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# Actuator platform for driving various functions in air/exhaust path of internal combustion engines

Turbochargers & Air/Exhaust Management

Sören Wiskandt, Heinzmann GmbH & Co. KG

Alexander Levchenko, Heinzmann GmbH & Co. KG
Peter Gaiser, Heinzmann GmbH & Co. KG

## ABSTRACT

Even though technical progress in the development of combustion engines has never come to a halt and has always focused on engine performance, efficiency, and last but not least, exhaust emissions, it cannot be compared with the new momentum triggered by the globally regulatory-driven decarbonization efforts. Especially the uncertainty regarding the future availability and pricing of the individual alternatives in sustainable fuels requires almost simultaneous research and development of technological solutions for multiple fuel options. The significantly differing properties of these energy carriers and various possible combustion concepts have highlighted the special importance of air path management in combustion development. However, the functions and necessary components along the air/exhaust path rarely take the spotlight at professional conferences, development continues in this technology area as well.

The diversity of functions in the air/exhaust path has continuously increased over the past decades. Wastegate, compressor bypass, and EGR valves, as well as different throttle valves, are part of the standard equipment of the most modern engines both individually and in combination, and they require a suitable drive in the form of an actuator. The requirements for torque, dynamic behavior, permissible operating temperature, and vibrations vary greatly depending on the function and type of application. Multiplied by the variety of engine series and the high number of variants within each series, this results in an extremely broad requirement matrix that engine OEMs must consider and address in development and throughout the entire product lifecycle. The reuse of as many identical components as possible across multiple engine series is only limited feasible with most actuator solutions available on the market. This leads to higher efforts and costs in development, validation, documentation, procurement, production, compliance, and last but not least, in service.

To address all the aforementioned challenges and support the platform approach of engine manufacturers, Heinzmann has developed a new product line of actuators. The paper and presentation will showcase the methodology of development, validation, and technical solutions for achieving high power density over a wide temperature range combined with excellent dynamics, flexible design for easy integration on the engines of this new actuator platform.

## 1 INTRODUCTION

In the early years of the history of internal combustion engines, air path management initially played a rather subordinate role. The engines had simple intake and exhaust channels, without turbochargers or variable valve timing. Air was essentially "naturally" aspirated. However, as the demand for power increased, it was quickly recognized that boosting was a crucial method to introduce more air into the cylinder and enhance combustion performance. [1]

In the first decades after the invention of exhaust turbochargers, the generated boost pressure was often not actively limited; instead, the turbocharger was designed for the desired full-load operating point. The objective was clear: to achieve the highest possible power per unit of displacement and maximum efficiency.

Over the course of the 20th century, further innovations emerged, such as charge air cooling and multi-stage turbochargers. From an actuator perspective, little sophistication was initially required: many of these systems were mechanically controlled, for example, via speed-dependent flaps or simple pneumatic actuators. The exhaust gases were - if at all - partially bypassed around the turbine using a rudimentary bypass valve to limit boost pressure. [2]

At the latest, with the introduction of the first emission regulations, it became clear that boost pressure, and thus the amount of air in the cylinder, was not only a tool for increasing power but also a key factor in emissions control. For example, a high excess air ratio can reduce soot formation but at the same time promote $NO_x$ emissions due to higher combustion temperatures. The balance between different types of emissions led to conflicting goals, which were addressed through various in-engine solutions and strategies such as exhaust gas recirculation (EGR) or variable valve timing (VVT).

At the same time, both fuel injection systems and engine control became increasingly sophisticated. Electronic control units enabled real-time adjustments of injection quantity, injection timing, and the regulation of air path components. As a result, actuators for wastegate, bypass, and EGR valves were no longer purely mechanical but increasingly electronically controlled. Today, the interaction between the injection system and air path control is highly sophisticated.

Alternative fuels such as liquified natural gas (LNG), methanol ($CH_3OH$), hydrogen ($H_2$), or ammonia ($NH_3$) pose new challenges for air path management, particularly in large engines. Fundamentally, the goal remains to supply sufficient combustion air and efficiently discharge exhaust gases to optimize both performance and emissions. However, the specific properties of these fuels require adapted technologies and control strategies. [3]

In the following chapters, we will explore the specific requirements and technological solutions for modern actuation in air path management in detail.

## 2 REQUIREMENTS

Engine OEMs' continuous efforts to enhance efficiency, performance, and exhaust emission characteristics lead to very specific requirements for actuators across the air path.

Those requirements can be divided into several areas, which in turn can be categorized into dynamic and mechanical requirements. The fulfilment of these requirements demands a series of combined and balanced improvements throughout the entire functional chain of an actuator.

### 2.1 Dynamic requirements

The driving force behind the increasing demands on the dynamic performance of actuators is the optimization of all above mentioned operational characteristics of internal combustion engines at stationary as well as transient conditions. The key aspects in this area are high control accuracy, actuation speed, and positioning stability of actuator-driven valves in various functions along the air path.

#### 2.1.1 Constant torque

Ensuring a constant torque across the entire range of motion at a steady current supply offers several advantages. On the one hand, it guarantees that sufficient torque is available at every operating point, and no performance drop is expected in the boundary areas. On the other hand, it allows highly accurate conclusions to be drawn about the torque demand based on the current consumption. This opens up new possibilities for diagnostics and monitoring of engine components and enables the improved implementation of predictive maintenance concepts.

#### 2.1.2 Fast response time

A fast response time of actuators in the air path is crucial for optimizing engine performance. It enables a fast reaction to the change of air supply demand, leading to improved mixture formation for more efficient combustion resulting in reduced emissions and fuel consumption. The rapid adjustment of the air supply helps manage transient operating conditions more effectively and enhances the total performance of the engine.

#### 2.1.3 Positioning stability

The stability of an overall system depends heavily on the control stability of its individual components. High positional stability of individual actuators enables precise control of dependent processes within the system and ensures consistent performance output with high efficiency. Unstable or undefined behaviour of actuators poses a significant challenge for control systems and can lead to efficiency losses. Furthermore, stable behaviour of actuators reduces mechanical wear, thereby increasing their lifespan or service lifetime. From a predictive maintenance perspective, stable behaviour is also advantageous, as it allows for better evaluation of condition data in regard to recognition of deviations from normal operation.

#### 2.1.4 Positioning accuracy

In both stationary and dynamic applications, positioning accuracy is a critical factor to ensure maximum efficiency, minimize deviations from the targeted system design. In almost all applications, even small deviations can result in significant energy losses over the system's lifetime due to cumulative effects. In highly dynamic applications, inaccuracies lead to unstable processes and can increase the mechanical stress on other components.

### 2.2 Mechanical requirements

The mechanical requirements focus on a robust and durable product with the simplest possible structural integration into the engine. In general, performance optimization of engines, their increasingly compact design and continuous improvement efforts in power to weight ratio are the key drivers [4].

#### 2.2.1 Packaging

A lightweight and compact product design simplifies integration into the engine and reduces dynamic forces acting on the component, such as those caused by vibration. Particularly in respect of the increasingly dominant platform approach in engine development, having a compact product that can be easily integrated into various platform variants and engine series is highly advantageous.

#### 2.2.2 Temperature resistance

The increasingly stringent legal regulations for compliance with emission standards require exhaust treatment concepts such as EGR systems. Further it is to expect, that more and more engines (e.g. dual fuel engines) will be equipped with electronically controlled wastegate valves [3]. The high temperatures in the exhaust tract pose significant challenges to the temperature resistance of the corresponding actuators and valves. The more compact design of engines offers fewer opportunities for thermal insulation and heat dissipation. For electronic actuators in particular, efficient heat dissipation and temperature resistant electronics with minimal heat losses are therefore essential.

#### 2.2.3 Robustness

Higher efficiency requirements for modern large engines lead to higher combustion pressure, which generally increase the vibration demands on actuators [5]. The lighter and more compact design of engines may result in reduced structural damping, amplifying vibrations within the engine. The understanding of vibration requirements at specific positions is enhanced by more precise engine measurements and increasingly comprehensive simulation capabilities. All of this results in higher and significantly more precisely specified vibration requirements across an expanded frequency range. To validate the durability of actuators in ALT (Accelerated Life Testing), these vibration requirements are intentionally amplified to simulate extended operational lifetimes under extreme conditions.

## 3 ACTUATOR FUNCTIONAL GROUPS

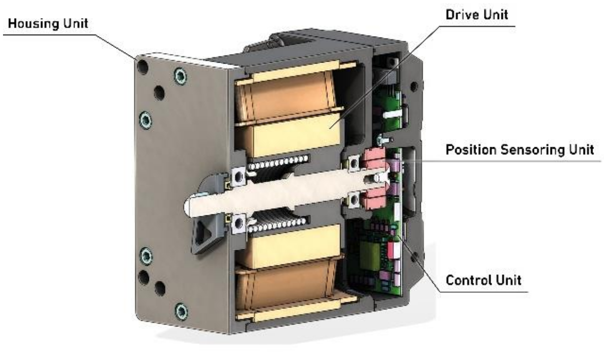


Figure 1. Actuator functional groups

Actuators can be categorized into functional groups. The central functional group is the drive unit, which can be electric, pneumatic, or hydraulic, depending on the actuator type. This functional group converts different forms of applied energy into mechanical motion. The drive unit may also incorporate safety mechanisms, such as return springs, which ensure a defined safe position of connected valves in the event of a power loss.

Depending on whether the actuator is active or passive, the control unit performs different functions. In active actuators, it manages internal control loops, regulates dynamic behaviour, and optimizes response characteristics. In passive actuators, it primarily facilitates communication with the overarching control system and processes incoming signals. In both cases, the control unit ensures seamless integration into the overall system.

The position sensing system is the crucial link between the control unit and the drive unit. It determines the position of the output shaft and communicates this information to the internal or overarching control system.

The housing unit protects all internal components from external influences, ensures the mechanical stability of the entire device, and facilitates the dissipation of heat from internal sources. Additionally, the housing unit provides the mechanical interface for mounting the actuator.

The gearbox unit serves to increase the torque provided by the drive unit. It is not included in every actuator. The use of a gearbox affects the dynamic properties of the actuator. The gear ratio amplifies the torque at the output shaft while proportionally reducing speed and range of motion. Depending on the concept used for rotational angle measurement, various additional challenges may arise regarding control and accuracy.

# 4 CONCEPTUALIZATION OF INDIVIDUAL SOLUTIONS

The challenge in developing modern actuators for air path management lies in identifying solutions for all previously mentioned functional groups that best meet the requirements and integrating them into a cohesive overall product.

## 4.1 Drive unit

### 4.1.1 Operating principle

The first critical question regarding the drive unit is the type of energy conversion. Hydraulic systems offer high power density, providing high torque in a compact design while enabling precise position control. However, these systems require significant maintenance and are relatively complex due to the integration of pumps, valves, and lines.

Pneumatic systems, on the other hand, are less complex and more cost-effective. They typically provide quick response times due to the low inertia of their components. However, they are less suitable for applications requiring high torque and precise control, and they suffer from high energy losses caused by compression and possible leakages.

Electric systems offer the advantages of a compact design and low or even no maintenance requirements. They are more efficient than pneumatic or hydraulic systems and provide a high level of precision in controlling position, speed, and torque. Compared to hydraulic systems, electric systems have a lower power density, which can be compensated by integrating a gearbox. Their increased sensitivity to high operating temperatures requires effective heat dissipation and may require additional cooling.

For applications with high demands on accuracy, positional stability, low maintenance and dynamic performance across various scenarios, electric systems are the most suitable. They also offer numerous advantages in terms of modular design. By incorporating additional magnetic poles and extended windings, higher torque can be achieved without increasing the drive's diameter.

### 4.1.2 Structure

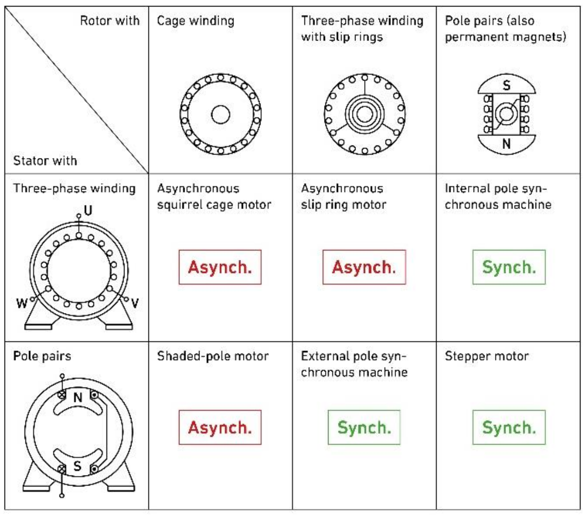


Figure 2. Overview of different types of electric drives

Figure 2 illustrates the possible combinations of common electric machine concepts by considering stator and rotor configurations with either windings or magnets, resulting in the various types of electric machines.

There are two main types of electric machines: synchronous and asynchronous machines. Asynchronous machines are less suitable for precise position control because there is always a difference between the speed of the stator's magnetic field and the rotor speed, known as slip. Synchronous machines do not have this difference, allowing for more precise control and stable positioning.

Another specification of the electric system is the choice between an inner-rotor synchronous machine, where the rotor contains permanent magnets or excitation windings and the stator has the three-phase winding, or an outer-rotor synchronous machine, where this arrangement is reversed. Inner-rotor synchronous machines are ideal for actuators because they provide high torque, precision at low speeds, mechanical robustness, and efficiency. These characteristics are crucial for controlling throttle and exhaust valves in large engines with precision, reliability, and energy efficiency. Their simple design and adaptability to harsh environmental conditions make them the optimal choice for these applications.

The inner-rotor synchronous machine can be equipped with either permanent magnets or excitation windings on the rotor. Excitation windings have the advantage of greater temperature resistance, as the magnetic properties of permanent magnets can fluctuate with changes in temperature. However, systems with excitation windings are more complex, larger, heavier, and require maintenance due to the presence of slip rings and brushes on the rotor.

In contrast, systems with permanent magnets offer greater efficiency, as they eliminate energy losses associated with excitation windings. Furthermore, permanent magnets are better suited for actuator applications in terms of dynamics, providing faster and more precise operation.

To meet the requirements for stability, speed, and high torque, permanent magnet synchronous machines (PMSM) are the most suitable choice.

### 4.1.3 Magnet materials

With the definition of the electric drive system, the PMSM, the selection of the most suitable magnet material for state-of-the-art actuators is the next development step.

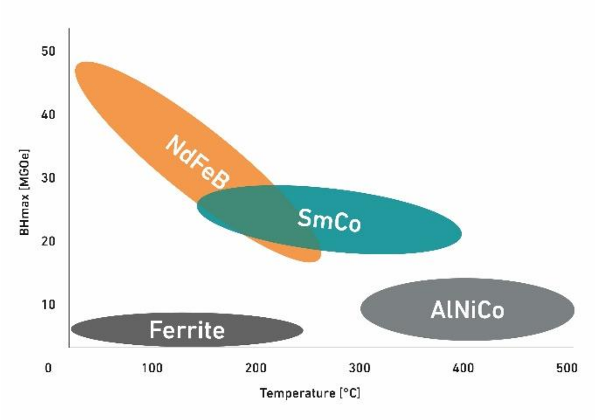


Figure 3. Temperature dependence of the maximum energy product (BHmax) for different materials.

Figure 3 shows the correlation between the maximum energy product BHmax for the most common materials for permanent magnets: Neodymium-Iron-Boron (NdFeB), Samarium-Cobalt (SmCo), Ferrite, and Aluminum-Nickel-Cobalt (AlNiCo).

Due to the compact design requirements of modern actuators, ferrite is unsuitable as a permanent magnet material because of its low maximum energy product of up to 4 MGOe. The maximum energy product of AlNiCo is approximately twice as high at 9 MGOe, but still does not reach the values of SmCo (up to 30 MGOe) or NdFeB (56 MGOe).

AlNiCo is particularly well-suited for high-temperature applications due to its excellent temperature resistance, but its lower energy density makes it unsuitable for compact actuator applications up to 200°C.

While NdFeB offers the highest energy density, it is highly susceptible to corrosion and has a high temperature coefficient, which causes significant changes in its magnetic properties within its operating range of 20–200°C.

SmCo provides a good balance of the relevant properties. With relatively high energy density and excellent corrosion resistance, it also features a relatively low temperature coefficient, resulting in good temperature stability.

### 4.1.4 Segmentation

The number of pole pairs in the rotor and the slots in the stator are crucial for ensuring a uniform torque profile across the entire range of motion.

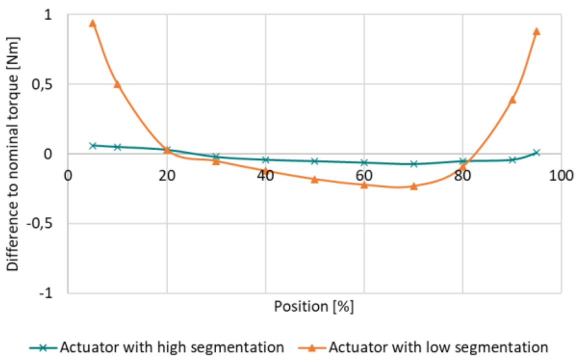


Figure 4. Influence of the number of pole pairs on torque deviation over the rotation angle

A low number of pole pairs can lead to significant torque fluctuations caused by high cogging torque. Cogging torque arises from the magnetic interaction between the rotor and stator and represents the required torque to move the rotor out of a preferred rest position. This results in a reduced torque output. While this effect is less significant at high speeds, it has a considerable impact on the performance and the maximum achievable rotation angle, particularly in actuators that typically do not perform full rotations.

A high number of pole pairs counteracts this effect, ensuring a consistent torque profile, even in the boundary regions of the movement range, and improving position control. However, an excessive number of pole pairs can negatively affect electrical efficiency and increase complexity in manufacturing, assembly, and actuator control. Therefore, a well-balanced compromise must be found between the number of pole pairs, structural complexity, and consistent performance.

Figure 4 shows the deviation from the nominal torque of 6 Nm at constant excitation over the rotation angle. It is clearly visible that the drive unit with a low number of pole pairs deviates by almost 1 Nm from the target torque in the boundary regions, which in this example corresponds to a performance deviation of approximately 15%. In comparison, it can be observed that the torque curve of the actuator with high segmentation shows a deviation of only 0.07 Nm from the nominal torque, which corresponds to just over 1%.

### 4.2 Position Sensing

PMSMs can be controlled and operated using senseless methods in high-speed applications. However, for high-precision positioning in actuator applications, sensor-based methods are necessary to ensure accurate control of position, speed, and torque. Various position detection concepts are available, differing in terms of precision, cost, and robustness.

Encoders offer the highest precision and resolution, providing exact position data with fine angular resolution. However, they are sensitive to vibrations, dirt, and moisture, which limits their suitability for actuators operating in harsh environments.

Resolvers present a robust alternative, as they are mechanically wear-free and offer high accuracy. However, they require more installation space and are comparatively expensive.

A less precise but still reliable option are eddy current sensors, which operate contactless and are highly resistant to vibrations, dirt, and moisture. Although well-suited for demanding environments, they are often not necessary for actuators, as the required precision level can be achieved.

Hall sensors offer a simpler and more cost-effective solution while providing the best balance between accuracy, affordability, and ease of implementation. They are compact, economical, and can be easily integrated into existing actuator designs. While their individual precision is limited, combining multiple Hall sensors to a sensing matrix can significantly enhance position detection accuracy, ensuring reliable and stable actuator control.

### 4.3 Customer Interface

The customer interface primarily refers to the electrical connection of the actuator to the customer's control system. In addition to power supply, it also includes communication and, if applicable, diagnostic signals. Many customers already have established strategies for connecting system components, which manufacturers must take into account. There are various approaches that vary depending on customer requirements and application areas:

- Direct Wiring: Simple cable connections without specialized plug solutions, often used for cost-sensitive or less demanding applications.
- Standardized Connector Systems: Use of proven and established connectors, such as circular or flat connectors, which ensure easy installation and interchangeability.
- Custom Solutions: Individually designed connector systems tailored to specific customer requirements, for example, regarding design, sealing, or locking mechanisms.

Not only the mechanical aspect of the customer interface but also the type of communication, the method of setpoint specification, and the scope of diagnostic capabilities pose challenges regarding the variety of customer interface configurations.

Setpoint specification is typically achieved either analogue, such as through 4-20 mA, 0-5 V, or PWM signals, or digitally via fieldbus systems. To ensure a product with broad applicability, these options should be made available. Additionally, it is crucial to enable the implementation of various CAN protocols, as customers often have established standards based on either standardized protocols like SAE J1939 or custom solutions.

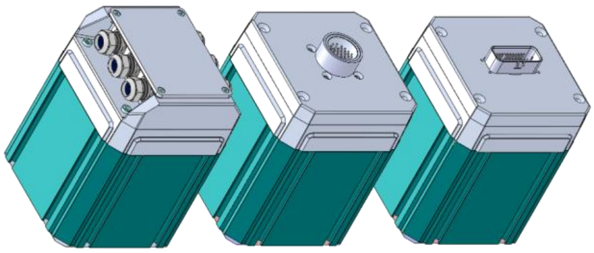

Figure 5. Modular approach to address different requirements regarding customer interfaces on the HEINZMANN StG EC actuator series

Given this wide range of solution options and customer requirements, it is essential to incorporate a certain degree of flexibility in the design of the customer interface.

## 5 MODULAR PLATFORM APPROACH

Figure 6. Exploded view of the individual modules of the HEINZMANN StG EC 6 / 16 / 32 actuator series

The wide range of customer-specific requirements for different functional groups highlights the importance of adopting a modular development approach for modern actuators. The primary goal is to enable flexible combinations of various functional group variants while maximizing synergies and the use of common components within those variants, thereby reducing costs, development and validation efforts.

One of the challenges in implementing a modular approach for actuators lies in scaling the torque through the drive unit. Increasing the torque by enlarging the unit's diameter significantly reduces the potential for using common parts across different variants. A more effective approach is axial scaling, where the length of the drive unit is extended. This method allows the use of identical sheet metal cuts for both the rotor and stator, optimizing material efficiency and production scalability.

The electronics, as outlined in the chapter on the customer interface, must be designed to provide sufficient flexibility to accommodate various connection options. However, many circuit components can remain identical across different performance variants. To implement the modular approach in electronics, it is advisable to separate the circuits into base components and interface-specific components.

This separation has both advantages and disadvantages. While it requires more installation space and increases assembly effort, it enables a more organized circuit layout and improved thermal management, which is particularly beneficial for the actuator's temperature resistance. Additionally, economies of scale can be better leveraged, as the production volume of the base board increases. A separate interface-specific board also offers flexibility to adapt to future requirements.

By combining a modular base board with a specific interface board, not only can costs be reduced and synergies created, but the adaptability of actuators to new requirements can also be ensured in the long term.

The housing unit must also support the modular approach. Suitable manufacturing methods, such as extrusion, allow housing components to be flexibly adapted for different torque variants with minimal machining effort. Using identical parts across the entire product line results in some components being overdimensioned for variants in lower performance segments. While these parts are more expensive compared to specifically smaller alternatives, economies of scale from the high volume of identical components provide cost advantages. Additionally, this overdimensioning positively impacts the durability of the components.

To avoid creating customer-specific housing variants, it is essential for the housings to offer the necessary flexibility in terms of mechanical connection to the engine. Modular systems with extruded profiles, which allow maximum flexibility in terms of combinations and mounting options, have already proven successful in other industries. These systems often rely on rotationally symmetrical base units. This concept can be applied to actuators, as it provides customers with a wide range of mechanical adaptation options and can even serve as a base for additional attachments.

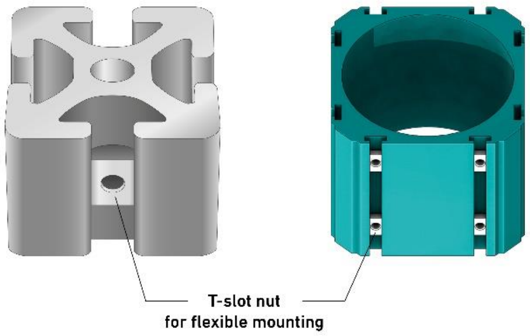


Figure 7. Development of a mounting concept for actuators based on flexibly applicable extruded profiles.

The central functional interface of an actuator is the output shaft. To avoid excessive variation at this interface, it must be standardized across the entire product range and seamlessly integrated into attachable components such as couplings, gear units, or throttle valves.

Kerb splines offer a flexible and compact solution for this purpose. Their even load distribution across the entire contact surface enables high torque transmission, reducing notch stresses and increasing service life. Additionally, the form-fit connection ensures a low-play coupling between the shaft and the attached component, minimizing unwanted relative movements. This allows for precise control, as positioning movements are transmitted with minimal delay and without noticeable elastic deformation.

Another advantage is the availability of detailed standards that can serve as a basis. This makes kerb splines ideal for modular designs, as they provide a standardized interface for various attachments such as couplings, gear units, or throttle valves. As a result, they reduce variation, simplify assembly, and improve component interchangeability, increasing efficiency in both production and maintenance.

The modular approach in the development of modern actuators significantly reduces the number of components. Using the example of the StG EC actuator series from HEINZMANN, the number of cost-intensive components was reduced by 45% compared to three independently developed actuators.

## 6 VALIDATION

The presented solution approaches for individual functional groups, considering the application requirements of modern actuators in air path management, were integrated, validated, and tested in the development of the StG EC actuator series.

The series consists of three actuators: StG EC 8, EC 16 and EC 32. Additionally, it can be expanded with a modular gearbox unit that is compatible with every actuator in the series. The gearbox has a transmission ratio of 4, extending the performance range up to the StG EC 64 and EC 100, with peak torque of 64 Nm and 100 Nm. Figure 6 shows the three base devices, modular customer interfaces, as well as the gearbox unit and various throttle valve units for different applications. Due to the standardized interfaces, these components can be flexibly combined.

Figure 8 illustrates the torque curve over a rotation angle of 90° with a constant current input.

For the torque test, the actuator is connected to a torque test bench, where a second actuator generates countertorque. A torque measuring shaft is positioned between them to capture the applied torque. During the test, the actuator moves through the range of motion in 5° increments. At each step, the maximum torque that can be generated at the specified current is applied. The test bench applies countertorque, allowing the torque measuring shaft to record the exact torque the test unit can produce at each position, enabling a comprehensive evaluation of its performance across the entire movement range.

The implemented solutions enable a consistent torque across the entire rotational range. Figure 9 shows the relationship between torque and current demand. Due to the linear correlation between these two factors, the applied torque can be inferred from the operating current consumption. This information can be utilized, for example, as an indicator of the wear condition of the actuators or the associated valves.

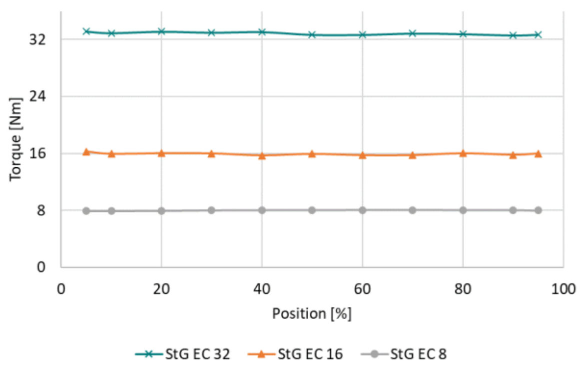


Figure 8. Torque curves

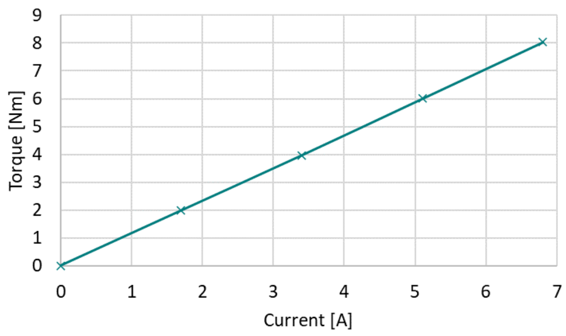


Figure 9. Correlation between current consumption and torque output

The response speed is determined through step-response tests. The step response is measured using an external resolver mounted on the actuator's output shaft. The setpoint changes abruptly from 10% to 90%, and the actuator responds according to the defined control parameters. The resolver continuously tracks the shaft movement, enabling a detailed analysis of the actuator's dynamic behaviour. The time from the setpoint command to the actuator reaching the target position is defined as the response speed. Figure 10 presents an exemplary step-response curve of the StG EC 8 with a response time of approximately 80 ms. The response times achievable with the StG EC actuator series are 85 ms for the StG EC 16 and 95 ms for the StG EC 32.

These values refer to the standard parameterization, though individual parameters can be adjusted to optimize the response behaviour for the specific requirements of the end system.

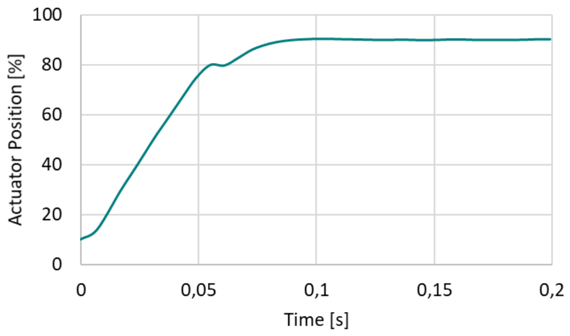


Figure 10. Step response curve

As a key performance metric, positioning accuracy is essential for meeting the challenges and high demands of air path management. To evaluate the implemented solutions, the actuator's shaft position was recorded using a high-precision resolver and compared with the internal position signal. The analysis in Figure 11 shows that the positioning accuracy remains within ±0.5°. This level of accuracy enables precisely controlled processes across the entire range of motion.

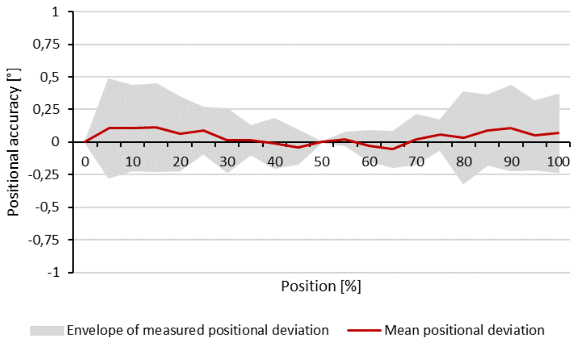


Figure 11. Mean and envelope of the positional accuracy

The actuator was subjected to an intensive vibration test, during which it was tested for 72 hours per axis with a load of 15g RMS in the frequency range of 20–2000 Hz. This RMS profile corresponds to a simulated aging of approximately 10,000 operating hours. Throughout the entire test, the actuator was held at a 50% position, with the position signal remaining constant. The position stability during the test remained within the specified range, even under the influence of vibrations. After completing the test series, the performance values were compared with the initial values and showed no changes. This confirms the high mechanical stability and reliability of the design under extreme vibration loads.

The investigation results of the StG EC actuator series confirm the reliability of the implemented solutions and efficiently leverage the resulting synergy effects. The combination of modular design, sensor-based control, and optimized mechanical interfaces ensures high positioning accuracy, dynamic response, and robustness, even under demanding conditions such as vibrations or changing load scenarios. These findings highlight the advantages of a standardized actuator platform that can be flexibly adapted to different applications while maintaining high performance and efficiency.

## 7 CONCLUSIONS

The use of actuators in internal combustion engines has a long history, which might lead to the assumption that no further innovations can be expected in this field. However, technological advancements in functional materials, electronic components, control algorithms, and manufacturing processes – combined with the operational experience accumulated over millions of operating hours in field – have enabled significant improvements in all performance-relevant functional areas. These include enhanced positioning precision, improved dynamic behavior, and optimized torque delivery, elevating the system to an entirely new level.

Nevertheless, the technological sophistication of individual components alone is no longer sufficient today. Let us consider the engine from the perspective of the air path: a multitude of functions along this path, the wide range of engine series, numerous application-specific variants within individual series, and – in the context of decarbonization – different types of conventional and alternative fuels, all present entirely new challenges in terms of variant diversity and complexity management.

The now well-established platform strategy at the engine series level helps to address these challenges. But only extending this platform approach consistently to the component level – as exemplified by the modular actuator platform for the air path with unified functional interfaces – provides engine manufacturers with another effective tool for further reducing variants and managing complexity.

## 8 DEFINITIONS, ACRONYMS, ABBREVIATIONS

**OEM:** Original Equipment Manufacturer

**EGR:** Exhaust Gas Recirculation

**VVT:** Variable Valve Timing

**LNG:** Liquified Natural Gas

**$CH_3OH$:** Methanol

**$H_2$:** Hydrogen

**$NH_3$:** Ammonia

**PMSM:** Permanent Magnet Synchronous Machine

**CAN:** Controller Area Network

**ALT:** Accelerated Lifetime Test

**AlNiCo:** Aluminum-Nickel-Cobalt

**NdFeB:** Neodymium-Iron-Boron

**SmCo:** Samarium-Cobalt

**MGOe:** Mega-Gauss-Oersted

## 9 ACKNOWLEDGMENTS

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