identify sensitive parameters to keep the number of parameters targeted for investigation as low as possible, thereby minimizing calculation times. When a finite element calculation is made, for example, the influence of temperature on the steel components in the cylinder head is not varied, since the elasticity module that relates to the temperatures prevailing in this area exhibits almost no change as the dominating influential parameter.

Model verification answers the question of which and how many parameters should be varied. Once this list has been defined, optimization algorithms such as DoE (Design of Experiments) allow the input parameters to be varied during the analysis until the desired characteristic statements are quantified. These methods can also be applied to leverage the calculation work so that recommendations for reference samples can be made to the testing department. Numerous additional methods are likewise available for optimizing earlier development stages.

Support for Design Drafting

Deriving draft or concept-based proposals is included among the core tasks assigned to the technical calculation department. The following example shows a holistic simulation for optimizing a timing drive to minimize friction.

In dynamic systems, friction provides for the necessary level of damping while at the same time exerting a negative effect on operating efficiency. To answer the question of the extent to which reducing the friction experienced in the timing drive can reduce fuel consumption, calibrated engine models must be created using corresponding data about the vehicle. In so doing, the same methods and models that were constructed to assess the potential improvements afforded by complex valve train strategies can be applied here as well.

The first step is to realistically map the effects on the internal combustion process in the model. Due to the many combinations of input data possible, the pronounced efficiency for projecting the rates at which heat is released makes quasi-dimensional internal combustion models the ideal choice in this regard. Altered operating conditions such as engine speed, load, residual gas content, air/fuel ratio, and changes in charge movement can then be evaluated. To analyze changes in knocking tendency and the resulting main combustion point, Schaeffler adopts an Arrhenius approach, while a physical-based method according to Fischer is used to account for mechanical losses. The parameters for realizing the best fuel consumption are determined at stationary mapping points that result from the frequency distribution for the combined engine and vehicle investigated in the respective driving cycle. In order to improve the design draft parameters for a large number of possible variants in the relevant section of the data map, stochastic optimization methods are leveraged. Final evaluation of the varying design draft strategies for the combined engine and vehicle is made in different driving cycles in conjunction with the overall vehicle simulation (Figure 9).

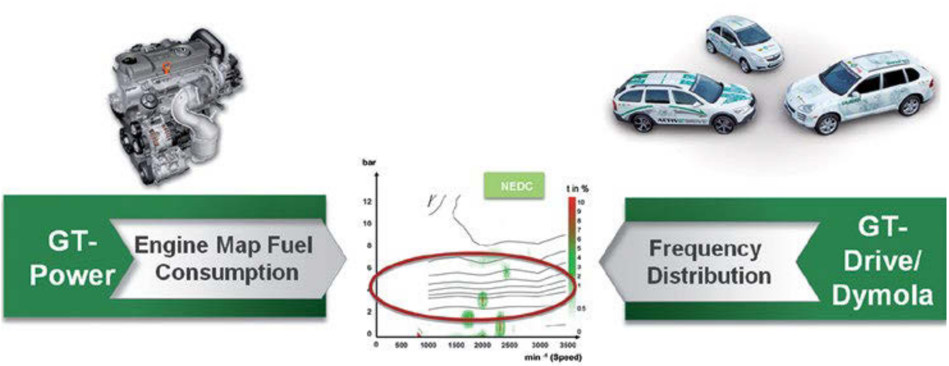

Figure 9 GT-Power modeling

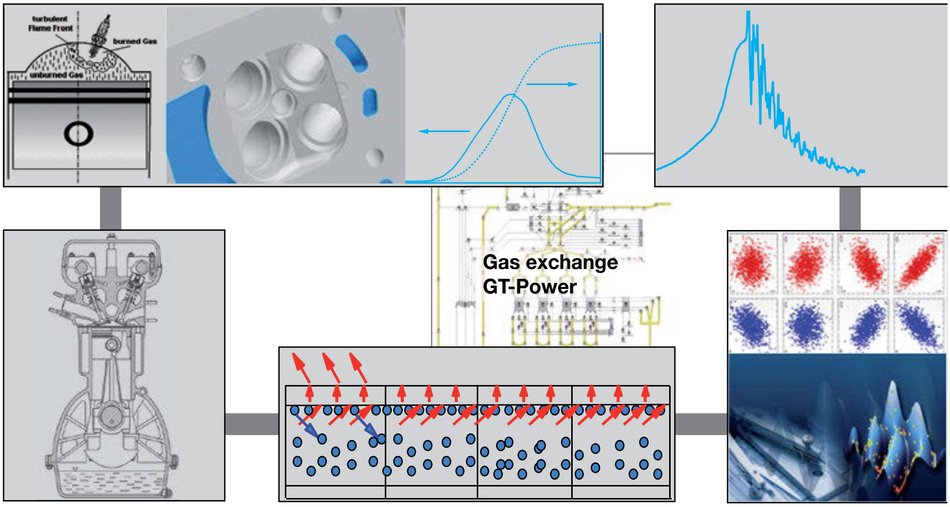

Figure 10 Calculating fuel consumption with GT-Power

The optimization models and tools shown in Figure 10 are leveraged to project combined fuel consumption [3].

To enter the corresponding data in the GT-Power model, the reduction in friction in the timing drive that is responsible for 0.5 to 2 percent of the overall loss in efficiency [4] must be examined in greater detail.

Friction can never be eliminated altogether. At the same time, however, losses must be minimized and the influential factors and interactions within the systems must be understood. By utilizing friction in a targeted manner to optimize the chain drive, the damping properties it affords can make a significant impact on limiting peak points in dynamic force. The majority of tribological systems in an internal combustion engine as it is operated or being started encounter the different types of friction (static, boundary, and hydrodynamic friction) at different frequencies.

After specialists have identified the friction phenomena that occur at specific times and in specific areas while taking the interactions in the relevant systems into account, suitable measures can be selected and combined to optimize efficiency as far as possible.

Figure 11 shows the friction types present in the chain-driven timing drive. This friction encompasses the mesh points of the chain (A), the friction in the chain link joint (B), and the friction between the chain and guides (C). Adding to this is the friction observed on the bearings of the crankshaft and camshaft as well as any auxiliary drives (D), and the losses within the tensioning elements (E).

Two problem areas arise when modeling friction in multi-body systems. The first involves correctly describing the configurations associated with static and sliding friction by making differential equations and numerically resolving them for a transient simulation. Frequently, the possibilities for physically describing static and sliding friction are defined by the solution algorithms available. With respect to the dissipation of energy and the pronounced dynamic characteristics of the timing drive and chain drive system, the variability of the coefficient of friction under static conditions is of minimal significance such that a breakaway torque can be specified. The second problem is determining the coefficient of friction under sliding conditions, or characterizing the kinematic variables and physical parameters that influence this friction.

The transition from static to sliding friction is described by a new model that is being used in a simulation program at Schaeffler for the very first time. To this end, the static potential of a contact that is momentarily stationary is balanced against a virtual displacement. This potential is calculated using the parameters that describe the contact and include the coefficient of static friction, speed, and normal force. When the static potential of a contact is exceeded, sliding friction occurs.

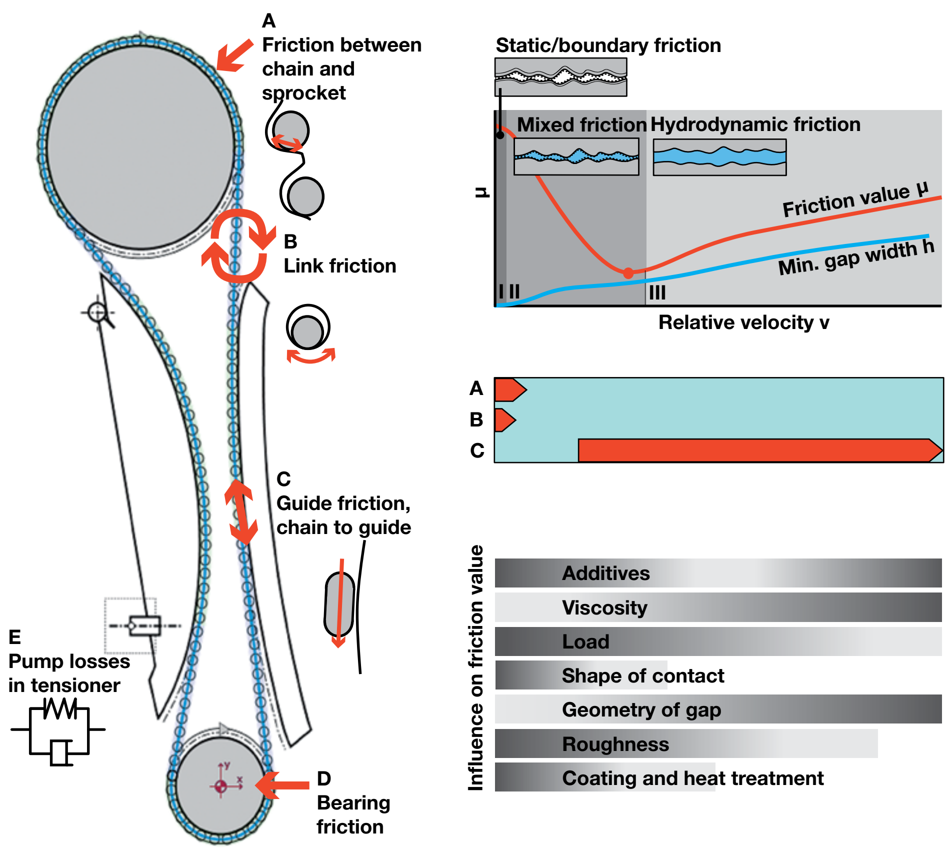

Figure 11 Friction points in the timing drive

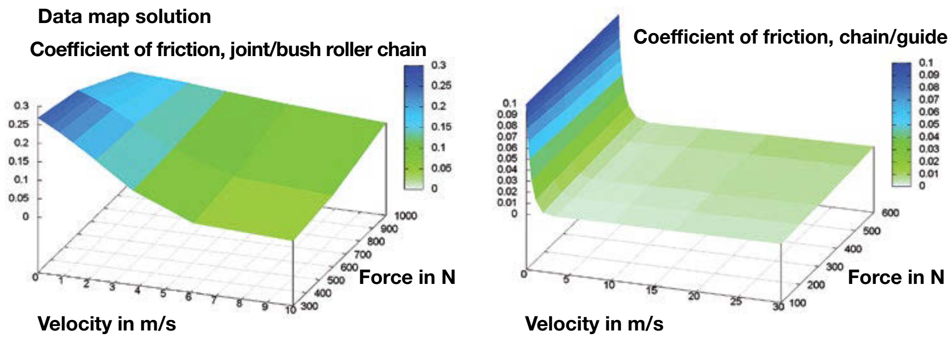

Figure 12 Data maps for the coefficient of friction and mixed-friction state

As soon as the system starts to move, the coefficient of sliding friction must be determined to quantify the friction at the contact. A single variable factor that changes depending on the type and state of the tribological system enters the equation at this point, which is why describing the coefficient of friction during the sliding phase is pertinent to observing the system from an energy perspective. When the system experiences sliding friction, the coefficient of friction is described by data maps using state variables such as speed and load.

The left side of Figure 12 shows, by example, the coefficient of friction determined for the contact point of the chain link joint in a bush roller chain during model testing with respect to the data map. This map was plotted in relation to the sliding speed and normal force. The coefficient of static fric-

Specification for the highly dynamic chain test stand

- Hydrostatically supported shafts
- Drive motor with rotational irregularities similar to a crankshaft
- Brake torques similar to a camshaft
- Constant brake torques possible
- Direct chain guide friction measurement
- Conditioning of oil temperature and oil quantity

Figure 13 Highly dynamic chain test stand tion is approximately 0.25. When local sliding speeds increase, the coefficient drops to around 0.01. Higher normal forces cause the friction level to rise as a result of the increased proportion of solid content. The diagram on the right side (Figure 12) shows the friction value map for the contact point between the chain and guide in identical fashion. These data maps are determined for every frictional contact point (A, B, and C) in the timing drive of each chain type taking into account all additional, relevant parameters such as oil quantity and quality, the material mix, and roughness. The maps are then made available to mark the boundary conditions for the simulation and allow friction losses to be quantified.

To validate the model and define parameters for friction modeling, Schaeffler and IFT designed and constructed a highly dynamic chain test stand that comprises a separate electric motor to produce driving and braking forces. This makes it possible to simulate not only the dynamic rotational imbalance near the crankshaft, but also the braking torque of a crankshaft assembly to reproduce realistic performance constraints. Figure 13 provides a schematic representation of the design configuration.

The supply unit for lubricating the chain is realized by an external oil assembly that is positioned in the immediate vicinity of the test stand. Heating and cooling systems allow the oil quantity and quality to be conditioned, and the friction observed between the chain and guide can be determined. Figure 14 shows the high level of conformity of the measurement data and simulation results. The method can therefore be used as a predictive tool for product development.

A high-resolution elastohydrodynamic simulation technique (EHD) is also employed to determine the dependencies surrounding the different frictional states. This technique accounts for the elastic characteristics of the contacting partners in conjunction with geometry, contact curvature,

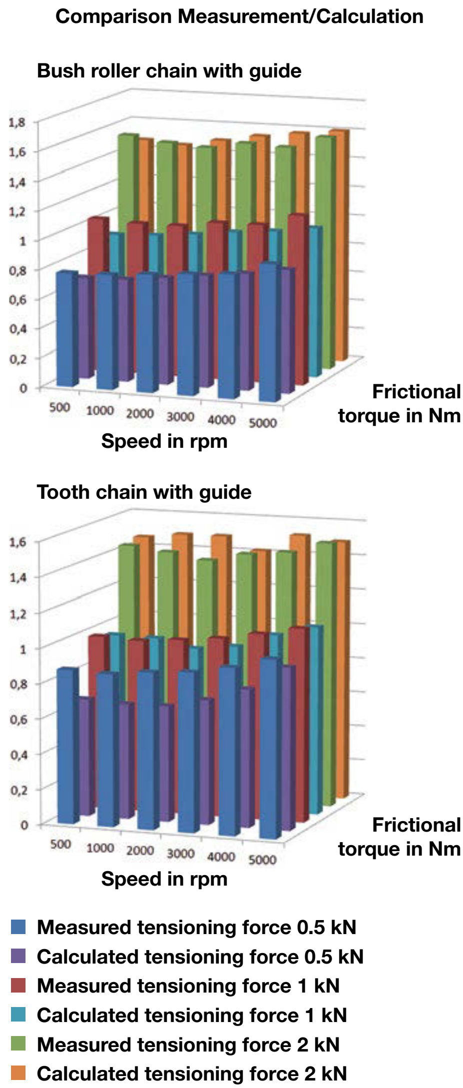

Figure 14 Comparison of measurement data and simulation results

roughness, oil properties, and the variables of load and speed that change with respect to time and location. Figure 15 shows the models used to determine the tribological system attributes of the contact point between the chain back and the guide.

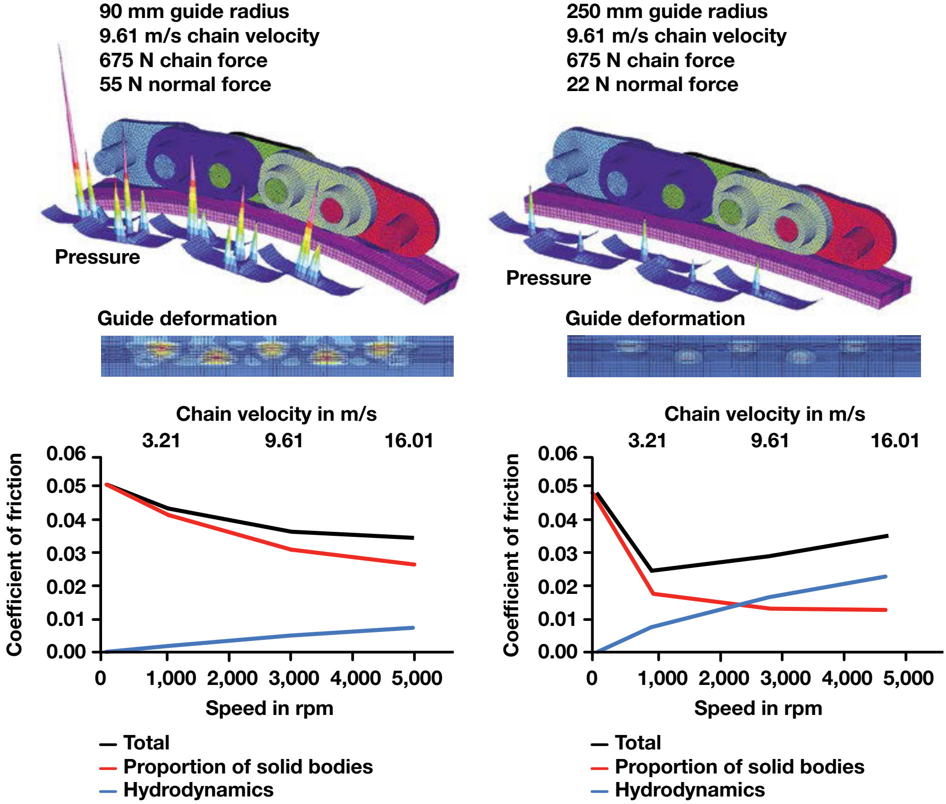

Figure 15 Influence of the guide radius on the friction between the chain and guide

The EHD simulation technique is capable of determining the proportional relationship of hydrodynamic response and solid body contact, which it turn makes it possible to systematically optimize the contact point between the chain and guide. Figure 15, for example, shows that with a guide radius of 90 mm, the proportion of the solid-body friction encountered dominates. The mixed-friction range is also constantly present, even when the system is operating at high speeds. When larger guide radii are introduced, however, the hydrodynamic proportion increases much more quickly as operating speed builds, while the overall friction value is much less pronounced.

Outlook

Digital tools have greatly accelerated the planning and development processes carried out at Schaeffler, and the transition from the pilot stage to commonly used practices has largely been finalized. Now is the time to firmly establish the tools in the organizational structures and further optimize the ratio of outlay to usable gain by leveraging the variety of digital methods available. Starting points include standardized processes, methods, and IT solutions as well as improved integration of production data in the product development process.

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