



WAVE ROTORS TECHNOLOGY AND APPLICATIONS

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ABSTRACT

This paper presents an overview of Wave Rotor technology and its most known applications. The Wave Rotors also known as Pressure Wave Machines or Pressure Exchangers, are unsteady-flow devices that can transfer energy directly between two fluids, by means of pressure waves (shock waves). In a wave rotor, two fluids with different pressures are brought into direct contact. Then pressure exchange occurs faster than mixing. The wave rotor can have a higher isentropic efficiency than steady-flow devices, like compressors or diffusers, but may be more challenging to control. In the past, because of the unsteady nature of the flow inside the wave rotor, process simulation was very inaccurate, time consuming and labor intensive. Recently, because of the increase in calculation power of the computers and more accurate commercially available software packages, significant progress was made in understanding the complex wave phenomena.

Among the most know applications of the Wave Rotor, the Comprex® Pressure Wave Supercharger developed in Switzerland for boosting the pressure in internal combustion engines has found its way into production. Several other research groups have been

working intensively on developing wave rotors for topping gas turbine, refrigeration or internal combustion cycles. At this time Michigan State University and University Transilvania of Braşov, together with partners like Indiana University Purdue University at Indianapolis, Warsaw University of Technology, ETH Zurich and Sherbrooke University are trying to develop wave rotor suitable for gas turbines at various scales and wave turbines (internal combustion wave rotors).

KEYWORDS:

wave rotor, shock waves, boundary conditions, pressure ratio, leakage

1 INTRODUCTION

Early experiments with the PE were made at the beginning of the 20th century by Knauff (1906), Burghard (1913) and Lebre (1928), but the first real application of a PWM was made by Claude Seippel (1940) of Brown Boveri Company (later Asea Brown Boveri), who used it as a high pressure stage for a gas turbine locomotive engine [2].

The best known industrial application of the wave rotor is the Pressure Wave Supercharger (PWS), which is an alternative pressure-boosting device to the more famous Turbocharger (TC). This type of

supercharger is more suitable for Diesel engines found on agricultural machines, light trucks, and passenger cars, but it can also be found on Spark Ignition (SI) engines.

Although extensive tests were made by the BBC from the late 40's until the 80's in order to develop the PWS, the real breakthrough came in 1986 when the Mazda Company introduced its Mazda 626 Cappela model, which had a 2 liter Diesel engine equipped with a Comprex® wave rotor. Mazda produced 150 000 Comprex® Diesel cars, this being the major industrial application for a wave rotor. Other car manufacturer like Opel, Mercedes, Peugeot and even Ferrari used the Comprex® with promising results. To date, the Comprex® is the only commercially available wave rotor, and Swissauto Wenko AG of Switzerland is the only company who produces a modern version of the Comprex®, called the Hyprex®. This type of wave rotor is designed for small gasoline engines applications [3].

In a gas-turbine engine, the Wave Rotor is used as a top-pressure stage, in order to obtain a higher overall efficiency from the power unit. Prestigious institutions like NASA, Rolls Royce, Indiana University Purdue University Indianapolis, and Michigan State University, worked, or are still working on various research programs for the development of the gas-turbine engine or other projects like Pulse Detonating Engine, (PDE) and Wave Turbines [4].

Working Principle

In a conventional arrangement, a wave rotor is placed in “parallel” to the combustion chamber. Figure 1 illustrates how a four-port wave rotor is used to top either an internal combustion cycle or a gas turbine cycle. The combustion chamber is either the cylinder in an ICE or the burner in a gas turbine. The only differences between the two cycles are that for gas turbine cycle, the air is pre-compressed by the compressor, and the exhaust gases are further expanded in the turbine. The figure presents a through flow (TF) and a reverse flow configuration (RF). In a TF configuration, both the air flow and the gases travel the same direction. In a RF setup, the two flows are separated, air ports being placed on one end of the rotor, while gas ports on the other. The active components of the wave rotor are the rotor which contains the channels and the end plates which regulate the flow to the channels. At the beginning of the compression, the rotor channels contain only fresh air. As the rotor revolves, the high pressure gas port (HPG) starts to open and the hot exhaust gases from the combustion chamber enter the channels,

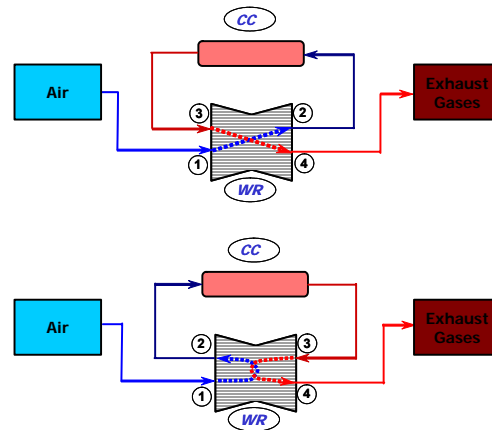


Figure 1. Four-port wave rotor schematic. Top – Through-flow configuration; Bottom – Reverse-flow configuration (CC – combustion chamber, WR – wave rotor).

compressing the fresh air within, by means of shock waves. Next, at the opposite end of the channels the high pressure air port (HPA) opens and the compressed air flows back into the burner. The HPA port has to be closed before the gas/air interface reaches the cold side, in order to avoid a very high Exhaust Gas Recirculation rate (EGR). After the HPG and the HPA ports are closed, the rotor channels contain a mixture of exhaust gas and air which still has a pressure higher than the atmospheric pressure. Thus, when the low pressure gas port (LPG) starts to open the remaining gases leave the rotor. This process created a pressure drop in the channels allowing the fresh air to flow into the rotor by the low pressure air port (LPA). When the LPA and the LPG ports are closed, the channels contain only fresh air, and the cycle starts over.

In order to obtain a more symmetrical thermal stress field and also to reduce the rotor speed and to have a more compact device, there may be several cycles per revolution.

2 APPLICATIONS

2.1 ICE Superchargers

Compared to the turbocharger, the wave rotor has the advantage of a better response time to engine acceleration, (no turbo-lag), and its efficiency does not decrease with the size reduction of the device. These characteristics make the wave rotor more suitable for small displacement engines than the TC, as it can be seen in Fig. 2. The wave rotor has also self-cooling capability, due to the continuous circulation of the air through the rotor.

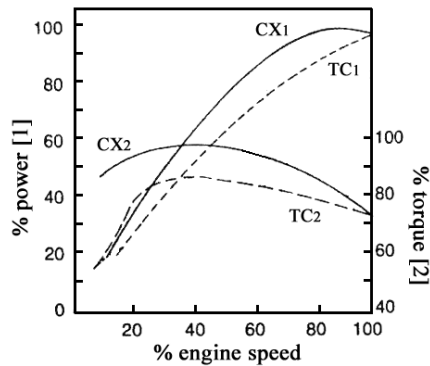


Figure 2. Comparison between the Compress® supercharged engine (CX) and the turbocharged engine (TC) performances [1].

Figure 3 displays the main components of the ICE-wave rotor system. The channels are placed axially at the periphery of a cylindrical rotor. In the Compress® case, it is a RF wave rotor, which determines the rotor to have a “hot” side and a “cold” one. The hot side contains the engine exhaust gases ports, while on the cold side the air port are placed, as well as the rotor bearings. The engine crankshaft drives the rotor via a belt drive [5]. The wave rotor does not use mechanical work from the engine to compress the air like a mechanical supercharger. Instead, the rotor is driven in order to match the wave phenomena with the load and speed requirements of the engine.

The wave rotor is more suitable for a steady-state function, but the ICE works on a wide range of speeds and loads, so there are mismatched working conditions between the two systems. In order to

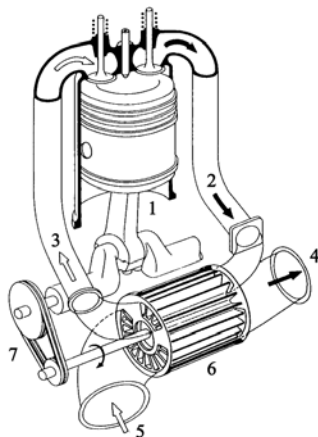


Figure 3. Compress® system: 1 - ICE; 2 – HPG port; 3 – HPA port; 4 - LPG port; 5 -LPA port; 6 - rotor; 7 - drive system.

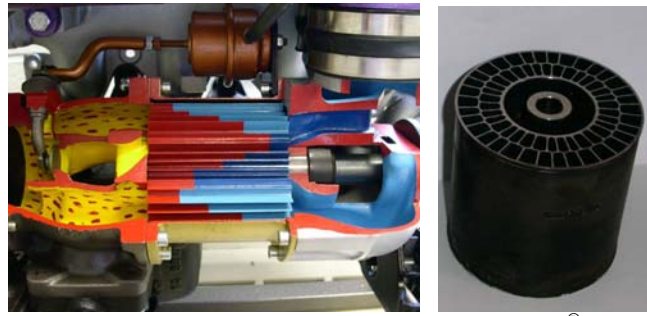


Figure 4. Mazda engine cut-view and the Compress® rotor

smooth out these problems, so called “pockets” were built inside the stator casing. There are two pockets on the cold side of the stator, the Compression Pocket (CP) and the Expansion Pocket (EP) and a Gas Pocket (GP) on the stator’s hot side. The CP deals with the unmatched processes when the engine works at low revs, and the EP and GP help the exhaust gas rotor scavenging process on all loads and speeds range of the engine [6].

The exhaust gas scavenging of the rotor is very problematic, such being the case at low engine loads, like start-up or idling. For these specific conditions, the wave rotor has a starting-valve, which blocks the exhaust gas from entering into the engine cylinders. When the wave rotor is cut-off from the inlet manifolds the ICE works in a natural-aspired mode. For a better control of the boost-pressure, the Compress® incorporates a “wastegate valve”, similar to that used on modern turbochargers.

Figure 4 shows a cut-away view of the Mazda’s 626 Compress® and its rotor [7].

The wave rotor can be driven by a belt drive system or by the exhaust gas, like the turbocharger. This type of Compress® is called the “free-running” Compress®. In this case, the speed of the rotor does not have the same importance like it has for the turbocharger, because the compression process is not influenced by it. The speed of the wave rotor has only a distribution role, so even if there is a turbo lag, it has little effect on the performance of the free-running Compress®. This type of wave rotor has a ceramic rotor in order to reduce the inertia and to improve the overall efficiency, unlike the original Compress®, which had a metal rotor [8].

Another interesting approach in the wave rotor for ICE area was made in the late 90’s by the Swiss Federal Institute of Technology Zurich, Switzerland in collaboration with Swissauto Wenko AG. Their version of Compress®, called the Hyprex®, is driven by an electrical motor, which is controlled by the engine’s Electronic Control Unit (ECU). The Hyprex® does not have pockets in its stator and rely

on a Gas Pocket Valve (GPV) to regulate the boost-pressure and the rotor's scavenging process. The GPV is also controlled by the ECU and has a very important role because the Hyprex® is designed to work on small gasoline engines, where the boost pressure and the EGR rate have a major influence on the energetic and pollution performances of the SI engine [9].

2.2 Gas Turbine Topping

The general advantage of using a wave rotor becomes obvious when comparing the thermodynamic cycles of baseline and wave-rotor-enhanced gas turbine engines. This is demonstrated in a schematic temperature-entropy diagram for a gas turbine baseline engine (dashed line) and the corresponding wave-rotor-topped engine (solid line) in Fig. 5.

While many other advantageous implementation cases of the wave rotor into a given baseline engine are possible [10]. The diagram shows that both the baseline and the enhanced cycle gas turbine are operating with the same turbine inlet temperature and compressor pressure ratio. However, the output work of the topped engine is higher than that of the baseline engine due to the pressure gain across the wave rotor. In the shown case the amount of heat addition is the same for both cycles. Therefore the thermal efficiency for the topped engine is higher than that of the baseline engine, which is indicated by the lower entropy production in the wave-rotor-enhanced cycle. Wave rotors as topping devices for gas turbine cycles have been studied extensively. Since the early 1960s General Electric Company (GE), General Power

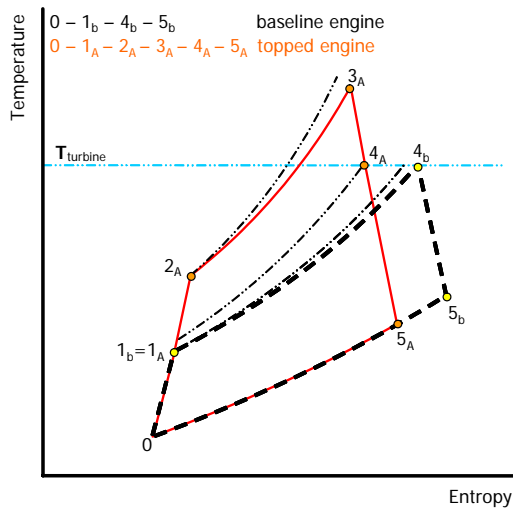


Figure 5. Temperature –Entropy Diagram for a gas turbine engine with and without wave rotor topping.

Corporation (GPC), and Rolls Royce were involved in the development of wave rotor prototypes for propulsion applications [11, 12]. Mathematical Science Northwest (MSNW) also studied various aspects of wave energy exchange and proposed a wave rotor design for an aircraft turbofan engine [11]. Since the late 1980s, A large research program at NASA Glenn Research Center (GRC) collaborated by the US Army Research Laboratory (ARL) and Rolls-Royce Allison has aimed to develop and demonstrate the benefits of wave rotor technology for future aircraft propulsion systems [13-15]. Experimental studies at NASA on four-port [16] and three-port [17-19] wave rotors enabled the estimation of loss budgets [20, 21] and simulation code validation [22]. The experimental work consisted of two phases. Initially, a simple three-port flow divider wave rotor was built and tested to evaluate loss mechanisms and calibrate the simulation code. Next, a four-port pressure exchanger was built and was tested to evaluate the pressure-gain performance for application to a small gas turbine (Allison 250). However, a study by Rolls-Royce Allison indicated that thermal loads on the rotor and ducting predicted for the NASA wave rotor cycle in real engine conditions may be difficult to manage. The rotor used in testing, as well as the test stand for a four port configuration are displayed in Fig. 6. NASA's wave rotor research was later extended to the concept of internal combustion wave rotors [23] in which both pressure exchange and combustion take place within the wave channels, and further to pulse detonation engines (PDE) taking advantage of constant-volume combustion for higher performance and better efficiency [24-27].

In a recent study, Akbari and Mueller have performed a thermodynamic analysis to calculate the thermal efficiency and specific work of two unrecuperated microturbines (30-60kW) topped with a four-port wave rotor [28]. The engines manufactured by Capstone Turbine Corporation have been widely used recently and efforts are currently being persuaded to increase their performance considerably. The results have predicted overall thermal efficiency and specific work enhancement up to 34% for the smaller engine

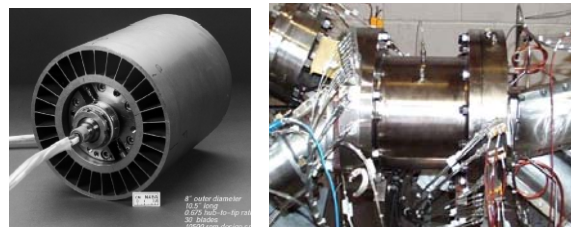


Figure 6. NASA four port wave rotor. Left – the rotor, Right – the test system.

and 25% for the larger engine, using a four-port wave rotor with a compression ratio of 1.8 [10].

2.3 Refrigeration Applications

Wave rotors also have been used for air-cycle refrigeration systems [29-31]. Power Jets Ltd in the U.K. utilized wave rotor technology in the design and development of two prototype air-cycle refrigerators used for environmental cooling purposes. Recently, a unique and cutting-edge application of wave rotors in refrigeration cycles using water (R718) as a refrigerant has been studied [32]. In fact, the wave rotor implementation can increase efficiency and reduce the size and cost of R718 units. A three-port wave rotor has been introduced as a condensing wave rotor that employs pressurized water to pressurize, desuperheat, and condense the refrigerant vapor - all in one dynamic process. Besides, giving the possibility of an additional rise of the vapor pressure, the condensing wave rotor eliminates the need of a bulky condenser because full condensation occurs inside the rotor channels.

3 NOVEL RESEARCH

3.1 Radial Wave Rotor (Wave Disc)

The Michigan State University and Warsaw Institute of Technology research group has developed a new wave rotor configuration, the radial wave rotor (wave disc) [33]. For all the above applications, so far most

widely axial-flow wave rotors have been used and investigated. Pure scavenging is a challenging task in the axial-flow configurations. Even though reverse-flow configurations can deliver pure compressed air to the combustion chamber, a buffer layer can remain in the channels. This residuum can remain permanently in the channels. Repeated compression waves increase the temperature of this buffer layer. This leads to high wall temperatures in the center of the channels [34]. It is possible to achieve a full scavenging process for both through and reverse-flow configurations using bypassing or bleeding of certain mass flows [35-37]. However, all of this leads to more complex configurations.

Jenny and Bulaty [38] have introduced a conical wave rotor with oblique channels in which a radial component is added to the axial flow. However, the flow still enters and leaves at the front and rear end respectively and predominantly in axial direction.

Here the wave disc concept is introduced employing a flow in the radial and circumferential directions. This can substantially improve the scavenging process by using centrifugal forces. Figure 7 shows schematically a simple radial-flow wave rotor with straight and curved channels and variable cross-sectional area. Compared with straight channels, curved channels provide a greater length for the same disc diameter, which can be important to obtain certain wave travel times for tuning. With curved channels also the angle against the radius can be changed freely. This allows modulating of the inflow direction acting accelerating component of the centrifugal force and also to choose the inlet and outlet angle independently. The latter enables independent matching with the flow direction through the stationary inlet and outlet ports or the use of a freely chosen incidence angle for a self-driving configuration. Furthermore, curved channels may be more effective for self-propelling and work extraction in the case of a wave turbine or work input for additional compression, analogous to the principle of turbomachines.

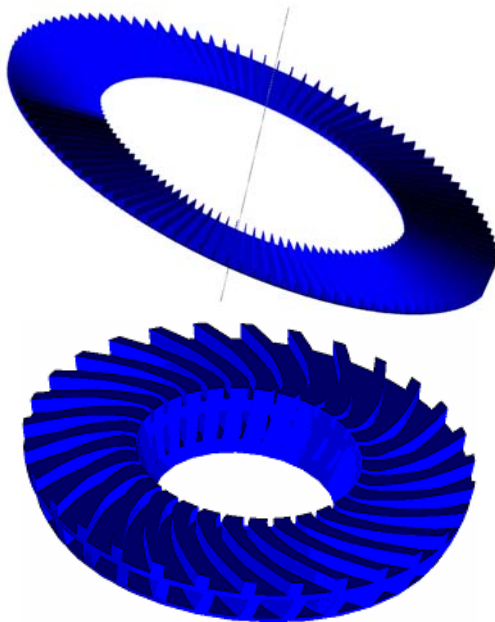


Figure 7. Radial-flow wave rotor with straight and curved channels.

3.2 Ultra-Micro Wave Rotor (U μ WR)

The end of 20th century was characterized by a search for an energy source with a high power density. The solution proposed here is a miniaturization of a gas turbine equipped with a wave rotor. The idea of a ultra-micro gas turbine is not new, but all the attempts so far have failed the efficiency test. Investigations have shown that there are many engineering challenges at microscale and the solutions found in the past half of century for large scale mechanical devices do not necessarily apply to the new design space [39]. U μ GT have shown difficulties in obtaining high

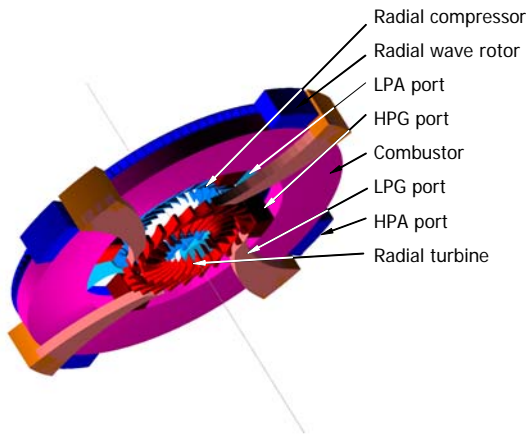


Figure 8. Wave rotor topped ultra-micro gas turbine

overall thermal efficiency and output power, resulting from miniaturization. Particularly, obtained compressor efficiencies have been as low as 40-50%, reducing optimum pressure ratios down to about 2. Integrating a four-port wave rotor will increase the overall cycle efficiency and power output, by increasing compressor efficiency and optimum overall pressure ratio.

Starting from a baseline engine similar to the one developed by the MIT research group, a wave rotor topped ultra micro gas turbine is proposed. The wave rotor works on a through flow four-port configuration, 4 cycles per revolution. The rotor is radial, its shape and overall surface to height ratio is ideal for microfabrication processes, most of them being 2D processes. Plus, the variable cross-sectional area has been proven to provide a more efficient shock wave compression [40]. The radial wave rotor (wave disc) will be incorporated, as the axial one, in parallel with the combustor, schematics are shown in Fig. 8. The rotor is etched in the same wafer as the radial compressor. The overall dimensions of the rotor are $8 \times 8 \times 0.5$ mm.

4 CONCLUSIONS

The paper is a brief compendium of wave rotor technology, past and present. Although wave rotors have been extensively investigated and have become state of the art knowledge, they are not known by the outside the research community involved in their development. Recent progress in knowledge and technology has provided the opportunity to consider wave rotor concept as innovative technology to show significant performance improvements for thermal cycles.

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