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A COMPREHENSIVE REVIEW OF TURBOCHARGER TURBINE EFFICIENCY ENHANCEMENT USING VARIABLE GEOMETRY SYSTEMS (VGS)

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Abstract

The continuous pursuit of higher efficiency, compact design, and lower emissions in internal combustion engines has positioned turbocharging as a critical enabler of engine downsizing and environmental compliance. Among the various boosting technologies, Variable Geometry Turbochargers (VGTs) have emerged as an advanced alternative to conventional Fixed Geometry Turbochargers (FGTs), offering superior adaptability across a wide operating range. This review provides a comprehensive evaluation of recent advancements in turbocharger turbine efficiency enhancement through the implementation of Variable Geometry Systems (VGS). The paper systematically compares traditional FGTs with modern VGT configurations, emphasizing aerodynamic optimization, actuator mechanisms, and control strategies. The study synthesizes recent experimental and computational developments that address challenges such as turbo lag, flow separation, and unsteady aerodynamic behavior. Various VGT architectures—including sliding nozzle, pivoting vane, and variable diffuser systems—are analyzed with respect to flow control, pressure ratio optimization, and turbine response. Additionally, the role of electric, hydraulic, and pneumatic actuators in improving real-time adaptability and control precision is critically reviewed. Emerging trends in model-based and artificial intelligence-assisted control systems are also discussed as enablers for next-generation engine platforms.

Keywords: Automotive turbocharging, Variable geometry turbocharger, Fixed geometry turbocharger.

Introduction

Due to the growing interest on environmental concerns, improving the quality of emission and reducing the consumption of fuel have become a significant driver in developing the internal combustion engines. According to the nowadays regulations, a desirable engine should deliver high power while maintaining low fuel consumption. Despite the fact that turbocharging was originally introduced to boost engine power, it now plays a significant role in meeting emission regulations and improving fuel efficiency [1]. Many major economies in the developed countries have put on increasingly aligned emission goals for new vehicles, as illustrated in Figure 1. Meeting these goals makes engine downsizing through forced induction a necessary approach.

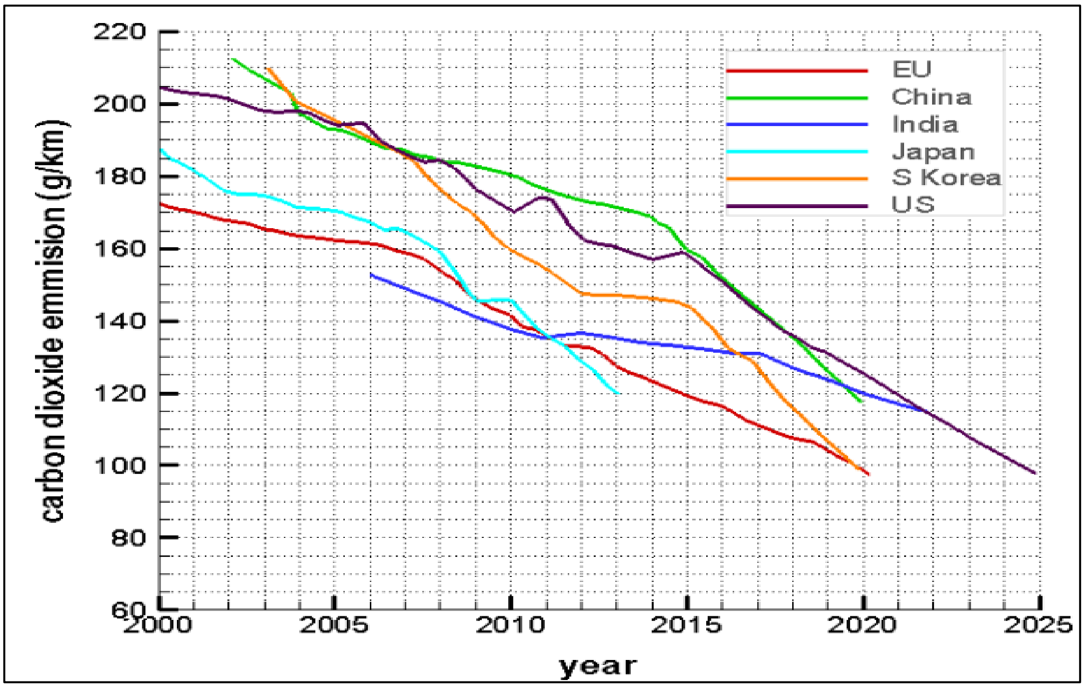

Figure 1 Global CO_2 emission standards for new passenger vehicles: a comparative overview for different countries [2]

Getting more power from the same engine is achievable via increasing the thermal efficiency, notably through a higher compression ratio of the engines. Though, increasing the compression ratio raises the maximum cylinder pressure, but less so than it increases brake mean effective pressure. Thus, for a given cylinder particular pressure limit, boosting intake pressure develops more power compared to raising the compression ratio [3].

Given the discussed points, turbocharging has become the important approach for engine downsizing. Environmentally, it allows lean boosting, which reduces the CO_2 emissions [4] and reduces fuel consumption [5]. Moreover, it contributes to engine weight reduction, leading to lower production costs. Turbochargers allow manufacturers to use smaller displacement engines by enhancing performance. This is because engine output depends on the force exerted on the piston, which generates the torque and work.

The simplest used form of turbocharging is the fixed geometry turbocharger (FGT), which uses a turbine and compressor linked by a common shaft. Electrically assisted systems improve the performance by adding power during low-load conditions. Variable geometry turbocharger (VGT) go further by adjusting the flow area of the compressor or turbine housing to optimize gas flow, regularly using movable parts or diffusers.

Generally, the turbocharger unit comprises two key components: a turbine and a compressor, its' main function is to enhance the volumetric efficiency of the combustion chamber. The compressor sucks ambient air and rises its density via rotating impeller blades. This high-density air is then mixed with the fuel inside the combustion chamber. The increased air density as well as the mass flow rate raise the brake mean effective pressure on the piston crown, enhancing the overall engine performance. This generates more force on the piston, allowing the engine to produce more power. The stronger combustion creates high-energy exhaust which drives the turbine and consequently powers the compressor. The turbine generates back pressure, raising exhaust pressure above atmospheric levels, and uses the expanding exhaust gas to spin the impeller, completing the cycle.

FGTs have several drawbacks, including poor low-end torque and delayed throttle response (turbo lag) which makes them less responsive than naturally aspirated engines. To overcome these issues VGT were introduced, offering improved flow control and better performance across a wider operating range.

VGTs are significant not only for their robust presence in single-stage boosting but also as a cost-effective alternative to modern technologies like electric turbocharging and supercharging. Their affordability also makes them a common choice in advanced multi-stage boosting systems [6].

The objective of the current review paper is to provide a comprehensive analysis of the VGT technologies, focusing on their development, enhancement technologies, and advancement in research approaches. The review will start by considering the limitations of traditional FGTs before delivering the state of the art in VGT turbocharging concept, exploring various types of variable geometry turbocharging systems and their role in gasoline engine performance enhancement. The paper will also highlight the growing complexity of VGT systems, covering the operating principles, a range of variable geometry (VG) systems for both turbines and compressors. It, also, covers and the currently adopted control systems and actuation methods. Lastly, the recent advancement in the analysis and optimization strategies is provided.

Technical limitations of FGT

Conventional FGTs suffer from issues like turbo lag and poor low-end torque [7] caused by many factors, mainly due to the high inertia of the turbine rotor. Figure 2 illustrates the principal contributors to the turbocharger lag. The main source of delay is the turbine's rotational inertia, caused by insufficient airflow to accelerate the rotor to higher speeds during transients. Another key factor affecting the lag issue is the aspect ratio (A/R), defined as the volute’s cross-sectional area divided by its distance to the center. A smaller A/R increases exhaust gas velocity, boosting turbine energy [6].

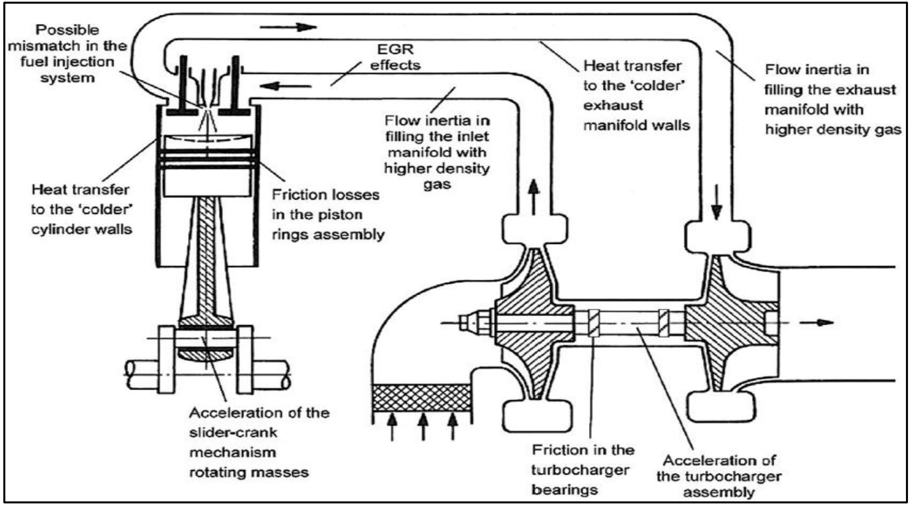

Figure 2 Primary factors contributing to system delay during the transient response of a turbocharged engine [8]

While using lighter materials [9] can contribute to improve transient response, the high temperatures and oxidizing conditions, in the exhaust, make it challenging to significantly reduce rotor mass. Another solution to overcome the issue is by employing the FGT in a two-stage turbocharging system. In this configuration, a smaller A/R ratio turbine housing is used at low engine speeds to increase receptiveness, while a larger A/R ratio housing is attached at higher speeds to sustain performance. A low-pressure turbocharger is employed at lower engine speeds, while a high-pressure turbocharger is activated at higher speeds to support engine demands [10]. Progressing the concept of matching the A/R ratio to engine speed leads to the development of VGTs [11]. Dissimilar from fixed geometry (FG) or two-stage designs that offer limited A/R arrangements, VGTs design, on the other hand, constantly adjust the A/R ratio to meet engine requirements. This increases the efficiency and the response across a wider functioning range. The following section explores diverse VGT designs, their features, mechanisms, and their functionality in gasoline engine.

Variable Geometry Turbine Technologies

VGT technology was developed to improve the low-speed torque and to minimize turbo lag under low-speed and steady-state conditions. Recently, this objective has attracted numerous scholars such as [12], [13], and [14]. Additionally, studies have considered the VGT different strategies and optimization procedures to enhance the performance [15]. In last decade, numerous VGT technologies have been employed to develop different VGT designs and to investigate their performance.

Sliding nozzle VGT

A commonly employed VG method is the sliding vane ring, favored for its durability and ease. This type is frequently used in truck and bus turbochargers, it enables higher boost at low speeds and powerfully supports Exhaust Gas Recirculation systems [6]. Sliding nozzle devices use fixed vanes fixed on a ring surrounding the turbine rotor (Figure 3). The ring moves axially to adjust the flow passage, guiding gas onto the rotor based on engine conditions. It is durable compact design that offer few wear points, and enhanced reliability.

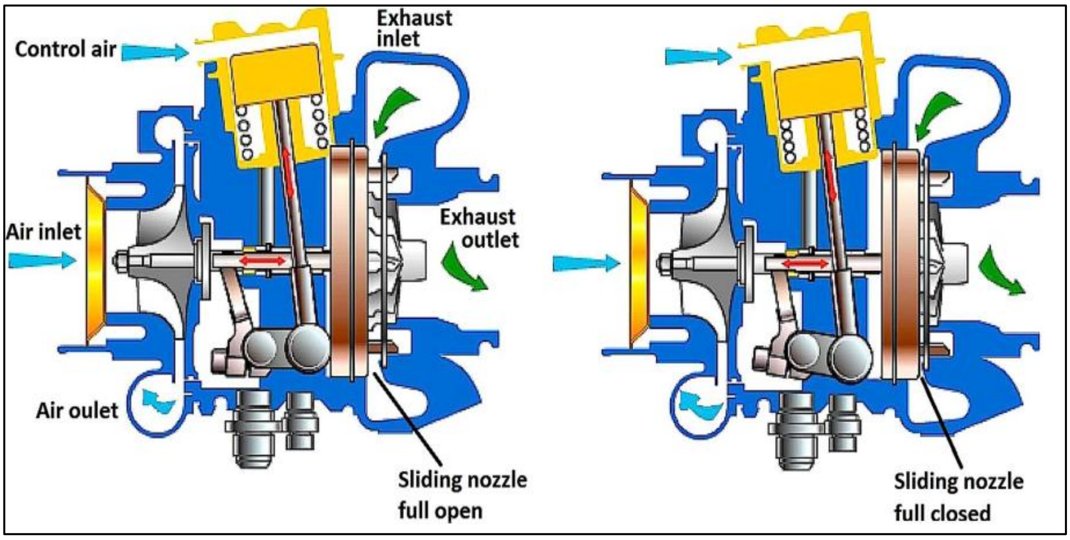

Figure 3 Cross-sectional illustration of a turbine with a sliding ring mechanism [16]

Numerous studies have been conducted to evaluate the performance of this technique and to investigate the enhancement visibility. Galloway, Kim [17] conducted a study to investigate the aerodynamic optimization of nozzle vanes in a VGT using ANSYS CFX and DesignXplorer. The geometry was parameterized using vital variables such as thickness, vane angle, and opening angle, and optimized over three critical engine operating points. Another study by Asanaka, Nishimura [18] used the computational fluid dynamic (CFD) to investigate the effect of the nozzle clearance on the VGT performance. Various clearances were examined, and the results showed that shroud clearance causes lowest torque efficiency, while leakage vortexes causes significant flow losses in the wheel domain. Unsteady simulations demonstrated that vortex direction and position affect turbine efficiency, with hub clearance causing more structured losses than shroud clearance.

Danlos, Podevin [19] conducted an experimental study to determine the crucial role of the VGT nozzle in stabilizing the compressor performance. By actively regulating the nozzle opening, the rotational speed was controlled to avoid entry into the surge zone. Surge was intentionally induced, and the response of the system to various VGT nozzle control profiles was analyzed. To reduce tip leakage and increase efficiency Gupta, Hoshi [20] developed a novel adjustable geometry nozzle and turbine rotor design. Using the CFD technique, a 3D-stacked vane profile was optimized for secondary vortices minimization and stability enhancement. The results confirmed efficiency gains of 2–7% and improved reliability, highlighting the nozzle's significant role in performance enhancement.

Pivoting vanes

Pivoting vane turbochargers adopt vanes fixed on pins that rotate axially to adjust airflow, dissimilar sliding vane systems. These vanes stay fixed in the gas stream, and airflow is controlled by rotating the vanes to open or close the passage (Figure 4). At low engine loads, the vanes close to accelerate flow; as engine speed increases, they open to prevent choking. Both pivoting vane and sliding vane mechanisms work effectively with exhaust gas recirculation (EGR) to reduce NOx. High-pressure EGR systems, which draw exhaust before the turbocharger, are commonly used in turbine setups [21]. EGR is more prevalent in diesel engines due to their lower exhaust temperatures (≈850 °C) compared to petrol engines (≈1000 °C) [22].

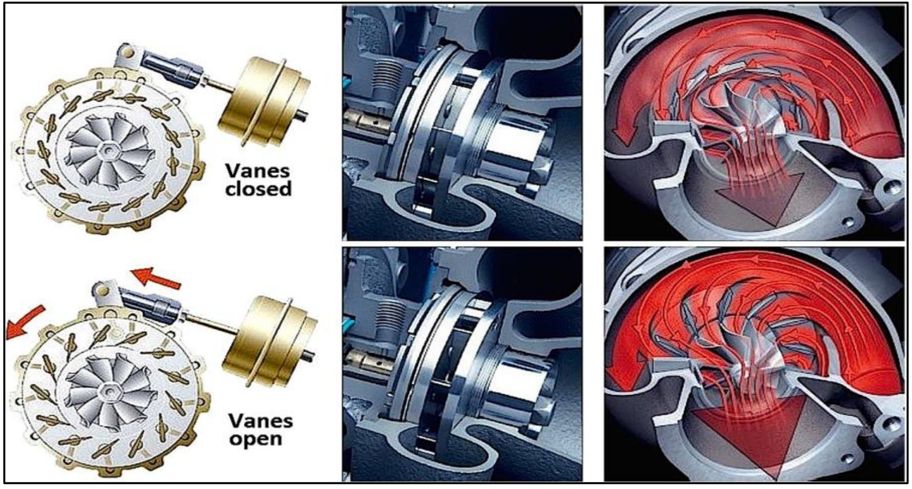

Figure 4 Pivoting vane turbocharger shown in fully closed (top) and fully open (bottom) configurations [23]

Lee [24] considered the implementation of VGT, particularly pivoting vanes to address turbo lag in diesel engines. The pivoting vanes are used to adjust exhaust gas speed and angle entering the turbine, significantly enhancing energy absorption during transient conditions. A study conducted by Stefanopoulou, Kolmanovsky [25] focused on VGT and EGR in diesel engines. Narrowing VGT vanes with a closed EGR valve raises exhaust pressure, enhancing turbine power and intake airflow, and opening the vanes reduces this effect. When the EGR valve is opened, recirculated exhaust gases lower combustion temperature, helping reduce NOx emissions.

Vaneless diffusers with variable geometry

A diffuser is a stationary component positioned around the impeller, it converts the kinetic energy of the air leaving the impeller into static pressure. In turbocharger systems, numerous types of diffusers are used, with vaneless diffusers being the most public when a broad operating range is required. The investigation of this component has attracted researchers such as Ludtke [29] and Whitfield, Wallace [30] to explore the impact on compressor performance by reducing the diffuser passage width and mitigating surge to widen the operating range. The results reported that constant area diffusers enhance the surge performance with margin effect on efficiency. In contrast, parallel diffusers offere higher efficiency but degraded surge behavior. Narrowing the passage reduces peak efficiency but improves surge resistance. Abdelhamid [31] suggested practical solution via a variable throttle ring at the diffuser exit. This ring was employed in a turbocharger compressor by Hagelstein, Van den Braembussche [32] who reported that using the ring with a vaneless diffuser enhances static pressure distribution at the impeller outlet.

Vaned diffusers with variable geometry

VGT with vaned diffusers enhance both the efficiency and operating range by adjusting vane angles to suit different conditions. Simon, Wallmann [33] confirmed that synchronously adjusting the diffuser and inlet guide vanes improves efficiency and expands the operating range. The study conducted by Harp and Oatway [34] examined wedge-shaped vanes used in military turbochargers. Their variable geometry mechanism employed a sliding pin along the vane chord to adjust the vane angles, enabling high flow rates, and optimizing throat area. Two novel variable geometry approach, using pipe diffusers, were examined by Salvage [35]. The first uses split rings to mechanically reduce the diffuser throat by shifting the surge line at small rotation angles. The second introduces controlled flow recirculation from the collector to the discharge, retaining diffuser flow stability at varying conditions. Best results were accomplished with 50% recirculating passage opening, significantly improving surge performance.

More recently, Demircioglu, Bogrekci [36] stated that the diffuser design plays a crucial role in the efficiency of turbo blowers. Vaned diffusers perform well at constant high flow rates but lose efficiency at lower flows, though vaneless diffusers are more efficient under variable conditions. HAUS Centrifugal’s XMP 122 Turbo blower, equipped with a variable geometry diffuser (VGD), was examined with both diffuser types across 19,000–33,000 rpm. Results showed improved volume flow rates, highlighting the VGD system's effectiveness in optimizing performance. Also Figure 5 illustrates that vaned diffusers generate big vortices, while vaneless diffusers exhibit flow separation but with much smaller vortices. As a result, vaneless diffusers experience considerably lower volume flow losses compared to the vaned diffusers.

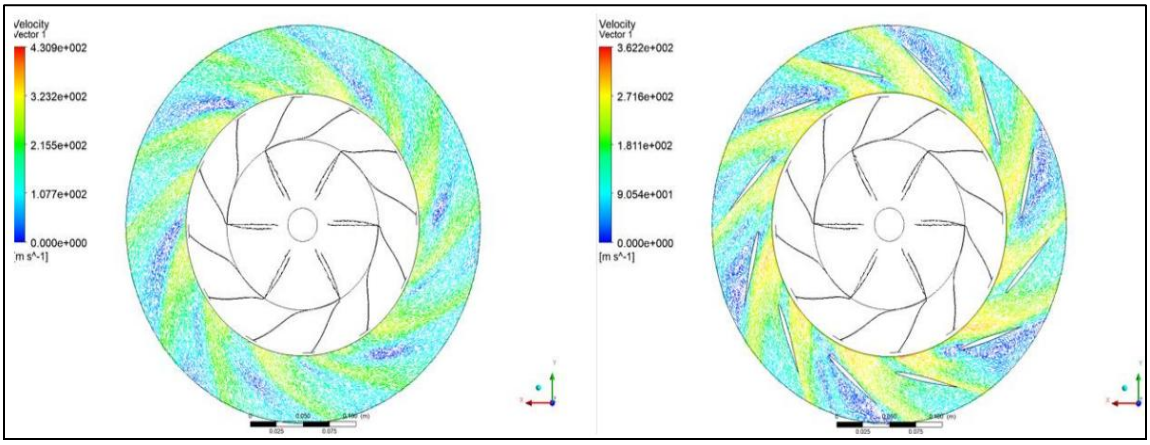

Figure 5 Velocity vector fields in vaneless and vaned diffusers [36]

Actuator Technologies for VGT

Although the different VGT flow designs have been discusses, exhaust flow cannot be adjusted without using an appropriate actuator. The most widely adopted actuator include electric, hydraulic, and pneumatic systems.

Electrical actuation

Electric actuators offer the highest accuracy actuation due to their fine voltage control. However, they require additional cooling to prevent overheating, unlike hydraulic and pneumatic systems, which dissipate heat through the fluid movement. Certain VGTs utilize a rotary actuator driven by a stepper motor to precisely open and close the vanes, as illustrated in Figure 6. This actuation system uses a rack and pinion mechanism (Figure 7) with a magnetoresistive sensor to provide real-time position feedback to the Electronic Control Unit (ECU), and to provide the desired position using a closed-loop system [6].

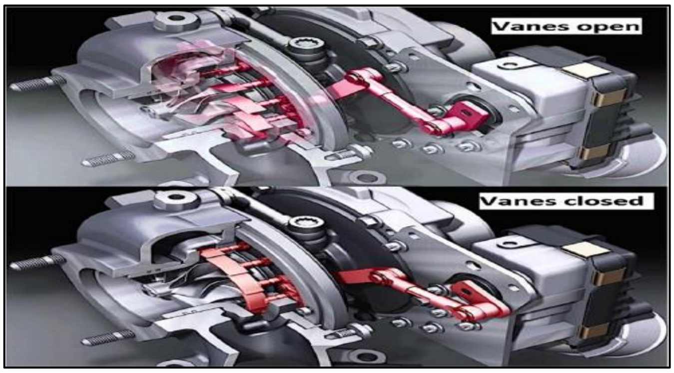

Figure 6 Operating principle of electronic actuation in a VGT Turbine [37]

Figure 7 Rack and pinion mechanism actuation system [38]

Hydraulic actuation

Hydraulic actuators use engine oil to move the nozzle ring or variable vanes, operating similarly to pneumatic systems but with fluid instead of gas. However, since the hydraulic fluid is incompressible, it provides more precise actuation control [39]. In this system, solenoid valve, operated by the ECU, is used to control the oil pressure and adjust the turbocharger's unison ring and a rack and pinion system. When no oil is supplied, the vanes are normally open; as oil pressure increases, the vanes gradually close [6].

Pneumatic actuation

Pneumatic actuators, the most common type, adopt compressed air to activate a piston that controls the VG mechanism. Though, as the air is compressible and its characteristics can change with heat [40], precise control is limited. Hence, hydraulic and electric systems are increasingly preferred for VGT [6]. In this system, as shown in Figure 8, a diaphragm-type actuator adjusts the vane configuration by moving a connecting rod attached to the vane control ring. The principle of operating of the actuator is by vacuum pressure, working against a reaction spring.

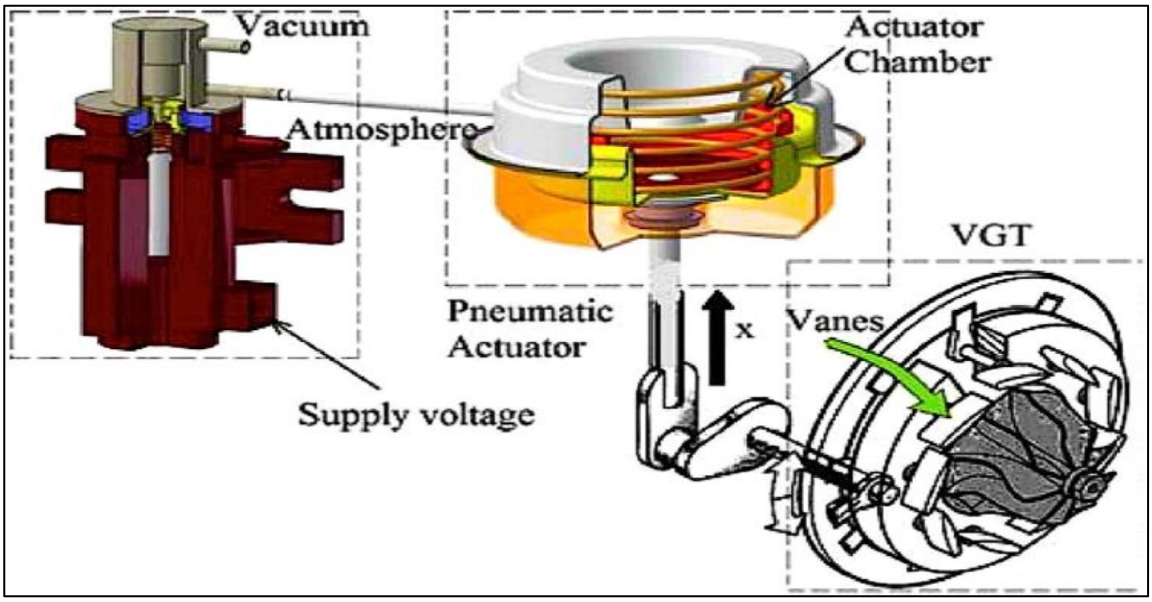

Figure 8 Operating concept of pneumatic actuation in a VGT turbine [41]

VGT control strategies

The control of the VGTs has become increasingly significant as their use has grown. A key challenge lies in the accurate adjustment to suit diverse engine conditions, as this directly affects the turbine performance. Effective control is a complex task due to the engine's dynamic behavior and the influence of emissions systems, making it a critical factor in VGT success. According to Feneley, Pesiridis [6], several studies have considered developing control strategies for VGTs which either aim to enhance the performance by adjusting the intake manifold pressure or to minimize emissions. However, the emissions optimizing often involves trade-offs, as the simultaneous reduction of nitrogen oxides, fuel consumption, and smoke levels can be challenging task that requires careful balancing.

Shirakawa, Itoyama [42] explored the correlation between exhaust gas recirculation (EGR) and the VGT control. An algorithm was developed, using the CAD tool and rapid prototyping, to the improve transient engine performance. Both EGR and VGT conditions were estimated using the created real-time controller model. The results obtained from the simulations and experiments confirmed the effectiveness of the optimized control strategy. Figure 9 illustrates the successful impact of combined VGT and EGR control, as observed during exhaust emission testing on an experimental vehicle.

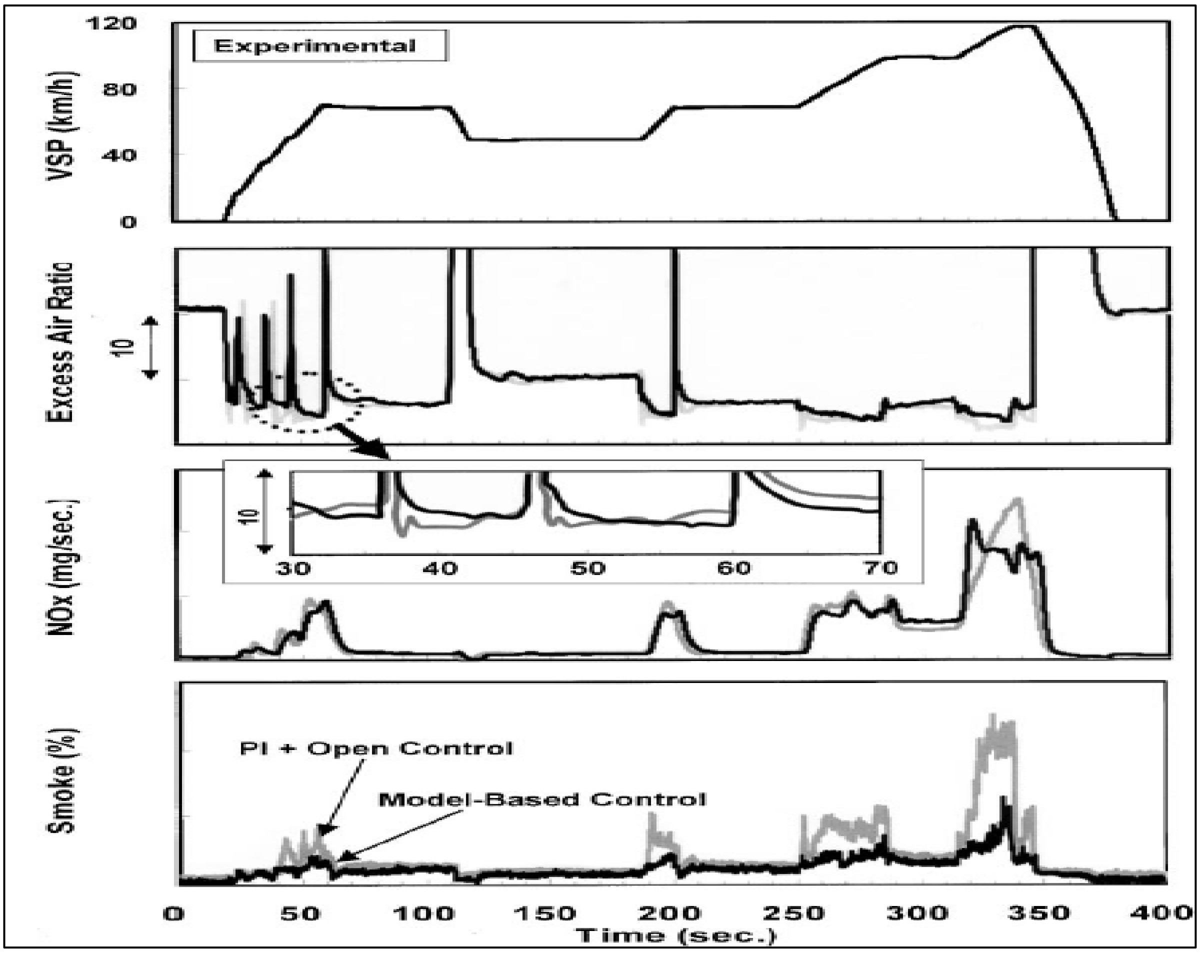

Figure 9 Results of optimized VGT and EGR system control [42]

Lookup table generation has developed alternatives to experiential methods. Mean Value Engine Models (MVEM) was developed by Eriksson, Wahlström [43] to evaluate vane and EGR positions through modeling. However, Artificial Neural Networks (ANNs) use map data to predict VGT vane positions under varying conditions. In another study by Filipi, Wang [44], used ANNs to model VGT behavior across different nozzle positions. Once the ANN is validated with a FGT, the VGT is incorporated into a diesel engine and vehicle simulation. A virtual Class VI vehicle is then examined under acceleration driving to assess VGT effects on engine response, fuel economy, and emissions.

Zhang, Wang [45] proposed a Variable Nozzle Turbocharger (VNT) control strategy merging a gain-scheduled PID feedback and an open-loop feed-forward controllers. Owing to tuning challenges on test benches, system identification was employed to model the engine behavior at different operating points, enabling tuning on a first order plus dead time (FOPDT) model. Simulation and engine examinations revealed that the designed control system accurately tracked target boost pressures over different conditions. More recently, Shanab, Elrefaie [46] provided a model for a Francis turbine hydro system using a test rig at Al-Azhar University, with a MATLAB simulation. A PID controller was adopted for governor control, while response to load disturbances was analyzed. Best performance was reported to be gained with PID gains KI = 45, KP = 50, and KD = 10, confirming steady turbine speed.

To optimizes a three-shaft recuperated VAN gas turbine a study was conducted by Zhou, Yin [47]. The conducted simulation showed that decoupling shaft speed and VAN angle contributes to enhancement of performance and control. The proposed technique yields output power increases of up to 47.80%, and thermal efficiency gains of up to 64.97% at relative shaft speeds of 0.85. Moreover, maximum efficiency was reported to be achieved at part-load when the temperature limits were relaxed. Later, Galindo, Serrano [48] introduced a physics-based VGT control approach for spark-ignited engines, targeting the transient response improvement. By maximizing the acceleration through energy balance, it outperforms or matches PID control while reducing calibration time. The research group concluded that the developed approach is adaptable to other thermodynamic systems with VGTs.

Recent advances in turbocharger research

Experimental approach

Experimentally, turbochargers are investigated using different techniques for performance evaluation. The standard methodology involves engine test benches with a dynamometer. Instead, standalone test arrangement can be used, where turbines are operated by cold or hot exhaust gases [49].

Liu, Gjika [50] validates, experimentally, an oil-free turbocharger with herringbone grooved gas bearings. It operated sturdily up to 170,000 rpm, with lift-off at 3,000 rpm and low friction. Power loss tests at 40°C and 100°C showed 50–70% lower losses compared to oil-supported systems, confirming its efficiency and viability. Aiming to enhance the reliability and efficiency, Silvestri, Marelli [51] integrated dynamic mass flow rate and pressure measurements with structural response data to analyze the surge conditions. The procedure involved adopting frequency and time-frequency data analysis techniques on inflow pressure and anemometric signals to identify stable or unstable operation.

To support zero CO_2 emissions, Nannetti, Usai [52] investigated the behavior of a turbocharger compressor under unsteady intake flow. A motor-driven cylinder head was used to simulate valve-induced pulsations, and the measurements of pressure, mass flow rate, and rotational speed were taken across various operating conditions. The results showed that pulsating flow significantly alters compressor performance.

Computational fluid dynamics

CFD is a powerful analysis tool, enabling precise investigation of the turbochargers' aerodynamic performance and flow phenomena, which is crucial for reliability and efficiency optimization.

El Hameur, Cerdoun [53] utilized a CFD model to match a downsized 1.5 L engine with a suitable turbocharger. The model was used to simulate the flow, predicting its performance and generating a turbine map. Another study by Liu, Spence [54] employed the CFD to investigate the stability and performance of compressor equipped with ported shrouds. The study focused on the flow dynamics near the impeller tip (80–100% span), where recirculated flow from the ported shroud was found to influence local flow conditions. Similarly, CFD was adopted by Singh, Sasane [55] to determine and refine the turbine geometry. The model delivered insights into velocity and pressure distributions, revealing key flow phenomena like separation and vortex formation. Additionally, Heidary, Nejat [56] employed the CFD to improve the performance by analyzing the impact of turbine bypass and wastegate geometry modifications.

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