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Turbine and Compressor Design: A Comprehensive Study of Gas Turbine Components, Cooling Techniques, Aerodynamic Instabilities, and Axial Compressor Design

Mrs.J.Jaisy
Assistant professor, Lord jegannath college of engineering and technology Ramanathichanputhoor,(2025-2026).

Abstract- Gas turbines are among the most important energy conversion systems used in aerospace propulsion, power generation, and industrial applications. This paper presents a comprehensive review of turbine and compressor design principles, thermodynamic operation, cooling technologies, aerodynamic instabilities, and axial compressor design methodologies. Particular emphasis is placed on compressor staging, velocity-triangle analysis, turbine cooling methods, stall mechanisms, and surge phenomena. The paper synthesizes fundamental design approaches and provides a structured framework suitable for engineering education and preliminary turbomachinery design studies.

Keywords- Gas Turbine, Axial Compressor, Centrifugal Compressor, Turbine Cooling, Compressor Stall, Dynamic Surge, Turbomachinery, Aerospace Propulsion.

I. INTRODUCTION

Gas turbine engines convert the chemical energy of fuel into mechanical energy and thrust. Their high power-to-weight ratio, reliability, and efficiency have made them indispensable in aviation and industrial power systems. The compressor and turbine constitute the core of the gas turbine engine. Compressor performance directly influences pressure ratio and engine efficiency, while turbine effectiveness determines the ability to extract energy from high-temperature combustion gases. Understanding the interaction between these components is essential for successful turbomachinery design.

II. HISTORICAL BACKGROUND

The development of gas turbine technology began in the nineteenth century with early concepts proposed by Dr. F. Stolze and other pioneers. Advances in materials science, aerodynamics, and manufacturing enabled the transition from theoretical concepts to practical engines. Modern gas turbines achieve significantly higher pressure ratios and turbine inlet temperatures than earlier designs due to improved blade cooling and aerodynamic optimization.

III. FUNDAMENTALS OF GAS TURBINE OPERATION

Gas turbines operate according to the Brayton cycle. Ambient air is compressed, mixed with fuel, combusted at nearly constant pressure, and expanded through turbine stages. Part of the turbine work drives the compressor through a common shaft, while the remaining energy produces thrust or shaft power. The operating principle also reflects Newton's Third Law, where accelerated exhaust gases generate an equal and opposite reaction force.

IV. COMPRESSOR TECHNOLOGIES

Compressors increase the pressure of incoming air before combustion. The two principal compressor types are centrifugal and axial compressors. Centrifugal compressors achieve compression through radial acceleration and diffusion of airflow. Axial compressors utilize multiple rows of rotating and stationary blades, enabling higher overall pressure ratios while maintaining compact geometry. Modern aircraft engines primarily employ multistage axial compressors due to their superior efficiency and scalability.

V. TURBINE TECHNOLOGIES

Turbines extract energy from high-temperature combustion gases. Axial-flow turbines are the most common configuration in aircraft engines due to their ability to handle large mass flow rates efficiently. Radial turbines are simpler and less expensive to manufacture and are frequently used in smaller engines and turbochargers. Turbine design requires balancing aerodynamic efficiency, structural integrity, and thermal resistance.

VI. THERMAL CHALLENGES AND COOLING METHODS

Increasing turbine inlet temperature generally improves thermal efficiency; however, blade materials impose temperature limitations. To overcome these constraints, advanced cooling techniques are employed.

Spray Cooling
Liquid coolant is sprayed onto turbine surfaces to remove heat through convection. This technique reduces thermal loading but introduces system complexity.

Internal Passage Cooling
Hollow turbine blades contain internal passages through which compressed air flows. Heat is transferred from the blade material to the cooling air, reducing metal temperature.

Transpiration Cooling
Air is forced through porous blade materials, forming a protective insulating film around the blade surface. This method provides highly uniform cooling and excellent thermal protection.

VII. COMPRESSOR STALL

Compressor stall occurs when airflow separates from blade surfaces due to excessive incidence angle or adverse pressure gradients. Stall reduces blade lift, lowers pressure rise capability, and decreases compressor efficiency. Localized stall cells may propagate through the compressor, potentially causing severe operational instability.

VIII. DYNAMIC SURGE

Dynamic surge represents a complete compressor system instability characterized by periodic flow reversal and pressure oscillations. Surge may produce loud acoustic events, severe vibration, reduced mass flow, and potential mechanical damage. Surge control systems and operating margins are therefore critical design considerations.

IX. AXIAL COMPRESSOR DESIGN METHODOLOGY

The design process begins with defining required thrust, mass flow rate, pressure ratio, rotational speed, and turbine inlet temperature. Designers estimate blade tip speed, axial velocity, and hub-to-tip ratio before determining compressor geometry. Rotational speed is then selected based on aerodynamic and mechanical constraints.

X. STAGE DESIGN AND VELOCITY TRIANGLES

Velocity triangles form the foundation of axial compressor analysis. They describe relationships among blade speed, absolute velocity, relative velocity, and whirl velocity. Rotor blades increase fluid energy, while stator blades convert kinetic energy into pressure. Proper velocity-triangle design minimizes losses and maximizes stage efficiency.

XI. DETERMINATION OF NUMBER OF STAGES

The number of compressor stages depends on the required overall pressure ratio and permissible temperature rise per stage. Assuming a reasonable polytropic efficiency, the overall temperature increase can be distributed across stages to determine the required compressor length and complexity.

XII. AIR-ANGLE DISTRIBUTION AND FREE-VORTEX DESIGN

Free-vortex design principles are commonly used to determine air-angle variations from blade root to blade tip. These calculations ensure acceptable loading distributions and stable aerodynamic performance throughout the blade span. Root, mean, and tip air angles are evaluated using velocity-triangle relationships.

XIII. ENGINEERING DESIGN EXAMPLE

A representative five-stage axial compressor design demonstrates the application of thermodynamic and aerodynamic principles. Parameters include compressor pressure ratio, rotational speed, stage temperature rise, blade-tip speed, and air-angle calculations. The example illustrates how theoretical design methods are translated into practical engineering solutions.

XIV. DISCUSSION

Modern gas turbine development increasingly relies on computational fluid dynamics, advanced materials, additive manufacturing, and digital optimization techniques. These technologies enable higher efficiencies, improved durability, and lower emissions. Nevertheless, the fundamental principles of compressor staging, turbine cooling, and aerodynamic stability remain central to successful turbomachinery design.

XV. CONCLUSION

The compressor and turbine are the primary components governing gas turbine performance. Efficient compressor design requires careful consideration of velocity triangles, stage loading, pressure ratio distribution, and air-angle variation. Turbine performance depends heavily on effective cooling methods and thermal management strategies. Furthermore, understanding compressor stall and surge phenomena is essential for maintaining stable engine operation. The principles reviewed in this paper provide a strong foundation for advanced turbomachinery analysis and design.

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