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Variable Geometry Turbocharger Technologies for Exhaust Energy Recovery and Boosting-A Review

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ABSTRACT

As emissions regulations become increasingly demanding, higher power density engine (downsized/down-speeded and increasingly right-sized) requirements are driving the development of turbocharging systems. Variable geometry turbocharging (VGT) at its most basic level is the first step up from standard fixed geometry turbocharger systems. Currently, VGTs offer significant alternative options or complementarity vis-à-vis more advanced turbocharging options. This review details the range of prominent variable geometry technologies that are commercially available or openly under development, for both turbines and compressors and discusses the relative merits of each. Along with prominent diesel-engine boosting systems, attention is given to the control schemes employed and the actuation systems required to operate variable geometry devices, and the specific challenges associated with turbines designed for gasoline engines.

1. Introduction

In response to increasing emissions regulations, engine manufacturers around the world have adopted a wide array of turbocharging technologies in order to maintain performance when downsizing their engines. Variable geometry turbocharging represents a large portion of the technology present in today's vehicles. VGT technology (also known as VNT-Variable Nozzle Turbocharger) is employed in a huge range of applications, such as in commercial on- and off-highway, passenger, marine and rail internal combustion engine applications. Aside from the emissions and engine downsizing components, other key developmental drivers include increased transient response, improved torque characteristics, over-boosting prevention and better fuel economy.

Turbocharger growth has been substantial in the last two decades and has experienced particular growth in areas where naturally-aspirated engine domination was until recently, still viable (USA and China in particular). Substantial growth figures are posted in recent years with a significant proportion of the realized as well projected market share being taken up by VGTs. VGTs are predicted to account for 63.3% of the global turbocharging market by volume by the year 2020. In the Asia/Oceania region, the adoption of VGTs is growing rapidly, and is projected to grow at a high compound annual growth rate of 14.61% from 2015 to 2020, when calculated by volume [1].

VGTs are therefore important not only due to the market share and value that they represent in standalone, single stage boosting terms but increasingly as cost-effective boosting devices compared to more recent and advanced technologies such as electric turbocharging and supercharging. In addition, and for the same cost-effectiveness reasons they are being increasingly encountered, as part of advanced, multi-stage (two- and three-stage) architectures.

In addition, the other part of the Variable Geometry (VG) equation, the compressor has seen little implementation but is also of significant interest especially in view of the persistent requirement for maximized boost per stage. In addition, the compressor is being asked to operate across an increasingly expanding operating envelope and this is seen as a potential enabler for advanced engine cycle (Miller/Atkinson for example).

The objective of this paper is to present the first complete review of variable geometry technologies that are available commercially, as well as those currently under development and to highlight the merits of the increasing more complex options now available to powertrain developers where VG turbochargers are encountered as components of a more complex boosting architecture. The operating principles of variable geometry are covered, initially, followed by details of the range of different VG systems for both the turbine and compressor. A summary of current control systems and strategies, actuation methods and VG efforts specific to the gasoline engine are covered before concluding with a discussion on future trends for variable geometry

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Nomenclature

AFR	Air to Fuel Ratio
ANNs	Artificial Neural Networks
AR	Aspect Ratio
BSFC	Break Specific Fuel Consumption
CFD	Computational Fluid Dynamics
CI	Compression Ignition
CTT	Cummins Turbo Technologies
EAT	Electrically Assisted Turbocharger
ECU	Engine Control Unit
EGR	Exhaust Gas Recirculation
FEA	Finite Element Analysis
FGT	Fixed Geometry Turbocharger
HTT	Honeywell Turbo Technologies
MAS	Multi-Agent Systems
MHI	Mitsubishi Heavy Industries
MVEM	Mean-Value Engine Models
NA	Naturally Aspirated
NOx	Mono-Nitrogen Oxides
PID	Proportional-Integral-Derivative
PWM	Pulse Width Modulation
SI	Spark Ignition
VFT	Variable Flow Turbocharger
VGT	Variable Geometry
VGT	Variable Geometry Turbocharger
VST	Variable Sliding Ring Turbocharger
VNT	Variable Nozzle Turbocharger
VVT	Variable Volute Turbocharge

Variables

A	Area
$\dot{m}$	Mass flow rate
M	Mach number
T	Temperature
p	Pressure
γ	ratio of specific heats

Subscript notation

*	Critical value
in	Inlet

turbochargers development and implementation.

2. Turbocharger systems

The modern day turbocharger market is diverse, as manufacturers strive to provide the improved technologies to lower exhaust emissions. There are numerous technology variants available on the commercial market, as well as under development. The most basic technology is the conventional, fixed geometry turbocharger, which consists of turbine and compressor wheels connected by a common shaft. Electrically assisted turbocharging systems use electrical machines in motoring mode to impart additional power onto the common shaft during low load operation to improve upon the performance of the fixed geometry variant. VG devices are employ different designs and/or are employed in different ways to alter the cross sectional area of the housing or inlet which guides the exhaust gas into the turbine rotor; these devices can also be coupled with diffusers to effect variable geometry for the compressor [2].

Even though not directly linked to boosting (but only to energy recovery) one additional system that can be included here is turbo-compounding. This is a waste-heat energy recovery technology using an additional power turbine to recover energy in two forms: mechanical or electrical. In electrical turbo-compounding, the energy is transferred as electrical power and transmitted to the engine or to vehicle auxiliaries through the battery; the mechanical variant feeds kinetic energy back into the engine using a high ratio transmission.

Sequential turbocharging is an additional option that involves using two (typically) or more turbochargers of different sizes operating entirely or partially in sequence. A small turbocharger is used at low speeds due to its low rotating inertia, and a second larger turbocharger is used at higher engine speeds, usually with an intermediate stage where both may be in operation. Despite clear weight, cost and thermal inertia disadvantages this technology is becoming increasingly important in meeting the increased power density demand from engines of

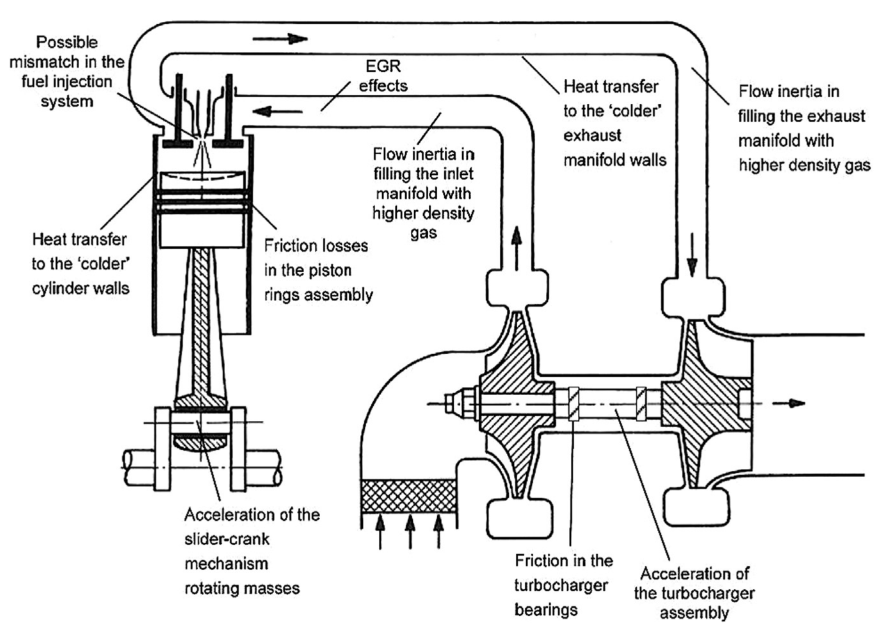

Fig. 1. A presentation of the major contribution to the system delay during transient response of a turbocharged engine [4].