MECHANICAL ENGINEERING THEORY AND APPLICATIONS

TURBOCHARGERS AND TURBOCHARGING

ADVANCEMENTS, APPLICATIONS AND RESEARCH

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PREFACE

One of the principal objectives during the design process of every engine type is to maximize the power output from a specific engine size. As regards internal combustion (IC) engines, the most successful means to achieve this is through supercharging. Supercharging increases the inlet air density, usually applying a compressor located upstream of the engine. By doing so, the amount of in-cylinder trapped air is increased accordingly. As a result, efficient burning of proportionately higher amount of fuel is enabled. The obvious benefit is the direct increase in the engine power; at the same time, downsizing (and perhaps down-speeding) of the engine is realized, with obvious advantages in terms of reduced mechanical losses.

Supercharging the IC engine is practically as old as the engine itself. Early supercharging ideas appeared near the end of the 19th century. Sir Dugald Clerk (1854–1932) designed a two-stroke spark ignition (SI) engine in 1878, having one working cylinder and an additional cylinder to charge the power-producing one; this was used to expel the exhaust gas through a port uncovered by the piston. Some sources consider this additional cylinder the world's first supercharger, although Clerk himself did not consider the expelling gases cylinder a compressing pump. A few years later, in 1885, Gottlieb Daimler (1834–1900) patented a technique through which more air was forced into the IC engine compared to naturally aspirated operation, using the bottom side of the piston (German patent No. DRP 34926). The first 'viable' supercharging configurations were realized by means of a gear-driven pump (*mechanical supercharging*). Initially, such supercharging schemes were limited to aircraft engines in order to compensate for the decrease in the air density at increasing flight altitudes, hence improve high-altitude performance. In the 1920s and 30s, however, an ever increasing number of gasoline-powered vehicles became supercharged for both commercial and racing applications. One notable example of the era's state of the art achievement in supercharging was the Auto Union Typ C racing car (1936/37), which exhibited maximum power of the order of 520 HP at 5000 rpm from a mechanically supercharged six-liter, V16 SI engine; a Roots blower was employed enabling an absolute inlet pressure of 1.95 bar.

In parallel (1905), Alfred Büchi (1879–1959) patented what later became the most successful version of supercharging, namely *turbocharging* (German patent No 204630). His design described a 'highly supercharged compound engine', employing an axial compressor, radial piston engine and axial turbine on a common shaft. The idea behind turbocharging is to recover part of the high-enthalpy exhaust gas. More specifically, the expansion in a turbine of the exhaust gases leaving the cylinders supplies the power needed to drive the compressor (instead of using a power-consuming gear-driven pump). Very early (marginally successful) examples of turbocharged engines can be found during the World War I period (aircraft engines); diesel-powered ships and locomotives appeared in the 1920s initially by MAN AG. It took nearly 30 years until turbocharging reached maturity in slow- and medium-speed diesel-powered applications. Turbocharging gained increased public interest in the 1970s and 80s when applied to F1 racing cars (SI powered), and has for many years now been established as the most preferred supercharging method applicable to IC engines. At the moment, practically all diesel engines are turbocharged (automotive, marine, locomotive, industrial, and, by default, aircraft), with a continuously increasing penetration in the highly competitive market of SI-powered vehicles. Nowadays, highly-turbocharged truck or industrial/marine (four-stroke) diesel engines achieve impressive values of brake mean effective pressure up to 30 bar, with an inlet charge pressure of approximately 6 bar (corresponding peak cylinder pressure of the order of 240 bar).

A principal reason for the universal acceptance of turbocharging is the fact that the turbomachines, rotating at very high speeds (up to and exceeding 250,000 rpm in small applications), enable considerable increase in the engine air supply from a relatively small turbocharger size, thus facilitating very high engine power-to-weight ratios. Another distinctive advantage of a turbocharged engine is its capability to operate more efficiently compared to its naturally-aspirated counterpart, hence emit proportionately less CO_2 (this derives from the combined effect of higher indicated and mechanical efficiency). Since concerns over greenhouse gas emissions are now reflected in the IC engines/vehicles legislation too, it is not surprising that the production of turbocharged vehicles has constantly increased in the last decades, given that turbocharging and downsizing are widely acknowledged as key technologies to achieve current and future CO_2 limits for passenger cars. Interestingly, Büchi initially experimented with turbocharging in an attempt to increase the very low at the time efficiency of IC engines; since, as stated in his patent, two-thirds of the energy is lost through exhaust heat, it appeared an important objective to try capturing that heat and use it to improve the engine performance.

Despite the aforementioned merits, turbocharging is also characterized by a serious operating disadvantage realized in the form of unfavorable low-end torque, which is then reflected into problematic *transient* behavior at low loads and speeds. The term transient refers to engine speed or load changes, such as acceleration (continuously experienced by automotive engines), load increase (more common in industrial or marine engines) or even starting. Obviously, the transient discrepancies are amplified when vehicular engines are involved since the biggest part of their daily driving schedule involves dynamic operation in the form of changing (engine) speed and fueling conditions. Probably the most notable demonstration of the problematic turbocharged engine transient response has been the particulate matter (PM) emissions overshoot evidenced as black smoke coming out of the exhausts of accelerating older-technology diesel-engined vehicles.

Apart from the usually applied single-stage turbo configuration involving one compressor and one turbine on a common shaft, many boosting variants have been developed over the years. The aim is to either increase the power output, or limit the turbocharger lag and consequently speed-up the engine and vehicle response, and mitigate exhaust emissions. Some notable examples are: combined supercharging (positive displacement compressor in series with a turbocharger), turbo-compound configuration (a power turbine mechanically connected to the engine crankshaft provides additional power), electrically assisted turbocharging, two-stage (series) turbocharging, sequential (parallel) turbocharging, use of variable geometry turbines (VGT) or compressors etc.

The current book on turbochargers and turbocharging, comprising 15 chapters, was conceived with the aim to gather important research on many of the aforementioned aspects of turbocharging. In the following pages, experimental or (experimentally validated) simulation results from research conducted all over the world are presented. These focus on various turbocharging issues intended for all kinds of SI and diesel-powered engine applications (automotive, truck, marine and aircraft). For example, characterization of the value proposition of turbocharged vehicles (Chapter 1), marine engines turbo-compounding (Chapter 3), variable geometry compressors (Chapter 4), dynamic operation of turbochargers including VGT and surging effects (Chapter 6), fundamental issues of turbocharger lag and its relation with engine-out PM emissions (Chapter 7), and automotive two-stage turbocharging (Chapter 14) will be analyzed.

The very critical, in terms of both emissions and performance/drivability, issue of transient turbocharged engine operation is discussed in detail in this book, most notably in Chapters 2, 6, 7, 11 and 14.

Review papers form a very important part of the book. Discussion and in-depth analysis of various automotive boosting systems (Chapter 2), heat transfer and pulsating flows in turbomachinery (Chapter 5), turbocharger reduced-order modeling (Chapter 10), mathematical modeling approaches for turbocharged engines (Chapter 11), and turbomachine-based engine throttling (Chapter 15) are amongst the review works included.

The usually conflicting objectives between customer needs for good drivability and low fuel consumption, and the legislators' directives for reduced pollutant emissions have led to a continuously increasing complexity of automotive IC engines in the last decades, and the need for a multi-variable optimization. Model-based systems engineering is becoming an important tool to meet these demands and cope with the complexity of engines. A considerable portion of the book deals therefore with various control-oriented modeling techniques relating to the turbocharger and/or the whole engine power-plant; both mapped and map-less approaches for the compressor and turbine are covered. Such models have proven valuable during the design of both turbochargers and turbocharged engines, and are described and discussed in detail in chapters 6, 8–14 for a variety of automotive and aircraft applications.

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