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Pratt & Whitney Canada Turboshaft Engines Product and Technology Evolution

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Introduction

Pratt & Whitney Canada is part of the $50 billion United Technologies Corporation that has a long history of pioneering innovation in aerospace, aviation, helicopter design, climate control, elevator design, security system and hydrogen fuel cells. Pratt & Whitney Canada Corp. (P&WC) is recognized throughout the world as a leader in the design, development, manufacture and support of gas turbine engines for the aviation industry. To date, P&WC has produced close to 65,000 engines. It is estimated that every two seconds an aircraft powered by a P&WC engine takes off somewhere in the world.

P&WC offers an impressive range of products, including turbofan, turboprop and turboshaft engines targeted for the regional, business, utility and military aircraft and helicopter markets. P&WC also designs and manufactures engines for auxiliary power units and industrial applications. More than 60 new engines have been developed in the last 12 years. Over the years we have built an outstanding reputation for dependability.

Pratt & Whitney Canada has been pioneering in the turboshaft industry for over 45 years, installing the first PT6 in a Hiller helicopter back in 1960. Since then, P&WC has demonstrated its ability to continuously serve the helicopter industry. With the PT6, P&WC has led the market with an engine that has become a world-class benchmark. Today, P&WC is a supplier of turboshaft engines to the foremost helicopter manufacturers; Agusta S.p.A. (Italy), Bell Helicopter Textron (USA), CHANGHE (China), Eurocopter, HAIG (China), Kazan Helicopter (Russia), MD Helicopter (USA), MIL (Russia) and Sikorsky (USA). The family of products (PT6, PW100 & PW200) ranges from 600 to more than 3,000 shaft horsepower (SHP) at takeoff, enough to cover light-single to medium and heavy helicopters. Future products have been considered with engine derivatives reaching up to 6000 SHP.

Our new dynamic line of helicopter engines captured the durability and reliability features of the PT6T Twin Pac engine legacy. The PT6 success in the small gas turbine engines market validates this approach, which is particularly well suited to the helicopter market. The PT6 turboprop engine family has accumulated in excess of 300 million hours. PT6 turboshaft engines have more than 33 million hours of operation in small and medium helicopter, including one of most innovative programs in the helicopter industry, the BA609 Tiltrotor with the PT6C-67A engine. The PT6C-67C equipping the AW139 and the PT6C-67E powering the EC175, incorporating P&WC’s latest generation of dual channel FADEC control system, are the latest addition to the PT6C family.

The PW200 competes in the 500 to 735 SHP class. Its layout, a centrifugal compressor, a single-stage compressor turbine and a free turbine, makes it one of the simplest turboshaft engines. The extensive usage of technology, such as electronic control, advanced material and coatings, has allowed P&WC to offer greater power and lower fuel consumption with low emissions and high reliability.

P&WC is involved in one of the most advanced programs currently under development in the helicopter industry, the PW210. Its layout; comprising latest advanced compressor design technology, a single-stage compressor turbine and a two-stage free turbines, makes it one of the simplest turboshaft engines in its class. The PW210 also incorporates a dual channel, full authority digital engine control (FADEC) system with a state-of-the-art diagnostic capability.

P&WC’s success in turboshaft engines has been largely due to the use of technology developed and incorporated throughout the life of all its engine models. The small gas turbine industry has witnessed a big leap in technology over the past two decades. This period was mainly characterized by a rapid development of advanced three-dimensional analytical tools assisted by a yearly doubling of computer capacity. P&WC uses the most advanced technology to provide performance, affordability and reliability in all its products.

PT6 Power Growth

PT6 ENGINE CONFIGURATION

Growth through evolution and continuous application of new technology has enabled a doubling of output power within the same engine diameter, while adding only 10 inches to the basic engine length. A unique feature of the PT6 is the single or two-stage “free“ power turbine. This feature allows great diversity of application as well as ease of hot section inspection and maintenance. The gas generator is comprised of a compressor with three or four axial stages and a single centrifugal stage, coupled with a single-stage compressor (high pressure) turbine. The reverse flow annular combustor is of sheet metal construction with splash louvre cooling for low weight and cost. The gearbox provides a speed reduction for helicopter installations (6,600 rpm). Recent PT6C applications have been configured with direct drive outputs (21,000 -30,000 rpm).

PT6 SERIES POWER GROWTH

In order to achieve power growth within the same engine size as the original PT6T-3, advancements have been made in all relevant engineering technologies including compressor and turbine aerodynamics, materials and structural analysis of rotating components and of the static structure of the whole engine. Improved nickel based alloys in particular have allowed for increased cycle temperature. This, combined with a 60 per cent increase of engine mass flow, has enabled power growth. Specific fuel consumption improvement has resulted from increased cycle pressure ratio and higher component efficiencies. Increasing mass flow and pressure ratio within the same diameter have imposed a continuing challenge on compressor designers to improve efficiencies while relative mach numbers and blade loadings have all significantly increased. Similarly, stress engineers have had to continually improve power-to-weight ratios while maintaining high durability with increased operating temperatures.

Accurate cycle synthesis of steady state and transient engine performance throughout the engine operating range and flight envelope has been used to select optimum growth paths for the PT6. Until now, every new model has been extensively tested in rigs, spin pits, and sea level and altitude test facilities. The PT6 turboshaft engine family had accumulated more than 33 million hours of operation. Improved understanding of engine operability has contributed to achieving the fast acceleration times required by helicopter applications.

PT6 turboshaft designations are as follow:
PT6T: Single combining gearbox for two power sections.
PT6B: Single gearbox mated with a single power section.
PT6C: Single power section with direct drive high-speed output.

The PT6B series follows PT6 family tradition. The PT6B is a turboshaft engine that integrates the proven PT6T-3D power section with an offset rear drive reduction gearbox and an electronic governing unit for precise helicopter rotor management. These features enable the PT6B engine series to deliver an effective combination of power and precision, providing safe economic operation, multi-fuel capability and easy starting. The PT6B-37A is currently installed on the Agusta A119 Koala single engine installation, whereas the PT6B-36A/B are installed in the Sikorsky S-76B helicopter. The latest addition to the PT6B family is the PT6B-67A for the Chinese Z8 3-engines helicopter. The PT6B-67A engine combines proven PT6C-67C and PW200 controls with common turbomachinery to the PT6C-67A, mated to a single stage offset reduction gearbox to produce the highest power PT6 turboshaft P&WC has certified to date.

The PT6C series of engine is derived from the industry proven PT6A-67 turboprop engine, which has accumulated over 13 million hours of operation. The PT6C builds up upon the demonstrated reliability, durability and low cost of operation of the PT6A-67 engine family.

P&WC developed the new PT6C series of engine rated from 1,679 SHP to 2,000 SHP take off (thermodynamic). The PT6C provides the best power to weight ratio in its class and has one of the lowest maintenance cost and emission levels in the industry. This state of the art engine sets new levels for operational and performance standards for the medium helicopter category. The PT6C-67C is currently powering the Agusta Westland AW139. Recently the PT6C-67E was selected to power the Eurocopter EC175. The PT6C-67E is a derivative of the PT6C-67C providing higher take off power and incorporated the latest design dual channel FADEC control system.

The PT6C-67A engine has been designed specifically for the unique challenges of the BA609 Tiltrotor application (figure 1), responding to the requirements for high-altitude performance and sustained, near-vertical operation. The latest technology available has been used to achieve performance, versatility and affordability. Representing the latest in the four-decade evolution of the venerable PT6 series, the PT6C-67A provides a takeoff rating of 1940 SHP, and an even more remarkable OEI (one engine inoperative) rating of 2492 SHP.

The PT6C-67A (figure2) is primarily a derivative of the large PT6A-67 turboprop series engine. In order to reconfigure this engine as a turboshaft for the Tiltrotor application, a number of changes were necessary. First, the turboprop gearbox was eliminated and replaced with a high-speed (30,032 rpm) drive shaft. A new single-port exhaust replaced the twin exhaust ducts. To meet the increased power requirements, the compressor rotor was upgraded to a higher flow and pressure ratio. A new "low smoke" combustor and fuel nozzle system was incorporated. In order to provide for engine operation at pitch angles ranging from 16° nose-down to 110° nose-up, the oil lubrication and scavenge systems were also redesigned. In addition, both the compressor and power turbine stages were reconfigured to withstand higher rotational speeds and temperatures. The installation of the engine in the BA609 also required the repackaging of external lines and accessories to meet the requirements of tighter nacelle lines. Although the engine design is based on the proven PT6 configuration, these significant design changes were required to meet the specific needs of the Tiltrotor installation.

Figure 1- Bell Agusta BA609

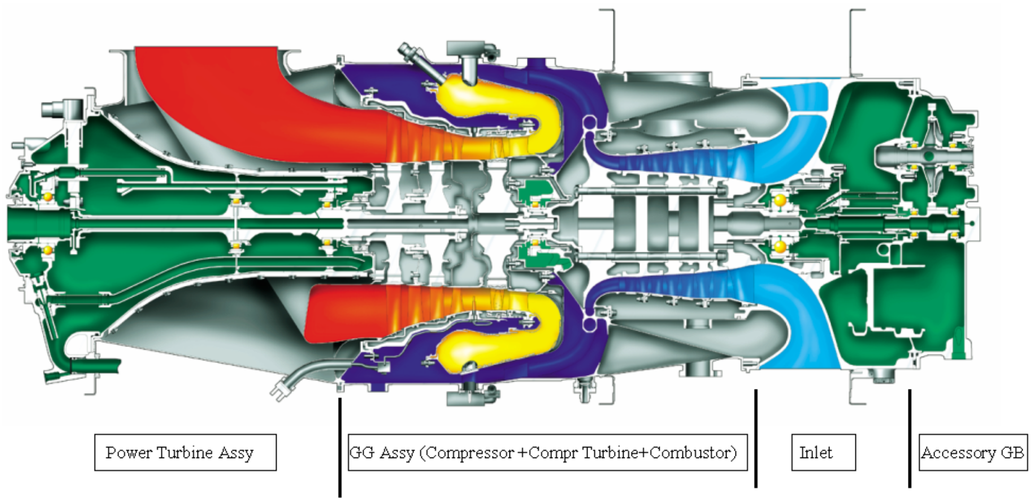


Figure 2- PT6C-67A engine Cross-section

PW200 Series Engines

PW200 ENGINE CONFIGURATION

The PW200 is a free turbine turboshaft engine intended primarily for twin engine installations. The engine features a radial inlet and a single-stage centrifugal compressor driven by a single-stage compressor (high pressure) turbine. The compressor air is admitted to a reverse flow annular combustion chamber. A single-stage free power turbine drives a reduction gearbox (RGB) comprising a two-stage helical gear train (6,000 rpm). The RGB housing also contains the accessory gear drives for airframe use and an integral oil tank. The engine power is modulated by a single channel digital electronic control system with a manual backup.

The PW209T, the first engine in the development series, became the PW205B after 3,140 test hours. The PW205B underwent extensive flight test work in a BO105LSB-1 helicopter to aid in the development of an electronic control for the new engine.

In 1989, McDonnell Douglas (now MDHI) selected the PW206A (with a TO rating of 640 SHP) for the *MD Explorer*; in 1990, Eurocopter chose the PW206B (TO = 621 SHP) for the BO108 (now EC135); and in 1995 Agusta selected the PW206C for the A109 *Power* (TO = 640 SHP). All three engines share the same gas generator module. The PW206B reduction gearbox differs to match the helicopter installation.

The PW207 engine is a recent addition to the PW200 series. The PW207D, selected to power the Bell M427 light-twin helicopter, was certified in 1998 (TO = 710 SHP), the PW207E and PW206B2 were selected as the growth engines for the MDHI *MD Explorer* (TO = 710 SHP) and the Eurocopter EC135 (TO = 621 SHP) respectively, and the PW207K was chosen to power the Kazan *Ansat* (TO = 710 SHP). The engine delivers increased power through component and material improvements, and by offering the conventional 2.5-minute or 30-second one engine Inoperative (OEI) rating structure. This engine also features compressor casing treatment for enhanced handling capability.

PW200 SERIES POWER GROWTH

After reviewing the engine availability of Turboshaft engines in the market place, PWC have decided to make available a new family of Turboshaft engines, the PW210. The new family of engine would be available in the 1000 to 1200 shp range and would have competitive SFC and power to weight with traditional PWC durability of 3500hrs TBO and target 10,000 cycles on LCF components. The engine is adaptable to fit both single and twin configurations

The design base for the engine draws on PW200 series, which is the best in class for light single and light twins applications. Also technology and lean principles used on the PW600 turbofan, the new family of small Turbofan entering into service with the very light jet class of aircraft, were incorporated to achieve the design goal for performance and cost.

The engine has a radial intake feeding two-stage compressor. Traditional pipe diffusers turn the compressed air into an effusion-cooled combustor to maximise performance and minimize emissions. Fuel is injected via primary and secondary nozzles controlled by an ecology flow divider. The single stage compressor turbine has single crystal blades with a high strength disc. Oil services for the CT turbine bearing cavity are routed through compressor delivery air as on the PW200 series allowing for rapid shutdowns if required.

The AGB is clustered at the top of the engine RGB module to provide easy access of the Line Replaceable Units (LRUs). Optional drives for Air Cooled Oil Cooler (ACOC) and a/c generator are available. The ACOC is driven from the high rotor allowing for APU mode operation with a rotor lock. A Fuel Oil Heat Exchanger (FOHE) also located at the top of the engine is available as an option for fuel de-icing. The output shaft has a phase shift torque shaft similar to the PW200 series of engines. The front cover is machined from solid allowing different optional configurations to be selected. With small changes within the basic concept of the gearbox both front and rear drives can be made available with an integral clutch. The oil system is self contained within the engine. The engine has one sight glass, which can be bolted to either side of the gearbox for easy visual maintenance check without "handing" the engine. Chip detectors are compatible with Fuzz Burners.

Initial performance is based on a 30 Second Rating OEI structure; a 2.5 min OEI structure is also available. Growths to 1200 SHP are available within the same frame size and will follow the growth path that the PW200 has demonstrated.

The control system builds on the turbofan and turboprop dual channel FADEC existing knowledge base which has given millions hours of field service. The FADEC and software will meet all of the latest certification regulations. The dual channel control concept allows for the removal of any back-up manual mode mechanical linkages, reducing a/c weight and cost. Dual channel FADEC systems further reduce pilot workload (no need for a manual mode training as with single channel systems with manual mode back-up), and eliminate the need for rigging maintenance at the fuel control interface.

The engine has boroscope access, which together with guide tubes can provide inspection of gearbox, compressors, combustor and turbines. There is no Hot Section Inspection requirement.. Both run time and LCF actual usage is calculated by the FADEC and stored in the engine mounted DCU.

PW100 Power Growth

PW100 ENGINE CONFIGURATION

The PW127T/S turboshaft engine (figure 3) is a derivative of the well-established PW100 turboprop family, which will offer safe economical operation, reliability and dependability and high power ratings for heavy weight multi purpose twin-engine helicopters.

The engine is being designed to power the new 30 passenger's Mil helicopter - MI-38 (figure 4), with a Take Off power of 2500 SHP and 30 sec OEI of 3697 SHP.

This new engine with common core of turboprop engines benefits from of 105 million hours of PW100 services. This family of turboprop engines is the leading regional airline powerplant in operating economics, reliability and durability, regularly achieving on-wing times of over 12,000 hours, an exceptional achievement considering its operation on flights normally less than one hour. The PW100 Series make up the family with over 4,800 engines delivered to date.

The PW127T/S engine is a free turbine turboshaft engine with electric starting, two module configuration - the direct drive and turbomachine.

Two spool turbomachine incorporating rugged twin centrifugal compressors with no variable geometry or interstage bearings for low complexity, two-stage «free» turbine directly driving the output shaft.

The PW127T/S also incorporates a dual channel, full authority digital electronic control (FADEC) system with state of the art diagnostics capability.

Main engine accessories are conveniently located on the top of the engine for accessibility and maintenance in twin installation.

Figure 3- PW127 T/S Engine

Figure 4- Mi 38 Helicopter

PW100 SERIES POWER GROWTH

The PW150T/S (figure 5) is a free turbine, turboshaft that is the latest derivative of the PW150 turboprop, it will offer safe economical operation, reliability and dependability and high power ratings (5000 SHP class) for heavy weight multi purpose twin & multi-engine helicopters

The PW150/TS is a derivative of the PW150A turbopropeller engine that entered service in the year 2000 on the Dash8-400 aircraft. The PW150A is modern turboprop engine designed by P&WC and certified on June 24, 1998. The general configuration follows a three-shaft layout, inherited from the PW100 engine family.

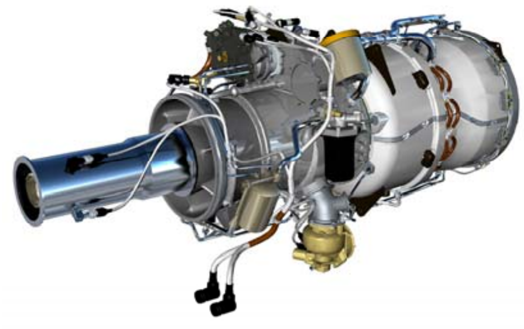


Figure 5- PW150T/S Engine

The two-spool gas generator section features a three stage axial low pressure and single stage centrifugal high pressure compressor on independent shafts, each driven by single stage axial turbines. The combustor is a reverse flow annular configuration.

The power turbine (free turbine) is an uncooled two stage axial design, which drives the rotor transmission via a Torque Shaft, supported by four bearings for resonant free shaft dynamic characteristics.

The PW150T/S also incorporates a dual channel, full authority digital electronic control (FADEC) system with state of the art diagnostics capability.

The main engine accessories are conveniently located on the top of the engine for accessibility and maintenance in a twin or multi-engine installation.

Compressor Technology

AERODYNAMIC

The Pratt & Whitney Canada Compressor technology program has contributed significantly to the recent advancements that have allowed P&WC to create exciting new products in the small and medium size turboshaft engines. Our highly focused research program is designed to further enhance the competitive position and create new concepts to meet future market demands. The emphasis of the future technology plan is in the following key areas:

- Optimized 3D airfoil design
- High fidelity analysis with interaction
- Leakage reduction
- Surge margin management

The high pressure ratio single-stage centrifugal compressor for the PW200 series engines has evolved and improved over the years to produce a compact and high efficiency compressor module which has utilized 3D transonic design to produce high pressure ratio while maintaining high efficiency.

In PW 200 engines, flow is induced into the compressor through a carefully designed inlet scroll, which provides benefits of excellent flow uniformity, lower total pressure loss and protection from foreign objects. The transonic impeller inlet mates with a large backswept exducer. The large backswept impeller design has proven to give superior surge margin. A combination of full and partial blades improves the compressor work as axial flow progresses into the radial direction at the same time the impeller losses are reduced.

The impeller rotor is coupled with a compact high recovery pipe diffuser, which was first introduced on the PT6 and refined in PW200 rig tests. The elliptical leading edges resulting from the diffuser bore intersections generate an ideal semi-vaneless space for the high Mach number flow exiting the impeller. Light sheet metal trumpets direct and diffuse the flow further prior to entering the combustion system. Both impeller and diffuser performance have been enhanced with three dimensional (3D) time dependent viscous analysis.

Neither variable geometry nor bleed flow is used to guarantee fast acceleration and surge-free operation with low production and operation cost. P&WC patented casing treatment design on the impeller housing assures compressor operability and performance. The casing treatment is maintenance-free. All the new design of components were tested on the rig first and engine before they are incorporated into production engines.

PW210 compressor is a derivative of PW600 turbo fan family engine. The compressor has one mixed flow stage and one centrifugal stage. The compressor is designed with latest CFD code from CFX. The code simulates multistage 3D flow with bleed cavity included. All the components were designed to take advantage of optimised 3D aero shape to achieve high efficiency.

STRUCTURE

Structural analysis on early turboshaft engines began with two-dimensional (2-D) analysis of each individual component. This was followed by a 2-D investigation of the full assembly (figure 6). Today, analyses are performed for the complete compressor assembly with 3-D finite element codes (figure 7). Temperature distributions are obtained from both steady state and transient thermal analyses. The complete compressor assembly is analyzed over the customer-defined mission cycles to study the changes in tip clearances that correspond to changes in centrifugal and thermal loads. Compressor geometry is optimized to give the best low cycle Fatigue (LCF) life, while satisfying often-conflicting dynamic, aerodynamic and weight requirements. The predicted LCF life is substantiated by thorough spin-pit testing, while rotor forgings are continuously monitored for the required quality.

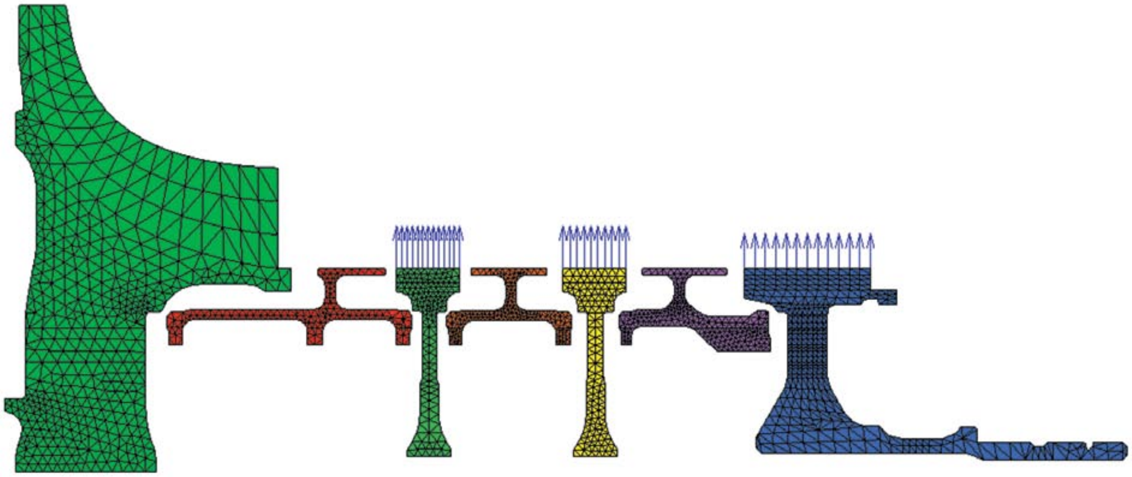


Figure 6- 2-D Finite Element (FE) of PT6T-3D Compressor

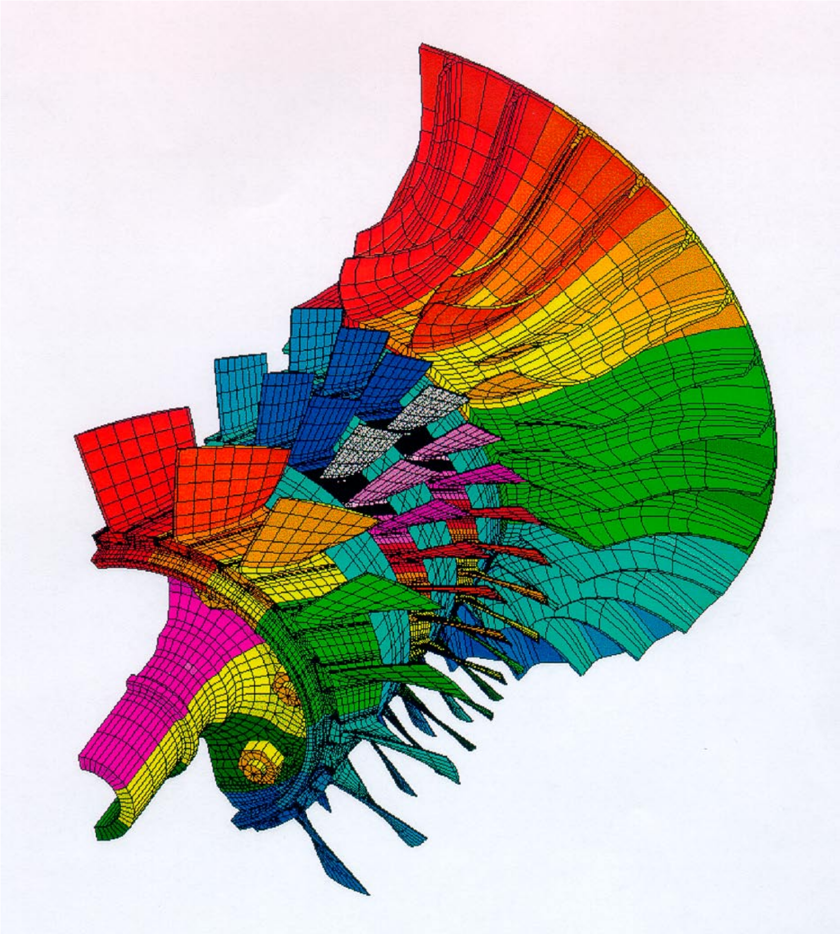


Figure 7- 3-D Finite Element (FE) Model of PT6T-3D Compressor

Combustion Technologies

Demands for small gas turbine combustion technologies from the market place continue to evolve; these have resulted in advancements of design and manufacturing processes and tools to reduce design lead times and improve quality of first designs. Market feedback analysis and controlled engine/rig tests have been successfully used to validate new design processes and tools. New combustor technologies are addressing need for low emissions and high reliability as well as low cost manufacturing methods.

Combustion technologies have kept pace with the requirements from engines for better performance and reliability. These include high temperature rise combustion, high altitude applications, low emissions minimizing tradeoffs in operability/performance, and improved understanding of combustion dynamics issues. Materials and coating advancements as well as advancements in combustor construction methods have advanced combustion system reliability to match those of larger engines. Operability challenges, especially with low emission combustion designs, have required innovative solutions involving both the air and fuel systems of the engine. Future challenges will continue to emphasize on compact combustion systems, and higher levels of reliability with continued emphasis on lower ownership cost.

Small engine combustion systems, including those on turboshafts, turboprops and small turbofans all have unique issues distinct from those with larger engines. Although the general requirements for a small turbine engine are similar to its larger counterpart, there are significant differences imposed by geometric scale render achieving these requirements more difficult with smaller engines. The flow geometry of many small engines include centrifugal final compressor stages and the most common combustor geometry embodies reverse flow combustors whereas large engines use axial flow annular combustors. While problems resulting from combustion kinetics are similar to larger combustion systems, aerodynamic and manufacturing problems arising from the smaller sizes are distinct. For example, the surface to volume ratios of small engine combustors are in the range of 10 – 15 ft^{-1}, whereas those from larger engines are much smaller (5-10) ft. $^{-1}$), resulting in increased wall quenching of combustion reactions at low powers such as idle. The larger surface areas of small reverse flow annular combustors will require proportionally more cooling air and less air available for tailoring emissions or exit temperature quality. Also the air flows of small engine combustors typically require smaller sizes of orifices (or holes) in liner walls, and the ability of machining or drilling orifices does not scale down in size, and this can cause more variation in air flow distribution and hence performance/emissions from smaller combustors.

The combustion systems for the PT6 and PW200 turboshaft engines represent compact combustor design, integrated with fuel injection systems that meet the needs of the application. The PT6 engines have reverse flow annular combustors with either all sheet metal or partially machined liner construction, depending on the temperature requirements. PW200 series also has reverse flow annular combustors with partially machined liner geometry to suit the demand for durability by means of accurate airflow control.

Thermal barrier coatings (TBC) are used to provide oxidation protection to liner walls where required. Fuel injectors include pressure atomizing nozzles and air assisted simplex or duplex injectors.

The performance demands from the combustion system include:

- ☐ Combustion efficiencies exceeding 99.5 per cent over most of the engine operating range,
- ☐ Exit conditions of air pressure, temperature and swirl matching turbine entry requirements,
- ☐ Cold start capability down to -45° C,
- ☐ Low (single digit) exhaust smoke levels, and
- ☐ Acceptable flameout and relight margins.

Combustor Design Process Evolution

The design process used for combustion systems must address the dual requirements of meeting manufacturability and engineering requirements of the product. In the past, the practice often was the engineering definition of a product to meet customer requirements without full consideration of manufacturability. Now the situation has changed where manufacturability and cost issues take equal emphasis as engineering issues are addressed concurrently and right decisions are taken to ensure Quality of First Design. Quality of First Design also requires clear definition of risks in a potential design, elimination of high risk areas and having risk mitigation plan for the rest. Market Feedback Analysis (MFA) and lessons learned are critically important in delineating the risks and taking corrective action early in the design cycle. Risk mitigation often requires institution of validation programs early in the product definition phase and where considered essential, providing for a back-up design. Research on a new design feature should be completed upfront or ahead of incorporation into product.

Advanced combustor modeling has contributed to improving quality of first design; these include Computational Fluid Dynamics (CFD), thermal and structural modeling; key performance requirements benefiting from modeling are pressure drop, internal flow paths, exit temperature uniformity, smoke and NOx emissions, wall temperatures and durability (Figures 8 & 9).

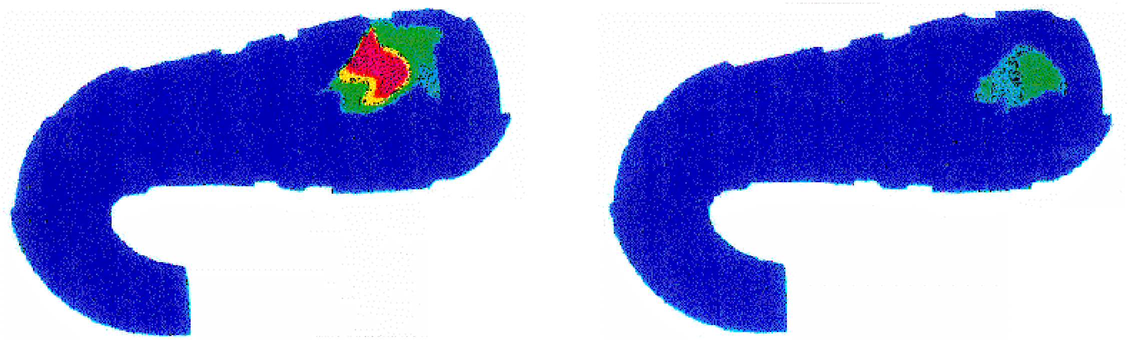


Figure 8: 3-D Modeling of PW206 Enables Accurate Prediction of Combustor Exhaust Smoke

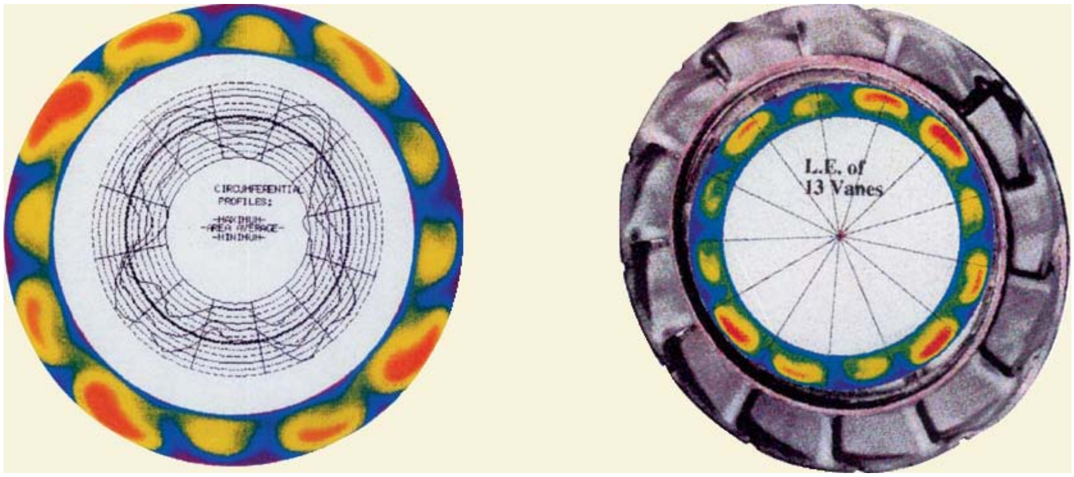


Figure 9: Comparison of Measured and CFD Predicted CFD Predicted Temperature Pattern at PW206 Temperature Field at Turbine Entry Plane Vane Leading Edge

The demands for low smoke emissions have been met by using 3-D numerical tools in combustor analysis, for which P&WC is a world leader. Ultra low smoke levels have been demonstrated on the new PT6C-67 combustor without resorting to any rig test work. Advanced numerical modeling is also being used in predicting and optimizing combustor exit conditions to match the requirements of the turbine. The fuel injection systems for environmentally friendly (green) engines must ensure good atomization and air mixing in the early part of the combustion process. This is being achieved on the PW206 and the latest PT6 engine models by the use of advanced radial air swirlers integrated with the fuel nozzles. Technology for ultra low NOx emissions in the engine exhaust is currently under development for future applications to P&WC engines.

Turbine Technology

AERODYNAMICS

The first of the PT6 family of turboshaft engines was the PT6T-3 Twin-Pac®, certified in 1970. It was also the first PT6 engine to incorporate cooled turbine vanes. Vane cooling permitted higher operating temperatures and hence thermodynamic horsepower while maintaining metal temperatures below those of earlier PT6 engines.

The late 1990s saw the latest PT6T-3-DF turbine section upgrade. Airfoils were designed using the latest 3-D multi-stage viscous analysis methods and low thermal expansion housing materials. These turbine efficiency improvements, coupled with advanced cooling design methods, enabled significant increases in thermal power ratings.

The late 1990s also saw the launch of a new large PT6 turboshaft engine family, the PT6C-67 series. The three initial models featured a single-stage compressor turbine followed by a two-stage power turbine. While derived from the PT6A-67D engine, the turbines were redesigned for each model using state-of-the-art turbine technology.

The PW200 series turbines feature a single-stage compressor with cooled vane followed by an uncooled counter-rotating single-stage power turbine. The first production engine, the PW206A, was certified in 1991 and featured 3-D inviscid single-stage aerodynamic analyses of the turbine. Current numerical advances have enabled the PW207 turbine to be supported by a full 3-D multi-stage viscous analysis including the exhaust duct (figure 10).

Research on optimal airfoil loading as well as more accurate prediction of combustor exit conditions have enabled airfoil aerodynamic loading of compressor turbine vanes to be increased to levels similar to downstream airfoils. The compressor turbine vane count was reduced from 17 to 13 on the PW206A resulting in lower cost and weight. Engine tests showed no deterioration in performance.

A demonstrator program aimed at PW207 growth was conducted in the mid 1990s. It featured a turbine designed for increased turbine inlet temperature using a cooled blade without a cover plate and the addition of showerhead cooling on the first vane. This was the first high-temperature demonstrator engine having an equal number of fuel nozzles and first vanes to allow alignment (clocking) of combustor hot streaks with cooled vane leading edges. The engine ran successfully and included a thermal paint test in the clocked condition to evaluate metal temperature levels on the first three airfoils and gaspath surfaces.

In 2005, the PW210 engine was launched incorporating the lessons learned from the PW207 demonstrator plus technologies derived from PWC's advanced turbofan engines. The PW210 features a single stage high work compressor turbine followed by a two-stage power turbine designed to deliver large efficiency improvements over the entire power range. The turbines were designed using 3-D multi-stage viscous analysis and the latest developments in airfoil and gaspath contouring and static pressure equalization. Advanced sealing methods have been employed throughout the turbines to minimize leakages and gaspath/cavity interactions.

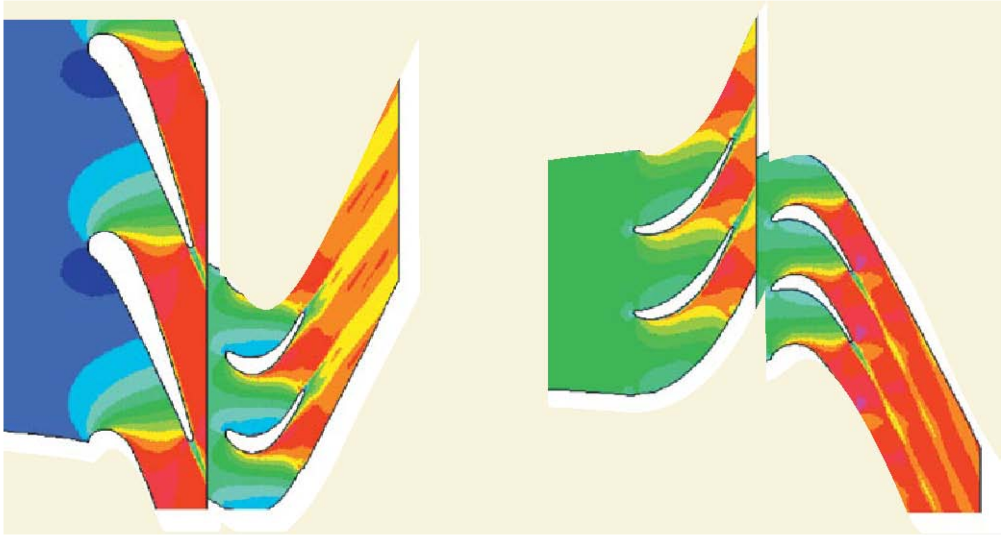


Figure 10- 3-D Multi-Stage Viscous Analysis for the PW207 Turbines.

STRUCTURE

The oldest family of P&WC turboshaft engines has evolved from the small PT6A series. Over time, the turbine rotors have been enhanced with constantly improving material technology. From the polycrystalline IN-100 airfoil, followed by directionally solidified, first-second-and third-generation single crystal superalloys, material selection has been the prominent means of evolution and adaptation for P&WC's turbine structures.

The PW200 series was designed using 3-D analytical tools and was supported by years of knowledge and experience with turbine material. The combined effect resulted in an optimized design with very efficient use of materials and without compromise on reliability. The latest models, such as the PW207D, benefit from the third generation of single crystal superalloy for the compressor turbine blade.

The PT6C family of engines was derived from the PT6A-67D turboprop application, known for its reliability. The new twin power turbines were redesigned using state-of-the-art computer technology to be optimized for low altitude operation. Like all P&WC power turbines, there is an inherent fail-safe mechanism in which airfoil release prevents uncontrolled overspeed of the power turbine disc. New technologies were also used for the design of the compressor turbine blade, where a high work airfoil sits on a cheveron platform (figure 11).

The PW210 series introduced powder metallurgy disc alloys to allow higher rotational speeds and this increased efficiency and power to weight ratios without any life penalties.

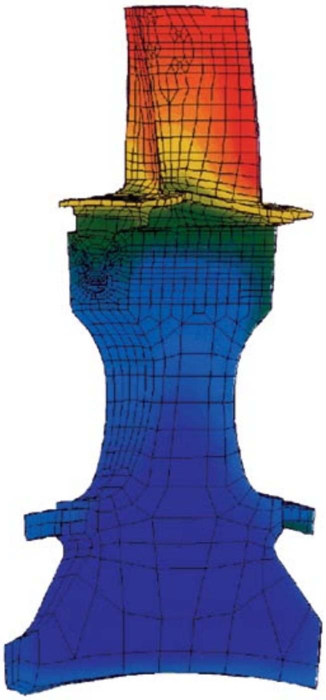


Figure 11- PT6C-67C Cheveron-Type Compressor Turbine Blade and Disc-Transient Thermal Analysis.

Systems & Structures Technology

SYSTEMS

Improvements in air and oil systems have been achieved through research and concept development, which have led to enhancement in analysis capability. Air/oil system analysis has been integrated with the use of computational fluid dynamics and two-phase flow predictions for system elements.

Turbine blade platform rim seals have been introduced to limit the air required for turbine disc cavity purging and cooling. Where possible, air bleeds have been used to minimize non-usable consumption; for example, to cool a component and, subsequently, to seal a bearing chamber. The use of non-contacting carbon seals in critical locations to replace labyrinth seals has reduced non-usable air consumption through the breather (engine air/oil separator) and has therefore diminished the amount of heat rejected to the oil and the oil consumption. Heat rejection has also been reduced by insulating bearing chambers and eliminating spurious heat sources, so much so that in one instance the engine air cooled oil cooler was replaced by a fuel-cooled oil cooler. A hydro-pad face seal has also been used to seal a power shaft where air was unavailable for buffering.

On turboshaft engines that include reduction gearboxes, engine layout changes have permitted the elimination of multiple oil systems, saving weight, component numbers and complexity. Oil systems regulated by flow, rather than pressure, have been introduced to reduce pump, cooler and filter size requirements. Whenever possible, scavenge pumps have been eliminated completely by the use of pressure blow-down scavenging combined with oil shut-off mechanisms to prevent flooding during engine starts.

STRUCTURE

For structural containment, advanced non-linear transient dynamic finite element methods are used on turbo-shaft engines to design the relative containment behavior of casings in blade release scenarios. Such methods permit accurate predictions of containment fragment trajectories and the resulting behavior of the structural casings. This leads to lighter, more reliable designs.

Considerable advances have also been made in tip clearance prediction between the rotors and structural casings. Clearances, and the resultant efficiency losses over the tips of airfoils, must be accurately predicted and carefully controlled throughout the entire engine mission because the impact on the overall engine performance can be significant, particularly for the compressor turbine rotor. In recent years, techniques have evolved from 2-D axi-symmetric FE models to complex 3-D FE models (figure 12) to transient thermal and structural models. Also, engine internal transient aerodynamic effects, such as surge, are assessed and included in the optimization of the internal engine structure and stiffness to minimize their effects on rotor tip clearances and engine performance.

With today’s tools, it is possible to analytically examine 3-D effects such as shroud segment curling and the resulting stress transferred to the shroud housing. It is also possible to assess the effects of an uneven circumferential temperature distribution in the gas path on the shroud housing or to include the effects of radiation heat transfer from surrounding hardware. Many of the calculations are fully automated, and the turn-around time for a complex 3-D transient analysis is a matter of weeks, rather than months. The turnaround time is moving toward days as computing capability increases.

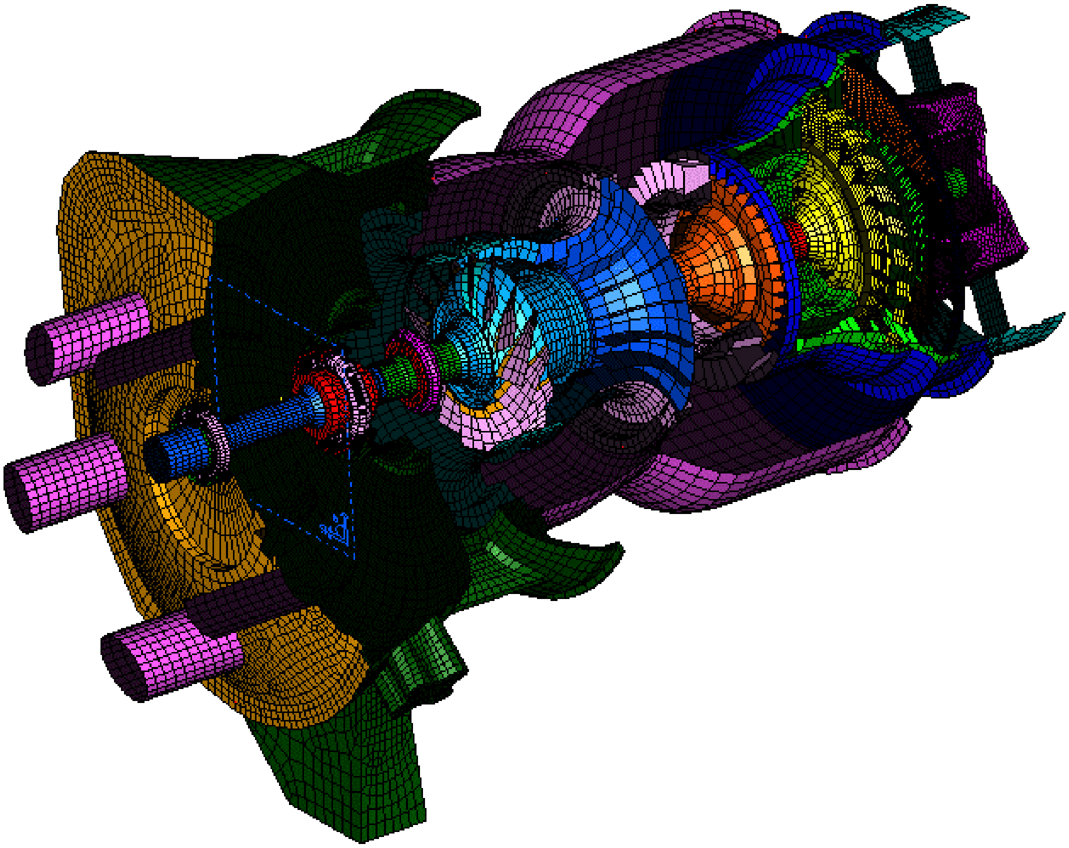


Figure 12- Full Engine Model for Shaft Shear Analysis

Installations Technology

The air induction system of P&WC turboshaft installations has not changed considerably since the PT6T Twin Pac®. The airframe inlet is characterized by either a forward-facing scoop type inlet or, in more recent applications, by side-facing inlets flush with the helicopter cowling. From the airframe inlet the air flows into a plenum and is subsequently directed radially inward to the engine. Additionally, an inertial particle separator (IPS), or filter pack, may be fitted to provide protection against ice, sand and debris. The engine is protected from foreign object damage (FOD) by a wire-mesh intake screen.

P&WC turboshaft engines offer a number of exhaust configurations. The "ski jump" diffuser has evolved from very early PT6 exhaust scrolls to better control diffusion of the turbine exit flow. The PT6C series engines are equipped with a continuous surface swept duct. The exhausts are denoted either as c-shaped or s-shaped depending on the position of the power turbine. The PW200 series engines are configured with a conventional straight exhaust duct.

The exhaust flow may be utilized as an ejector to drive the scavenge flow through the IPS. Alternatively, the exhaust may be used as an ejector to ensure adequate engine compartment ventilation and cooling.

Aerodynamic analysis methods have advanced dramatically since the early P&WC turboshaft engines. Today, the exhaust system loft lines are designed using fully three-dimensional viscous flow analyses to minimize pressure losses and maximize pressure recovery. The optimization process is completed without the need to undertake rig tests. The same numerical tools are applied to provide guidance in the design of rotorcraft air induction systems.

Gearbox & Bearing Technology

P&WC has two families of turboshaft engines with reduction gearboxes: the PW200 and the PT6T engine families.

The Twin-Pac® (PT6T) reduction gearbox is used both to reduce the power turbine speed to a speed suitable for helicopter operation and to combine the output of two identical turbomachines into a single output. This is done by means of two stages of gear reduction, utilizing offset spur and helical gears with an idler gear, for a reduction ratio of 5.0:1. The input speed of 33,000 rpm is reduced to 16,500 rpm at the clutch gear, and the second stage further reduces the speed to 6,600 rpm. The gearbox is rated for up to 1,875 SHP. 3D FE model is shown in figure 13.

The Twin-Pac® gearbox includes a clutch arrangement that allows the power sections to drive the aircraft's main transmission and prevents the main rotor from driving the engine. In addition, the clutch disconnects one power section from the other in the event of an engine malfunction and also allows for the possibility of auto-rotation.

The PW200 series has a two-stage reduction gearbox available in two configurations: with an output shaft that is co-linear with the engine axis or with one that is angled at 28° upward to suit the aircraft transmission installation (Pw206B/B2). The PW206A reduction gearbox has a two-stage helical type reduction geartrain, which reduces the power turbine output speed of 39,800 rpm to an output shaft speed of 6,030 rpm (6.6:1 reduction ratio). The PW206B/ B2 angled gearbox also has a reduction ratio of 6.6:1 with a spur gear first stage and bevel gears in the second stage to provide the change in angle on the output shaft. Both gearboxes have a phase shift torquemeter, which uses the output shaft twist for torque measurement.

The Twin-Pac® gearbox was used as part of the development and calibration of the FE modeling technique for the complete geartrain (figure 14). The FE model included seven main reduction gears, seven drive shafts, three housings and 16 bearings. In all, there were 39 subsystems modeled for 600,000 degrees of freedom. This detailed FE analysis has provided a means to increase the capacity of the Twin-Pac® gearbox and provide opportunity for improved reliability without major design changes.

The gear designs of the PW200 gearboxes have also benefited from the latest technology in 3-D finite element gear tooth contact analysis (FEA). This technology was applied to the helical gear design, and the FE analysis of the bevel gear web distortion was combined with an in-house method for the design of the bevel gears. The benefit from this advanced technology allowed to maximizing the power to weight ratio in PW210.

Bearings for all P&WC turboshaft engines are designed in-house using state-of-the-art techniques. Gas turbine bearings operate under severe conditions and the PT6 and PW200 bearings are no exception with speeds up to 2.6 x E06 DN (bore diameter in mm x rpm). P&WC bearing designs address all aspects of their operation including skidding, skewing, thermal distortions, lubrication and internal stresses. Extensive field experience has been used to calibrate the bearing design methods to ensure their reliability, achieving expected life.

The PW200 gearbox was designed for ease maintenance and accessibility with high level of integration between the various components and sub-systems. This resulted in a very compact layout with an integral oil system.

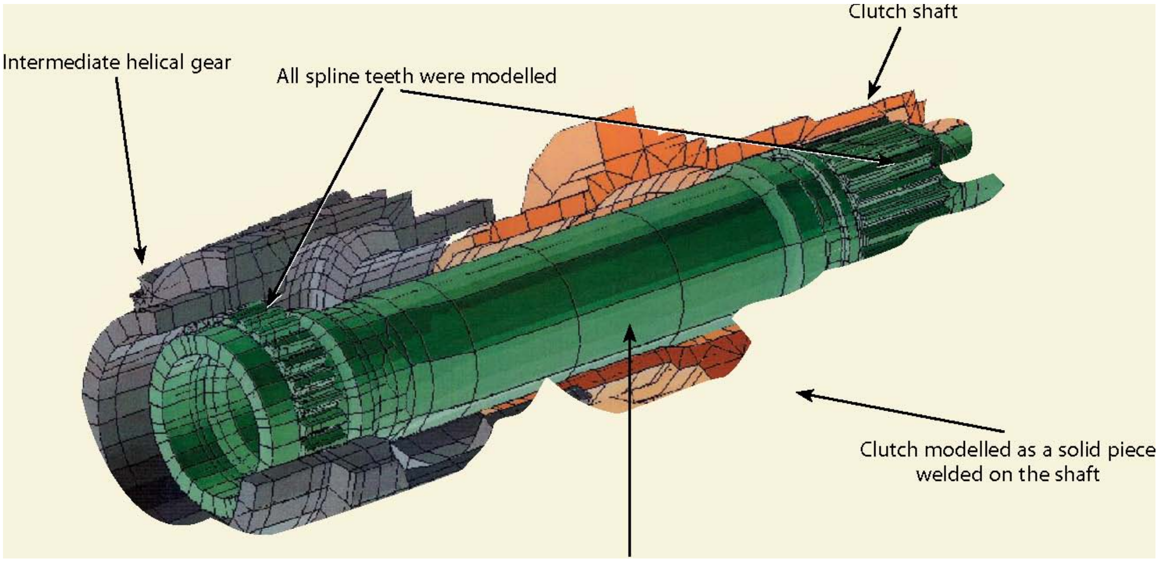


Figure 13- PT6T-3D Shaft 3D FE Model

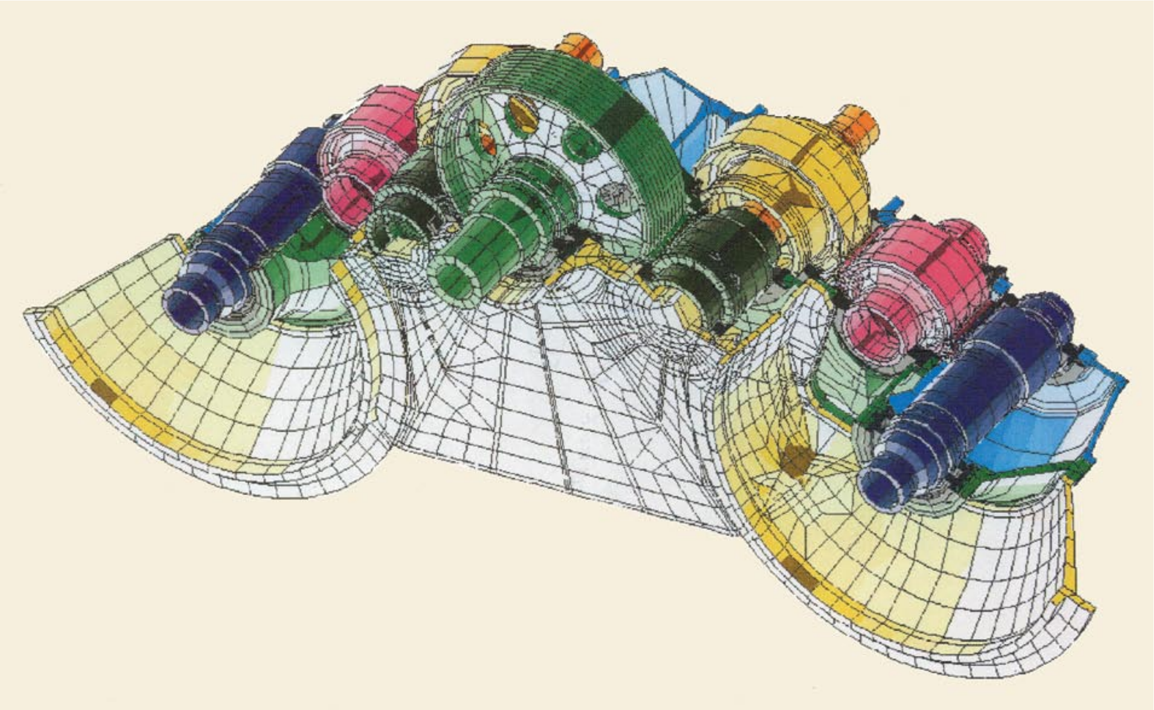


Figure 14- PT6T-3D Complete RGB 3D FE Model

Control Systems Technology

P&WC's initial foray into helicopter control systems more than a quarter of a century ago made extensive use of hydro-mechanical technologies. PT6T turboshaft engine control systems are based on the Wf/P3 control used on all low-power PT6 turboprop engines. Features have been added to meet the demands of helicopter operation. The system currently comprises a gas generator speed (Ng) governor, free power turbine (Nf) governor and a backup manual fuel control.

The Ng governor is a mechanical spring-loaded flyweight based proportional governor that provides accel limiting matched to the compressor characteristic, decel limiting, minimum flow setting and steady state governing. Governing is achieved by modulation of gas generator pressure in the bellows of the metering valve. Varying the throttle position varies the spring load on the governor. In normal flight operation, the throttle is set to the normal maximum fuel flow position. The Nf governor trims this input by overcoming the Ng governor spring load to allow modulation between idle and maximum power.

Like the Ng governor, the Nf governor is a proportional flyweight governor. Through a spring loaded flapper, the Nf governor adjusts a gas generator derived air pressure used to modulate a plunger and hence spring force in the Ng governor load path. The Nf governor is set to maintain 100 per cent rotor speed by this modulation of fuel flow through the Ng governor.

The manual fuel control provides a backup to the main Ng governor in the case of degradation. Through a separate input, the pilot modulates fuel flow directly by acting on a fuel metering valve. It should be noted that there is no feedback from the engine and there are no governor set-points.

These hydro-mechanical systems gave way to P&WC's first dual-channel electronic engine control (EEC) on the PT6B-36 engine conceived in the early 1980s. To match customer requirements, this system has a limited capability back-up system in the hydro-mechanical unit (HMU), making it, in effect, a three-channel system. The electronic channels are not full authority, being bounded by the fuel schedules in the HMU. However, they have sufficient authority to take advantage of the electronics to govern the gas generator speed and the rotor speed, to command starting and to provide limiting on rate of change of parameters during transients. The electronics sense collective lever position and can anticipate load changes. Through engine-to-engine cross talk, load matching is achieved. Overspeed limiting of the engine rotors is also incorporated. Very precise control of the rotor is achieved through isochronous governing.

The PW200 family incorporates a single-channel EEC that controls fuel flow through input to a hydromechanical fuel control device (Fuel Metering Unit [FMU] or Fuel management module [FMM], depending on the specific engine model). The FMU uses a stepper motor interface, while the FMM uses a torque motor interface. Both types of fuel control provide full capability manual back up in the event of EEC degradation. Most functions of the PT6B-36 control system have been incorporated into the PW200 system. To cope with the rapid response requirements of modern low inertia rotors, advances in accel request and accel tracking algorithms have been made. In addition, enhanced training mode features have been added to allow one engine Inoperative (OEI) simulation with both engines operating above idle. Fault accommodation, display and logging have also made significant strides. The PW200 features an engine-mounted data collection Unit (DCU) that is used to record faults, exceedances and mission data, such as low cycle Fatigue (LCF) counts.

The PW200 control system temperature limiting and precise power management have allowed P&WC to offer enhanced OEI ratings including the recently approved 30sec/2min. maximum OEI ratings. These ratings supplant the earlier 2 1/2 min. rating and allow a significantly higher power delivery during the critical cat A take off transition period should a loss of power from the opposite engine occur.

Today PWC is developing the control systems for the PW210 and PT6C-67E engines with dual channel FADEC's without the mechanical back up provision. PWC is leveraging the extensive work on the turbofan systems over the past 15 years. One significant contributor is the ease by which the fully electronic system adapts to various airframes. Essentially the hardware of the system is independent from the OEM and the Interface Control Document concentrates on the digital communication with the avionics. There is one significant variation as compared to the majority of our experience from the turbofans. The system is designed with added flexibility such that in the event of a complete dual channel electronic failure the system can either fail to an engine shut down state, like most turbofans or it can fail fixed at the last commanded fuel flow. It is envisioned that the latter being used for single engine applications whereas the information indicates that with the complete loss of electronic control and displays the majority of the multi engine applications will elect to have the engine secured by being shut down.

This summary would not be complete without a discussion on the process modifications that have taken place over the past 25 years. At that time the majority of the electronic components were military specified and qualified. This significantly drove cost due to the limited parts available, system complexity. In the 1980's PWC electronic controls began using commercially available components that were up-screened to be used in aerospace. The rapid increase in both the reliability and complexity of today's automotive industry electronic systems has generated a new generation of commercially available electronic components that are designed to comply with the aerospace environment. This allows for the use of improved commercially available software design and simulation tools. The result is that the software design time cycle is improved and software issues are found earlier in the design cycle. The newer electronics have orders of magnitude higher levels of integration; therefore the overall the parts count is significantly reduced. This results in improved cost, weight and improved reliability.

Today's aircraft have very integrated systems; with the ever advancing digital communication data available many systems share common sourced data. An example of this is the aircraft altitude signal. It is prime for most aircraft yet historically it has been very difficult to take full advantage of these signals. Another example is the abundance of electrical power available on most aircraft yet an independent engine supplied generator is required. These types of issues will slowly be challenged and resolved in the coming years as new aircraft are designed with ever increasing levels of integration. Good example of increased system integration where Transport Canada special conditions were required to enable certification of both the aircraft and engine is the PT6C-67A in the

BA609 tilt rotor aircraft. The design of the aircraft and engines is evolving at a faster pace than the regulations thus special conditions were appropriate to address these novel designs.

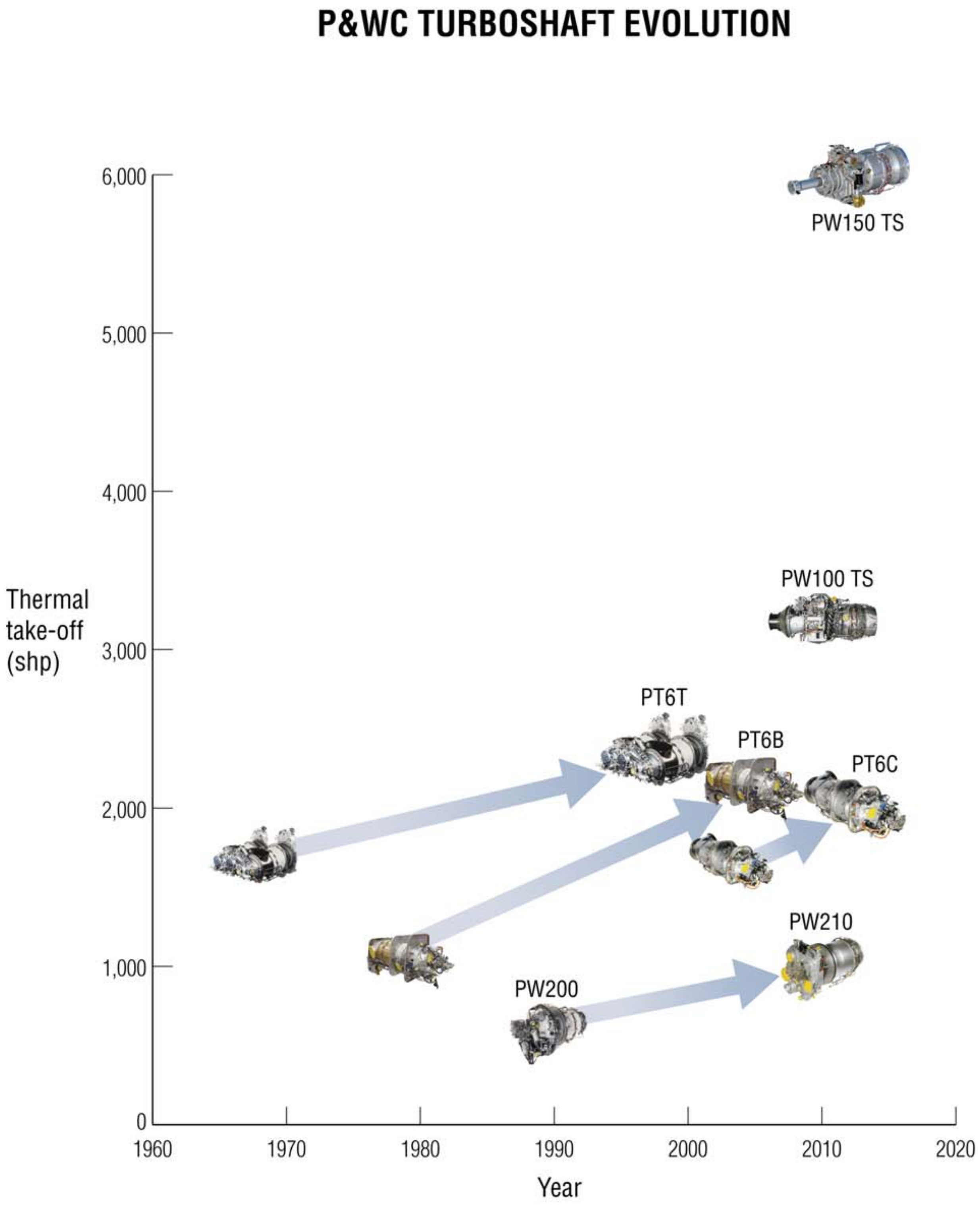
In the coming years the “line“ between engine and aircraft will become increasing more grey as both the airframers and engine manufactures strive for the best integrated package. Things like more electric aircraft and fully integrated engine/aircraft are coming.

Conclusion

The last 30 years has seen continuous technology development for turboshaft applications at P&WC, beginning initially with a derivative approach using the PT6 and more recently expanding into specialized configurations such as the PW200, which have been optimized for rotorcraft applications since their inception. New turboshaft design concepts are presently being explored at P&WC, and this trend of new product development for the rotorcraft market will continue well for many years (figure 16). These new products will expand the range of power output classes offered by P&WC as well as provide the most competitive levels of fuel consumption, weight and reliability. Turboshaft applications remain one of the most challenging and fascinating fields of aviation gas turbine technology development. Improvements in weight and specific fuel consumption have a very significant impact on the overall helicopter vehicle performance, and the prizes are high for the engine manufacturer that can yield such gains in its products. Compared to most fixed wing applications, the turboshaft engine must operate efficiently over a very wide spectrum of power. A lot of time and most of the fuel is spent cruising at around 60 per cent normal take-off power, but in emergency situations a turboshaft may be required to spool up to 120 per cent normal take off power within two to three seconds. Such requirements place a heavy emphasis on the operability of the engine and a deep understanding of technologies such as compressor stall margin, combustion stability, transient heat transfer and fatigue life limits. The requirement to operate efficiently at low power to minimize fuel burn is a particular challenge for turboshaft applications, which requires a good understanding of the off-design behaviour of key components. On the other hand, the requirement to have high power-to-weight ratio limits the complexity of the engine and pushes the requirements for high strength, high temperature materials along with efficient structural design.

A general conclusion on P&WC turboshaft technology would not be complete without mentioning the substantial role that systems technologies have played in its successful development. For example, the ability of the engine control system to maintain a stable rotor speed during manoeuvres is a major consideration in the handling qualities of the helicopter, and this has led to the fairly widespread application of electronic controls in recent years, even on smaller engines such as the PW200. levels of capability that were once the exclusive domain of the military are now becoming the norm in commercial applications. The turboshaft engine is possibly the most heavily integrated with the airframe of all powerplant types. In addition the management of other system technologies such as installation aerodynamics, structures and transmission are all equally vital to achieving a successful turboshaft power plant installation.

P&WC focus on the turboshaft technology is highlighted in figure 17. Fuel consumption and Technical Excellence will continue to be the key drivers for all technology programs. Technology strategy for the future will be focused on continuous improvement of design and manufacturing process and rapid technology deployment into engines. The environmental issues such as noise, and emissions reduction and elimination of hazardous waste will take more importance, particularly with aggressive regulatory requirements.



With its latest addition, the PW210, the PW200 engine family now competes in the 600 to 1,000 SHP class.

Figure 16- P&WC Turboshaft Evolution

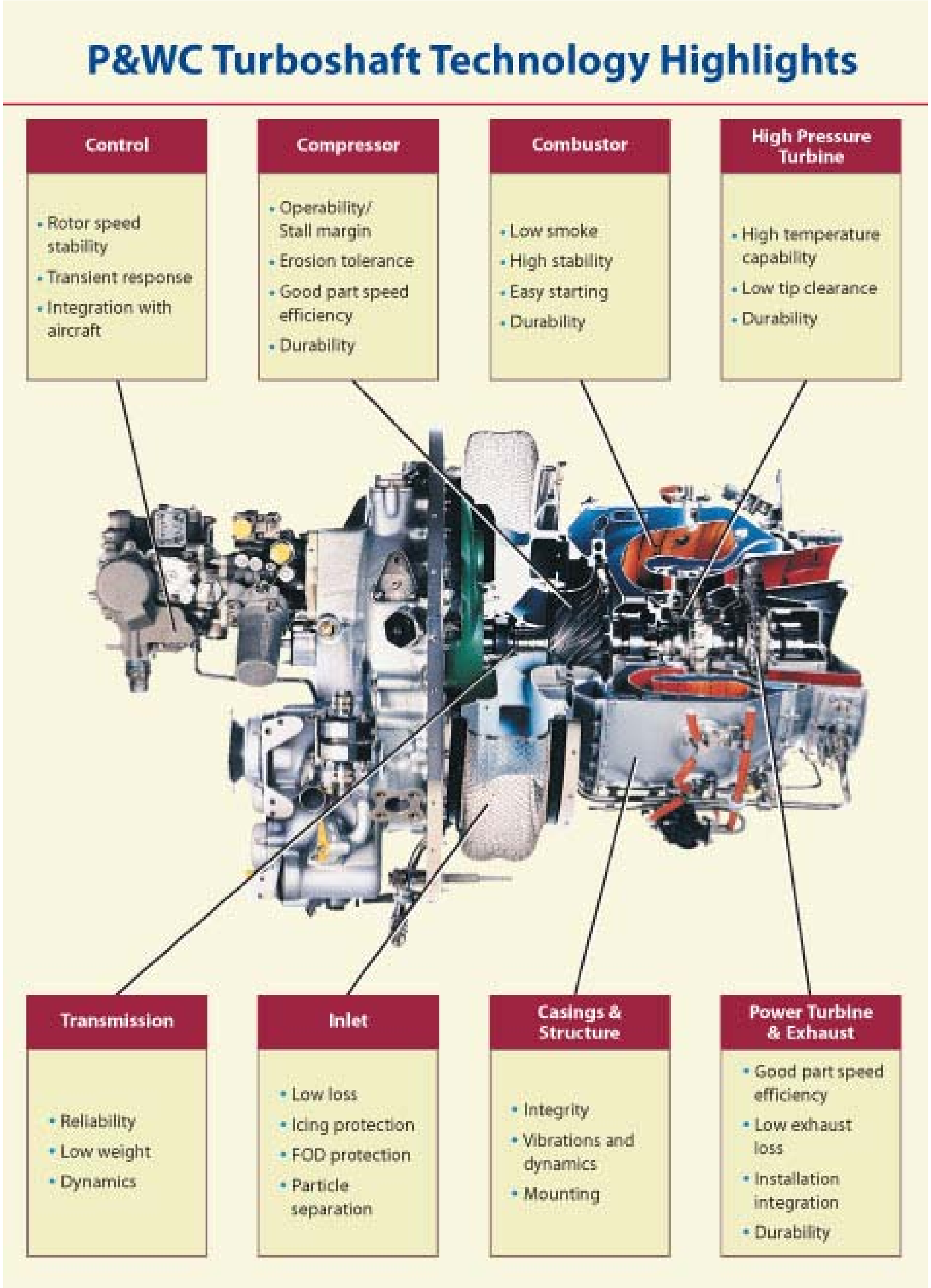


Figure 17- P&WC Turboshaft Technology Highlights

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