AUTOMATED TOOL FOR SIMULATION AND DESIGN OF PRESSURE EXCHANGE WAVE DISCS FOR POWER MEMS APPLICATIONS

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Abstract: With the increased demand for micro-scale power generation, wave disc technology has been investigated to replace low efficiency, steady-state turbomachinery at micro-scale. A wave disc acts as an unsteady pressure exchange device and is used to provide compression, expansion, and torque generation in a Wave Disc Engine. The design of wave discs consists of determining the port timing required to achieve a desired shockwave pattern. Typical design validation is performed using 2-D CFD simulations. This work presents a new automated tool developed to complete the porting design and CFD simulation of pressure exchange wave discs. The tool reduces the time required to model and simulate a single design, and it allows designers to vary geometric and operating parameters to determine the best design point for a wave disc.

Keywords: Wave disc, pressure exchanger, CFD, automated simulation

INTRODUCTION

One of the most investigated fields of Power MEMS is the creation of micro-sized heat engines for power generation. Such engines could fulfill the energy demands for portable electronics [1] or for unmanned air vehicles (UAV) and micro air vehicles (MAV) [2].

With this objective, the MIT Micro Gas Turbine Engine Project [3] was developed by scaling the compressor, combustor, and turbine of a conventional gas turbine engine using micro-fabrication methods. However, it was shown that the polytropic efficiency of conventional steady-state turbomachinery decreases with size [4].

A wave disc, shown in Figure 1 is an unsteady flow pressure exchanger that utilizes shockwaves to transfer energy from a high energy fluid to a low energy fluid. The operating principle of the wave disc allows it to compress the inlet air while expanding the exhaust gas. In this manner, it acts as both an air compressor and a gas turbine but within a single rotating part.

A wave disc may be used to enhance the performance of a micro gas turbine engine similar to the MIT Micro Gas Turbine Engine [5]. The inlet air enters through the compressor and then travels through the wave disc for a second compression stage. The compressed air is then ducted into the combustion chamber, mixed with fuel, and ignited. The exhaust gas then re-enters the rotor, which expands the gas before it enters the turbine, and is exhausted. Such a configuration of this engine is shown in Figure 2.

Figure 1. Micro-scale wave disc, the bottom showing a cutaway view of the rotor channels

Figure 2. Schematic for a radial wave disc enhanced micro gas turbine engine design [5]

In this configuration, the wave disc produces an additional pressure boost for the engine. The radial configuration of the disc improves scavenging using centrifugal forces, avoiding exhaust gas recirculation.
(EGR), which could negatively affect its performance [6]. Additionally, the wave disc may extract energy from the flow by modifying the channels so they are curved.

The possibility of extracting energy from the flow using only a wave disc has opened a promising new research area, Wave Disc Engines (WDE). The basic concept behind the WDE is to simply replace the turbomachinery components with a single pressure exchange wave disc [7]. In a single rotating part, the wave disc alone provides the compression and expansion needed for the cycle to be completed. It is also designed to produce torque by integrating a generator-starter [4]. A schematic of the WDE is shown in Figure 3.

![Figure 3. WDE configuration schematic [7]](image)

**WAVE PATTERN AND 1-D DESIGN CODE**

The wave disc operates by transferring energy between two fluids using a set of shockwaves and expansion waves. These waves are created within the discs channels by the sudden opening and closing of the inlet and outlet ports. The channels are exposed to a high pressure, high temperature gas at the Exhaust Inlet port (EI) and to low pressure, low temperature air at the Air Inlet (AI) port at the inlet side of the rotor. After the energy exchange within the rotor is complete, the outlet side of the channels is opened to release the pressurized, low temperature air at the Air Outlet (AO) port, and the expanded, high temperature gas, at the Exhaust Outlet (EO) port.

In order to solve for the wave pattern and port timings, a 1-D design code was developed in MATLAB at the MSU Turbomachinery Lab [8]. The operating conditions of the wave disc are required as inputs, and the code calculates and displays port timings and flow velocities along the inlet and outlet ports.

The 1-D design code results are shown in Figure 4, where the horizontal axis represents the position within the channel, and the vertical axis represents time. They include some EGR at the end of the channel. However, the code does not take into account important effects such as centrifugal forces and leakage. The centrifugal forces should help reduce or eliminate the EGR present in the disc. To account for this, the preliminary design must be simulated using 2-D CFD software.

![Figure 4. Wave pattern outputs from the 1D design code](image)

**AUTOMATED SIMULATION CODE**

To improve and speed up the design process for the wave disc, a MATLAB code was developed to automate the numerical simulation process. The code is capable of performing a full simulation given a set of input matrices. The input matrices define geometric parameters, meshing parameters, solver settings, and boundary conditions for a single simulation. The code is flexible in order to accommodate for many different designs, simply by changing the input variables.

The first step in the automated code is defining the geometry in GAMBIT 2.3. A set of input variables are used to calculate the shape and size of the wave disc porting and of the individual channels. The input variables required to create the porting geometry are shown schematically in Figure 5.

![Figure 5. Wave pattern outputs from the 1D design code](image)

The input variables required to create the channel geometry are shown in Figure 6. The channels may be straight or take on any curvature required. The channel shape is defined by a set of points spanning the length of the rotor, each at a user-specified radius and angle from the horizontal.
Convergence is determined by comparing mass flow and velocities at the beginning and end of each cycle.

RESULTS

The 1D design and 2D simulation codes were used to develop a millimeter-scale wave disc, to be used for topping of a gas turbine engine. Two simulations are presented, the first using straight channels to confirm the wave pattern design and the second with curved channels to extract energy from the flow.

Figure 7 presents the simulation results for a rotor with straight channels. The shockwaves and expansion waves are well defined and follow the wave pattern as predicted. The temperature contours for this geometry show that all the exhaust gas is scavenged out of the rotor before each cycle.

In order to rotate, the wave disc must either extract energy from the fluid or have is supplied by a motor. This amount of energy may be determined from Euler’s turbomachinery equation [9] and the FLUENT simulation results. The first wave disc has straight channels and straight porting, which is an inefficient
configuration in terms of energy. The specific work required by the rotor was calculated to be 57.2 kJ/kg. The disc would have to be driven by an external motor.

The final design includes curved channels and angled porting to improve the energy extraction within the rotor. The results of the simulation are shown in Figure 8. The pressure contours show the same wave pattern, but the waves follow a more curved path caused by the channel curvature. The temperature contours show more EGR present than in the previous simulation. Since energy is extracted from the flow, the resulting flow velocities are reduced, resulting in reduced scavenging of the disc.

The specific work extracted by the rotor was found to be 3.5 kJ/kg. The negative sign in the result indicates that the energy is extracted from the flow. While this is a relatively small amount, the rotor itself is very small compared to traditional turbomachinery. This should be enough for the rotor to be self-driving, requiring no external work input.

CONCLUSIONS
As with radial flow turbines, it is much more challenging to extract energy from the flow when it is flowing from the inner radius to the outer radius. The higher blade speeds at the outer radius make it easier to extract energy if the flow enters from there. However, the simulation results prove that even for this flow configuration, the wave disc can extract energy from the flow while still maintaining the desired operating conditions.

The simulations show that a self-driving disc is feasible for micro gas turbine engine enhancement. Further improvements in the channel curvature should allow the wave disc to extract enough energy to run a Wave Disc Engine.

The solution could be optimized to find the maximum power generation for a single design. The 2-D numerical code is ideal for optimization software. It is flexible and controlled only by the input matrices and may be used to automatically improve the designs further than what can be done manually.

REFERENCES