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DEVELOPMENT OF DYNAMIC CONTROLLER FOR STATIC PISTON RING TEST RIG

School of Technology

2025

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TIIVISTELMÄ

Tekijä	Riku Lautamäki
Opinnäytetyön nimi	Dynaamisen ohjaimen kehitys staattiseen männänrenkaiden testilaitteeseen
Vuosi	2025
Kieli	Englanti
Sivumäärä	54 + 5 liitettä
Ohjaaja	Jani Leppämäki

Opinnäytetyö on tehty Wärtsilä Finland Oy:n Engine Structure&Power Systems-osaston toimeksiantona. Työn aiheena oli kehittää staattisesta männänrenkaiden testilaitteesta dynaaminen versio. Työ on toteutettu suunnittelemalla ja valmistamalla olemassa olevaan testilaitteeseen helppokäyttöinen ja monipuolinen paineohjaus. Työn tarkoituksena on poistaa nykyisen testilaitteen ongelmat, ja tuottaa luotettavampaa dataa.

Nykyistä testilaitetta on käytetty staattisiin männänrengasmittauksiin, joiden tarkoituksena on havainnollistaa männänrenkaiden ominaisuuksien vaikutusta ohivuodon määrään, sekä vertailla tuloksia simulointeihin. Testien aikana huomattiin, että toistotarkkuus vaihteli ja manuaalisten painesyklien välillä samalla renkaalla saattoi ohivuoto vaihdella huomattavasti. Tämä viittaisi männänrenkaan hakevan paikalleen. Monirengastesteissä saattoi paine kasaantua 1-2 männänrenkaan väliin, joka aiheutti ylemmän renkaan nousemisen, täten paineenlaskun ja ohivuodon kasvun.

Paineensyöttöä sykleittäin säätelemällä voisi saada renkaat hakemaan paikkansa paremmin, ja täten myös luotettavampaa dataa. Työn aikana suunniteltiin kaksi eri prototyyppiä, joista toinen valittiin jatkojalostukseen. Viimeisen version testaukset osoittivat, että renkaan tiivistäminen on jokseenkin sattumanvaraista. Tiivistys kuitenkin yleensä tapahtui äkillisen paineistamisen seurauksena ison poikkipinta-alan omaavan syötön avulla. Kun renkaat saadaan tiivistämään ja pulssi käyntiin, toimii järjestelmä kuten pitää, ja ohivuodosta saadaan halutulla aikavälillä ohivirtauksen keskiarvo. Ohjauksella saadaan karsittua staattisen testilaitteen vaihteleva toistotarkkuus. Testien perusteella voi todeta, että ohjaavat ja mittaavat komponentit pitäisi optimoida parhaiden tulosten saavuttamiseksi.

Avainsanat Wärtsilä, dynaaminen, männänrengas, ESP32

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ABSTRACT

Author	Riku Lautamäki
Title	Development of dynamic controller for static piston ring test rig
Year	2025
Language	English
Pages	54+5 Appendices
Name of Supervisor	Jani Leppämäki

This thesis was done for Wärtsilä Finland Oy- Engine Structure & Power Systems department. The aim of the thesis was to develop a dynamic version from the static piston ring rig. The thesis was executed by designing and manufacturing a pressure controller for the current test rig. The aim was to make it simple but flexible as possible for ease of use. The purpose of this thesis was to correct the existing problems and offer more reliable data.

The current static test rig is used to obtain data from various piston rings, to clarify the ring characteristics effects on blowby and comparison of data to actual measured values. During the tests it was noticed that the results varied, and the repeatability accuracy wasn't the greatest. During a manual pressure cycle on the same ring, the blowby changed which indicates that the piston ring is moving and trying to seat properly. Some multiring tests showed that during pressurising, the pressure builds up between the piston rings which results in the upper ring lifting. The lifting of the piston ring causes increase in blowby, giving faulty results.

The solution could be adjustable pressure cycles. With the help of pulsing action, the piston ring might stay seated better during the tests. As a result, the data relevancy and accuracy would be improved. During the work two prototypes were made, where the other one was selected for further processing. The tests made with the final version showed that the sealing of the piston rings takes place quite randomly, but usually as a result of sudden pressurising through a large orifice. When the rings start to seal the system works as intended, and the average flow can be extracted from the measured blowby. Based on the tests, it can be stated that the controlling and the measuring devices should be optimized to achieve the best results.

Keywords Wärtsilä, dynamic, piston ring, ESP32

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ABBREVIATIONS

NOx	Nitrogen-Oxide
PM	Particulate Matter
CO	Carbon Monoxide
PAH	Polycyclic Aromatic Hydrocarbon
VOC	Volatile Organic Compounds
TS	Twin Stage
So2	Sulphur Dioxide
NPT	National Pipe Thread
MAF	Mass Airflow Sensor
ADC	Analog to Digital Converter
Vdc	Voltage Direct Current
MCU	Micro-Controller Unit
GPIO	General Input/Output
Wi-Fi	Wireless Fidelity
N.C	Normally Closed
ΔP	Delta P/ Pressure differential
N.O	Normally Open
PWM	Pulse Width Modulation
PID	Proportional Integral Derivate
DAQ	Data Acquisition
PLA	Polylactic Acid
IDE	Integrated Development Environment
Hz	Hertz
GW	Gigawatt
kW	Kilowatt

LCD	Liquid Crystal display
PETG	Polyethylene Terephthalate Glycol
ASA	Acrylonitrile Styrene Acrylate
PA	Polyamide/Nylon
SSR	Solid State Relay
EMF	Electromotive force
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
EMOSFET	Enhancement- Metal-Oxide-Semiconductor Field-Effect Transistor
DMOSFET	Depletion- Metal-Oxide-Semiconductor Field-Effect Transistor
BLE	Bluetooth Low Energy
UART	Universal Asynchronous Receiver Transmitter
SPI	Serial Peripheral Interface
I2C	Inter-Integrated Circuit
DAC	Digital to Analog Converter

1 INTRODUCTION

Piston rings are in a key role in a combustion engine, and the tightening emission regulations and decarbonization with new fuels require even tighter specifications and tolerances of components. For that reason, blowby and oil consumption need to be optimized. The test rig is a useful tool for validation of simulation models or examining various ring designs and their effects on blowby.

The subject of this thesis started from the tests made on the static ring rig meant for testing various piston rings. The static ring rig is a combination of parts from a Wärtsilä medium bore engine, customized to form a test rig, where various kinds of rings or ring combinations can be tested. The test rig layout will be explained in more detail in Chapter 4.

The problem, as shown in Figure 1 below, is the upper ring lifting during multiring tests. This can be seen as a pressure rise between the rings, visualised by the blue line. This phenomenon shows as an increased blowby and therefore false results. On single ring tests this is not a problem, as pressure cannot build up under the ring.

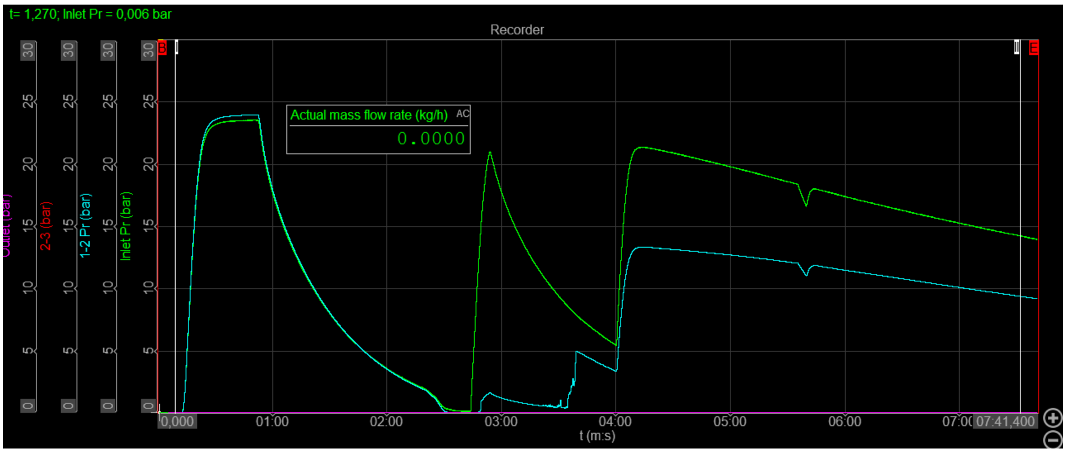

Figure 1. Graph presenting upper ring lifting viewed in Dewesoft X.

During a manual pressure cycle the ring would always reseat differently, resulting in flow and pressure deviation. It was assumed that adding some dynamism would help with the noticed problems, as it is more realistic regarding the usual environments of piston rings. With the dynamic pressure curve and possibility of sudden pressurising, it could be that the ring would stay seated and the averaged flow data from the pressure cycling would be more relevant.

The aim of this thesis was to develop a dynamic version of the existing static piston ring rig, by designing a simple to use controller and leaving the rig as is. The purpose is to have minimal external modifications to the rig itself. This ensures the possibility of going back to the base version easily. During this thesis, two prototypes are made to clarify the best solution regarding the controller itself. When prototyping is done, the improving of the base version and implementing of features to the actual controller is started. The results of this thesis is a working and tested controller, which has the needed features and functions as expected.

2 WÄRTSILÄ IN GENERAL

Wärtsilä was founded in 1834 and started as a sawmill in a small village called Värtsilä located in Tohmajärvi in the north Karelian region. Later in 1852 an ironworks was built on the premises and in 1898 the company was renamed as Wärtsilä Ab. A major setpoint in the company's history was in 1938, as their era of diesel engines started when Wärtsilä signed a license agreement with Friedrich Krupp Germania Werft AG in Germany. The first licensed diesel engine was built in November 1942 in Turku, Finland and the first own designed engine called V614 in 1960. (Wärtsilä, 2025)

Figure 2. Old Wärtsilä logo (Wärtsilä, 2025).

Wärtsilä offers multiple products and services but it is particularly known for its medium speed four-stroke engines. Their catalogue consists of multiple size and type of engines, with varying power outputs and the possibility of running multiple kinds of fuels. Marine and energy sectors are accountable for approximately third of the worlds carbon emissions, which is why new engines and solutions are constantly being developed. (Wärtsilä, 2025)

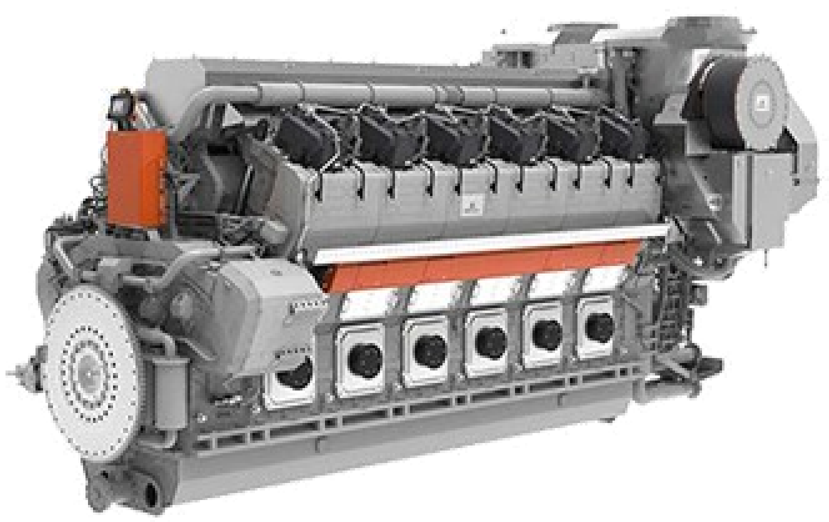

Figure 3. Wärtsilä 46TS engine (Wärtsilä, 2025).

Wärtsilä`s organization consists of three sections: Marine, Energy and Portfolio business with each focusing on different tasks. Wärtsilä Marine provide customers a wide range of products and services, such as power and propulsion (engine related), liquid and gas handling (fuel related) and voyage and fleet optimization. The Services used to be an own section in the organization but has then been integrated into Marine solutions and provides customers with spare parts, expertise and all kinds of tech related services. The Marine solutions focuses on decarbonisation and future fuels. Wärtsilä has become a global leader in innovative technologies and lifecycle solutions on the marine and energy markets, with over 17,800 employees in 79 countries and a total net sale of around EUR 6 billion as of 2023. (Wärtsilä, 2025)

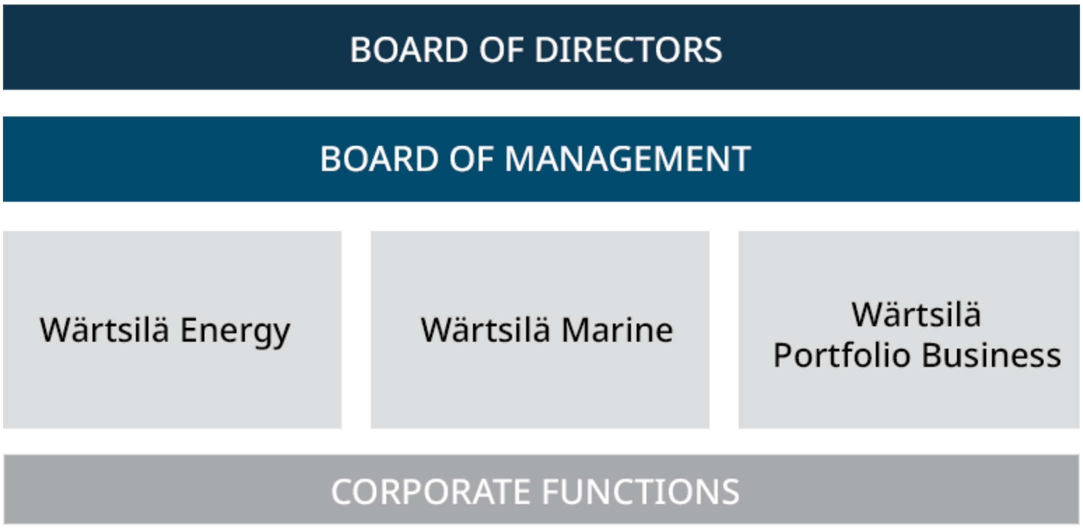

Figure 4. Wärtsilä organisation (Wärtsilä, 2025).

Wärtsilä Energy's main products are different kinds of power plants, either engine or hybrid powered, and energy storage solutions and optimization. Energy solutions is the leader in the change towards the future, where all the electricity is produced with 100 percent renewable energy. Wärtsilä has delivered a total of 79GW of powerplant capacity and over 110 energy storing solutions to 180 countries. The Portfolio business units are run independently to improve performance and unlock value through divestment or other strategic alternatives. The units included: Automation, Navigation and Control Systems (ANCS), Gas solutions, Marine electrical systems, and Water & Waste. (Wärtsilä, 2025)

3 PISTON RINGS

Piston rings are metallic rings that sit in the piston ring groove between the piston and the cylinder wall. The main three functions of the piston rings are to seal the combustion chamber keeping the gases from entering the crankcase between the piston and the cylinder wall. Heat dissipation from the piston, and the control of oil on the cylinder walls also belong to the piston rings. There are many things to be taken into consideration regarding friction, material, ring profile and overall design. As engines develop, emission restrictions get tighter, and new renewable fuels are introduced, the piston ring development is crucial to meet the requirements. (Van Basshuysen & Schäfer, 2016, pp. 102-109)

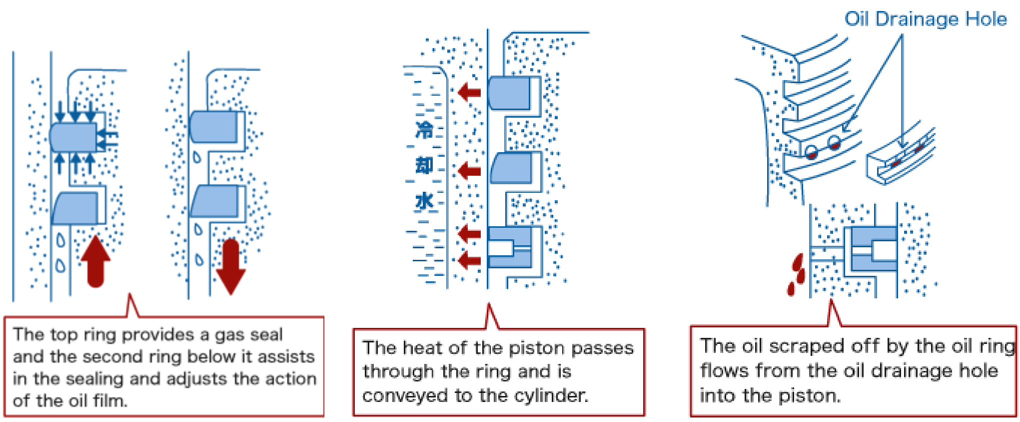

Figure 5. Piston ring properties (Riken c, n.d).

Illustrated in Figure 6 below the support effect of the piston ring can be seen. As the piston itself is not cylindrical but rather conical, some rocking motion can be generated. Piston rings provide some extra support for the piston, reducing the rocking motion of the piston or so called "piston slap". (TPR, 2021)

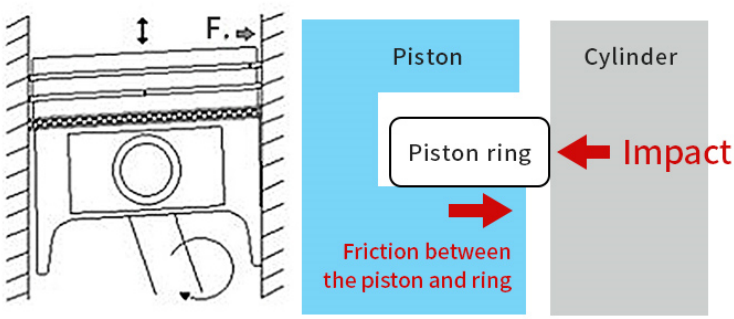

Figure 6. Piston ring support effect (TPR, 2021).

A basic piston ring assembly usually consists of three rings as shown in Figure 7 below. The first compression ring on top which serves as the primary seal of the combustion gases. This ring takes the most load regarding thermal stress and mechanical loading. The profile of the piston ring running face affects performance, and the top ring face is barrel shaped to keep the contact area small thus achieving higher contact pressure. (Riken d, n.d; TPR, 2021)

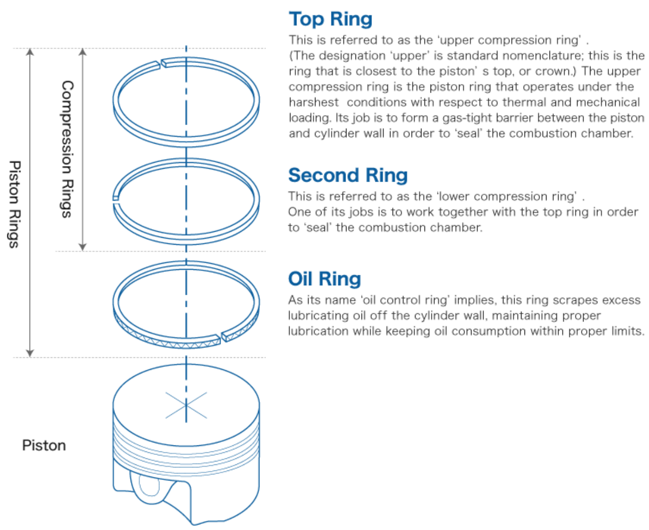

Figure 7. Piston ring assembly (Riken d, n.d).

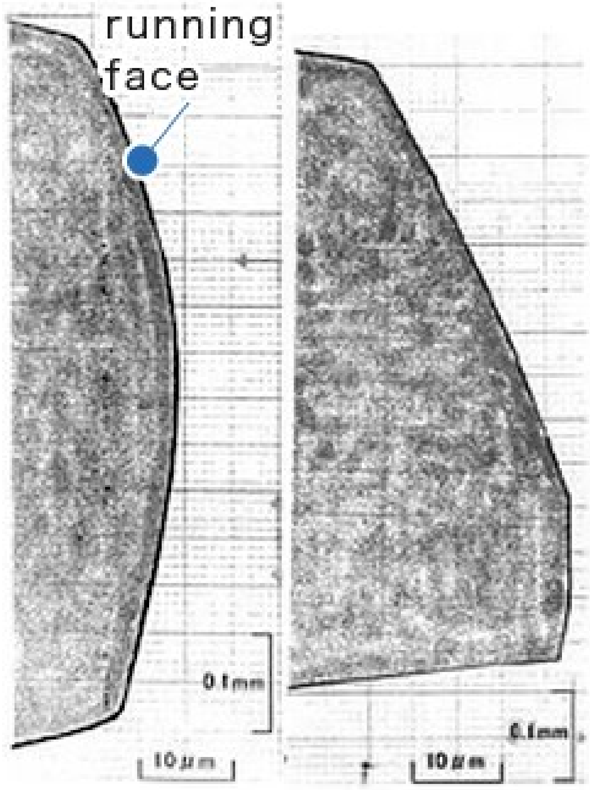

Figure 8. Top ring running face on left and second ring on the right (Riken f, n.d; Riken g, n.d).

The second compression ring has the same task but also scrapes off the excess left from the oil scraper ring, and it is not subjected to the same kind of loading as the top ring. The second compression rings profile differs by having a bevelled edge, helping with oil retention and control. The third ring is known as the oil scraper ring, and it serves as the main oil control ring. This ring scrapes off the excess oil from the cylinder walls, and the oil flows through the holes in the piston ring groove back to the crankcase. This ring prevents excessive amounts of oil from reaching the compression rings. (Riken b, n.d; Basshuysen & Schäfer, 2016, pp. 102-109)

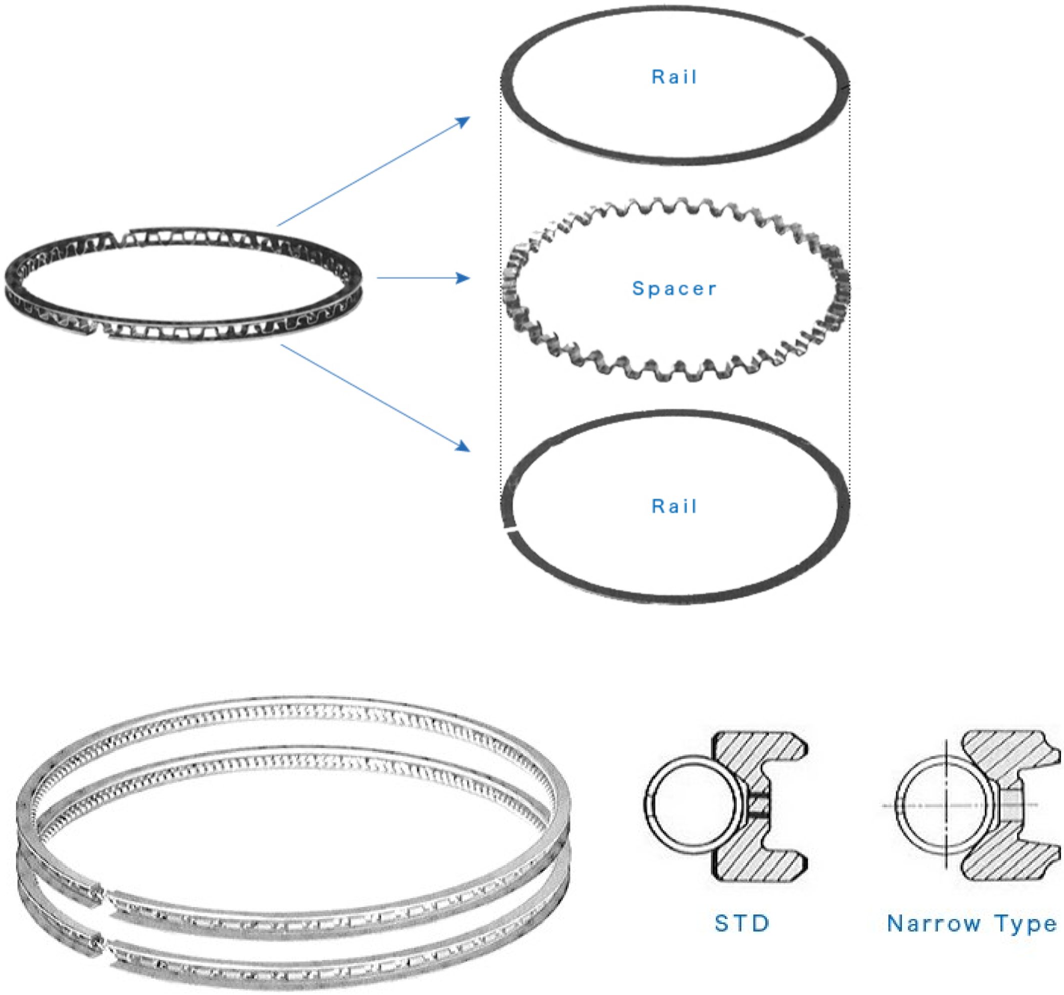

Figure 9. 2- and 3 -piece oil control rings (Riken b, n.d).

The structure of the oil scraper shown in Figure 9 is the most common design usually seen in automotive applications. The 2-piece configuration is more common in diesel applications, but also in some gasoline engines. Both configurations can be seen in Figure 10, and how the 2-piece design differs by having an m-shaped steel rail paired with a cylindrical spring coil. Piston rings also dissipate heat from the piston to the cylinder liner and to engine coolant from there on. The heat dissipation rate chart can be seen in Figure 10 below. (Riken b, n.d)

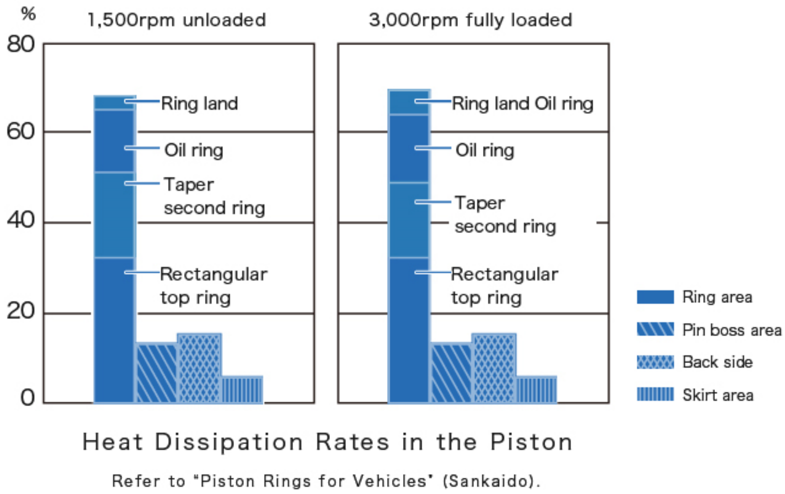

Figure 10. Heat dissipation chart of components (Riken h, n.d).

Piston rings are subject to a lot of forces and thermal stress, so they need to cope with those extreme conditions, therefore material selection and design criteria are crucial for functionality and longevity of the component. The piston rings are developed, tested and checked according to the set criteria, before making their way to a production engine. Several materials are used but most common ones are flaked graphite cast iron, nodular cast iron or steel. Different kinds of heat treatments and coatings are used to achieve wanted properties and resistance against wear. The rings can be hardened, nitrided or coated, where the basic hardening is the most usual one. Regarding the coating, certain rings are usually chrome or chromium ceramic plated. The right methods always depend on the application of the ring. (Riken h, n.d; Basshuysen & Schäfer, 2016, pp. 102-109)

Piston rings are internally spring loaded which means that the piston ring is oval shaped in free form and circular in compressed form. This results in a tangential force which is expressed as applied force on the piston ring end to compress the gap to a certain distance, and it determines the contact pressure thus the sealing function of the ring. Figure 11 shows the ring properties. (Basshuysen & Schäfer, 2016, pp. 102-109)

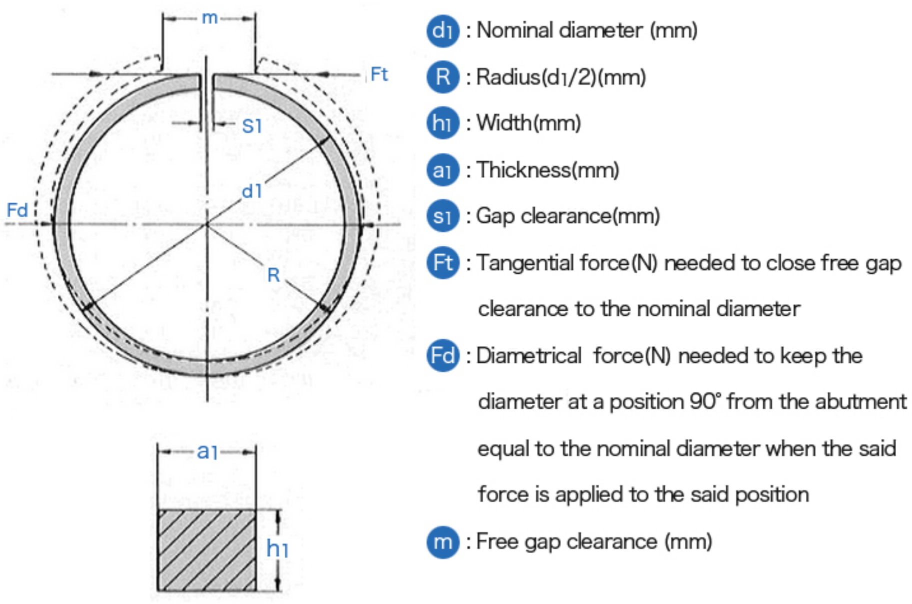

Figure 11. Ring properties (Riken e, n.d).

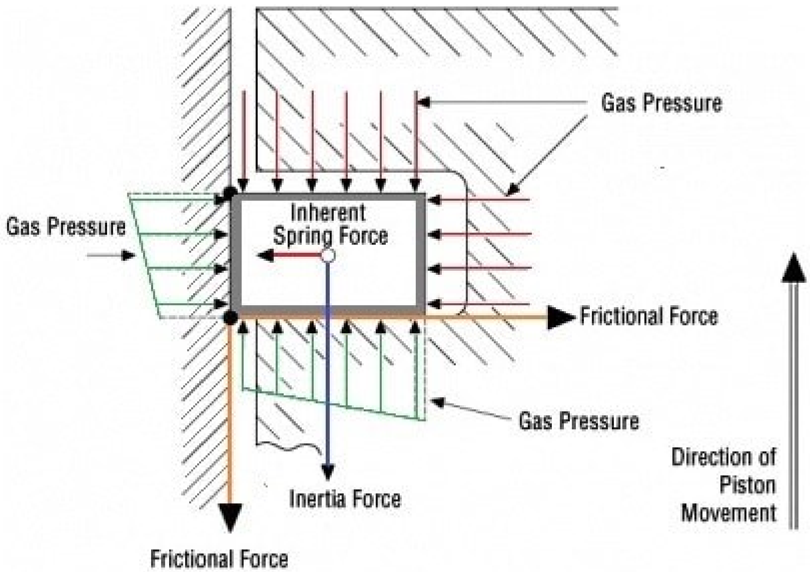

Figure 12. Forces acting on the piston rings (Euroring, n.d).

Blowby describes the combustion gases escaping between the piston and the cylinder wall, past the piston rings to the crankcase. Blowby is normal to a certain level as the piston rings and grooves are not perfectly sealed. Most of the blowby comes from piston ring end gap, which is to prevent ring ends to butt against each other due to thermal expansion. Too much blowby is an indicator of some kind of mechanical failure or a bad design, resulting in excessive crankcase pressure. Blow by is a feature that is to be kept at a minimum level. (Solberg, 2023; National Library of Medicine, 2017; Riken h, n.d)

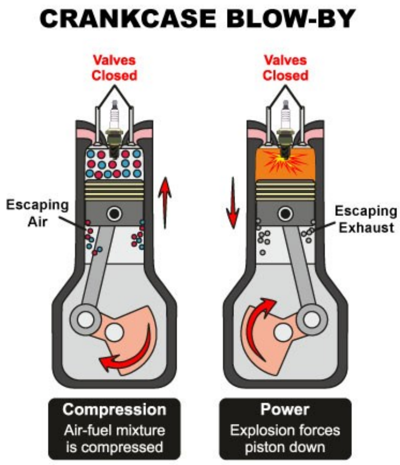

Figure 13. Blow-by in piston engine (Solberg, 2023).

Following the decarbonisation and tight emission-restrictions, the oil consumption plays a big role on low-emission engines. Burning oil produces multiple kinds of pollutants, such as nitrogen oxides (NOx), volatile organic compounds (VOC), sulphur dioxide (So2), polycyclic aromatic hydrocarbons (PAH), carbon monoxide (CO), and particulate matter (PM). Emission altering devices are fitted on the engine, but they are not designed to cope with excessive burning oil. Excessive oil consumption can be caused by defects in the components for example, carbon buildup on the rings causing them to get stuck. New fuels such as hydrogen are more susceptible to burning oil, thus the oil consumption plays even a bigger role than with regular fuels. Excessive burning oil can also cause preignition in gas powered engines. (Solberg, 2023; National Library of Medicine, 2017; Riken h, n.d; Koeser & Dinkeacker, 2019)

4 STATIC PISTON RING TEST RIG

The piston ring test rig is custom made utilizing existing parts from a certain engine. The main parts are the piston crown, base plate and the pressure chamber itself. The rig utilizes a modified cylinder liner and piston crown from a certain Wärtsilä medium bore engine, so it’s an engine specific test rig. The rings are mounted in the piston grooves and the package is fitted inside the liner and bolted down. The rig also has adjustment for the piston crown base, so the eccentricity of the pack can be adjusted via four screws, thus the ring end gap sealing area adjustment is possible. Figure 14 displays the cross sectional cut of the rig shows the main features.

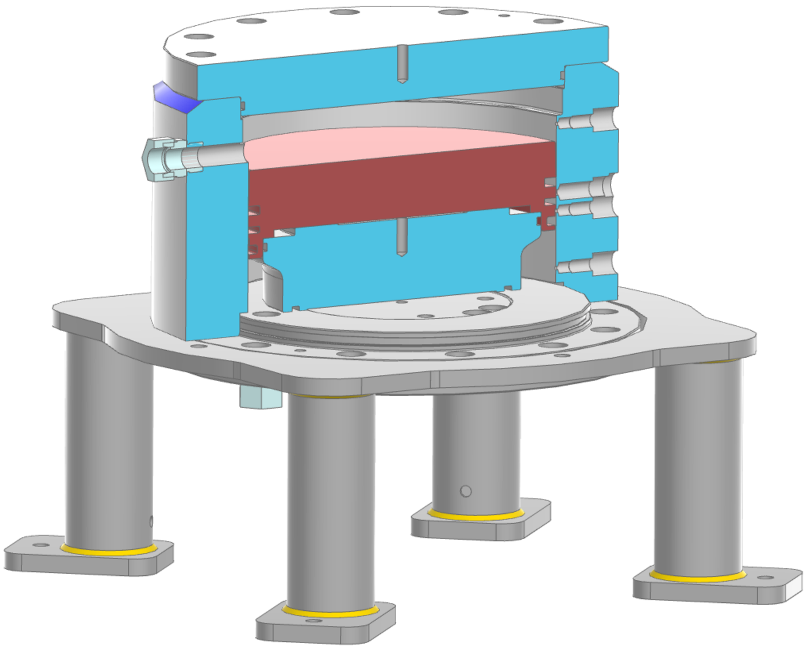

Figure 14. The test rig.

Air is fed to the top chamber and ventilates out at the bottom, as it travels past the piston rings. The rig is designed to be operated at 0-30 bar pressure though the higher range is rarely achievable. Total of 4 pressure sensors are connected to the rig as shown, and they are logged through Dewesoft Sirius to the Dewesoft X software.

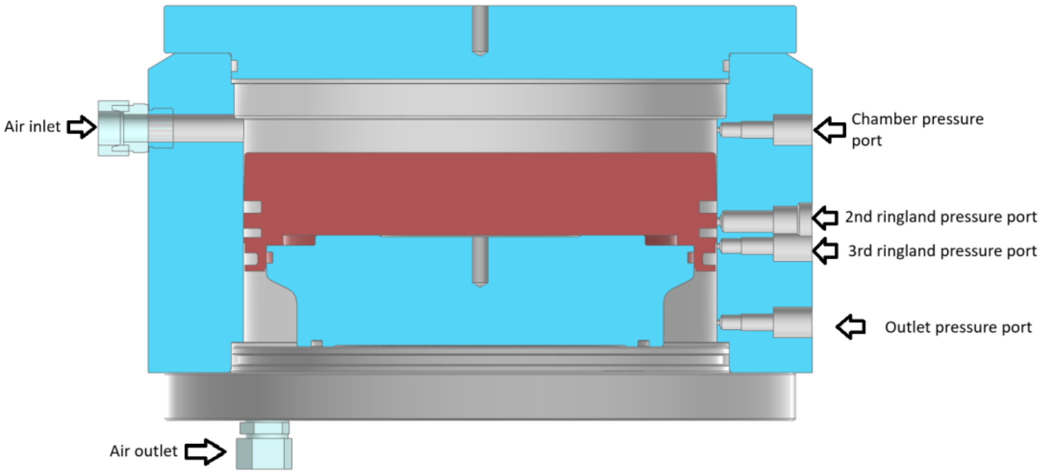

Figure 15. Pressure ports & inlet/outlets.

A high accuracy Emerson Coriolis twin tube mass airflow sensor is fitted either on the inlet or outlet side to measure the escaping air past the rings. On the static version the flow meter was on the inlet side but for the dynamic version it must be placed on the outlet side to measure actual flow past the rings, due to the design and plumbing of the controller. If fitted on the inlet side the readings will be false, due to the venting action of the solenoid.

The solenoid orifices are relatively small; thus, no backpressure should be formed in the bottom chamber, caused by the outlet placement of the MAF. With bigger orifice solenoids the bottom chamber pressure should be monitored if the MAF causes restrictions resulting in backpressure. The purpose of the test rig is to gather data from various rings and combinations and compare them to simulation results and real measured values to determine the validity.

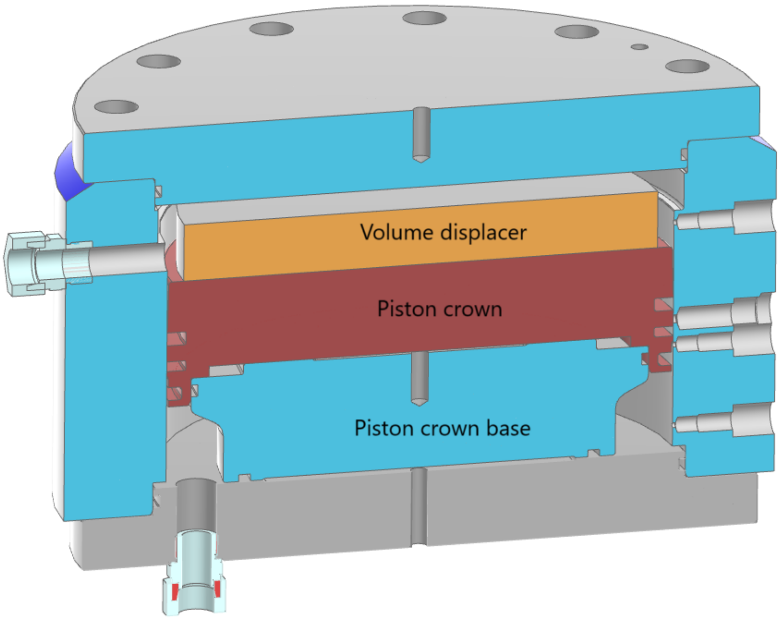

Figure 16. Cross-section with volume displacer displayed in yellow.

To get the controller to work on the actual rig only one necessary modification needs to be done, so a 1/8 NPT pipe thread must be made somewhere on the rig for the pressure sensor. Supposedly the thread should be made on top of the rig as it is the easiest and the most accessible place. Secondly, moving the MAF from the inlet side to the piston ring rig bottom vent port to see the actual airmass going past the rings. The chamber volume will be modified with a use of 3D-printed spacer shown yellow in Figure 16. As the solenoid orifices are relatively small the chamber volume must be greatly reduced from original.

5 RIG CONTROLLER PROTOTYPES

In this chapter we will go through the first and second controller prototypes. The final version to be tested on the rig is a redeveloped version based on the second prototype. The first prototype was made based on assumptions, so the work started by designing and testing different solutions. The idea was simple: welding a small pressure tank with a certain displacement, attaching a pressure sensor to the tank and connecting the lines from pressure source through a single 3-way MAC 35 series valve, through a needle valve to the tank.

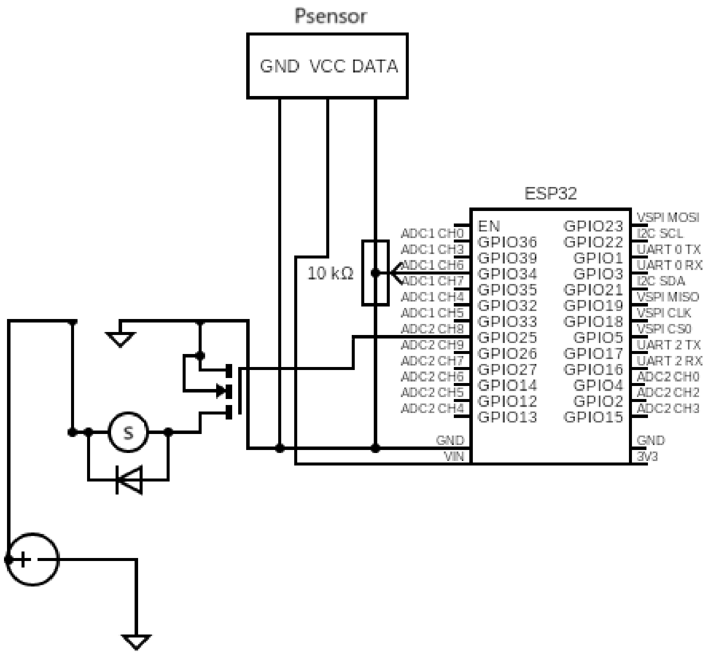

Figure 17. First prototype wiring diagram.

The solenoid is controlled with an ESP-32 clone via transistor with feedback from the sensor, making it a simple closed loop controller. The idea behind this was to have a variable orifice size and just use a solenoid with a big orifice and control the flow via the needle valve. As the system only had two pressure thresholds for the solenoid to activate and deactivate this made it simple, easy to use and lastly it would be reliable.

With this system the solenoid would be only driven on/off and the pressure oscillation frequency would be controlled with the needle valve. The needle valve restricts the flow thus the affecting pressurizing and depressurizing as the valve is bidirectional. This method results in almost symmetrical waveform. Instead, two flow control valves could be fitted to control both slopes separately. The control behaviour of first prototype is illustrated below as an example image. Note that the actual pressure wave produced is not perfectly symmetrical, but rather sawblade teeth shaped, caused by the bleeding action of the rig and the solenoid configuration.

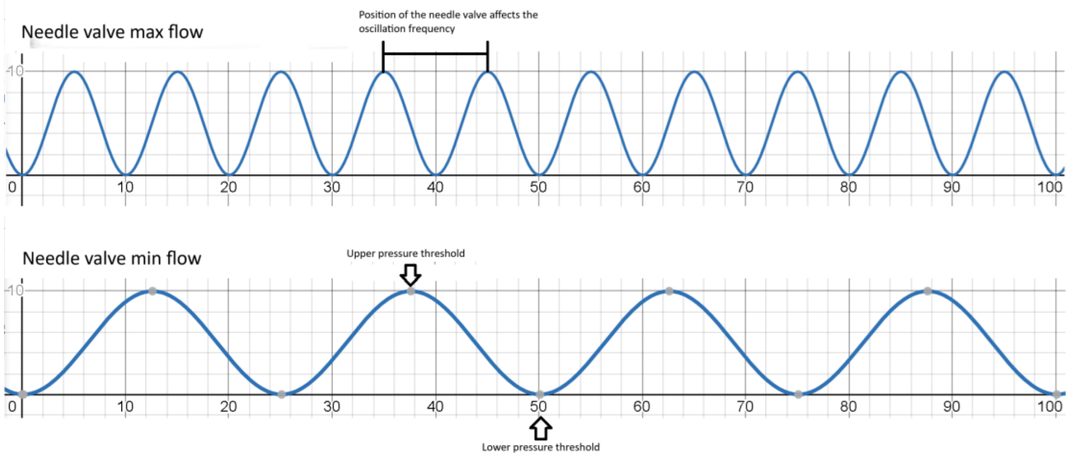

Figure 18. Needle valve at various positions.

This prototype works well, but finding a proper needle valve rated for higher air pressures and flow seems to be hard. Hydraulic needle valves were available for much higher-pressure rates. They are not designed for pneumatic applications but could work. This type of controller would be a considerable option regarding the simplicity and the reliability of the more mechanical design if a proper restrictor valve can be found.

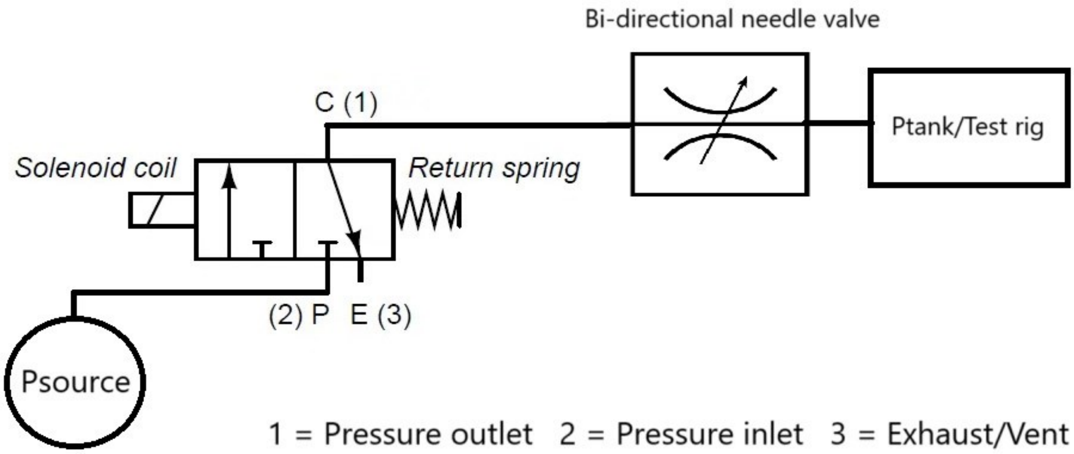

Figure 19. First prototype pneumatic connection diagram.

5.1 Second Prototype Design

The second prototype was made as an alternative option for the first version. This version uses components mainly from the previous version, without the needle valve and has another 3-way MAC valve connected to the first solenoids bleed port. Two potentiometers are connected to the ESP-32 ADC pins, controlling the duty cycles and pressure setpoints. In Figure 20 below, a test version of the second design hybrid can be seen. This version has both designs built as one package, so it has the flow restrictor valve and both solenoids.

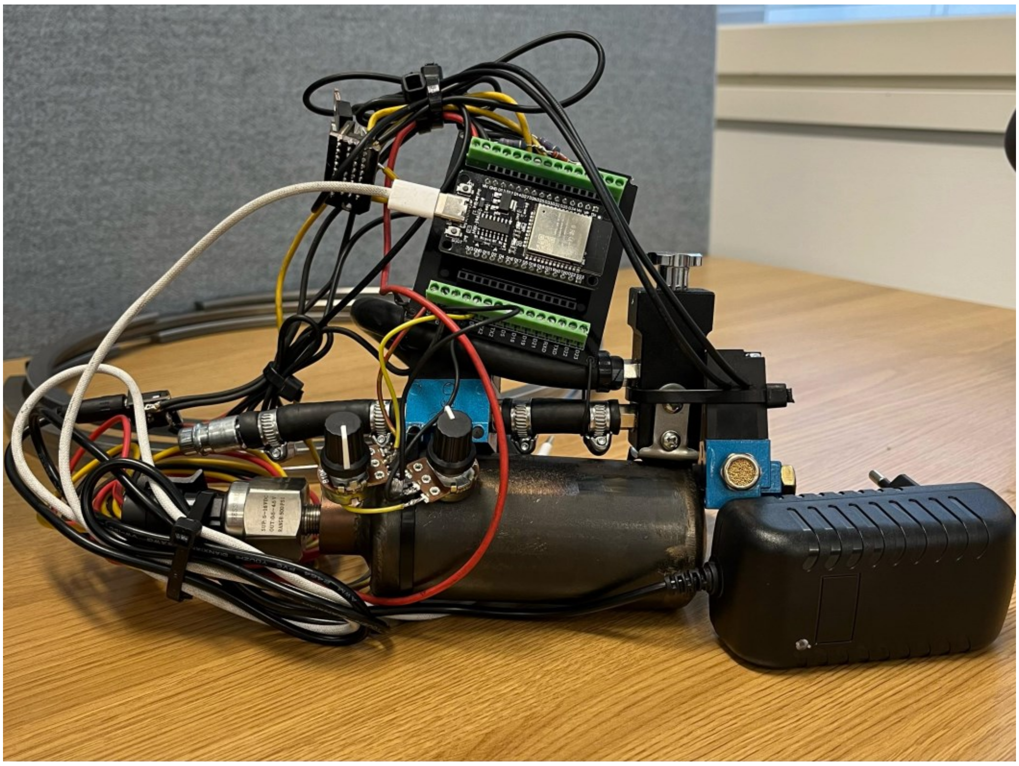

Figure 20. Second prototype built on top of the mechanical version.

The idea of this version is to control both up- and downslope separately with two solenoids by PWM-signal of a certain frequency. This system works by pressure thresholds where the solenoids switch on and off according to logic state and during the solenoid on-time the PWM duty cycle is controlled via the potentiometer. This system is fully electrical and does not feature any mechanical control. Shown in Figure 21 below is the final test version wiring diagram. This has additional two potentiometers, a dc-dc converter and a 4A fuse added, compared to the second prototype version. Other than the previously mentioned, the wiring stays the same. The wiring and the box electronics can be seen in Appendix 2 A/B.

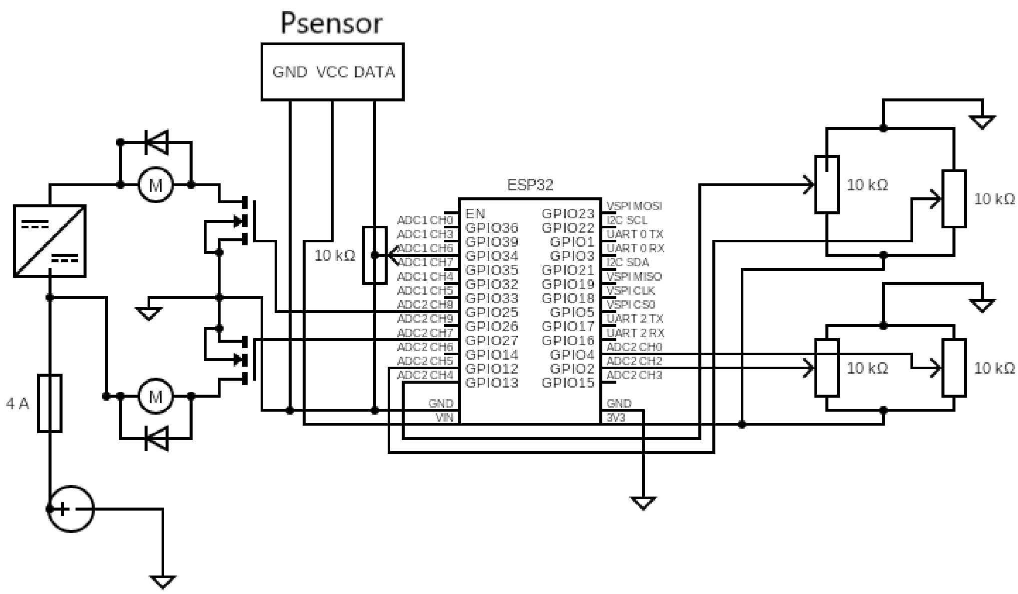

Figure 21. Final test version wiring diagram.

In Figure 22 below, the routing of normally closed and open 3-way solenoids can be seen, and the connections are made accordingly. The term normally closed indicates that the solenoid is closed in de-energized state and vice versa for normally open configuration. 3-way solenoids allow flexibility as they can be used either in N.C or N.O configurations just by changing the plumbing.

Solenoid 1 is controlled during increase state and solenoid 2 is controlled during decrease state. Duty cycles for the solenoids are regulated by the user with use of a potentiometer. Both solenoids are never on simultaneously, as the logic states are triggered by the pressure thresholds. The pressure thresholds are also controlled by the user the same way as the duty cycle, in a range of 0-30 bar on both solenoids.

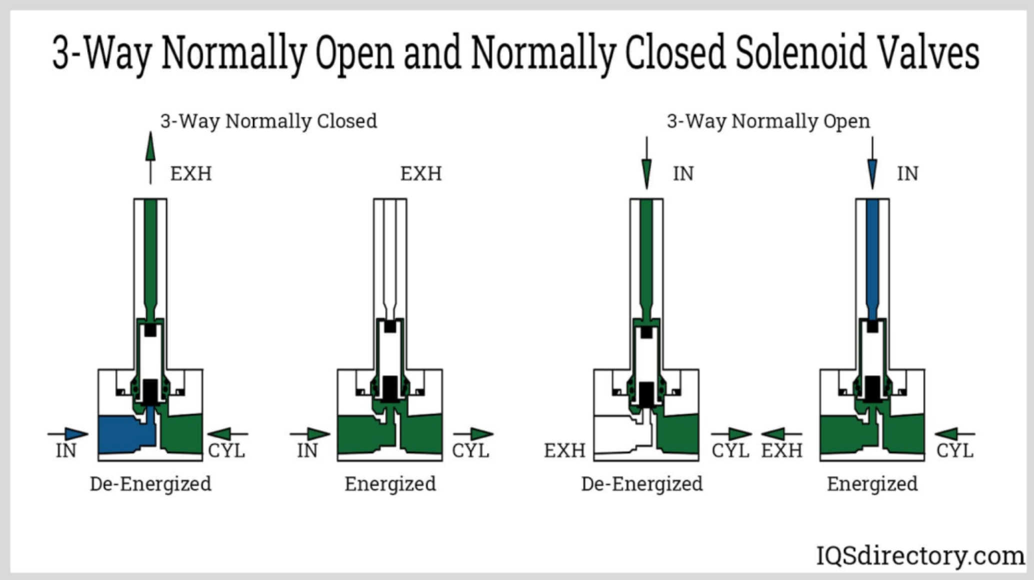

Figure 22. 3-Way solenoid plumbing (Industrial Quick Search, n.d).

Shown in Figure 23 when energized during the increase state, air flows through the solenoid to the tank until upper pressure threshold is reached, and logic state is switched to decrease. During decrease state solenoid 1 is de-energized thus the feed is closed.

Air flows from the tank through the solenoid 1 to the feed port of solenoid 2. During decrease state the microcontroller controls solenoid 2 the same way as during increase state/solenoid 1 control, until the lower pressure threshold is reached. The controlling order can be seen in Figure 23 below, where numbers 1 and 2 refer to the first solenoid and number 3 refers to the second solenoid.

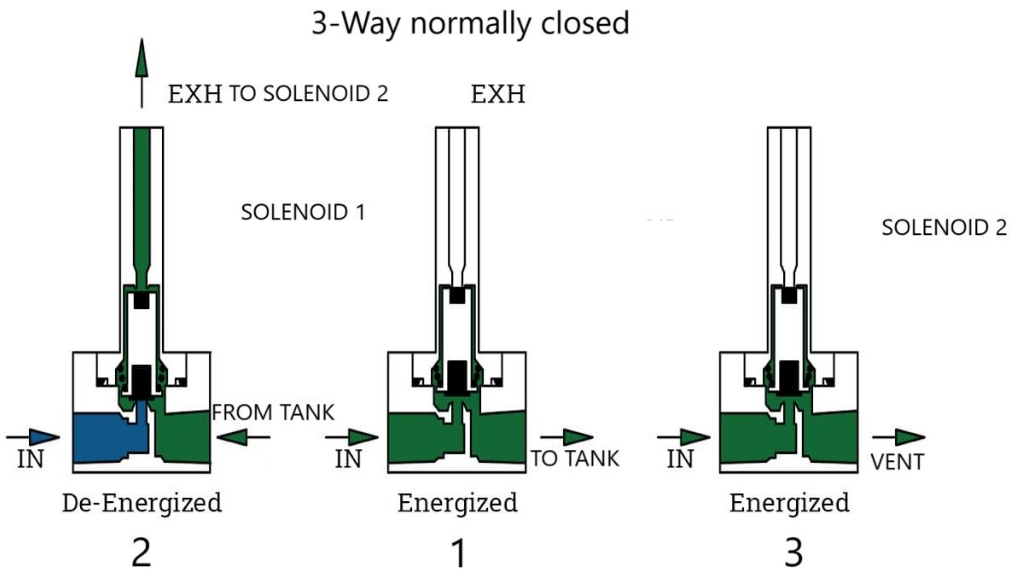

Figure 23. Solenoid connections (Industrial Quick Search, n.d).

The use of 3-way solenoids is not necessary, and they could be replaced with 2-way versions instead, with a physical divider connecting the pressure lines. This might be the case with higher pressures, as 2-way solenoids are easier and less expensive to source. Also, a combination of 3- and 2-way solenoids can be used as the second solenoid essentially works as a 2-way solenoid visualized in Figure 24 below.

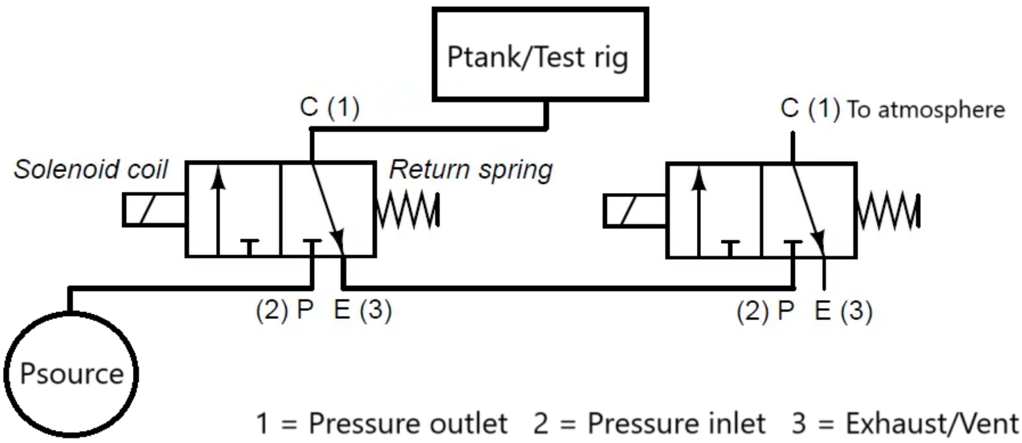

Figure 24. Second prototype pneumatic diagram.

The idea of this type of controller is the ability to control the slopes separately, as in the first prototype the pressure curve remains quite symmetrical. This design allows the shape and the frequency of the curve to be controlled. Also, with this design the solenoid orifice and control frequency should be matched to the pressure tanks displacement, regarding the controllability of the curves. Alternatively, the displacement inside the pressure tank could be reduced by placing objects in it. This would displace some volume from the tank and result in the ability of using a smaller orifice solenoid.

Most of the higher pressure rated solenoids work on 24 VDC instead of 12 which the ones in the prototype use, but in the final controller there would be 4A fused outputs for both 12 and 24 VDC for flexibility. The outputs also have flyback diodes, to protect the transistors from harmful voltage spikes known as back EMF during solenoid deactivation. This phenomenon will be explained in more detail in Subsection 5.4.

5.2 ESP 32 and Arduino IDE

ESP32 is a microprocessor made by Espressif. It’s a powerful MCU with a high level of integration and wide usage capabilities. ESP32 has a 240Mhz 32bit dual core processor, 8mb flash, 24 GPIO pins and onboard Bluetooth and Wi-Fi. All variants have built-in BLE and various I/O interfaces such as UART, SPI, I2C, ADC, DAC and PWM. ESP32 boards are very versatile and can be used in wide range of electrical applications. The ESP32 specification sheet can be seen in Appendix 1. (Zulfiqar, A. 2024)

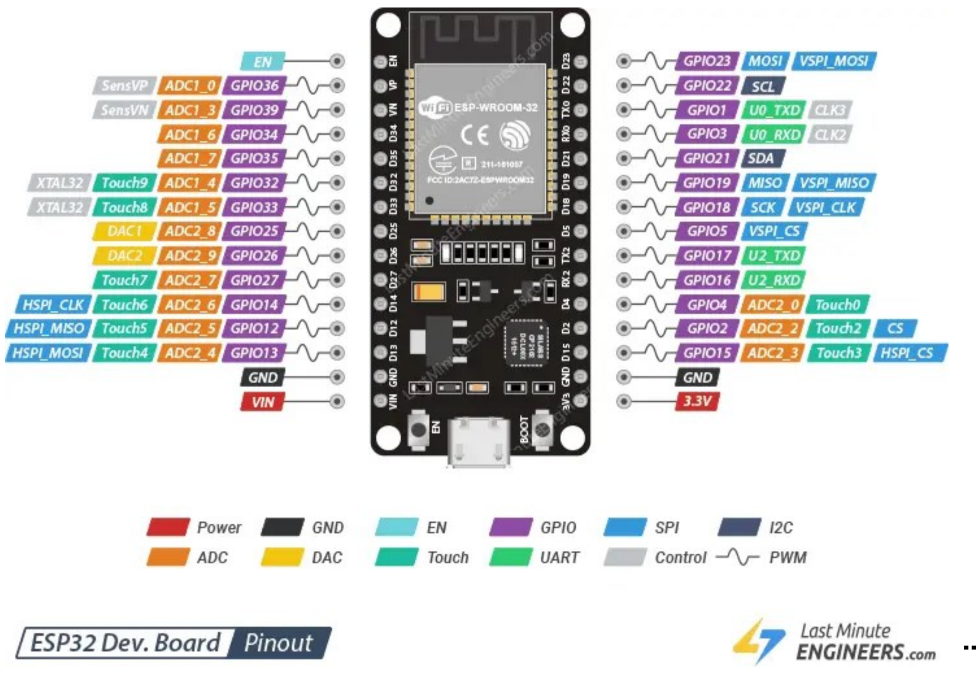

Figure 25. ESP-32 30p pinout. (Last Minute Engineers, n.d).

Note that the over/undershooting of the setpoints in Figure 26 below are partially caused by the sampling of the readings to get an average value, meant to stabilize any erratic readings. With setpoints close to each other there will be slight over/undershoot, but with bigger pressure gaps this will be reduced. After testing it was noticed that the program code also had a slight flaw, as the logic used the non-averaged threshold values. This led to slightly fluctuating pressure setpoints, thus the noticed over/undershooting. This was not an actual problem, as accurate thresholds were not needed. The code was corrected after the testing and can be seen in Appendix 3 A/B.

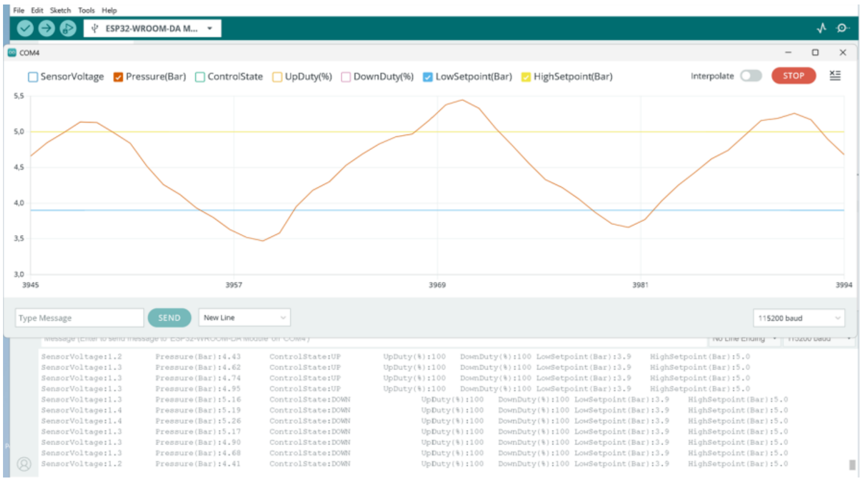

Figure 26. IDE serial monitor & plotter data.

Arduino IDE or Arduino Integrated Development Environment is a software meant for coding, debugging and writing data to Arduino boards. It's also used for coding the ESP32 boards, as they run on the same code. The coding language is C/C++, and the suite is quite user-friendly and easy to use. The software includes basic debugging and logging abilities, such as the serial monitor and serial plotter shown in Figure 26. In this figure the pressure setpoints and actual pressure measured by the sensor are illustrated.

5.3 MOSFETs & Flyback Diodes

As the solenoids need to be powered with 12 or 24 volt and the ESP32 pins are rated to a maximum of 3.3 volts, some kind of controller or relay is needed. A relay would be an option, but a normal contactor relay relies on 12V control signal and cannot be used with PWM due to the physical structure of the relay. An SSR or so-called solid-state relay would be a better option, as it can be switched on with 3-32Vdc signal and operated via PWM due to its differing structure. These relays tend to be much more expensive and noticeably larger in size than a logic level MOSFET. Taking into consideration compactness, the maximum control voltage of the ESP-32 and the need for the normal state of the component to be OFF, the best option is an N-channel EMOSFET.

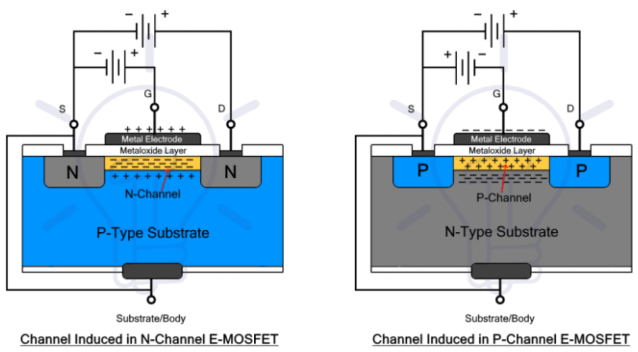

Figure 27. Channel basics in EMOSFETs (Electrical Technology, 2021).

There are two types of enhancement and depletion mode MOSFETs, the N-channel and the P-channel version. The N-channel features a lightly doped p-substrate and heavily doped n-regions which form the source and drain terminals. The P-channel version on the other hand features a lightly doped n-substrate and heavily doped p-regions which form the source and the drain terminals. (MADPCB, 2025; Elprocus, 2025)

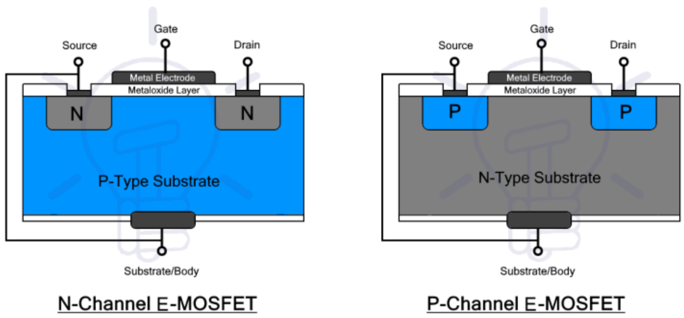

Figure 28. N/P EMOSFET structure (Electrical Technology, 2021).

EMOSFETs are normally OFF at zero gate to source voltage and cannot carry current in OFF position. They do not feature a permanent channel, and the gate voltage is directly proportional to the drain current. The DMOSFETs, differ from the previous ones by being normally ON at zero gate to source voltage, and can carry current in OFF position. They feature a permanent channel, and the gate voltage is inversely proportional to the drain current. (MADPCB, 2025; Elprocus, 2025)

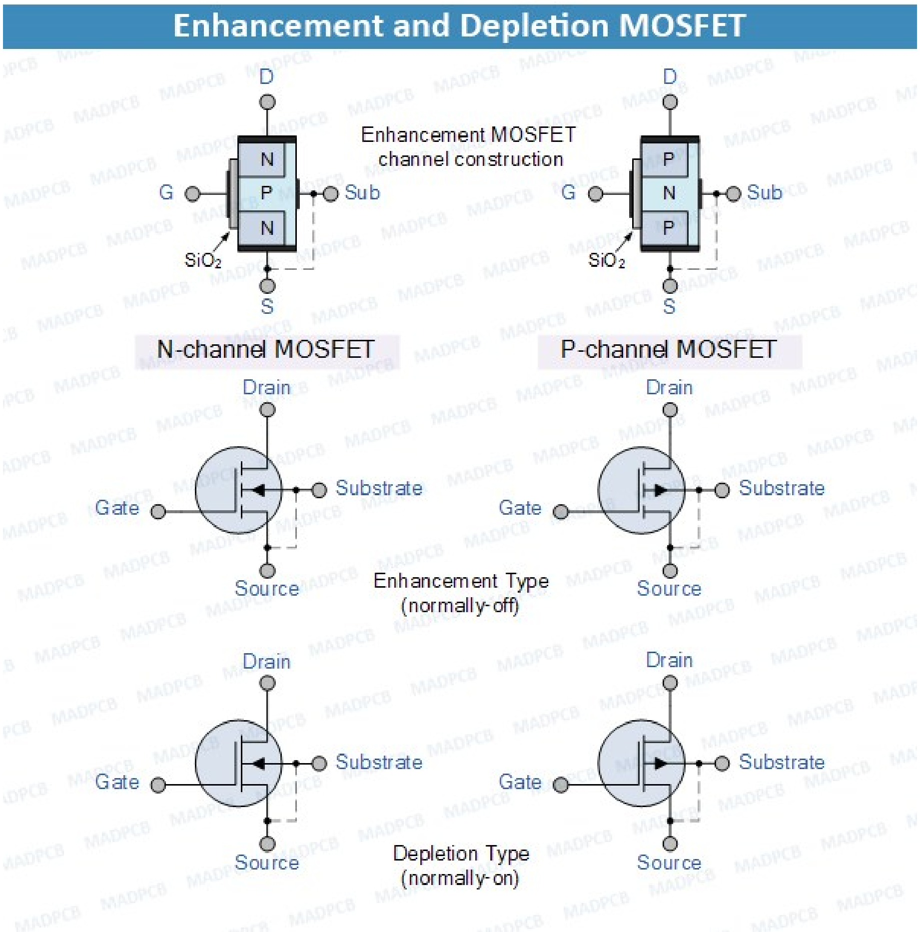

Figure 29. MOSFET types (MADPCB, 2025).

To turn a MOSFET on, it needs voltage on the gate terminal. To put it shortly, the main difference between the two is that the N-channel MOSFETs need a positive voltage, and the P-channel ones need negative voltage to be applied on the gate to turn them on. The gate voltage threshold of the component is known as Vth or VGS(th), which is the minimum voltage to turn the MOSFET on. This can be found on the manufacturer's datasheet of the component. (Infineon, n.d)

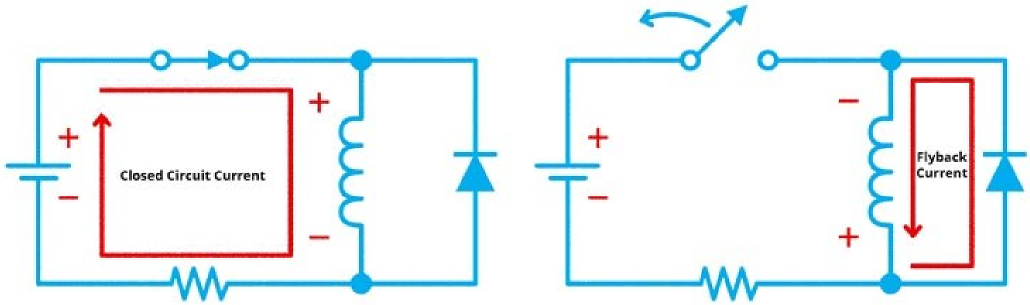

Figure 30. Flyback protection diagram (Components101, 2023).

For the protection of the MOSFETs a flyback diode is installed between the terminals to prevent voltage spikes reaching the transistor and damaging it. The voltage spikes across an inductive load are caused by the interrupt or sudden change of supply voltage. In this case the solenoid causes the back EMF to form when it is switched on and off. The placing of the diode should be across the terminals and as close as possible to the inductive load. The cathode of the diode should be facing the positive terminal and the anode facing the negative terminal. (Components101, 2023)

5.4 Solenoid & Sensor & Step-up Module

The solenoids used in this prototype are known from the automotive side as boost controller solenoids. The ones used are spring loaded poppet style MAC 35 series 3-way solenoids with a power of 5,4Watts, max pressure of 8bar and they run on 12 volts. The orifice size cannot be found in any official manual or document but assuming its around 1mm, it is not optimal for bigger volume pressure control, but for testing and validation purposes for now it will be sufficient, as the test rig volume can be modified.

Figure 31. MAC 35 series solenoid used (MAC Valves, n.d).

These solenoids run best on around 30hz base frequency. The duty cycle control range depends on the frequency used as in lower frequencies the range is wider, but control is not that stable, and vice versa. The right PWM-frequency always depends on the specific solenoids and should be adjusted and tested accordingly. The sensor used in the prototype is a general 3-pin 0-500 psi sensor, so converting to bar it has approximately 0-34,5 bar of range with an output range of 0,5-4,5 volts. The sensor needs 5v feed, ground and outputs a signal of 0,5 to 4,5 volts to the ESP32. The ESP32 pins are not designed for this kind of voltages as the official statement is 3.3 volts. Because of this a voltage divider is needed, to scale down the incoming voltage from the sensor. This is done with a 10Kohm potentiometer.

Figure 32. Controller box pressure sensor (AliExpress, n.d).

For the calibration, the sensor voltage must be scaled down correctly and, the ADC-conversion in the program needs to be modified. The voltage from the pin must be matched to the voltage converted and used by the program to get accurate readings. The voltage difference between the sensor and the value in the program can be calibrated rather easily, but the actual pressure calibration must be done on the rig, with Dewesoft DAQ connected.

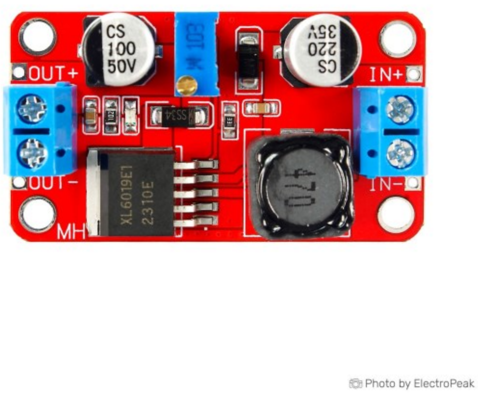

Figure 33. XL6019 step-up module (ElectroPeak, n.d).

To be able to control the 24V solenoids a power feed for that is needed. As the PWM control is on the negative side the positive side can be done with a use of a step-up module. The used module is a XL6019, and it is rated for 5A and claims to have a max efficiency of 94% but 85% in normal conditions. It takes an input voltage of 3-35V and can output in a range of 5 to 40V. The switching frequency is 220KHz and regulation tolerance +-0.5%.

5.5 Determining Solenoid Orifice Size

The solenoid should be sized according to wanted pressure oscillation characteristics as to small valves will be to slow to fill the chamber and too big on the other hand might be hard to control. The main value informed by the solenoid manufacturer is the Kv-value known as the flow coefficient, which directly indicates the expected flow of water at 1 bar pressure differential known as ΔP. The basic formula for expected flow is $Kv*\sqrt{(\Delta P/\rho)}$. (Mousdell, D. n.d)

When viewing data from previous test, some conformity can be seen regarding the pressurising time. As the cross-sectional area is directly proportional to the flow thus the filling time, it can be used to get a rough approximate on the proper orifice size. If the orifice is too small the pressure build up will be too slow. On the other hand, too big of an orifice causes problems in the controllability, as the pressures fluctuate too fast. The right orifice size should be determined by course of testing to find the proper size for desired characteristics.

6 SOLENOID CONTROL STRATEGIES

Controlling solenoids or a specific electrical component can be done in multiple ways. The right strategy depends on application and purpose of the component. In this chapter the basics of control strategies are explained.

6.1 Open Loop and Closed loop

Open loop means that there is no feedback from the output process. For example, controlling a solenoid to reach a certain pressure there is no feedback if the pressure is reached. The controller relies completely on predefined values instead. Open loop controllers are good solution for cases where you do not need adaptability, for example turning a lamp on and off with a timer. (Nantian Electronics, 2024)

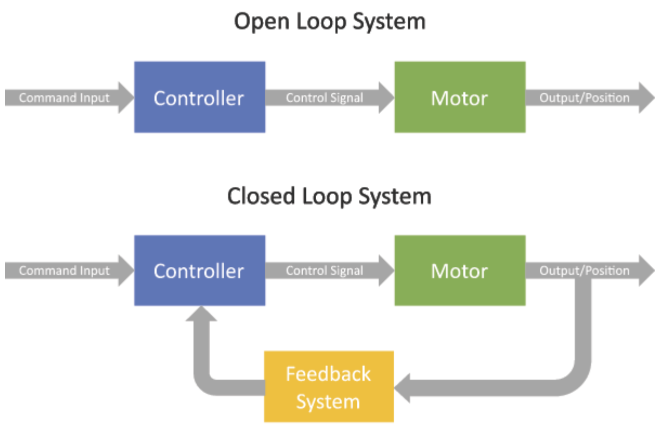

Figure 34. Open & Closed loop systems visualized (Nantian Electronics, 2024).

Closed loop on the other hand is completely different. With this strategy there is feedback from the output process and which the name applies closes the loop of data. This system is great in terms of adaptation as the controller can monitor and regulate according to feedback from various sensors or transmitters. A good example would be a closed loop lambda control system, where the engine control unit looks up a lambda target. The ECU then monitors the oxygen sensor feedback on how the injection time should be altered, to reach the desired lambda target. (Nantian Electronics, 2024)

6.2 PWM-Control

PWM stands for Pulse Width Modulation, and it's common in various kinds of electronic applications. It works by controlling the average voltage or amplitude of a signal in a pulsing matter. PWM-signal is between 0 and 100%, and this range is the duty cycle. (Byjus, n.d)

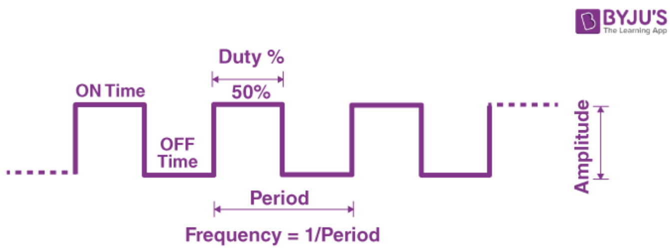

Figure 35. PWM-signal visualized (Byjus, n.d).

The duty cycle represents the high and low times of the signal in a period presented in hertz. When the signal goes from low to high and back to low it counts as one cycle, also known as the period. During 1 second the number of cycles is defined by the frequency. In short, duty cycle defines the amount of time the electrical component is on in a certain period. For example, a solenoid with 50% duty cycle results in around half of the solenoids maximum flow. With 100% the solenoid is completely open and with 0% completely closed. In Figure 36 below, different duty cycles are shown. (Byjus, n.d)

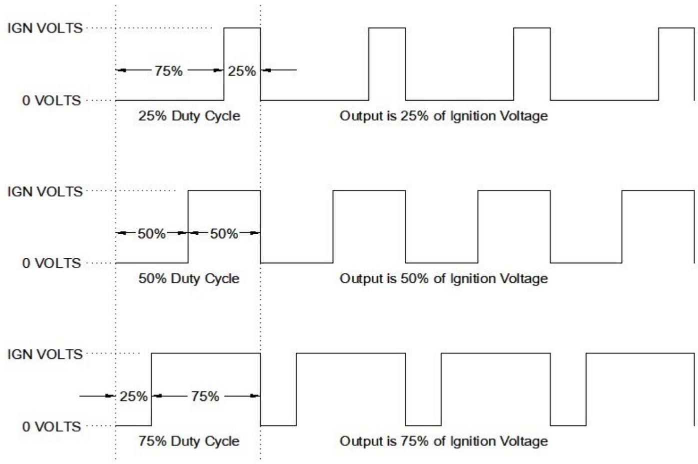

Figure 36. PWM duty cycle (Go4trans, n.d).

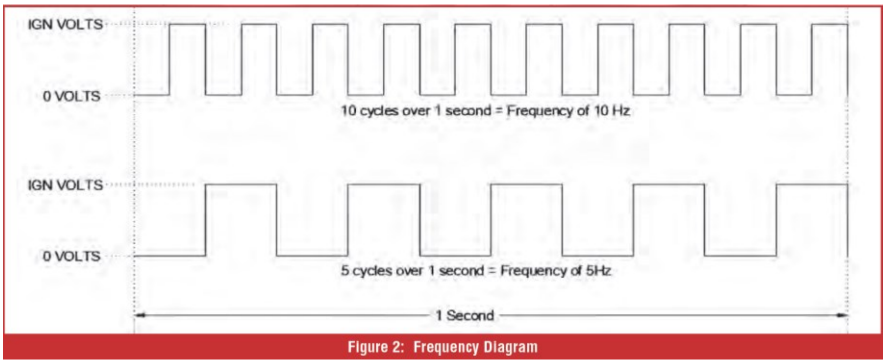

Figure 37. PWM frequency (Gears Magazine, 2020).

As shown in Figure 37 above, the frequency represents the cycle count. With 10Hz the signal is low ten times and high ten times during one second. The base frequency should always be set correctly according to component manufacturer specifications. (Byjus, n.d)

6.3 PID-control

PID stands for Proportional, Integral, Derivate, and it is a closed loop algorithm that can adjust the output value according to three elements. The main use of this system is to reach a predefined target, for example a solenoid that is controlled by PID to reach a certain level of pressure.

These values must be fine-tuned for the system to work correctly. (MaxxECU, n.d; National Instruments, 2025)

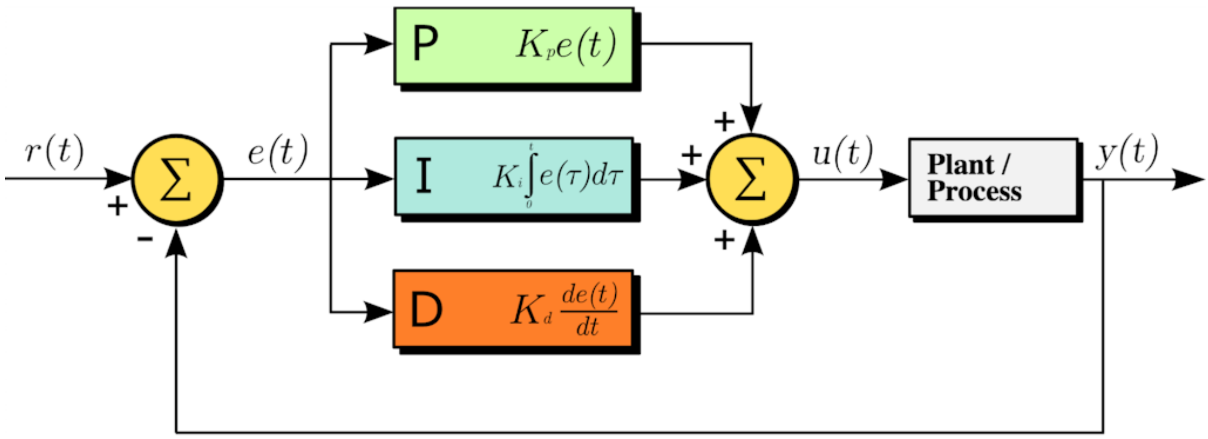

Figure 38. PID-control schematic (Smith, G.M, 2024).

The proportional component is used to bring the value close to the desired target and is also known as the gain. Integral component sums the error over time, which is used to bring the error as close to zero as possible. Derivative component decreases the output in case of rapid process variable changing, and the main purpose of this element is to dampen the response. (MaxxECU, n.d; National Instruments, 2025)

7 FINAL DESIGN AND RESULTS

The final design is an upgraded version of the second prototype, with the same components and basic features but with additional control for the lower and upper pressure setpoints which control the solenoid states. The casing was revised to have cooling ports and a small fan, as the transistors and other electronics might heat up during use. This depends on the electrical load.

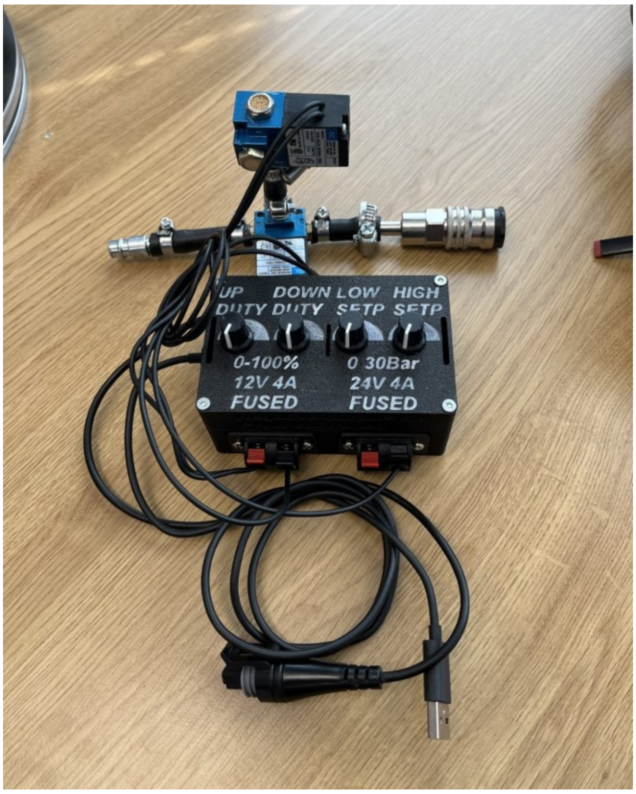

Figure 39. Final test version.

7.1 Protective Casing

The protective casing was designed with Autodesk Fusion, with a main target to be compact and simple. Already existing 3D models of the Esp-32, expansion board and the voltage step up module from CrabCad were used to help visualizing the design during modelling. The drawings and schematics were done with free online programs or basic office tools.

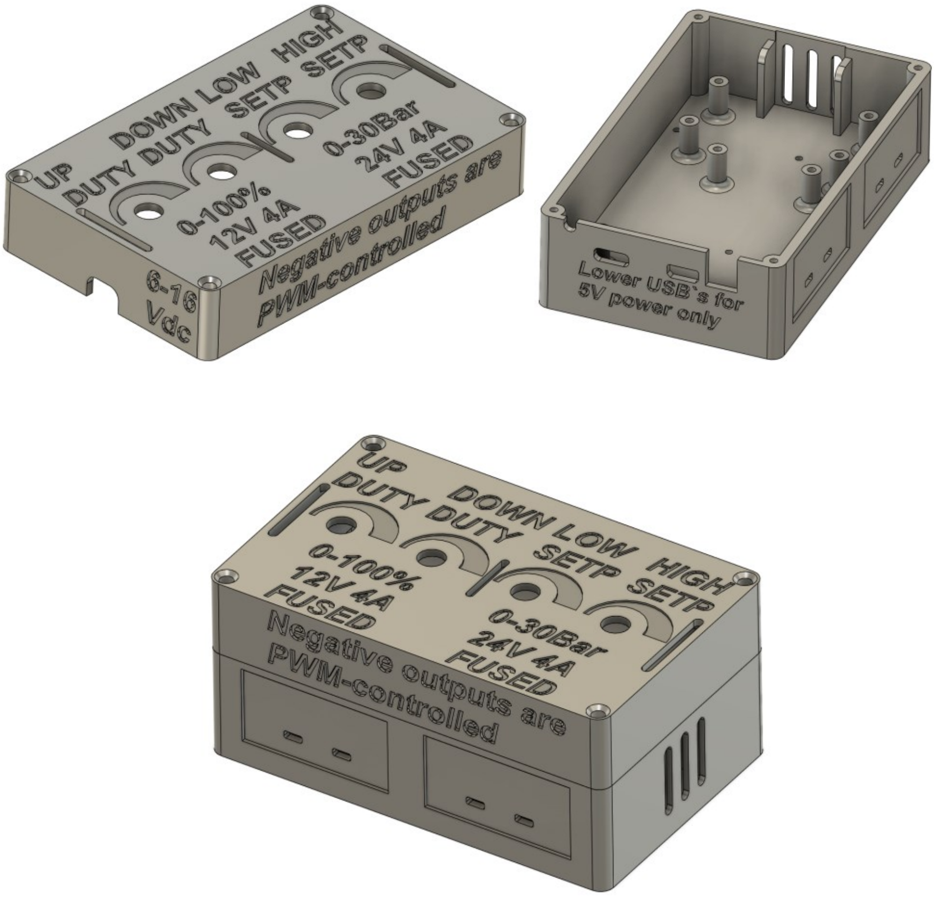

Figure 40. The casing.

The casing is made from PLA (Polylactic Acid), and it was printed with Bambulab X1 Carbon. PLA was the preferred choice as the casing does not need to have great physical properties neither chemical resistance. For now, the casing will be sufficient but for further development it should be made from better materials such as PETG, ASA or PA6/PA12 with fibre reinforcement. The final design of the casing features improvements based on previous versions such as added cooling fan and overall features. The design is optimized to be simple to print utilizing big fonts and simple shaping, thus reducing support for overhangs and reducing printing time.

7.2 Examination of Data and Results

The controller was tested with 7 bar of maximum line pressure and various settings to observe the functionality of the device. The device performed as expected without any noticeable flaws. During the testing different frequencies between 25 and 35Hz were tested to see if it had any impact on the performance, and based on the tests the specific solenoids were the most stable around 30Hz. The cheap pressure sensor tended to drift a little during the testing, leading to small inaccuracies of around 5% on the measured pressures. The sensor needed some calibrating but managed to stay quite stable. The tests were made with the volume displacer attached, thus reducing the chamber volume to around 0.5 Liters. This way a quicker control with the small orifice solenoids was achieved. These solenoids still were not large enough for quick pressurising of the chamber as expected.

In Figure 41 below the fastest achievable pulsing with the current setup is shown to be around 60 pulses per minute with 100% duty cycles. The slowest pulse on the other hand is around 3 pulses per minute, with both solenoids at 25% duty cycle shown in Figure 42. The lowest usable duty cycle with 25Hz base frequency was around 20%.

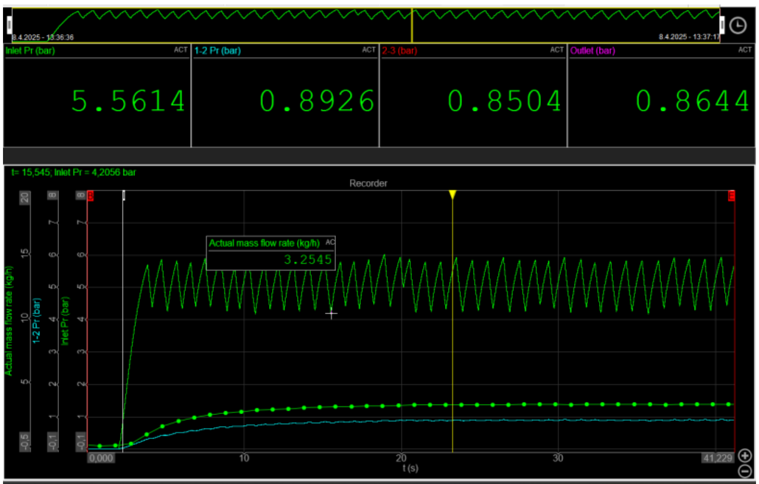

Figure 41. 60 ppm oscillation.

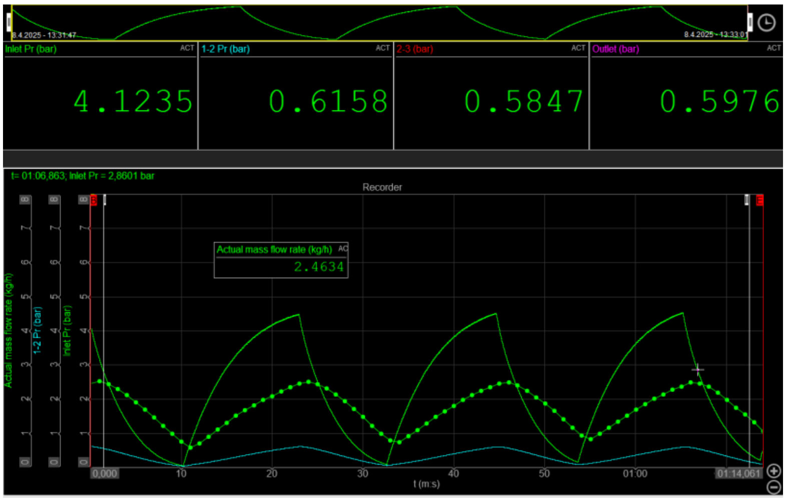

Figure 42. 3 ppm oscillation.

The possibility of fast pressurising could give the ability to observe special occasions. For example, when the pressure drops extremely fast on top of the piston, the pressure between the first and second piston ring momentarily stays the same. This pressure differential can force oil past the piston rings to the combustion chamber. This specific situation of slight pressure curve overlapping can be seen marked in yellow in Figure 43 below.

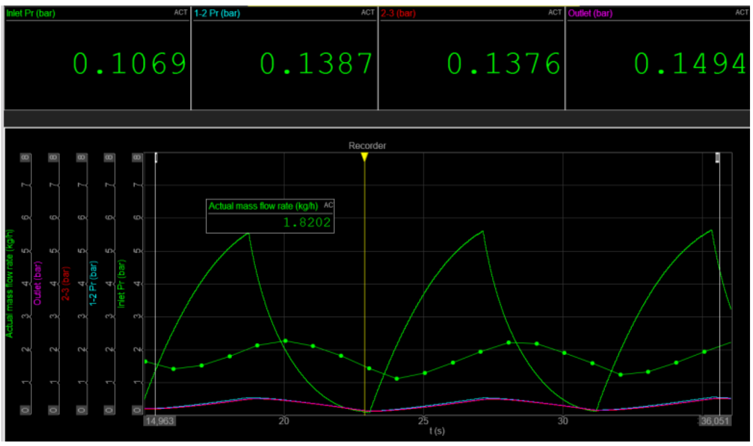

Figure 43. Ring land pressure overlapping with chamber pressure.

In the figures above a small pressure deviation from the setpoints can be seen. The setpoints are not exact because of the sampling of values and a slight flaw in the program code. These were explained in more detail in Subsection 5.2. The tests showed that the mass airflow meter was too small as pressure started to build behind it. When the piston rings started to seal, the top pressure was at 7 bar and the bottom chamber pressure was around 0.5 bar. With the rings unseated the pressure behind the sensor could climb up to 2.5bar, which indicates a restriction of flow. The ring sealing usually happened when the plug between the 1-2 ring land was removed, and air was fed through the quick connection bypassing the valves. In Figure 44 below the top piston ring sealing can be seen in yellow as pressure differential between the inlet and the second ring land.

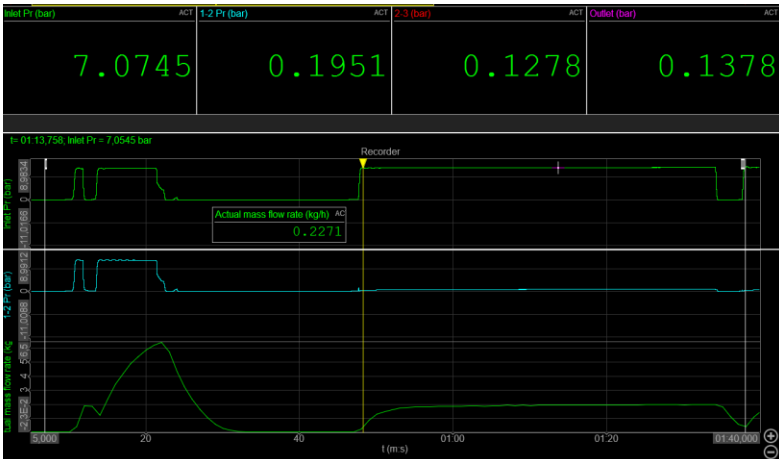

Figure 44. Top piston ring sealing caused by rapid pressurising.

This sudden pressurising and only atmospheric pressure below the rings resulted in the ring sealing in place. When the plug was reattached the pressure behind the airflow meter started to rise to the previously mentioned 0.5bar. Based on this it can be assumed that the idea behind this concept is correct, and the reconfiguration of the hardware needs to be done.

8 SUMMARY AND FUTURE DEVELOPMENT

During this thesis a controller for a static piston ring test rig was made. The main purpose was to add dynamic pressure curves with the use of an external controller. Two test prototypes were made to clarify the idea, and the final controller was successfully developed. The testing went according to expectations, some data was gathered and the results were good.

For future development it can be said that the electrical components could be improved and revised, as this was just a prototype with cheap consumer grade components. The solenoids should be upgraded to bigger ones, as well as the mass airflow meter. The solenoid configuration should also be revised, regarding the basic solenoid states. Solenoid 1 should be normally closed and solenoid 2 normally open. Currently the solenoid 1 is venting only through the rig. Another possibility is to use Dewesoft X alone for datalogging and controlling the solenoids providing one package, but more experience with this specific software is needed.

In addition to this version, an LCD-display could be integrated to show duty cycles and other relevant data directly from the box itself. This would remove the need to use a second computer to check the controller operating data. Datalogging is done via Dewesoft so the pressure switching points can be determined from there, but the duty cycles and logic states would be good to have.

The overall thesis and the prototypes were successful, and the thesis gives a good baseline regarding the controller configuration. By using PWM it is possible to implement different hardware in the future, for example, a stepper motor-controlled valve instead of a typical plunger type solenoid. The official version should be made from proper industrial grade components, with good manuals and schematics of the wiring and working principle.

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APPENDICES

Appendix 1. ESP32 specification sheet (The Engineering Projects, 2020).

ESP32 FEATURES & SPECS

ESP32 TECHNICAL SPECIFICATIONS

No.	Parameter Name	Parameter Value
1	Microprocessor	Tensilica Xtensa single-/dual-core 32-bit LX6 microprocessor(s)
2	CoreMark® score	1 core at 240 MHz: 504.85 CoreMark; 2.10 CoreMark/MHz
		2 cores at 240 MHz: 994.26 CoreMark; 4.14 CoreMark/MHz
3	Operating Voltage	3.3V
4	DC Current on 3.3V Pin	50 mA
5	DC Current on I/O Pins	40 mA
6	Maximum Operating Frequency	240MHz
7	Frequency Oscillators	8MHz (Internal Oscillator)
		Internal RC Oscillatoror
		2MHz ~ 60MHz External Crystal Oscillator(40MHz required for WiFi/BT)
		32kHz External Crystal Oscillator(For RTC)
8	Timers	2 x 64-bit Timers, 1 RTC Timer,

ESP32 PINOUT

1	DAC	2 Channels (8-bit, digital to analog converter)
2	ADC	2 Channels (8-bit, digital to analog converter)
3	Capacitive Touch Sensors	10
4	LED PWM	16 Channels

ESP32 COMMUNICATION PROTOCOLS

1	Wi-Fi	802.11 b/g/n (Speed upto 150Mbps)
2	Bluetooth	Supports Classic Bluetooth v4.2 BR/EDR & Bluetooth Low Energy(BLE)
3	Bluetooth Low Energy	Supports BLE
4	UART Protocol	3 Channels
5	SPI Protocol	4 Channels
6	I2C Protocol	2 Channels
7	I2S Protocol	2 Channels (for digital audio)
8	CAN Protocol	1 Channels

ESP32 BUILTIN MEMORY

No.	Parameter Name	Parameter Value
1	SRAM	520kb
2	ROM(Flash Memory)	448kb
3	RTC SRAM	16kb

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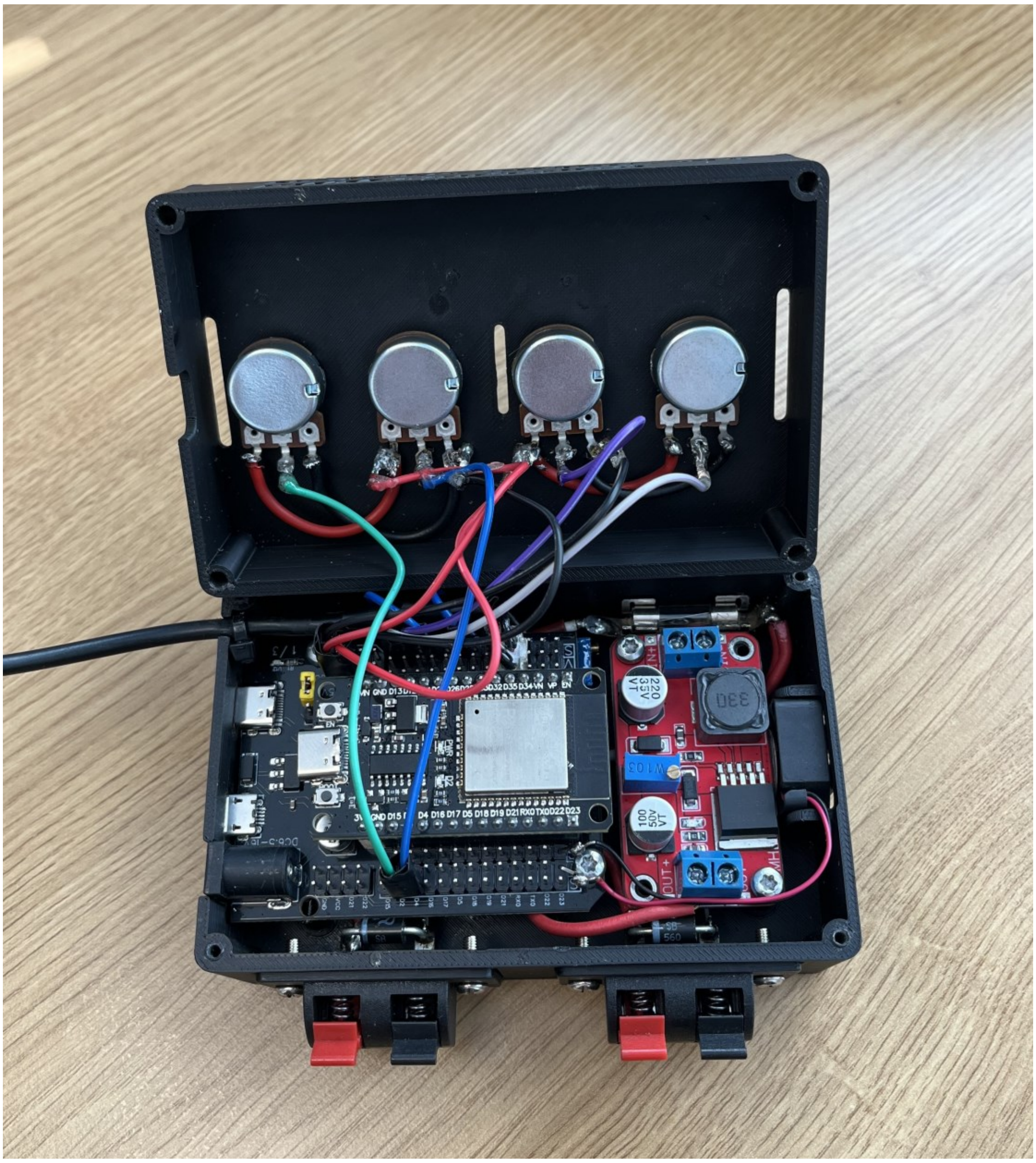
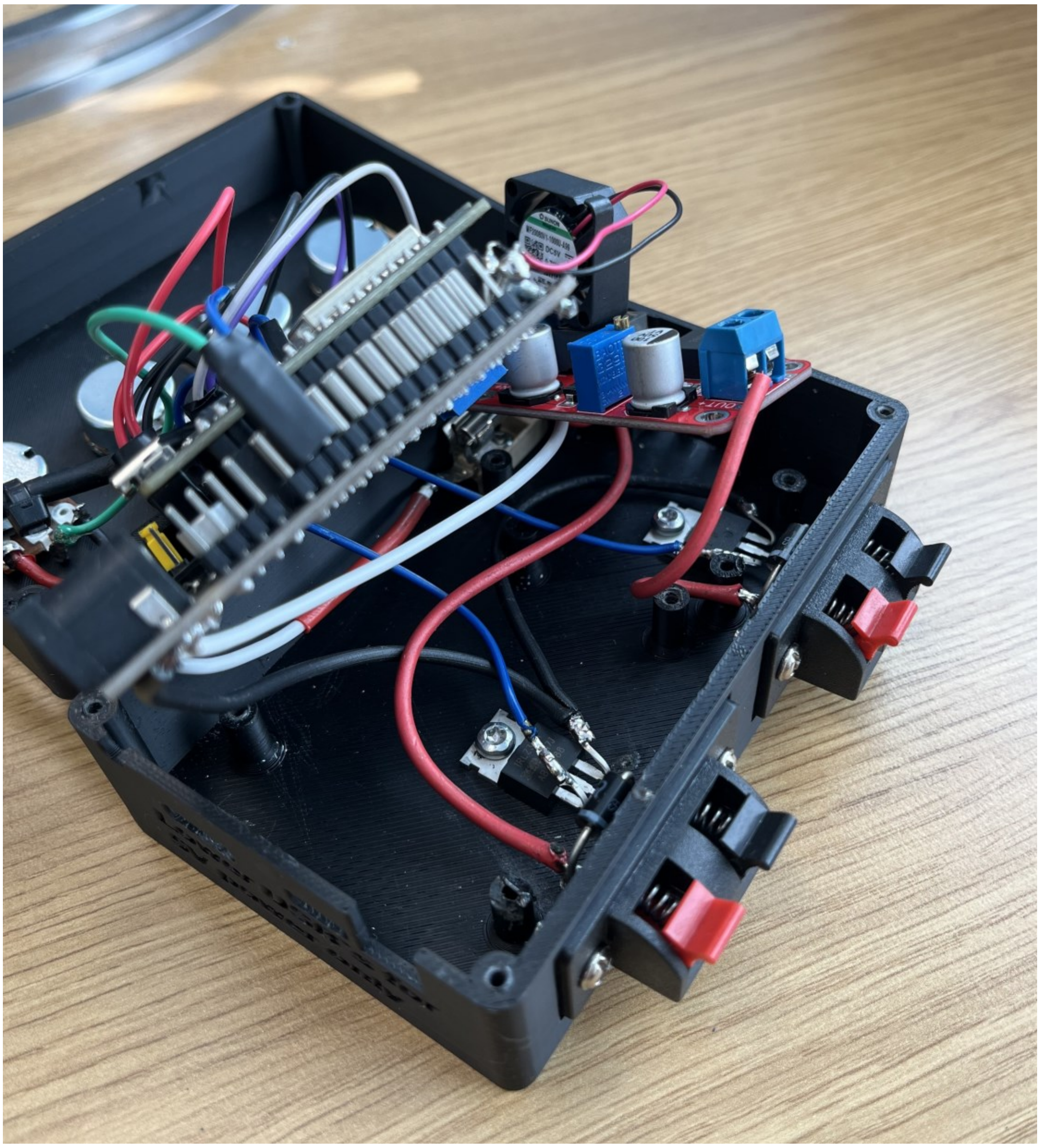
Appendix 2 A. Controller electronics.



Appendix 2 B. Lower casing electronics.



Appendix 3 A. First half of the program code converted to an image at https://carbon.now.sh

```
#include <driver/ledc.h> // ESP32 LEDC library for PWM

const int sensorPin = 34; // ADC pin for pressure sensor
const int pwmPin1 = 27;   // GPIO pin for solenoid 1 (Upslope)
const int pwmPin2 = 25;   // GPIO pin for solenoid 2 (Downslope)
const int potPin1 = 2;    // GPIO pin for "Up duty"
const int potPin2 = 4;    // GPIO pin for "Down duty"
const int potPin3 = 12;   // GPIO pin for "Low setp"
const int potPin4 = 13;   // GPIO pin for "High setp"

const int pwmFreq = 25;   // PWM frequency in Hz (25-35Hz for mac 35 series)
const int pwmResolution = 8; // PWM resolution 8 bit (0-255)
const int numSamples = 10; // Number of samples for smoothing of voltage and pressure
const int NUMsamples = 20; // Additional separate number of samples for setpoints, reducing fluctuation
float pressure = 0.0;      // Store current pressure
float voltage = 0.0;       // Store sensor voltage
float lowerThreshold = 0.0; // Store lower pressure setpoint value
float upperThreshold = 0.0; // Store upper pressure setpoint value
float lowerThresholdSum = 0.0; // Sum of pressure readings for averaging
float upperThresholdSum = 0.0;
float voltageSum = 0.0;    // Sum of voltage readings for averaging
float pressureSum = 0.0;   // Sum of pressure readings for averaging
float voltageBuffer[numSamples]; // Buffer for voltage readings
float pressureBuffer[numSamples]; // Buffer for pressure readings
float lowerThresholdBuffer[NUMsamples]; // Buffer for setpoints
float upperThresholdBuffer[NUMsamples];
int bufferIndex = 0;       // Buffer index
int BufferIndex = 0;

enum State {
  INCREASING,
  DECREASING
};

State currentState = INCREASING;

void setup() {
  ledcAttach(pwmPin1, pwmFreq, pwmResolution); // PWM setup for solenoid 1 (upslope)
  ledcAttach(pwmPin2, pwmFreq, pwmResolution); // PWM setup for solenoid 2 (downslope)
  Serial.begin(115200); // Baudrate
  Serial.println("Voltage:\tPressure:\tState:\tDutyCycle1:\tDutyCycle2:\tLowerThresh:\tUpperThresh:"); //
Header
}

void loop() {
  // Read potentiometer values and set to duty cycles
  int potValue1 = analogRead(potPin1); // 0-4095
  int dutyCycle1 = map(potValue1, 0, 4095, 0, 255); // Duty for solenoid 1 (upslope)

  int potValue2 = analogRead(potPin2); // 0-4095
  int dutyCycle2 = map(potValue2, 0, 4095, 0, 255); // Duty for solenoid 2 (downslope)

  // Read potentiometer values and set to pressure thresholds
  int potValue3 = analogRead(potPin3); // Low setp potentiometer
  float lowerThreshold = map(potValue3, 0, 4095, 0, 3000) / 100.0; // Range 0 - 30 bar, though sensor has range
up to 35bar.

  int potValue4 = analogRead(potPin4); // High setp potentiometer
  float upperThreshold = map(potValue4, 0, 4095, 0, 3000) / 100.0; // Range 0 - 30 bar

  // Ensure Lowsetp doesn't exceed Highsetp
  if (lowerThreshold >= upperThreshold) {
    lowerThreshold = upperThreshold -1; // Pressure setpoint gap
  }

  // Read sensor voltage
  int sensorValue = analogRead(sensorPin); // Raw ADC value (0-4095)
  voltage = sensorValue * (6.5 / 4095.0);  // Convert ADC to voltage (ok, matched with multimeter)

  // Convert voltage to pressure in bar
  if (voltage >= 0.5 && voltage <= 4.5) {
    pressure = (voltage - 0.5) * 6.0;  // Conversion formula (ok, pressure matched with Dewesoft).
  } else {
    pressure = 0; // Out-of-range voltage
  }
```

Appendix 3 B. Rest of the program code converted to an image at https://carbon.now.sh

```
 // Update moving average buffers
  voltageSum -= voltageBuffer[bufferIndex];
  pressureSum -= pressureBuffer[bufferIndex];
  lowerThresholdSum -= lowerThresholdBuffer[BufferIndex];
  upperThresholdSum -= upperThresholdBuffer[BufferIndex];

  voltageBuffer[bufferIndex] = voltage;
  pressureBuffer[bufferIndex] = pressure;
  lowerThresholdBuffer[BufferIndex] = lowerThreshold;
  upperThresholdBuffer[BufferIndex] = upperThreshold;

  voltageSum += voltage;
  pressureSum += pressure;
  lowerThresholdSum += lowerThreshold;
  upperThresholdSum += upperThreshold;

  bufferIndex = (bufferIndex + 1) % numSamples;
  BufferIndex = (BufferIndex + 1) % NUMsamples;


  // Calculate smoothed values
  float smoothedVoltage = voltageSum / numSamples;
  float smoothedPressure = pressureSum / numSamples;
  float smoothedlowerThreshold = lowerThresholdSum / NUMsamples;
  float smoothedupperThreshold = upperThresholdSum / NUMsamples;

  // Convert from 0-255 to 0-100%
  float DC1 = dutyCycle1 / 2.55;
  float DC2 = dutyCycle2 / 2.55;

  // Control logic by state
  if (currentState == INCREASING) {
    if (smoothedPressure < smoothedupperThreshold) {//Updated after testing to use "smoothedupperThreshold"
instead of "upperThershold", eliminating setpoint fluctuation.

      // Increase pressure
      ledcWrite(pwmPin1, dutyCycle1);
      ledcWrite(pwmPin2, 0);
    } else {
      // Switch to decreasing state when upper setpoint is reached
      currentState = DECREASING;
    }
  }
  else if (currentState == DECREASING) {
    if (smoothedPressure > smoothedlowerThreshold) {// Updated after testing to use "smoothedlowerThreshold"
instead of "lowerThershold", eliminating setpoint fluctuation.

      // Decrease pressure
      ledcWrite(pwmPin1, 0);
      ledcWrite(pwmPin2, dutyCycle2);
    } else {
      // Switch to increasing state when lower setpoint is reached
      currentState = INCREASING;
    }
  }

  // Output data
  Serial.print ("SensorVoltage:");
  Serial.print(smoothedVoltage, 1);
  Serial.print("\t");
  Serial.print("Pressure(Bar):");
  Serial.print(smoothedPressure, 2);
  Serial.print("\t");
  Serial.print("ControlState:");
  Serial.print((currentState == INCREASING) ? "UP\t" : "DN\t");
  Serial.print("\t");
  Serial.print("UpDuty(%):");
  Serial.print(DC1, 0);
  Serial.print("\t");
  Serial.print("DownDuty(%):");
  Serial.print(DC2, 0);
  Serial.print("\t");
  Serial.print("LowSetpoint(Bar):");
  Serial.print(smoothedlowerThreshold, 1);
  Serial.print("\t");
  Serial.print("HighSetpoint(Bar):");
  Serial.println(smoothedupperThreshold, 1);

  delay(50); // Loop delay
}
```