WAVE-DISK ENGINE CONTROL, SYSTEM DESIGN AND IMPLEMENTATION

Ву

Eric Tarkleson

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ABSTRACT

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By

Eric Tarkleson

The wave disk engine is a type of internal combustion gas turbine engine invented by Dr. Norbert Mueller, and Dr. Janusz Piechna and patented in 2009. Unlike a typical automobile engine which operates as an Otto cycle engine, the wave disk engine operates under the Atkinson cycle. This can lead to a higher theoretical maximum efficiency. Further the wave disk engine can be realized with only a single moving part, which can minimize system parasitic losses. Michigan State University received an Arpa-E grant in 2010 that financed the first major push in the advancement of the underlying principles and the building of a modest engine testing facility at Michigan State University's East Lansing campus.

The test facility features state of the art data acquisition and control equipment. It has over 500 channels available for monitoring and control. The Test Cell is a blast safe, environmental controlled room, it has industry standard 3 level E-stop system and has complete video and audio feedback and recording. The remote control room allows all engine parameters to be monitored, recorded and controlled. The engine can even be controlled by a wireless tablet for easy sub-system verification. The intent of this paper is to show the reader the design and implementation of the wave disk engine control systems. This will cover all electrical and electromechanical systems from ignition systems to gas flow monitoring and control, to motor/generator control.

Copyright By ERIC TARKLESON 2013 To my parents, Scott and Jonie. To my grandparents, Beverly and Arlene.

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PREFACE

"Out there things can happen And frequently do To people as brainy And footsy as you"

Dr. Seuss

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1 INTRODUCTION TO THE WAVE-DISK ENGINE PROJECT

Michigan State University received a 2.5 million dollar ARPA-E grant in 2010 that financed the first major push in the advancement of the underlying principles and the building of a state of the art facility at Michigan State University to test the wave disk engine. The project was initially scheduled to last two years and planned to build a complete test facility and develop a 10kW first generation prototype engine.

The wave disk engine is a high speed internal combustion gas turbine engine. It is a torque producing axial turbo-machine designed to produce torque for conversion to electricity. This type of engine could provide generated electricity as a range extender or fuel powered backup for an electric vehicles drive system by generating power to recharge the battery while at rest, or during operation.

The test engines used during this project are very small, less than .5x.5meters including the wave disk engine itself and the electric motor/generator used for startup, control, and power extraction. While our first generation test engines don't measure up to the full potential, an engine this small eventually could provide up to 20kW continuously. This type of generator system would provide a higher power density (output power/ unit size) than is commercially available.

A wave disk engine can be described as a constant volume combustion machine, utilizing turbomachinery principles. The mini-turbine, compressor and combustor are achieved in a single rotating turbine/fan blade structure to generate torque. **Figure 1** shows a simple wave disk engine design and describes its combustion process.



Figure 1: Wave Disk schematic illustration. (For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this thesis)

The engine consists of a stator or external casing and an inside gas injection zone; and a rotor, or gas turbine which rotates. The rotor is attached to a shaft which transmits torque the motor/generator. A fuel/air mixture is pumped into the center stator section which injects the fuel mixture into the channels as they rotate past the injector, the chamber is given some time for the gases to fill the chamber and then the mixture is ignited. The ignition causes a rapid pressure rise and the curved blades provide torque once the pressurized channel is opened to the atmosphere. This process happens continuously in each channel creating a quasi-constant combustion process that is effectively a mix of turbine technology and IC engine technology.

One of the wave-disk engines advantages is that it is a relatively simple system to control, and when combined with todays mature and cost effective power electronics and

automotive technology, results in an integrated generation system with many advantages over traditional technologies. In fact it may benefit from reduced cost and cheaper control than traditional automotive engines because the design inherently has a low number of rotating parts, which significantly reduces machining and production costs.

1.1 THE CHALLENGE

While the first prototype of a wave-disk engine was being designed and manufactured, a complete test cell needed to be designed and built to allow testing this brand new technology. Since this was a relatively short term project, two years, and low budget, 2.5 million USD, it was imperative to be able to begin testing the prototypes as soon as possible.

The test cell was designed and built in under six months. The facility features state of the art data acquisition and control equipment. It has a virtually unlimited number of input and output channels available for monitoring and control, due partially to its highly reconfigurable nature. The completed wave-disk test facility consists of a gas storage room, a test cell, a control room, and an outside courtyard housing exhaust fan and cooler compressors. The test cell is a blast safe, environmental controlled room, it has a 3 level E-stop system and controls designed to protect the operators. Both test cell and control room have complete video and audio feedback and recording. The remote control room allows all engine parameters to be monitored, recorded and controlled simultaneously in real time. The engine can even be controlled by a wireless tablet for easy sub-system testing and verification. The intent of this paper is to show the reader the design and implementation of the wave disk engine control systems as well as the implementation of the entire project. This will cover all electrical and

electromechanical systems from ignition systems to gas flow monitoring and control, to motor/generator control. **Figure 2** describes the overall system layout.



Figure 2: Wave-disk control block diagram (from (1))

1.2 WAVE DISK SUBSYSTEMS

The wavedisk engine is completely controlled via electric control systems controlling electro-mechanical actuators and sensors. There is an ignition system, fuel and airflow systems, motor/generator and their associated controllers, environmental feedback such as temperature sensors, speed sensors and pressure sensors and. All of this is controlled via National Instruments Compaq DAQ series data acquisition systems. All programming is in Labview, a visual programming environment which excels in parallel data processing such as is required when many variables must be monitored and controlled simultaneously.



Figure 3: Wave Disk Engine Showing multiple spark plugs, temperature and pressure sensors

Proper Ignition of fuels in the wave disk engine was a large obstacle in running the first prototype. Several design iterations have produced several highly reliable and well controlled systems that have very good ignition characteristics. See **Figure 3**.

A motor/generator is a critical component in the wave disk engine. The motor will first act as a starter, spinning the engine up to its intended operating speed. After combustion begins the engine starts producing torque and the motor begins acting as a generator as the motor torque becomes negative. The two components are coupled directly to each other by a stiff shaft. Two workhorse PMDC motors are used to fulfill all of these requirements. See figure

4.



Figure 4: Thingap Motor mounted underneath the wave disk engine

In order to achieve fine control of all system parameters in the wave-disk engine a wide array of sensors were purchased according to the type of tests that needed to be performed. This posed a challenge because the test cell needed to be able to accommodate a huge array of different tests, under different wave-disk designs. All of this while still providing test and sensor flexibility has resulted in an extremely capable and reconfigurable test environment while still being safe and easy to learn and operate. All gas, air and fluid flow in and out of the engine is controlled and monitored to allow testing the engine under a wide variety of operating conditions. The system has the ability to use virtually any type of compressed gas including ethane, methane, and hydrogen and only small modification are needed if liquid fuels were to be tested in the engine. See **figure 5**.



Figure 5: fuel and air system

High quality pressure data is important in virtually every engine or turbine test environment and the wave-disk engine is no different. The prototype design allows for pressure taps to be located directly on the engine housing and can be moved to an almost unlimited number of locations due to the top stator plates design. This data gives us important insights into the combustion process inside the engine and helps to provide data to match with simulated engines also developed at MSUs turbomachinery laboratory. Like pressure data, temperatures inside the engine are important for proper engine characterization and validation and the test cell features a large array of different technologies to match any test requirement.

The environment of the engine and test cell provided a challenging environment to obtain accurate electrical measurements from the various sensors. The motors are high voltage PMDC motors which can cause significant EMF interference near their windings which can couple into the engine housing and from there onto the instrumentation. The ignition system is designed to provide over 40k Volts during a very short intervals. This makes for extremely energy dense EMC pulses that have actually been measured outside of the room. However, proper wiring and labview programming practices have effectively mitigated these artifacts in most of the sensing equipment.

The following chapters will describe the mechanical operating principles and well as electronic control and data acquisition in more detail. Further, actual test results will prove the power and flexibility of this system.

2 TURBOMACHINERY BACKGROUND

The wave disk engine is a high speed internal combustion gas turbine engine. It is a torque producing axial turbo-machine designed to produce torque for conversion to electricity. A wave disk engine can be described as a constant volume combustion machine, utilizing turbomachinery principles. The mini-turbine, compressor and combustion chamber are achieved in a single rotating part to generate torque for transmission to power (2) . Unlike a typical an automobile engine which operates as an Otto cycle engine, the wave disk engine operates under the Brayton cycle. This can lead to a higher theoretical maximum efficiency. Further since the wave-disk engine can be realized with only a single moving part, instead of hundreds as a modern IC engine has, the design inherently minimizes system parasitic losses (3) due to mechanical friction. The wave disk engine can be described as a axial, interior inlet configuration of a wave rotor, where the rotor is designed to produce torque instead of compression, which is typically used as a 2 or 4 port compression device. Wave rotors will be explained in the next section

A unique feature of the wave disk engine, especially compared to traditional IC engines is that it is designed to run only at its most efficient operating point. A traditional IC engine is designed to produce usable torque over a large range of speeds. The wave disk engine, however, is easily configured as a constant power generator, meaning that its output power does not depend on the total system load. The engine would be turned on for battery charging in a serial hybrid car and generate maximum power, and then turned off once the batteries are fully charged. This means fuel is never wasted during idling. In a traditional IC engine the power output is constantly changing depending on the torque and speed required by the user, because of this the engine almost never runs at its most efficient operating point. Also the maximum efficiency the engine could be designed for must be compromised in order for the engine to be reasonably efficient over its entire speed range. This is also the same scenario as in a typical IC engine generator, such as used for emergency backup power in homes and businesses. The load and power requirement depend on the current which must be supplied in order to maintain the AC voltage. These IC generators typically have an output power proportional to the load of the electrical side.

2.1 BASIC SHOCKWAVE THEORY

The wave disk engine is designed to take advantage of unsteady flow phenomoma in order to enjoy increased efficiencies in its thermodynamic cycle. Unsteady flow phenomena has historically been viewed as a detriment to turbomachinery. Shock waves and other transient effects cause unwanted and unpredictable vibrations, decreasing the life of most rotating machinery. However some have studied this effect and found ways to use shockwaves as an added advantage (4). A wave rotor is a type of compression device which caused pressure increase by utilizing shockwave principles.

A shock wave is a fluid disturbance characterized by an almost discontinuous wave front propagating outwards. This differs from a normal pressure wave front in that its pressure differential is very large and the wave travels very fast. A sound wave is not a shockwave, while the noise created by a supersonic jet is a shockwave. See **figure 6** for a picture of a jet shockwave. In this paper all useful shockwaves are caused by sudden opening and closing of

the channels inlet and outlet ports of the wavedisk engine. Since a shockwave travels much faster than a traditional pressure wave-front and has a very high pressure differential between ambient pressure and the wave-front, this phenomenon may be used for compression of fluids (5).



Figure 6: Shockwave illustration from sonic aircraft (from Wikipedia)

2.2 WAVE ROTORS

Wave Rotors use rapid openings and/or closings of ported channels to generate shockwaves which propagate away from the port. The Wave rotor is typically constructed as an axial flow device with many small channels in a cylindrical tube as seen in **figure 7**. The inlet and

outlet ports are seen before and after the rotor and are timed to allow the wave to travel the port length exactly when the port is opened. The channel is closed immediately after the wave passes through. This leaves a high pressure area in the outlet port of the wave rotor and a low pressure zone in the rotating port.



Figure 7: model of comprex wave rotor

The wave-disk engine is like a wave rotor with several important differences. First it is configured as an axial-turbo machine with inlet in the interior and outlet on the outside. This orientation is advantageous because scavenging, compression and aspiration is helped by the centrifugal forces created from the disks rotation. Further the wave disk engine has curved interior channels which are optimized for torque production instead of compression. Finally the current wave disk engine uses the interior channels for the combustion chamber as well as the turbo-fan, this makes the whole engine smaller (less a separate combustion chamber) and has some of the advantages gained by a constant volume combustion, as in a traditional IC engine (6). This leads to a higher power to weight ratio than turbine engines.

The engine is tuned so that the opening of the inlet port creates a shockwave which travels towards the outside of the engine. This can pre-compress the fuel mixture before combustion, leading to more powerful and faster combustion. It is even possible that a very large shockwave could compress and ignite the fuels if the engine casing was hot enough. This would mean that a traditional ignition system may not be needed after the engine is heated. This eliminates all losses stemming from the ignition system.

The only current commercially available shock wave compressor is called the "Comprex wave rotor". The comprex has been successfully used in the Mazda 626 Cappela model in place of a turbocharger. Michigan State University has been working with unsteady flow devices since 1991. The Turbomachinery lab built several test rigs to examine wave rotor technology between 2006 and 2008. This research is what led to the invention of a new wave rotor configuration designed for torque production instead of compression, the Wave-Disk Engine.

Michigan State University has built two test rigs for the comprex wave rotor. The author built the data acquisition and test sequences for both test rigs. Dr Piechna and Dr. Mueller did an investigation into new uses for wave rotor technology (4) and found several interesting design topologies which promise unique and exciting advantages over current unsteady flow devices as well as applications in modern IC engine. This led to the invention of the "wave-disk engine", which successfully combines the separate components of a traditional multi-stage turbo-machine, as well as integrating some components of IC engines, leading to a combustion engine with only 1 moving part. In addition the motor may be tuned carefully to utilize shockwaves to enhance the engine efficiency even further by aiding in pre-compression before combustion. (6)

2.3 POWER EXTRACTION PRINCIPLE

The wave-disk engines thermal cycle may be described by the Brayton cycle. A standard Brayton cycle engine has three main components; a compressor, a combustor, and a turbine. The wave disk engine combines these components into a single part. It can also be argued to operate under the Aktinson cycle, because instead of having constant combustion such as in a Brayton cycle engine the wave-disk has quasi-confined combustion if it is tuned to burn completely before the chamber is open to exhaust. In order for this to be true the engine must have very tight tolerances and low airgaps once it is heated up to operating temperature. A gas and air mixture is injected directly into the turbine, the large centrifugal forces from inertia help to compress the mixture, and then the mixture is ignited causing rapid pressure and temperature rise, the turbine is able to extract this energy in the form of rotational torque. Equations 1-3 describe the power extraction principle. As the turbine generates torque the total mechanical power generated depends on the rotational speed and the torque developed by the combustion process.

$$P_{mech} = \omega * \tau$$
 Equation 1

The speed is dependent on the relationship between the torque produced by the engine and the motor. The power the motor is able to convert from mechanical to electrical power depends on its efficiency at that operating point (speed, current).

$$P_{elec} = V * i$$
 Equation 2

$P_{ele} = P_{mech} * E_{motor} Efficiency$

Equation 3

This shows how the electrical power generated depends on a relationship between the torque produced by the engine and the negative torque produced by the electric motor. The balance that insures maximum power transfer is discussed in detail in following chapters.

A wave disk engine operates most efficiently at high speeds and temperatures. The torque produced by a wave disk engine is relatively small and its speed very high when compared to today's IC automobile engines. This makes it difficult to couple the engine to traditional mechanical systems in vehicles, ie wheels. Therefor this engine is suitable for conversion from mechanical to electrical power using a high speed PMDC or reluctance motor. Modern high speed motors have a high efficiency, currently up to 90%. In a vehicle the electrical power can charge batteries for an electrical drivetrain. Also this design could be used for small to medium scale power generation.

When compared to todays IC engines like those used in automobiles and small scale power generation; the wave disk engine has many advantages. It is small (high power to weight ratio) meaning that it can be cheaper and use less space than a similar power output IC engine; it has a single moving part making it easier to build, troubleshoot and fix, and it can easily be modified for small scale power generation as well as automobile power trains.

3 INITIAL TESTS AND FACILITY DESIGN

Initially wave disk testing was performed at the engine research lab (ERL) @ MSUs research facility. But it was apparent there was a need for a separate test cell designed specifically for the wave-disks unique design. So in October 2010 the turbomachinery laboratory was given two small unused rooms, part of a compressed gas storage area, and an exterior courtyard in the engineering building. One room was designated as a control room, the other was turned into a combustion safe test cell. The test cell consists of a blast door; designed to vent an explosion and gases into the locked courtyard in the case of a massive fault, two air exchange systems, 4500 and 600 CFM used for exchanging exhaust gases with fresh air, a fluid cooling system, gas and air supplies and an environmental monitoring system with fully automatic shutdown in the case of dangerous levels of C02, hydrogen ethane or methane. Emergency stop switches were installed both inside and outside the area. This work insured the room was safe and to code before the turbo lab began installing its own equipment. The outside courtyard also hosts the large fans and cooler equipment.

The author was in charge of the system design and implementation of the test cell and control room hardware, software, implementation and management. The MSU physical plant installed the room piping, fans, coolers, gas lines and some of the safety instrumentation systems under the supervision of the author. During this time the initial acquisition and control wiring was being built, tested and installed in the turbomachinery work area.

As with any electromechanical system the wave disk engine must be controlled properly. This includes controlling all inputs and outputs of the entire system including air flow, gas flow, speed, torque, power output, temperature, internal pressures and ignition among others. The wave-disk engine test cell monitors, records, calculates and controls all data being used for any test in real-time. The system is designed so that all data is recorded so none is ever lost. The system is fast enough that there is almost instantaneous feedback from the data acquisition system if any variables are changed. Figure 8 shows a simplified diagram of the Wave Disk System and its input/output scheme.



Figure 8: DAQ block diagram (from (1))

3.1 THE TEST CELL

The test cell is designed for safely testing the wave-disk engine while lending itself towards quick changes and ease of equipment access to facilitate numerous types of testing. Even though it is a small area compared to many engine testing facilities it houses everything needed for every type of test the lab could conceive and also has room for future expansion.

6 enclosures were installed in order to safely house the various electrical and mechanical systems needed for running the prototype wave-disk engines. These are shown in Figures 9 - 10. Box 1 is a power box allowing power supplies to be mounted away from sensitive sensors and data acquisition and control equipment, box 2 houses all ignition equipment, box 3 is the data acquisition box, it is a DC power only box to prevent unnecessary noise, and box 4 is available for future expansion. On the opposite wall, a smaller box, 5, houses different pressure sensors for various purposes and larger box 6 houses flow controllers for the various air and gas lines.



Figure 9: test cell pictures south wall showing boxes 1 through 4



Figure 10: Test cell picture of north wall

3.2 THE CONTROL ROOM

The control room is located a short distance away from the test cell. It houses several computers for control and storage, a large TV to view tests in action, VFD and control hardware for the test cells climate control, air evac, and water chiller systems as well as a small electronics work bench. See figures 11 and 12.



Figure 11: Control room computers and test viewing screen



Figure 12: Control room electronics workbench

A small Ethernet network connects all labview hardware, motor controllers, video and audio feedback between the two rooms. The network is isolated for safety and speed, insuring no outside network traffic impedes the data flow between the various systems. Hardwired Estop controls have dedicated and redundant controls for maximum safety.

All controls for the air exchangers, fluid cooling system, environmental safety and test cell power are located in the control room for quick access and control. Figure 13 shows the components situated along the wall behind the data acquisition computers.



Figure 13: test cell control and feedback hardware inside the control room

3.3 IGNITION

The ignition system must be controlled to have the ability to spark at exactly the same position in each channel as the individual channels rotate inside the engine casing. This allows for the consistent combustion therefor leading to the most efficient and continuous combustion.

The electric ignition system is composed of a low voltage, 13.5V, high current, 100 amp power supply, a boost converter, a medium voltage bus and a triggering circuit connected to a high voltage transformer. See figure 14 for a view of the actual system and figure 15 for a simplified schematic. The spark plugs themselves are tip-less because the channel walls don't allow for a tip to be inside the channel, else the tip would interfere with the channel walls during operation as the channels pass under the spark plug.



Figure 14: Ignition system box showing MSD modules and high current power supply



Figure 15: Ignition system schematic

Ignition of fuels in the wave disk engine is accomplished using a custom timing sensor and a high voltage spark system, similar to an IC engine in today's automobile engines. After each rotating channel is purged of exhaust and fresh gas and are injected, the channel rotates under a spark plug and the mixture is combusted.

In order to achieve the desired operation a custom sensor was designed for each wave disk engine. The sensor has magnets aligned with each channel in the wave disk engine. A magnetic sensor sends a pulse to the ignition system whenever the magnets pass by. The sensors were designed and manufactured in the turbomachinery lab using CNC retrofit mills outfitted with custom built machine controllers. See figure 16 for a 3d model of the sensor.



Figure 16: 3d model of a 24 channel timing disk sensor

The system is tuned by moving the magnetic sensor, and different wave-disk rotors with different channel numbers each have their own sensor disk which is easily exchanged. This sensing solution also can be interfaced with labview, or the motor controllers easily allowing for engine speed, acceleration, and rotor position to be extrapolated. This data can be used for

better system control and are important variable in characterizing the system. Further this solution is extremely cheap. See figures 17 and 18.



Figure 17: Timing disk rotor and sensor underneath wave-disk engine



Figure 18: Timing disk rotor coupled to wave-disk shaft

The wave disk engine must spark at rates much higher than a traditional IC engine, and it must have to operate at longer duty cycles than specialized high speed starting igniters used in jet engines which are used only for initial combustion and are turned off once the engine is self-igniting. The timing and ignition system is a mix between traditional ignition technology and variations on other types of control systems to realize.

In a traditional IC engine or generator a timing belt or disk controls each cylinders spark plug telling it when to fire. The sparking rate (x) is related to the speed of the engine.

$$x (hz) = \frac{2 * RPM}{60}$$
 Equation 4

A wave disk engine operates much faster, a relationship between its rotational speed (ω) , channels(c), and firing rate(x) is

$$x (hz) = \frac{\omega * c}{60}$$
 Equation 5

For instance, for a WDE with 32 channels rotating at a speed of 10,000 rpm, a spark plug must fire at a rate of 5.33 kHz to fire once per channel. This represents a large departure from current technology where a typical 4 cylinder 4 stroke automobile engine runs around 4000 rpm, or sparks at a rate of only 8000 sparks/minute or 133 Hz.

As the speed of a commercially available ignition continues past its maximum specifications, the energy in the spark decreases because the capacitor (and/or inductor) cannot fully charge before the next spark.

High-speed, high-voltage ignitions are well within our current capabilities to design but cannot be easily purchased because there is no market for this type of ignition. Therefor the wavedisk engine uses a top of the line MSD ignition which works up to approximately 10k RPM. For speeds higher than this a new custom ignition must be designed and built. It is possible in the future that the wave-disk engine could be configured to run hot enough to be self-igniting. Self-ignition could also be caused by a properly tuned shockwave. The shockwaves large pressure front should have sufficient energy to compress a fuel mixture enough to combust it in the hot engine, this could be compared to ignition in a diesel engine, where the glow plugs and the compression work together to cause a well-timed ignition event.

3.4 MEDIUM SPEED MOTOR/GENERATOR

The wave disk engine uses an electric motor for spinning it up to a predetermined speed before ignition is turned on, then the motor acts as the controller/generator to transfer mechanical torque to electric energy. This is an extremely important component not only because it generates the power produced by the wave-disk, but also because it is the instrument used to extrapolate many variables from the engine, including speed, torque, acceleration and power. This data is used to determine the efficiency of the wave-disk combustion process and helps to determine different operating states such as the maximum power output possible or the most efficient point of transferring chemical energy in the form of fuels to mechanical and finally to electrical power.

Several obstacles must be overcome in order to insure maximum system efficiency. The electric motor must be designed to handle the unique characteristics of the engine. First it must operate at relatively high speeds for combustion engines, up to 30k rpm @ 30kW (40 hp). Also, it must withstand the heat produced by the wave-disk. It also must be able to handle the transient effects caused by starting and stopping the ignition as well as the torque ripple caused by individual channels combusting.

The motors chosen for wave disk control are both permanent magnet Direct Current (PMDC) motors. This type of motor uses a 3-phase stator winding and high strength permanent magnets in the rotor for torque production. This type of electric motor is becoming more common despite its usually higher price due to its high power density, reliability, and ability to achieve very good control.

For comparison purposes with traditional IC engines, an equation which describes the relationship between horsepower and kilowatts is.

$$1hp = 746Watts$$
 Equation 6

The electric motor should have its efficiency peak at the engines rated speed and torque to insure maximum power transfer from mechanical to electrical power. The equations below explain the relationship between torque and motor voltage inside of a PMDC motor such as used for both electrical motor/generators in the wave disk engine. V is terminal to terminal voltage between any two phase legs, R is stator resistance, L and M are terminal and mutual inductance, respectively; p is # of pole pairs, I is current, and E is the back EMF created by the machine during operation.

$$V_{xs} = R_s * I_{xs} + (L - M)p * I_{xs} + E_{xs}$$
 Equation 7

The next equation shows torque created where T is torque, I is current w is speed and e is an equation that relates the voltage waveform supplied by the controller.

$$T_e(Nm) = (e_{as}i_{as} + e_{bs}i_{bs} + e_{cs}i_{cs})\frac{1}{\omega_m}$$
 Equation 8

The motors electrical control system (motor drive, vfd, inverter) needs also to be matched for maximum power transfer at the intended operating speed. For this it is imperative to understand the mechanical losses and system behavior when the PMDC motor is coupled directly to the wave disk engine. Here J is system inertia, wm is speed, B is the friction coefficient, and B*wm represents the power lost due to mechanical friction, Tl is load torque, or the torque produced by the wave-disk engine, Te is electromagnetic torque which may be positive or negative depending on whether the system is in motoring or generation mode.

$$J\frac{d\omega_m}{dt} + B\omega_m = (T_e - T_l)$$
 Equation 9

Accurately recording power transfer was a challenge during testing the wave disk engine. First, between disciplines there can be ambiguity as to where the power is measured and what type (electrical or mechanical) of power it represents. Consider the following example. The motor is 90% eff, the VFD (variable frequency drive) is 90% and the power the motor is generating from the wave-disk engine is 100 watts. Only the 100 watts obtained from the VFD is useful for power generation. The actual mechanical power produced by the system is below.

$$Pmech = \frac{100W}{.9*.9} = 123.4W$$
 Equation 10

This example shows how important power transfer between components is. Even when operating near todays limits for well-designed systems almost ¼ of the power produced is lost

during transfer. This is why it is important to insure that the motor is designed to be most efficient at the same speed and torque as the wave-disk engine. Further this example does not take into account losses stemming from the combustion process, such as heat losses, unburned fuel, and losses from non-ideal sealing inside the engine.

A last critical design variable that must be taken into account is the temperature of the motor and its environment. The permanent magnets in PMDC motors (or any magnets) can be demagnetized if they are heated past their demagnification point. To reduce total wave-disk system size it is desirable to place the motor close as close as possible to the engine, this also leads to a shorter shaft, better power transfer, less shaft vibrations, and ultimately better control. However, the wave-disk engine is designed to have case temperatures in excess of 300 degrees Celsius. This temperature is detrimental to any motor, especially modern DC motors, whose magnetic materials tend to be very susceptible to heat.

Together these challenging requirements fit a specific type of motor design well. It is called a "ducted fan motor" or a "ring motor" and has been developed, by Thingap Corporation (7). See figures 19 and 20. In theory a ring motor is a permanent magnet Brushless DC machine but its construction is so novel this is not immediately apparent. A ducted fan motor has a very unique mechanical design where the motor structure itself is a large diameter ring and it is attached to a shaft in the center. This design is low loss because the magnetic circuit is low loss, it consists of a U shaped steel ring that wraps around the magnets making for a short magnetic path and small air-gap; it is self-cooling because there is little bulk iron to build up heat and the air turbulence near the copper quickly removes heat buildup from the winding structures (7), finally the physical separation from the shaft isolates the hot engine from heating up the electric motor while still taking up less vertical space than a typical motor. A motor like this also

can be designed to fit different parameters easily. The copper rings can be machined with any number of pole and radius combinations to fit desired torque and speed parameters. The motor chosen for the wave-disk engine is a TG8251. It is a 6800 rpm, 1500 Watt, 8 pole pair motor that can produce 1.12 NM of torque at its rated speed.



Figure 19: Thingap motor mounted on plate ready for install



Figure 20: Thingap physical structure (picture from (7))

This motor is controlled using an Advanced Motion Control B100A40AC analog motion control drive. Because it is an analog drive it has a very fast transient response when tuned properly. This type of motor controller is good for use in a testing environment because it is very versatile, however a knowledge of PID loops and analog controls is required to get maximum performance from this controller.

The wave-disk engine coupled with a thingap or other type of ring motor is a unique configuration which leads to a novel method for integrating multiple system components into the motor/generator assembly. For example, instead of straight stator rings from the outside of the motor to the shaft, a fan structure could be inserted. This could be a cooling feature for the engine, an inlet airflow *supercharger* or both!

Several novel designs exist for motors with blades whose angle can be electrically controlled during operation (8), See figure 21. The Thigpen rotary subwoofer is a motor controller fan whose blades angles are controller via a voice coil, like in a speaker cone.



Figure 21: Thigpen rotary subwoofer with voice coil driven adjustable blade angles (from (8))

Implementing this in the wave disk engine can lead to a single integrated motor/fan assembly that acts a motor/generator, cooling system, inlet air super-charger or precompressor, with each component having its own degrees of freedom and therefor independently controllable. This means that at a constant speed the inlet airflow can be controlled by changing the blade angles, or as the motor is ramped up or down the airflow can still be kept constant or varied as the control system sees fit. This will lead to an extremely efficient, intelligent, real time control of most of the engines variables while reducing overall complexity significantly.

3.5 CUSTOM HIGH SPEED PMDC MOTOR

The Thingap TG8251 motor is very suitable for low speed testing under 10k rpm, however the wave disk engine may operate at speeds up to 30k rpm. For this purpose the Electrical Machines and Drives research group @ Michigan State University designed and built a 2 pole high speed 30kW permanent magnet machine to drive the engine to speeds up to 30k rpm. **Table 1** shows machine parameters, **Figure 22** shows a picture of the motor on a dynamometer. Samarium Cobalt was chosen as the permanent magnet material instead of the more often used neodymium because samarium cobalt can withstand higher temperatures before demagnification.

Machine Paramete	ers Value	
Rated power	33.5 kW	
Rated torque	10 Nm	
Rated current	42 A	
Rated line voltage	480 V	
Rated speed	32000 rpm	
Stator diameter	100.0 mm	
Rotor diameter	50.0 mm	
Stack length	100.0 mm	
Air gap	1.0 mm	
Stainless steel sleeve thickness	1mm	
Stator slots/poles	24/2	
Stator slot current de	nsity 9 A/mm ²	
Stator core	M15G29	
Rotor shaft	Magnetic steel	
Table 1:	Motor properties	



Figure 22: Motor on dynamometer

Figure 23 shows the simulated torque/speed curve. The torque on the motor remains constant up to the designed operating speed, after this the motor and controller enters phase

advancing operation. Here the controller maintains maximum motor current and begins to advance the voltage phase angle allowing the motor coils time to develop the back EMF necessary for faster operation. This method of control allows the motor to over-speed as long as the torque the motor is producing is less than required by the rest of the system.



Figure 23: Simulated torque vs. speed curve

Equation 11 shows the torque under normal and phase advancing. Under normal operation Cos(Theta)=1 and maximum torque is available, the phase advance angle Theta lowers maximum available torque.

$$T = I * \cos(\theta)$$
 Equation 11

Phase advancing on the wave disk engine would only be used during testing and design because phase advancing limits the torque and therefor the power the motor is capable of producing and generating. A production wave-disk/motor/generator would be designed to produce maximum power without the motor moving into phase advancing operation.

This motor was designed, by Tariq Abdul under the direction of Dr Strangas. However the control system for the motor had to be custom designed for the motor and the wave disk engine. To accomplish this task a Yaskawa A1000 drive was purchased. This drive can operate up to 400hz, significantly higher than standard digital servo drives, in fact higher speed drives require goverment approval because of their possible use in uranium enrichment. This insures that high speeds can be reached even if another motor with higher pole count, such as the Thingap TG8251 is used. This drive is a robust digital drive designed for industry applications. The high speed digital control insures better transient response at normal operating speeds, however, the PID loops and motor parameters must be tuned carefully to insure short settling time and rapid response as the wave disk begins generating torque. The drive can operate the motor under sensorless control algorithms built into the drive. However the motor also was tested with a position sensor for better transient control. This motor has allowed some high speed testing of the Wave disk engine assembly allowing testing for structural stability.

3.6 ELECTRO/MECHANICAL ACTUATORS AND SENSORS

Electro-mechanical actuators, controls, and sensors are a mature technology that has found wide use throughout all aspects of industry and especially in the automotive industry. However, in a new engine design it still is pertinent to point out the specific uses and design considerations for the necessary actuators and controls.

All gas/fluid flow in and out of the engine is controlled and monitored to allow testing the engine under a wide variety of operating conditions. This starts with the inlet, both air and fuel must be controlled precisely. This is accomplished with several 500 and 1500 CFM air flow controllers. Several controllers with different ranges were purchased in order to accomplish well-tuned control over the whole operating range.

The fuel system operates similar to the air inlet system. The fuel may be liquid, but the current wave disk engines operate on compressed gaseous fuels, such as ethane, methane, and hydrogen. For liquid fuels a gas pump will be necessary, for current gaseous fuels, a flow controller regulates the fuel flow between the engine and the compressed tank. Both the gas and air systems work together to maintain a constant mix of gas/air into the intake of the engine. The ratio can be computer controlled and adjusted for maximum power or maximum efficiency. The air and gas is injected into the inlet at the center after being mixed in a mixing tube. Gas can also be injected directly into the channels if desired to achieve a more controlled injection right before combustion.

The Gas is controlled by smaller 20CFM and 50CFM flow controllers. They were chosen to fit the flow ranges required by the wavedisk engine, taking into account the different types

of fuels being tested. They are all controlled via the labview interface and also have a feedback signal to check for actual vs, controlled flow. Each controller can be turned off and bypassed if it is not being used. Each of these controllers has independent PID controls and digital logic allowing the user to select the gas and tune the controller for the accurate response. This allows for quick gas changover because the PID systems built into labview do not need to be changed for different controllers or gases. They are controlled and monitored via a labview programming insuring consistent air/fuel ratios, which can be changed at the touch of a button. The resulting gas/air delivery system is both intuitive and powerful.

Several pressure transducers monitor the pressure to record pressure variations as well as pressure loss throughout the system.

Outlet pressure and flow is not currently monitored because the wave disk is operated without an exhaust system, ie, the exhaust is ported directly into the environment. This reduces pressure buildup at the outlet and allows visual confirmation of some flame characteristics. However the system has extra channels available for pressure measurements wherever is needed. No additional programming or setup is necessary. The extra sensors needed for outlet pressure and flow measurements are already installed and only need to be attached to the measurement point using the supplied tubing. The necessary programming inside of labview is already finished.

3.7 ANALOG TO DIGITAL CONVERSION

The environment of the engine and test cell provided a challenging environment to obtain accurate electrical measurements from the various sensors. The motors are high voltage PMDC motors which can cause significant EMF interference near their windings which couple into the engine housing and from there onto the instrumentation. The ignition system is designed to provide over 40k Volts during very short firing intervals. This system is also coupled directly to the engine housing. In addition to this the wave-disk engine itself induces eddy currents in the housing due to the movement of the rotor with relation to the stator. Together this makes for an inherently high noise environment that demands careful wiring and sensor choices, not only to reduce interference but also to insure safety, especially concerning the ignition system. The interference from this environment is so extreme that a multimeter hooked up to nothing will read random voltages from outside the room during the wave-disks operation.

In order to reduce interference most sensors are isolated and run as 4-20mA signals. Signals of this type have a 4mA excitation voltage and the signal is between 4mA for minimum reading and 20mA for full scale reading. Current signals of this sort are common in industry and have the inherent benefit of high noise rejection due to their low effective resistance. In addition many signals can be chained off of a single power supply, and small power supply fluctuations don't have a large impact on sensor performance. Lastly 4-20mA signals have an inherent fault detection because an unpowered sensor will read 0mA whereas a powered sensor will always read at least 4mA. All signals that are not 4-20ma are collected as differential voltage measurements, which have a high noise immunity if wired and grounded properly as

well as shielded. After the analog to digital conversion the signals are averaged and sampled as necessary in the labview program to provide a highly accurate and low noise signal.

All input and output hardware is mounted in a separate DC only acquisition and control box, this helps to isolate the low level instrumentation control and feedback signals from the high voltage/high EMF environment of the motor, rotating machinery and ignition systems. Several ethernet based NI Compaq Daq systems connect to the control room and signal conditioning equipment is built into most of the DAQ modules, allowing for quick set up and troubleshooting see figure 25.



Figure 24: Data acquisition and control cabinet

3.9 HIGH SPEED ACQUISITION SYSTEM

Many custom sensors were built in order to capture data that was not available using typical technology. This allowed gas temperature, differential and absolute pressure inside and between channels to be monitored during operation.

There was a need to watch, in real time, the pressure and temperatures inside the engine during combustion. This data is needed in order to monitor the rate and completion of combustion events. Combustion between channels should be the same for each radial location in the engine. This can be monitored using sensitive pressure transducers placed on the top plate measuring into the engine. Specifically we wanted to watch the pressure variations both between channels, and before and after combustion. This allows actual inlet to outlet pressure, it also allows us to see how non-ideal sealing leads to some pressure transfer between channels. Further this data can be used to construct a reliable combustion map (like figure 1), showing how the combustion process expands over time and radial position as the channels rotate from the inlet position to the exhaust, where excess pressure is converted to usable torque for power generation.

In addition, Isolated, high temperature, high speed thermocouple elements can be used to monitor the temperature inside the combustion chamber. These can also be used to track flame propagation. These measurements must be made using special thermocouple or RTD elements that respond quickly to changes in environment temperature. In order to achieve this very low mass thermocouple elements must be used so that they have a small heat capacity, meaning they heat up and cool down as quickly as possible. Further they must be isolated well from surrounding objects such as the engine housing which has a substantial heat capacity. In

order to achieve this, the sensors have very small elements and are exposed in a recess in the engine chassis. They are mounted using ceramic tubing, which has a low heat capacity. This allows the sensing elements to measure the air temperature during every combustion event and stays isolated from the engine chassis temperature.

Figure 25 shows the custom pressure transducer assemblies, they consist of a small, low cost Honeywell transducer, which can be easily configured to give absolute or differential pressure. Sensor assemblies with ranges of \pm 5 and \pm 1 psi were built. They are calibrated using a homemade manometer gauge. This consists of a large u shaped clear tube with colored water in it. A slight pressure is applied to the tube and the sensors simultaneously, the resulting water displacement can be measured and used to find the exact pressure exerted. This data is used to create a scale for the sensors. These sensors are carefully shielded from the high harmonics created by the ignition system and the thingap motor. The temperature sensor is shown in figure 26. Both sensors can be mounted in a M10 thread whole, allowing it to fit in place of a standard spark plug hole.



Figure 25: Custom pressure transducer assemblies

The sensors work as promised delivering low noise, high speed profiles of pressure and temperature inside the engine. The following tests prove the sensors performance and than compare the performance to a commercially available Kistler tranducer purchased for the same purpose. Figure 26 shows a transient test, showing how the sensors adjust to a rapid change, figure 27 shows pressure fluctuations created as the channel walls pass over the sensor placed on the engine top-plate. The airflow is causing the rotor to rotate so there is no electrical interference, notice the third graph which shows the commercially available Kistler transducer.



Figure 26: Transient performance test (the x axis represents time and the y-axis represents pressure.)



Figure 27: Motor off, air flow 1000 slm, approx 1000 rpm. (the x axis represents time and the yaxis represents pressure.)

Figure 28 shows a similar test with the motor turned on, notice the motor controllers electrically induced switching transients on the Kistler transducer. Figure 30 shows a test with combustion, you can see the transient behavior from the channels passing underneath the sensor on the left and the total or DC pressure on the right. Combustion is turned on when there is an obvious rise in DC pressure showing a pressure gain from hot gases inside the engine.



Figure 28: Motor 1000 rpm, air flow 1000 slm, ignition off. (the x axis represents time and the yaxis represents pressure.)



Figure 29: Test with combustion, 900 rpm, transient pressure on left, DC pressure on right. (the x axis represents time and the y-axis represents pressure. Leftmost is transient response, rightmost is absolute or amplitude.)

It is apparent that the sensors work as expected; they are very resistant to noise and perform much better than the Kistler sensor. Notice the very clear switching harmonics created by the thingap motor that the Kistler is picking up in figure 28. These are not changes in pressure but are electromagnetic fields that are being induced onto the Kistler. This can cause problems if the source of the induced signal is not identified and is mistakenly thought to be actual pressure variations inside the engine.

The temperature Sensors are small footprint k or j type thermocouples with a custom housing that fits the standard M10 threads used in all wave disk engines for instrumentation. They are isolated from the chassis by a ceramic casing. See figure 30. The small size and isolation insures high speed temperature profiles to be measured. See figure 31 for a temperature profile during combustion.



Figure 30: Temperature sensors.



Figure 31: Temperature profile during ignition event (the x axis represents time and the y-axis represents temperature. The different lines are separate sensors.)

3.10 VIDEO MONITORING

Due to the layout and location of the test cell and control room a direct viewing window between the two spaces was not possible. This poses more than just an inconvenience, it is important to be able to view the test at all times to insure proper operation and to see if something goes wrong. To get around this problem, a four channel, 4 camera DVR system has been installed in the test cell. The DVR can be backed up or monitored through the control computer or the Ethernet network, consequently allowing a live view of a test anywhere in the world, using the assigned IP address. There is also always between two and four HD USB based video cameras used that allow high resolution video feedback of each test, and since they are small and portable they can be positioned almost anywhere inside the cell.

For audio feedback and recording there is an Audio Technica USB condenser microphone installed in the test cell. This allows high quality audio capture, which have be used to perform FFTs to monitor combustion or ignition discrepancies. It also allows for high quality audio feedback in the control room, making it easier for human based engine control and testing. Simple hearing the engine rev, as any mechanic can attest to, helps to gain insight into the operation of the wave-disk engine.

3.11 SAFETY

The system has been well designed and tested to insure safe operation. Room environmental controls monitor gas levels and temperature and several high speed fans allow the air in the room to be evacuated quickly. The engine controls include a keyed start box as well as several layers of E-stop.

An on screen E-stop stops the motor but leaves all peripherals running. A manual E-stop, forces all controls to zero to insure gas controls stop and ignition is disabled. A room E-stop shuts off all power to the test cell in the event of a major malfunction where uncombusted gases may be in the room or leaking. The environmental controls are built into the "major" Estop so the system will trip without human interaction any time certain percentages of ethane, methane or hydrogen are detected.

3.12 LABVIEW BASED CONTROL

The data acquisition and control system for the WDE test facility was designed to control engine tests and measure relevant data. The controls include motor-generator speed control and feedback, fuel and air flow control and feedback, and ignition system control and feedback. The data acquisition includes real time power measurements, rotational speed measurements, pressure and temperature measurements, and gas flow measurements. The computer interface was implemented in National Instruments's (NI) Labview software. An image of the computer interface is shown in figure 32.



Figure 32: Labview Control Screen (This screen shot of the user interface is for visual reference only and text is not meant to be readable)

The electrical I/O hardware is all state-of-the-art NI Compact DAQ equipment. One of

the advantages to using a modular acquisition system like this is that it can be easily

reconfigured as test needs and parameters change. However, the system is typically setup to

accommodate 8 pressure measurements, 16 temperature measurements, 4 mass flow controller interfaces, 1 motor controller interface, 1 ignition control relay, 1 tachometer input as well as all safety monitoring and feedback instruments. In addition to the Compact DAQ system, one of the motor drives is directly controlled by Labview via Ethernet Industrial Protocol. A block diagram of the DAQ is illustrated in figure 34.



Figure 33: DAQ block diagram

An Ipad is used for system maintenance, setup and testing. A remote log on application allows the entire Labview interface, and consequently, the whole test cell to be run from the Ipad. This helps greatly in debugging before a test, because each aspect of the system can be controlled safely from within the test cell, and every systems operation can be manually verified before the room is sealed and the test begins. It turns out the Ipad is also very handy for standing outside the control room during a test. If a user does not prefer the video camera feedback of the control room, they can simply stand outside the door and control the entire test from their hands. Often times this technique is used to get the engine operating well before running a test matrix, which is composed of many tests varying all variables around a specific operating point, a task which is best performed sitting down since there are thousands of combinations in each test matrix.



Figure 34: Labview VI on I-pad, sitting on wave disk engine (text is not meant to be readable in this photograph)

4 OPTICAL WAVE DISK ENGINE TEST CELL

A second Wave Disk Engine was set up in the Laser Diagnostics laboratory at MSUs EARL (Energy and Automotive Research Laboratory). The engine was designed with quartz viewing windows installed so high speed imaging and laser diagnostics could be performed to study the propagation of the flame front in the curved, rotating channels of the wave disk engine. A high speed camera was purchased for the task. An 8020 rig was constructed to provide safety from the engine and provide a sturdy stand which to house the Wave Disk and its associated electronics. See figure 35 for a view of the test cell.



Figure 35: Second WDE test facility with optical access.

The entire system consists of an ignition system, a motor/generator fuel and air control and complete data acquisition system. This test cell, while using a much smaller footprint, still has full control and feedback functionality. Like the larger test cell, a National Instruments Compaq daq data acquisition unit controls and monitors fuel and airflow into the engine, several temperatures, ignition, and motor control. The system has been very successful in studying flame propagation patterns and has helped to tune the other wave disk engines to have complete combustion inside the channels.

5 CONCLUSION

A new prototype engine design and a custom test environment was designed, built and the prototype was tested In only 30 months. The system uses modern data acquisition hardware and is able to control and monitor hundreds of analog and digital signals in order to complete test sequences on an engine prototype. This feat is possible because advances in technology allow larger data acquisition and control systems to be designed and implemented in a shorter period than previously possible. Advanced simulation and design programs allow fewer prototypes to be tested before a suitable real design is finished. Also todays engineers and scientists are as captivated as ever at the idea of inventing, designing, and developing something new. More than ever the need for more efficient, cheaper power generation systems are needed in order to curb current fossil fuel use and pave the way for a future with cheap limitless energy.

When compared to todays IC engines like those used in automobiles and small scale power generation; the wave disk engine has many advantages. It is small (high power to weight ratio) meaning that it can be cheaper and use less space than a similar power output IC engine; it has a single moving part making it easier to build, troubleshoot and fix, and it can easily be modified for small scale power generation as well as automobile power trains.

This small but efficient engine design promises to hold exciting potential for serial hybrid vehicles and small scale power generation. The team at MSU has been solving each obstacle as it is encountered. The wave disk engine pushes the state of the art in many mechanical and electrical systems.

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REFERENCES

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