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Faculteit Industriële Ingenieurswetenschappen

master in de industriële wetenschappen: elektromechanica

Masterthesis

Analysis of pump pressure ripple as a source of noise in a hydraulic roll control system

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ir. Gert VANHEES

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BEGELEIDER :

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Nick Breugelmans, Wout Olaerts

Scriptie ingediend tot het behalen van de graad van master in de industriële wetenschappen: elektromechanica

Gezamenlijke opleiding UHasselt en KU Leuven

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UHASSELT

KU LEUVEN

Foreword

In this master's thesis, the pressure ripple of a hydraulic pump will be examined in collaboration with Tenneco Automotive Europe BV. For this, a test setup will be made. The examined hydraulic pump is used in a wide range of cars, varying form track-focused sports cars to big SUV's, to reduce the roll, pitch and squat of the cars while cornering, braking and accelerating. This master's thesis is written in the context of our master's degree in Electromechanical Engineering Technology in the joint study program of UHasselt and KU Leuven and will span from August 2021 to June 2022.

We chose this subject for our master's thesis mainly because of our interest in cars and the technologies used to make them faster or more comfortable. The system in which this pump is used, can be applied for both these cases. Our passion for cars started when we were very young. One of us got fascinated by cars when members of their family restored a classic car. Another aspect that appealed to us in this project, was the practical approach, since we both like to make and repair things ourselves.

We would like to thank Tenneco Automotive for the opportunity to realize this project. Within Tenneco, we want to especially thank our external promotor ir. Frank Gommans and our supervisor ing. Stein Slootmaekers for the continuous support and feedback provided during the realization of this thesis. We also want to thank our internal promotor from UHasselt and KU Leuven, ir. Gert Vanhees, who made this thesis possible thanks to his contacts at Tenneco, and who was always available to answer any possible questions.

For the practical realization, we would like to thank Pierre Franssen from AFMECH s.a., for the constructive cooperation, especially as the realization of the project underwent several iterations that required changes to be implemented in a short time window. We would also like to thank prof. dr. ir. Elke Deckers for providing the background information to better understand the problem. Lastly, we would also like to thank our family, and in particular our parents, to enable us to follow this study program and support us in, and outside of our education.

We sincerely hope that you enjoy reading this thesis, and find it interesting.

Nick Breugelmans and Wout Olaerts

Diepenbeek, 30th of May 2022

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Glossary

BDC	Bottom Dead Center
CVSA	Continuously Variable Semi Active
ECU	Electronic Control Unit
FFT	Fast Fourier Transformation
ICE	Internal Combustion Engine
PWM	Pulse Width Modulation
TDC	Top Dead Center

Abstract

This master's thesis is performed on behalf of Tenneco Automotive Europe BV and focuses on the hydraulic pump of the CVSA2/Kinetic® system. This system uses semi-active dampers and hydraulic connections between the dampers to provide the stiffness to control the rolling of a vehicle while cornering. The pump used to adapt this stiffness, is expected to introduce a pressure ripple into the system, which causes noise in the vehicles. The main objective in this thesis is to develop a means to quantify the pressure ripples causing this noise.

To fulfil this, a test setup is built after performing a literature study on the generation of pressure ripples and similar problems. In this test setup, the pressure ripple is measured using high-frequency piezoelectric pressure sensors. The oil flow and the absolute pressure are also measured to define all parameters of the system. The pressure in the system is controlled by a needle valve. A pressure relief valve is installed to ensure that the components do not get damaged. The data is acquired via a CompactDAQ and processed via LabView and MATLAB.

To carry out the tests on the setup in a repeatable manner, a test procedure is composed. Next, several tests are carried out to verify the repeatability of the tests. The data from the tests clearly show the pressure ripple that needed to be measured. The other measurements ensure all parameters of the system are known. Now the magnitude of the pressure ripple is known, future developments can reduce the ripple in the system.

Abstract in het Nederlands

Deze masterproef is uitgevoerd in opdracht van Tenneco Automotive Europe BV en focust op de hydraulische pomp van het CVSA2/Kinetic® systeem. Dit systeem gebruikt semi-actieve dempers en hydraulische verbindingen tussen de dempers om stijfheid te bieden voor rolcontrole van een voertuig. De pomp die deze stijfheid aanpast, introduceert een drukrimpel in het systeem die lawaai in de voertuigen veroorzaakt. Het doel van deze masterproef is het ontwikkelen van een manier om de drukrimpels te kwantificeren.

Hiervoor is een testopstelling gebouwd na het uitvoeren van een literatuurstudie over de opwekking van drukrimpels en soortgelijke problemen. In de testopstelling wordt de drukrimpel gemeten met hoogfrequente piëzo-elektrische druksensoren. De absolute druk en het oliedebiet worden gemeten om alle parameters van het systeem te definiëren. De druk in het systeem wordt geregeld door een naaldventiel. Een overdrukventiel wordt geïnstalleerd om te verzekeren dat de onderdelen niet beschadigd raken. De meetgegevens worden verzameld via een CompactDAQ en verwerkt via LabView en MATLAB.

Om de tests op een herhaalbare manier uit te voeren, is een testprocedure opgesteld. Hierna worden er verschillende tests uitgevoerd om deze herhaalbaarheid te verifiëren. De resultaten tonen duidelijk de drukrimpel die moest worden gemeten. Samen met de resultaten van de andere metingen zijn alle parameters van het systeem bekend. Nu de grootte van de drukrimpel gekend is, kunnen toekomstige ontwikkelingen de rimpel in het systeem verminderen.

1 Introduction

This master's thesis will be performed on behalf of Tenneco Automotive Europe BV in Sint-Truiden, which is a part of Tenneco Inc., with its head office situated in Lake Forest, Illinois (U.S.). The experiments carried out in this thesis are performed at METC (Monroe Engineering and Technology Center) in Sint-Truiden (Belgium) [1].

This thesis focuses on Tenneco's CVSA2/Kinetic® suspension system which combines semi-active dampers hydraulic connections between the different dampers to achieve a body control system [2]. The Kinetic system uses a hydraulic pump and electronic valves to set and adjust the stiffness which controls the body roll of a vehicle during cornering as well as the pitch and squat during braking and accelerating. The system is applicable to sports cars as well as to SUVs to improve handling whilst providing a good level of comfort. The pump is powered by the ECU (Electronic Control Unit) of the car via an integrated PWM-controlled (Pulse Width Modulated) power source. This PWM-signal controls the electric power delivered to the pump, and in doing this also the hydraulic performance. The pump motor and the pump casing are identical for every use case, while the hydraulic oil tank and the noise cover for the entirety of the system are custom built for every application. As such, the volume of the oil tank can be adjusted to fit the needs of different vehicles. Figure 1 shows an example of a vehicle system layout.

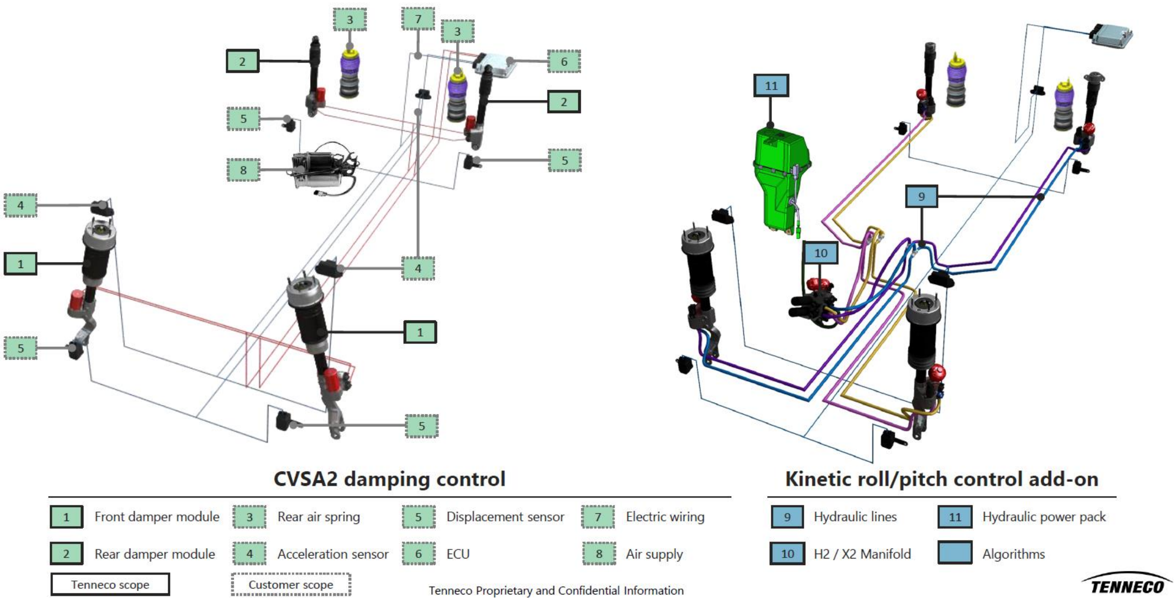


Figure 1: Vehicle system layout and key components [3, p. 5]

As seen in Figure 1, the system consists of several main components. When a vehicle is fitted with a CVSA2 damping system, the dampers are mounted to the chassis of the vehicle and to the wheels. Additionally, the vehicle is fitted with various sensors to monitor the displacement of the wheels and the acceleration of the body. These sensors are then electrically connected to the vehicle's ECU. If the vehicle is additionally equipped with a Kinetic anti-roll system instead of a traditional anti-roll bar, a hydraulic pump, an electronically controlled hydraulic manifold and hydraulic lines to connect the manifold and the dampers are installed in the vehicle.

1.1 Problem statement

The problem at hand is that the current hydraulic pump for the Kinetic anti-roll system is suspected to generate pressure ripples in the system which, in turn, can result in noises that may be experienced as unpleasant or even cause concern to vehicle owners. This problem is more notable in hybrid and electric vehicles due to less noise produced by the ICE (Internal Combustion Engine). In addition to this, partly due to the electrification of cars, car manufacturers are also setting high standards to eliminate unnecessary noises in their vehicles.

To solve this problem, there is a need for a method to quantify the magnitude of these pressure ripples that cause noise. This can be accomplished by examining similar examples in other industries or by building a test setup. After the quantification of the pressure ripples, different possible solutions can be examined and/or applied.

If no solution for this problem is found, vehicles are required to have more sound insulation. Adding more sound insulation in vehicles will raise the price of said vehicles as well as their weight. Another problem is that not every vehicle has a sufficient amount of space to accommodate additional sound-proofing.

1.2 Objectives

The main objective of this thesis is to develop a way to quantify the magnitude of the problem. To achieve this, there is a need for a method to quantify the pressure ripples which cause the noise. When the main objective is completed, a secondary objective can be treated. This secondary objective consists of examining and issuing propositions for solutions that mitigate the amount of noise heard by the vehicle owners.

The development of this project includes a study for a test setup to measure the pressure ripples generated by the hydraulic pump. With the results of this study, the setup will also be built. For this project, there are no strict limitations, but all the needed components and their price will be discussed with the promotors within Tenneco.

Tenneco has prepared a requirements package that the project must take into account. This requirements package consists of multiple categories.

- Mechanical
    - Dimensions of the climate chamber
    - Rigid setup that is transportable
- Electrical
    - Power supply from 230 V AC to 9.7 – 16 V DC (25 A continuous, 60 A peak)
    - Necessary sensor power supplies
    - Shielded wires to prevent signal loss
    - The power supply needs to be excluded from the "Device Under Test"
        - Include options to register the (external) DUT power supply
        - Include options to control the (external) DUT power supply
- Hydraulic
    - Working pressure up to 120 bar, burst pressure >150 bar
    - Service temperature from -40 °C to 80 °C
    - DUT output flow from 0.5 to 3 L/min
    - Resolution of flow measurement 0.01 L/min
    - Compatible with CHF-202 hydraulic oil
    - Pressure ripples measurable with a minimal resolution of 0.01 bar
    - Total pressure measurable with a resolution of 0.2 bar

1.3 Preview

In this thesis, experiments will be executed on a system with a hydraulic pump. The test setup will have the ability to be connected to a manifold and dampers in a later stage of testing.

In chapter 2, a literature study will be performed to understand how pressure ripple are generated in hydromechanical systems. If the source of the pressure ripple is determined and the pressure ripple can be measured, it is possible to look for ways to reduce the noise heard by the vehicle owners. This can be achieved by tuning various design parameters to lower the measured pressure ripples. To achieve this, there will be a second part in the literature study to explore similar problems and their solutions. If the timespan of this thesis allows it, some of these solutions obtained for the problems researched in the literature study will be tested.

After the literature study, a test setup will be developed in chapter 3. The development of the test setup consists of selecting suitable components as well as building the setup. Following the development of the test setup, different tests will be carried out with the selected sensors to establish a baseline of the current system.

After the realization of the test setup and the performance of the tests, the experiments and their results will be discussed in chapter 4, before exploring some additions and future developments that can be performed on the subject of the thesis in chapter 5. Finally, a conclusion will be formulated in chapter 6.

2 Literature study

Pump flow in hydraulic systems has a large, steady component and a smaller, cyclical component superimposed upon it. This smaller, cyclical component reacts with the fluid in the system and causes fluid-borne noise or pressure ripples. The fluid-borne noise can be transmitted through the pressurized liquid and result in unwanted noise and vibrations of attached components and structures [4]. The first part of this literature study examines the working principle of the pump that will be researched during this thesis. The second part describes the influence of pump and pipe parameters on the generation of pressure ripples and noise. After researching the pressure generation phenomena, the literature study will focus on the reduction of pressure ripples and noise. This reduction can take place at the main source, the pump or in the pipe system.

2.1 Working principle of the pump

2.1.1 General overview radial piston pump

To better understand the principle behind the generation of the pressure ripples from the pump that will be examined in the setup, a paper about radial piston pumps will be researched. Figure 2 shows an example of the pump kinematics of a radial piston pump.

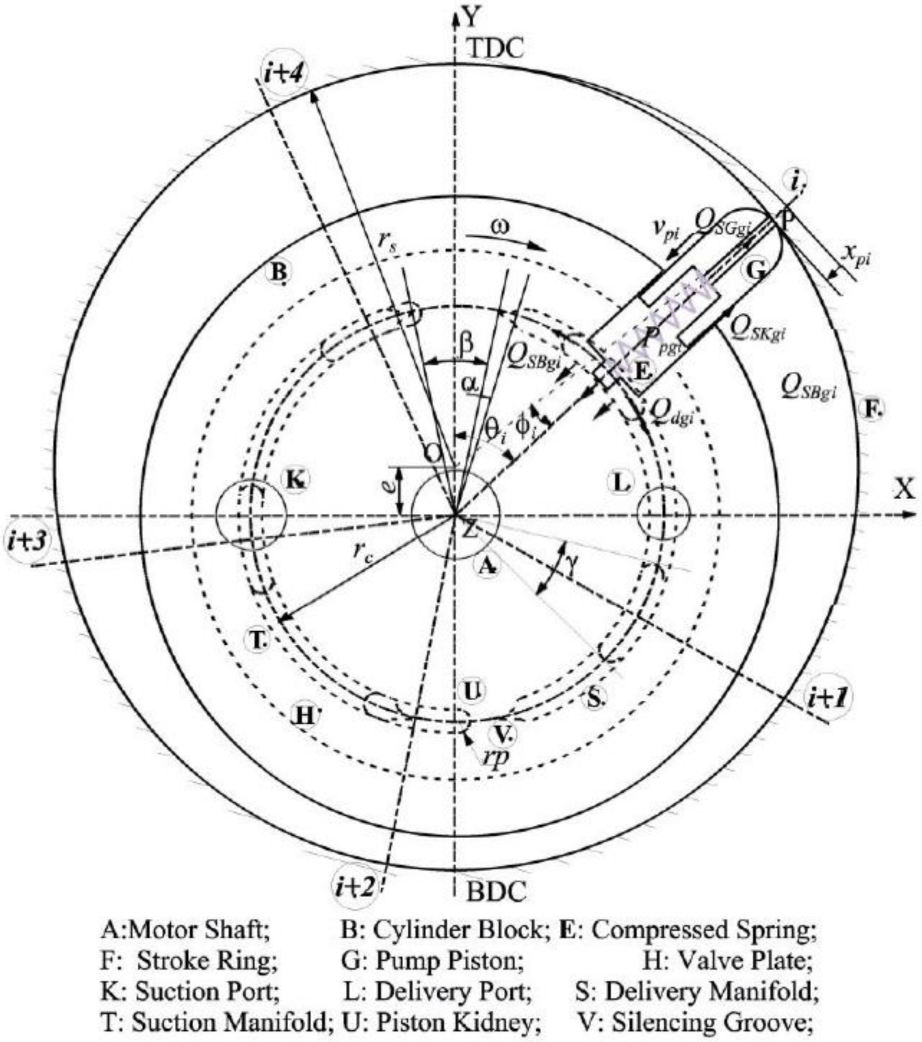


Figure 2: Pump kinematics of radial piston pump [5, p. 41]

In radial piston pumps, the displacement of the piston x_{pi} and the velocity of the piston v_{pi} can be calculated through formula 1 to formula 3 [5].

$$x_{pi} = r_s + e(1 - cos\theta_i) - r_s cos\phi_i \quad (1)$$

$$\text{Where } \phi_i = \sin^{-1}\{(e/r)\sin\theta_i\} \quad (2)$$

$$\text{And } v_{pi} = e\omega\{\sin\theta_i + (e/2r_s)\sin 2\theta_i\} \quad (3)$$

In these formulas:

- r_s equals the radius of the outer ring,
- e represents the eccentricity of the axis of the piston housing,
- θ_i represents the angle between the i^th piston and the TDC-point (Top Dead Center),
- ω is the angular velocity of the shaft.

Formulas 1 and 3 result in the graphs shown in Figure 3.

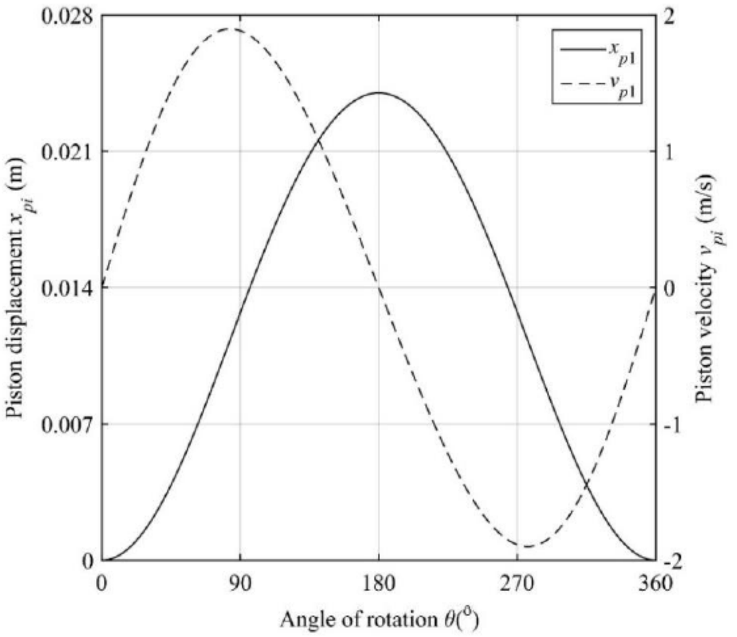


Figure 3: Displacement and velocity in radial piston pumps [5, p. 46]

As the displacement of the piston equals the stroke of this piston, it is visible that due to the eccentricity of the cylinder block (B in Figure 2), a sine wave is generated with a peak-to-peak value of two times the eccentricity of the pump used in [5]. The velocity reaches its maximums at 90° and 270° in to the rotation. When the piston is at TDC or BDC (Bottom Dead Center), the velocity is zero.

According to [6], the flow rate Q is linked to the velocity of the piston v, as shown in formula 4.

$$Q = v * A \quad (4)$$

In formula 4, A represents the area of the piston head. The evolution of the velocity and the flow rate are shown in function of the time in Figure 4.

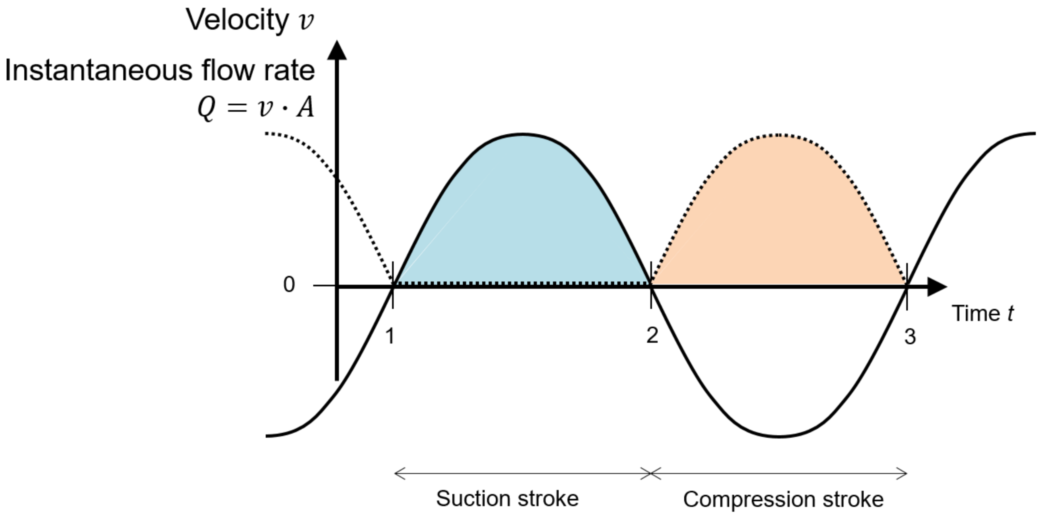


Figure 4: Velocity and flow rate in function of time [6, p. 17]

In Figure 4, the blue part represents the flow rate in to the piston chamber during the suction stroke and the brown part shows the flow rate that is pumped out of the chamber during the compression stroke. Figure 4 also provides a visual representation of the relation between the velocity of the piston and the flow rate, as given by formula 4. If this is applied to multiple pistons in one rotation, the evolution of the flow will take shape as shown in Figure 5.

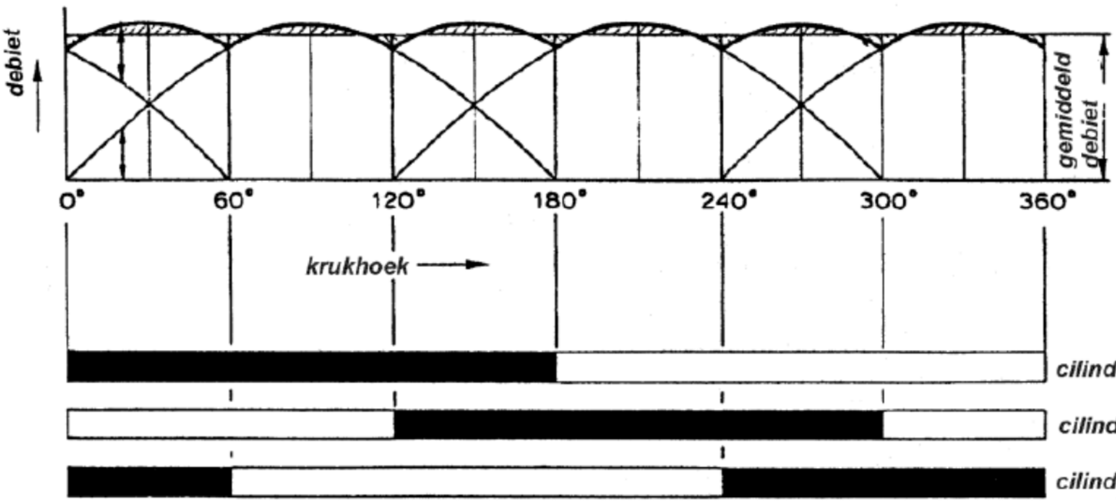


Figure 5: Flow rate triplex implementation [7, p. 5]

In Figure 5, the flow rate of a three piston pump is shown in function of the angle of rotation. The black parts in the bars at the bottom represent the compression stroke of the three different cylinders, while the white parts represent the suction stroke. The graph at the top in Figure 5 shows the flow rate in the discharge line of the pump. The cross-hatched sections show the instantaneous flow rate in the discharge line.

From the upper graph in Figure 5, the relation between the frequency of the pressure ripple and the rotational speed can be deducted. In Figure 5, six pressure ripples are visible while the pump has three pistons. When this result is multiplied with the rotational speed of the shaft, the frequency of the first harmonic of the pressure ripple can be calculated, as shown in formula 5.

$$f = 2 * N * \frac{n}{60} \tag{5}$$

In formula 5, N represents the number of pistons used in the pump, and n gives the rotational speed of the pump shaft in rpm (rotations per minute). Figure 6 shows the start-up of a 5-piston radial piston pump.

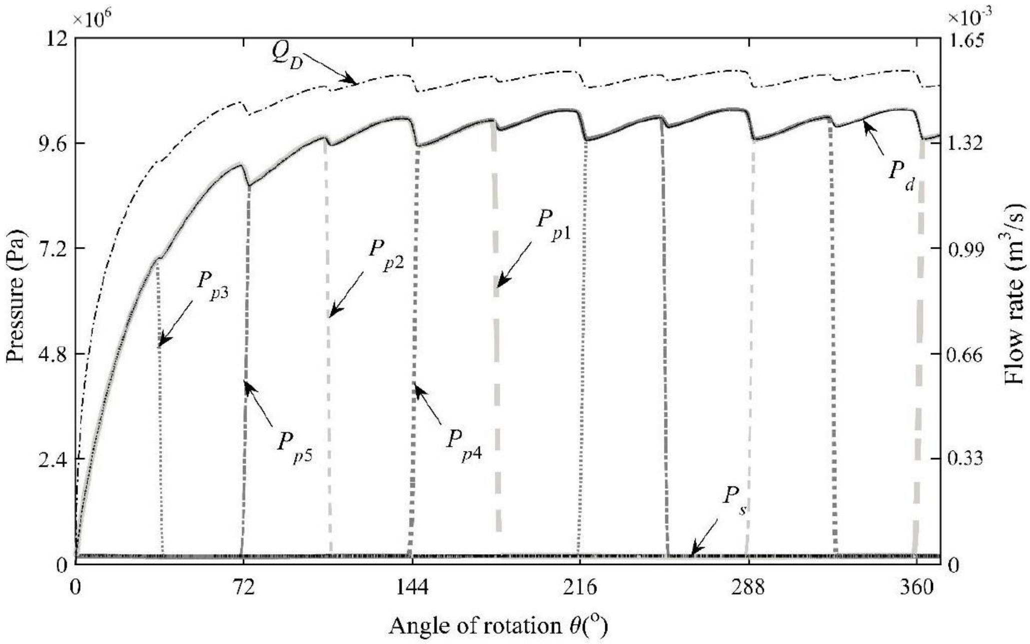


Figure 6: Pressure and flow rate of a radial piston pump in function of the angle of rotation [5, p. 48]

When Figure 6 is compared to Figure 5, it can be seen that the pulsations in the flow rate happen more often when the number of pistons is increased. Because of the increased number of pulsations within one rotation, the flow pulsation frequency of the pump with the higher number of pistons will be higher when they rotate at an equal shaft speed. Since the two pumps that are shown in Figure 5 and Figure 6 are different from each other, no statement can be made about the magnitude of the flow pulsation.

The pressure generated by the pump is considered to be a pure dynamic pressure (static pressure differences are negligible). This means that the pressure in the discharge line can be calculated with formula 6, provided that the losses in the pump are p_L.

$$p = \frac{1}{2} * \rho * v^2 - p_L \tag{6}$$

In formula 6, ρ is the density of the fluid and v is the piston speed. In practice, p_L is dependent on the velocity of the piston v and the density of the fluid. This is why the practical measurements in Figure 6 do not have a symmetrical evolution as opposed to the theoretical values shown in Figure 5. If formula 4 and formula 6 are combined, the relation shown in formula 7 is found between the pressure and the flow rate in the discharge line of the pump.

$$p = \frac{1}{2} * \rho * \left(\frac{Q}{A}\right)^2 - p_L \tag{7}$$

Formula 7 is used to calculate the instantaneous pressure created by one piston. When the pressures of five different pistons are added up, the evolution for the pump unit is obtained. This evolution is also shown in Figure 6, during the start-up of the pump.

2.1.2 5-piston pump

One of the pumps used in the test setup is a 5-piston radial piston pump. The composition of the pump is shown in Figure 7.

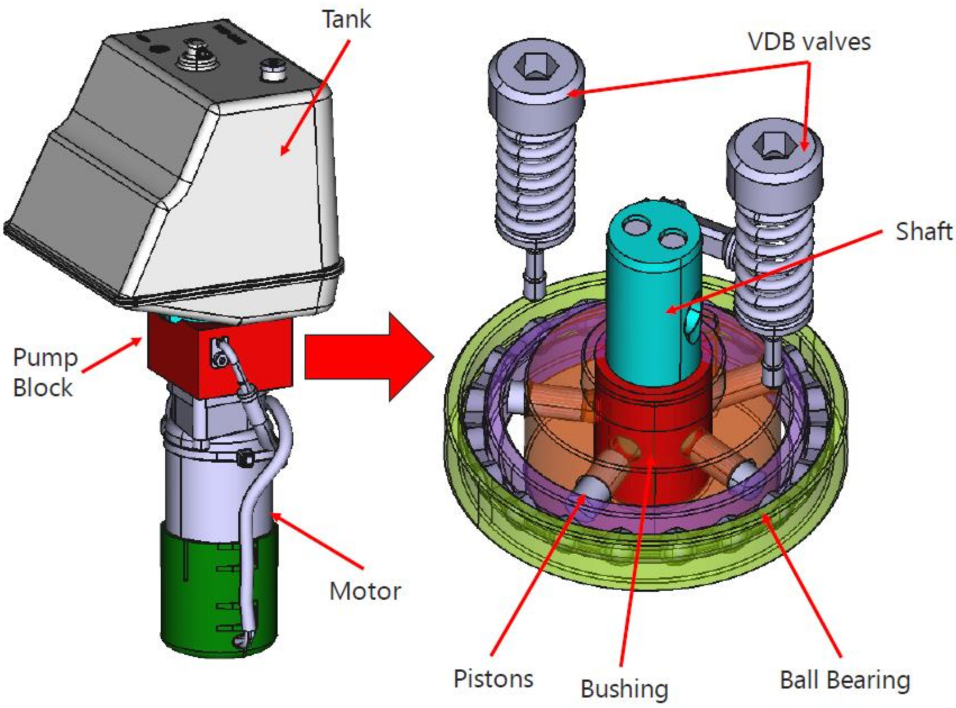


Figure 7: Composition of 5-piston pump [8, p. 8]

On the left in Figure 7, the pump is shown with the pump motor and a hydraulic oil tank attached. On the right in Figure 7, the internals of the pump are visible. The pump uses 5 pistons which are able to move freely in the radial direction when no pressure is applied to the pump. When the pump rotates, the housing of the pistons rotates around the eccentrically (in relation to the ball bearing) placed shaft. The ball bearing rotates due to friction of the backside of the pistons, and by rotating, it reduces the friction between the pistons and the ball bearing. Multiple non-return valves are installed in the pump block to ensure the oil follows the desired path. The operating pressure of the pumps used in the vehicles varies between 50 and 60 bar.

2.1.3 7-piston pump

The composition of the 7-piston pump that will be used in the setup is nearly identical to the composition of the 5-piston pump. To achieve the same flow rate as the five piston pump, the diameter of the piston heads is reduced to 3 mm instead of 3,5 mm in the 5-piston pump. To accommodate the additional pistons, only the piston housing and the bushing shown in Figure 7 have to be replaced. The operating pressure of the 7-piston pump is identical to the one of the 5-piston pump, since they are used in the same system.

2.1.4 Difference between 5-piston and 7-piston pump

The biggest difference between the two pumps is the number of pistons and the volume of the pistons. The different number of pistons has an effect on the frequency of the pressure ripple, while the different volume has an influence on the flow rate generated by the pump.

2.2 Generation of pressure ripples

Now the working principle of the examined pump is known, a study can be carried out to compare the findings from paragraph 2.1 to other researches. As found in paragraph 2.1, [9] confirms that the main cause for pressure ripples (and noise) are flow pulsations. In gear pumps this is mainly caused by the intermeshing of the gear teeth. A secondary effect of the intermeshing of a gear pump is noise due to the impact of the teeth. The increased impact noise is caused by the meshing characteristics of gears. This means that a difference in base pitch between the driving and the driven gear will occur. This difference can be caused by:

- profile error,
- installation error,
- bearing deformation during meshing transmission.

This noise can be reduced by reducing the impact energy of the gears and ensuring that the intermeshing of the gears is more stable. [10] shows that the reasons for noise generation in axial piston pumps are similar to these in gear pumps due to the similar periodic pumping dynamics.

As per [11], in axial piston pumps one of the major noise sources is the pressure variation characteristics in the cylinder and the discharge line. This can be measured by fitting a miniature pressure transducer on the rotating cylinder block of an axial piston pump. In this setup, the data gets transmitted by a slip ring unit to ensure a continuous measurement. The magnitude of the pressure ripple is dependant on the exhaust pressure and the rotational speed. The influence of the exhaust pressure is shown in Figure 8.

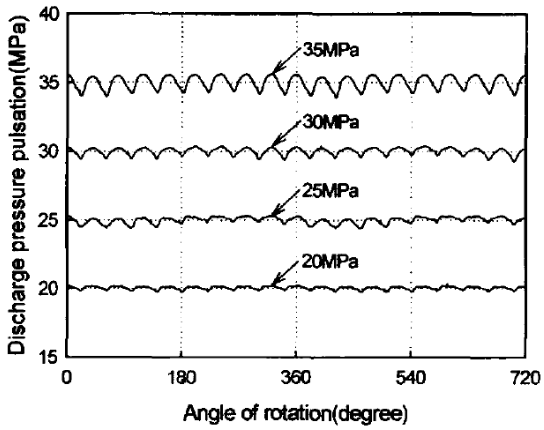


Figure 8: Pressure pulsations in the discharge line [11, p1024]

Figure 8 shows the relations between the pressure variations in the discharge line compared to the absolute pressure in the discharge line. Other factors of the axial piston pump which influence the pressure ripple are the pre-compression angle and the addition of a V-notch between the cylinder and the exhaust. The V-notch provides a leak path from the cylinder to the discharge port, which leads to a more constant pressure at the exhaust. Finally, [12] and [13, para. 7.8] state that the flow speed has a negative impact on the generated noise of a pump.

According to [13, para. 7.9], in pipe systems, coincidence is the dominant source for noise in straight runs downstream of bends, valves and other components. Local flow disturbances induced by these components cause pressure changes and internal noise pressure fields. Noise can also be generated through mechanical vibrations of the fittings. Other sources of noise can be:

- diffusers,
- flow spoilers,
- flow through grilles,
- jets,
- cavity resonances.

Finally, the vibration response of pipe walls to excitation is determined by the coincidence of higher order acoustic modes and the resonant flexural modes of the pipe wall.

2.3 Measuring pressure ripples

2.3.1 ISO 10767-2

To set a reference in the development of the test setup, ISO 10767-2 [4] was used. ISO 10767 gives the determination of pressure ripple levels generated in systems and components. The second part of this norm specifies a simplified method for pumps.

While flow pulsations are the cause of pressure ripples in hydraulic systems, they are more difficult to measure accurately. Therefore ISO 10767-2 gives a method to measure pressure ripples to characterize the fluid-borne noise generation potential of hydraulic power pumps. Measuring pressure ripples depends greatly on the pump design and the test circuit. To achieve uniform test results, the circuit needs to be controlled. The second part of ISO 10767 is used in this thesis because the pressure levels in the examined system are not deemed low, and the frequency of the ripple is expected to be relatively high.

ISO 10767-2 gives the hydraulic scheme to measure pressure ripples caused by a hydraulic pump. This hydraulic scheme is shown in Figure 9.

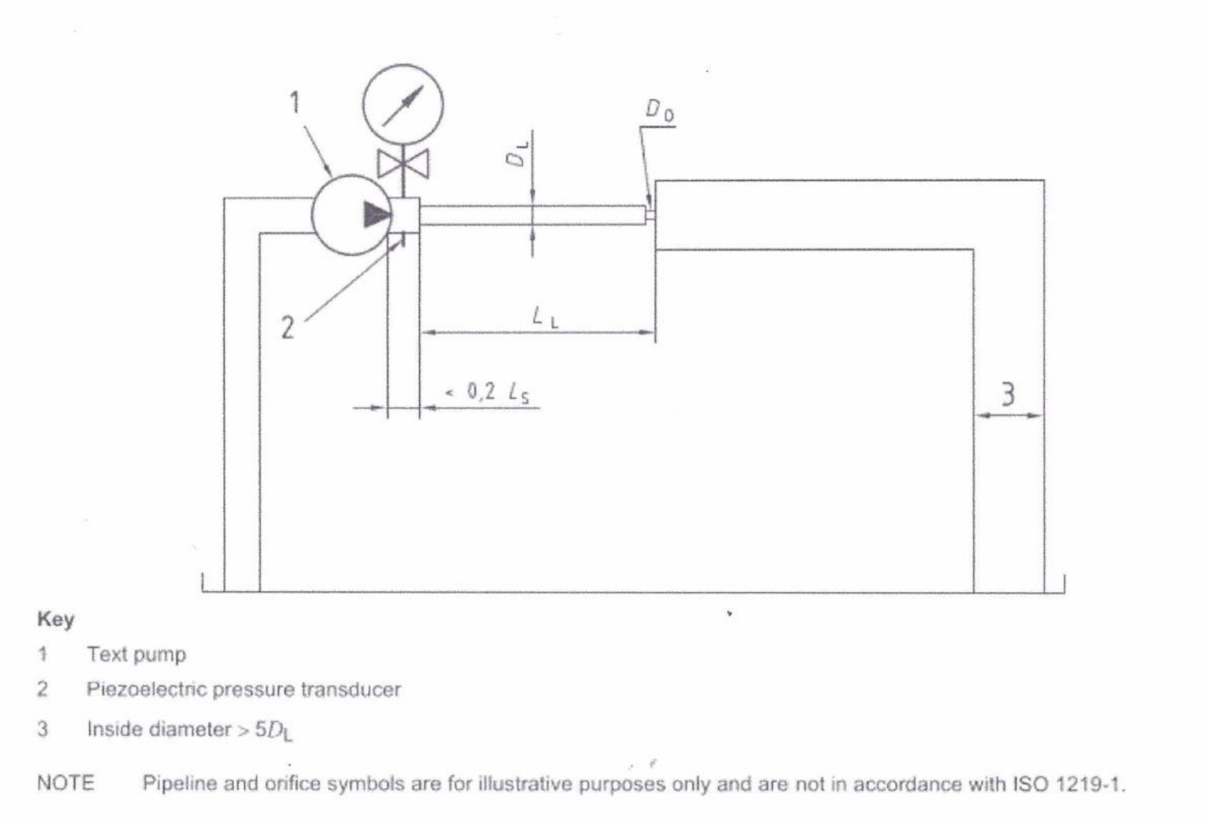


Figure 9: Schematic diagram of test circuit [4, p. 5]

The diagram in Figure 9 shows the main components of the setup:

- the examined pump,
- a piezoelectric pressure transducer,
- an orifice,
- different pipeline segments with defined lengths and diameters.

After the composition of the test setup, a test procedure is given. This procedure consists of eight steps describing the installation of the components, the adjustments of the valves and the recording of the measurements.

2.3.2 Examples of test setups

In addition to the ISO-norm, other research subjects have been explored for use as a reference to develop the test setup. Figure 10 shows an example of a test setup.

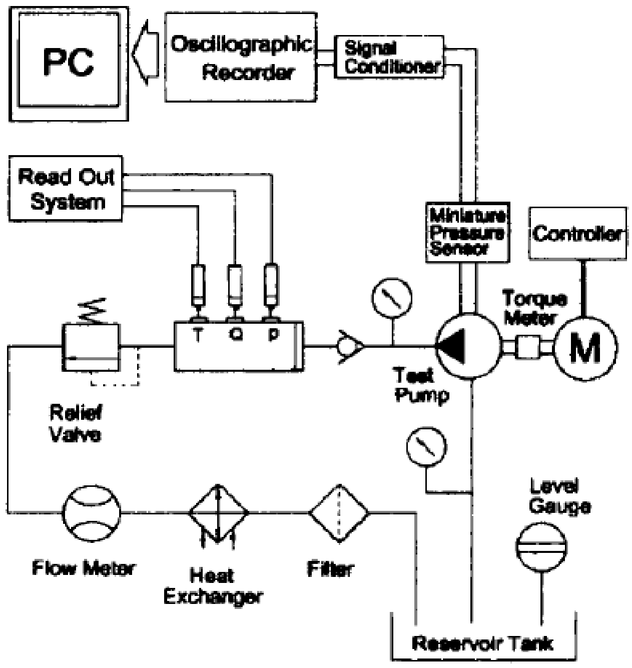


Figure 10: Hydraulic circuit for test equipment [11, p1021]

In Figure 10, [11] gives an example of a test setup to measure pressure ripples. One of the main difficulties of this setup is the incorporation of a miniature pressure sensor, which is built into the pump body and uses a magnetic pickup for the read-out. This principle is not usable with the pump examined in this thesis, because of spatial constraints, technical difficulties because of fragile components and protection by intellectual property of the manufacturer. Figure 11 shows another test setup used to measure a hydraulic system.

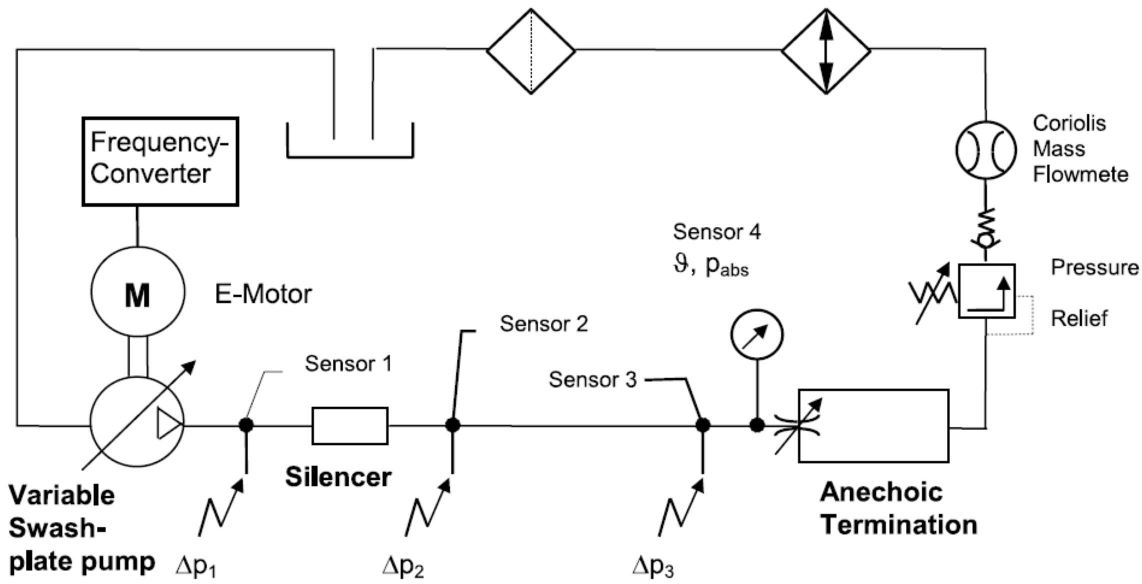


Figure 11: Silencer test rig hydraulic circuit [14, p. 5825]

In Figure 11, a test setup is shown to test the effectiveness of a silencer in the hydraulic system. Since Tenneco wishes to research the influence of the pipe that connects the pump to the manifold, many parts of this setup will be carried over to the test setup developed later in this thesis.

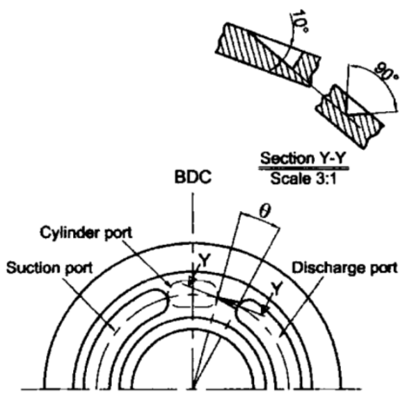
2.4 Reduction of pressure ripples

There are multiple ways to reduce noise. [5] gives three aspects to control noise generation: the noise source, the transmission path and the receiver. In the automotive industry, there is very little influence on this last aspect, so this paper will focus on the first two aspects.

2.4.1 Reduction at the source

The most effective way to control noise is at the source. According to [9], a possible solution is to increase the number of gear teeth of a gear pump, which results in lower flow pulsations. A similar effect can be seen in piston pumps: by increasing the number of pistons, the magnitude of the flow pulsations can be lowered. In axial type piston pumps, there are various other parameters which influence the generated noise [10], some of which can also be applied to a radial type piston pump like the pump discussed in this thesis.

The pump tested in [11] uses suction and discharge ports that can result in a bigger pressure ripple if the timing of opening and closing the ports is not correct. Opening the discharge port too early can result in a reverse flow if the pressure in the discharge line is higher than the pressure in the piston itself. If the discharge port is opened too late, a pressure overshoot occurs, which leads to an even bigger pressure ripple in the system. Figure 12 shows the shape of the valve plates used during testing.



	Pre-compression Angle(θ)	Notch
VP1	0°	None
VP2	13°	None
VP3	13°	V-notch

Figure 12: Shape of test valve plates [11, p. 1021]

Figure 12 shows the implementation of the pre-compression angle and the V-notch in the test plates of the pump. The addition of a pre-compression angle in the pump significantly reduces the generated pressure ripple because the piston pressure that is exposed to the discharge line is at approximately the same pressure, since it has already been compressed. Adding a V-notch to the valve plate of the axial piston pump gives a leak path between the discharge port and the piston in the cylinder. This leads to a gradual increase of the pressure due to the pressure in the discharge line. In adding this V-notch, the pressure difference between the discharge line and the piston gets reduced, which reduces the pressure ripple in the discharge line.

In addition to changing the shape of the valve plate of the pump, the influence of the rotational speed of the pump was researched.

- The width of pressure variations increases slightly if the rotational speed of the pump is increased from 500 to 1000 rpm.
- The width of the pressure variations increases more when the rotational speed is increased from 1000 to 1500 rpm.

This is caused by the fixed size of the components of the system. As the rotational speed increases, the flow rate increases and the components experience more resistance in the system. This leads to an increase of the pressure variations in the cylinders. The losses through the V-notch and the reverse flow increase as well if the rotational speed increases.

The parameters best applicable to radial type piston pumps are the variation in the pre-compression angle, adding a leak path from the discharge port into the cylinder and lowering the rotational speed of the pump. These changes will reduce the pressure ripple and therefore the noise generated in the system.

2.4.2 Reduction in the transmission path

If noise control at the source is not possible, there are possibilities to control the noise in its transmission path. In the case of noise control in the transmission path, the most commonly used solutions, according to [9], are:

- sound insulation,
- sound absorption,
- vibration damping,
- noise elimination.

Sound insulation can for example be achieved by using rubber inserts in the mounting hardware. By insulating the vibrations of the pipe from the chassis of the vehicle, the sound will be damped as well [13, para. 7.9]. Foams or other sponge-like materials can be used to absorb the energy of the noise, or to insulate the source from the receiver. An example of vibration damping using free-layer visco-elastic damping materials is experimentally tested in [10]. Adjusting the wall thickness of the pipes also provides some variations in the coincident frequencies [13, para. 7.4].

According to [15], a nitrogen charged hydraulic accumulator can be used to absorb hydraulic pressure pulsations. Figure 13 gives an example of an in-line nitrogen charged noise suppressor.

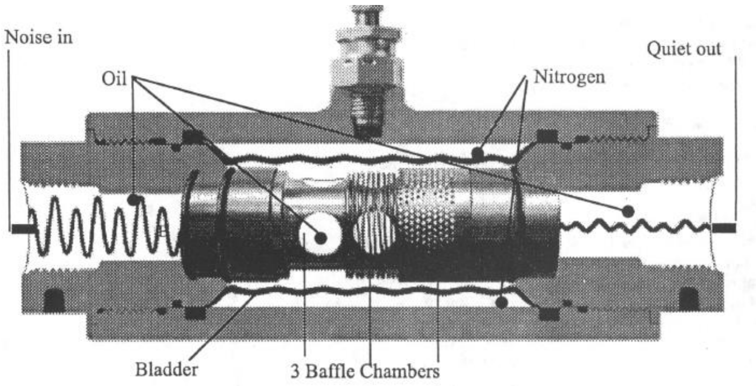


Figure 13: Section of an in-line nitrogen charged noise suppressor [15, p. 387]

With a normal accumulator, there is a possibility that the pulsation will not enter the accumulator, depending on the frequency of the pressure ripple. If the frequency of the pressure ripple in the system is not constant, as is the case with the pump in this application, an in-line nitrogen charged noise suppressor (as shown in Figure 13) is a better solution for pressure ripple damping in systems with a more variable frequency of the pressure ripple. The pressure ripple has no possibility to bypass the in-line suppressor as is the case with a normal accumulator. Another type of in-line suppressor is a reflection type silencer [14]. This silencer has a wider frequency range than a traditional accumulator, and can be used to eliminate multiple frequencies at once. The frequency range of a traditional accumulator is shown in Figure 14, the frequency range of an in-line suppressor is shown in Figure 15.

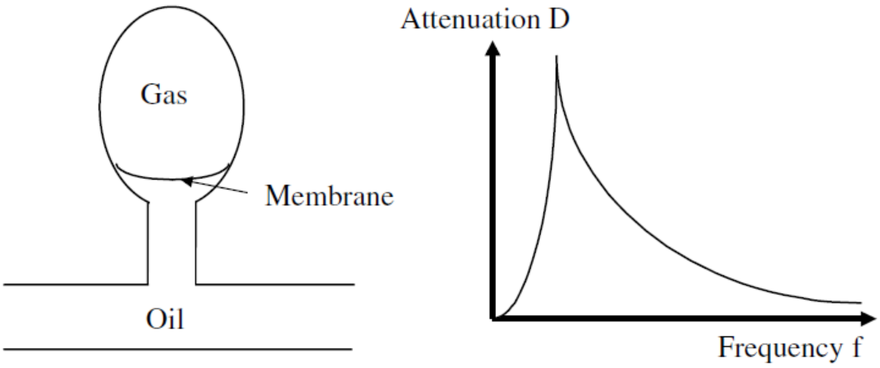


Figure 14: Absorber type of fluid power attenuator (accumulator) [14, p. 5824]

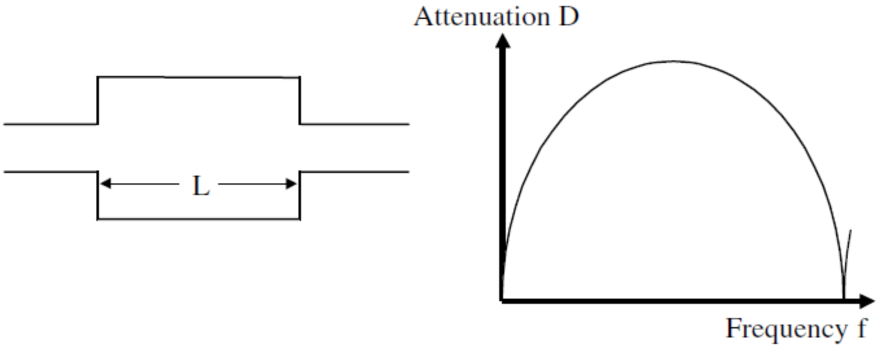


Figure 15: Reflection type of fluid power attenuator [14, p. 5824]

The type of silencer shown in Figure 15 uses a local bigger diameter, which creates an expansion chamber in which the pressure ripples are reflected at the opposite end of the silencer due to the sudden increase in diameter and volume. The reflected pressure ripple will interfere with the normal pressure ripple by reflecting back and forth between the wall at the end of the silencer and the wall at the beginning of the silencer. To solve some of the problems that occur when using traditional accumulators, systems are developed to direct flow in to accumulators, as shown in Figure 16.

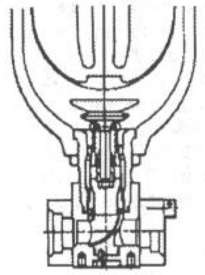


Figure 16: Accumulator with flow directing unit [15, p. 386]

Figure 16 shows a method to direct flow into an accumulator. The design of the components to direct the flow is complex and therefore very expensive. Additionally, these systems generate a very high pressure drop, which can cause problems.

Another subject treated in [15] is the influence of bends in hydraulic hoses on the generated noise. Different types of bends are shown in Figure 17.

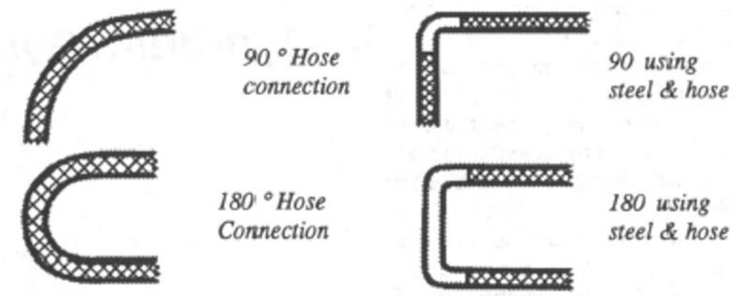


Figure 17: Types of bends in hydraulic hoses [15, p. 386]

Figure 17 shows two different approaches to making bends in hydraulic hoses. Research shows that the configurations using only hydraulic hoses can increase the noise level in hydraulic systems. Replacing the bends in the hydraulic lines with metal tubing bends and using the hoses only in straight lines can reduce generated noise by up to 5 dB(A).

3 Development of the test setup

After researching possible test setups in the literature study, a proposition for a test setup was made. Because of difficulties with the availability and lead time of the selected components, a second test setup was designed. Due to the time limitations of this thesis and to consult additional specialist knowledge, the practical realization of the test setup is done in cooperation with an external partner: AFMECH s.a., located in Visé, Belgium.

3.1 Iteration 1: Test setup with differential pressure sensors

The first iteration of the test setup uses differential pressure sensors to acquire accurate measurement data. As mentioned before, there were difficulties concerning the availability and lead time of the components selected for this setup, so this setup will not be made within this thesis.

3.1.1 Setup overview

Figure 18 shows a proposition for a hydraulic scheme of the test setup for the measurement of the pressure ripples caused by the Kinetic pump.

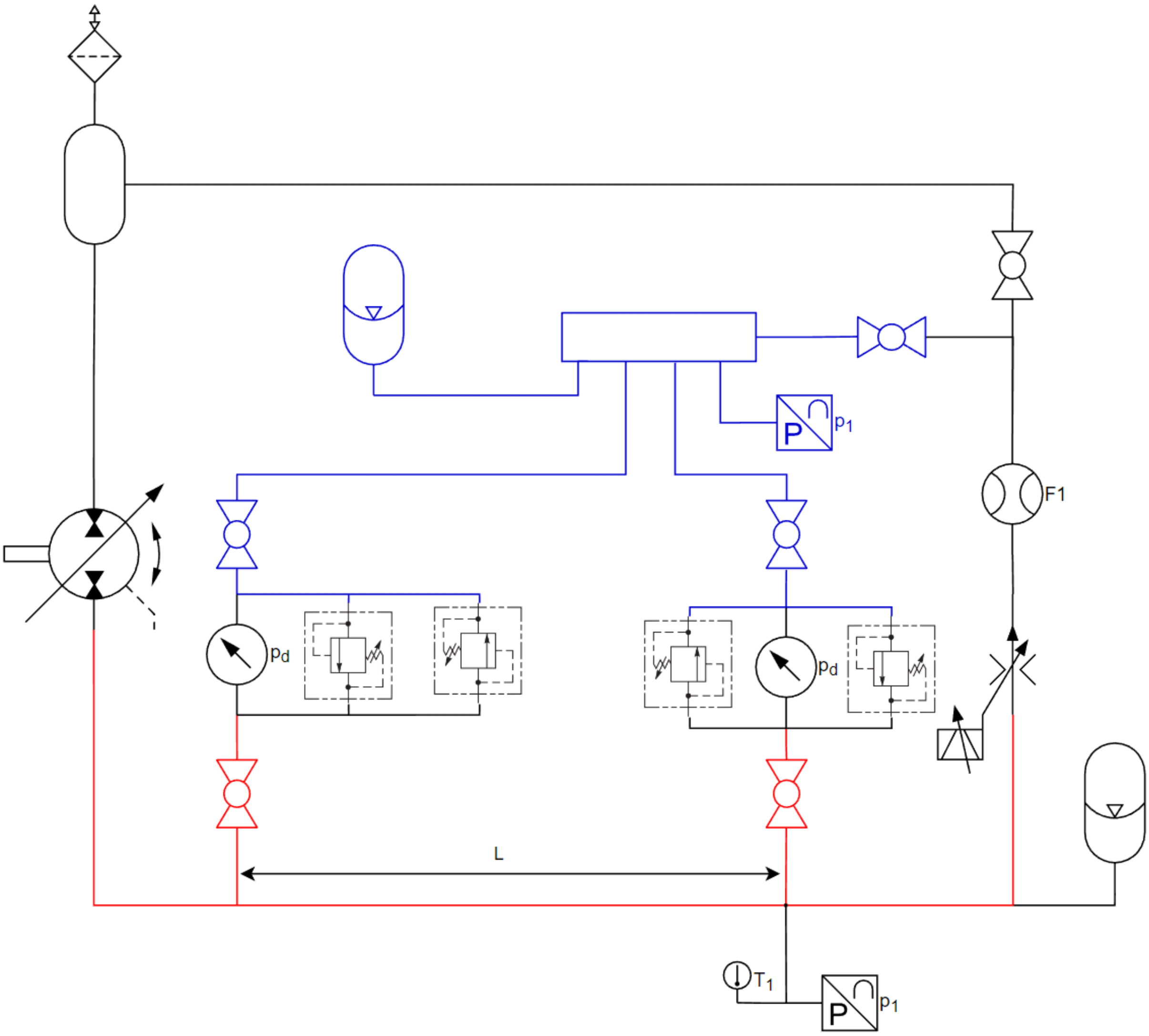


Figure 18: Test setup for measuring pressure ripples using differential pressure sensors

The system can be divided into three parts. The first part, shown in blue in Figure 18, is the reference circuit. This circuit provides a constant reference pressure so the pressure ripple can be measured more precisely. In addition to providing a constant reference pressure for the measurement of the pressure ripple, there will also be an accumulator to diminish any minor pressure ripples carried over from the differential pressure sensors (p_d) and to compensate for the expansion due to temperature differences. A pressure sensor will be added to measure the absolute pressure in the reference circuit.

The circuit that is shown in red in Figure 18 is the measuring part of the system. In this part, the pump will introduce the pressure ripple, and the ripple will be measured close to the pump as well as after a known length (L) of piping. By measuring at two separate points, the effects of the piping can be taken into account. In this part of the circuit, the absolute pressure will be measured in addition to the temperature of the fluid.

The circuit shown in black in Figure 18 is the part of the system that returns the hydraulic oil to the reservoir that is attached to the pump. This part of the system operates at atmospheric pressure. The flowmeter is installed behind the pressure measurement to reduce the interference between the pressure ripple and the inline sensor.

3.1.2 Components of the test setup

- Absolute pressure sensor (

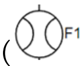
)

In addition to measuring the pressure ripple in the system, the absolute pressure needs to be measured. This can be achieved by using a Keller Series PA-23 pressure transmitter with a full-scale of 200 bar. This results in an accuracy of 0.4 bar (0.2% FS). The read-out of the sensor will happen through a measurement of 0 - 10 V via a 3-wire connection.

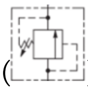
- Differential pressure sensor (

)

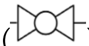
To achieve a higher accuracy than the absolute pressure sensor, a differential pressure sensor will be used in the test setup. The selected differential pressure transmitter is a Keller Series PD-23. The version used will be one with a range of 0 – 5 bar differential pressure and a sampling rate of 5 kHz. This last option is needed because of the high frequency of the ripple that needs to be measured. The use of this transmitter results in an accuracy of 0.01 bar (0.2% FS). The maximum static line pressure of this pressure transmitter is 200 bar, which is sufficient for the system with a burst pressure of 150 bar. Since there is a maximum overpressure of 10 bar on the measuring side and 5 bar on the reference side, a protection against higher pressures is needed on both sides. This protection will be achieved by placing a ball valve on either side of the pressure transmitter. The read-out of the sensor will happen through a measurement of 0 - 10 V via a 3-wire connection.

- Flow meter ()

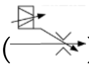
To measure the flow through the system, a HySense QG 100 gear volume flow sensor will be used. The version used has a measuring range from 0.2 to 30 l/min at an allowed working pressure of 160 bar, which leads to an accuracy of 0.015 l/min at the maximum flow that will be used in the tests (3 l/min). The read-out of the sensor will happen through a measurement of the frequency via a 5-wire connection.

- Pressure relief valve (parallel to p_d-sensor) ()

The differential pressure sensors (p_d) have a maximum overpressure on either side of the sensor. To protect the sensor from possible overpressure, pressure relief valves will be installed to reduce the pressure difference if needed.

- Valves ()

To stop the oil flow in the system, valves need to be used. To minimize the amount of flow resistance, ball valves are used. The valves are also used to control the path followed by the flow, as Figure 18 shows. Additionally, the valves are installed to protect the differential pressure sensors from pressure differences exceeding the maximum overpressure. The selected valves are Electric high pressure ball valves: KH 38 HD ELI 230. These are electronically controlled with a voltage from 24 to 240 V_{AC} or 24 to 135 V_{DC} and have threaded connections of G3/8". This size is optimal for the use in combination with DN10 pipes. These valves will be installed on either side of the differential pressure transmitters.

- Pressure control valve ()

To regulate the pressure in the system, a pressure control valve will be used. It is important that this valve does not introduce a pressure ripple or interferes with an existing pressure ripple. Therefore, the selected valve is a direct operated proportional pressure relief valve RE06M10T2N1F0. This valve is able to control the pressure between 0 and 105 bar. The regulation of this valve can be done by using a threshold between which the pressure may vary before the valve opens. The valve is controlled by a signal from 0 to +10 V_{dc}.

- Accelerometer

To measure the vibrations of the system, accelerometers will be used. To determine the influence of the pipe network, three sensors will be placed in the system: the first one on the pump itself, the second one on the start of the test pipe and the last one at the end of the test pipe. The selected sensors are Wilcoxon 787A- sensors. These sensors were selected because of their low sensitivity tolerance (±5%) and the correct measuring range (0,5 Hz – 10 kHz). The electrical connection for this sensor is a standard 4-pin M12 connector.

3.2 Iteration 2: Test setup with piezoelectric pressure sensors

The main reason for the design of this second test setup is the unavailability or long lead times of the selected components from the first test setup. Since the unavailable components had no substitute with specifications that met the requirements, a second test setup was made with different components and a different principle. An additional advantage of the second test setup is that it does not need the reference system and the needed safety precautions for the differential pressure sensors, which greatly simplifies the setup. Instead, it uses piezoelectric sensors with a high measuring frequency to measure the pressure ripple. The setup is not built as described in the ISO-norm for determination of pressure ripple levels generated in system and components (ISO10767-2) [4]. The reason for this being that Tenneco also wants to take into account the influence of the line that connects the pump to the manifold. In comparison to the ISO-norm, some additional components will be added to ensure that the hydraulic behavior of the system can be measured accurately.

3.2.1 Setup overview

Figure 19 gives another possible hydraulic scheme for a test setup for the measurement of the pressure ripples caused by the Kinetic pump.

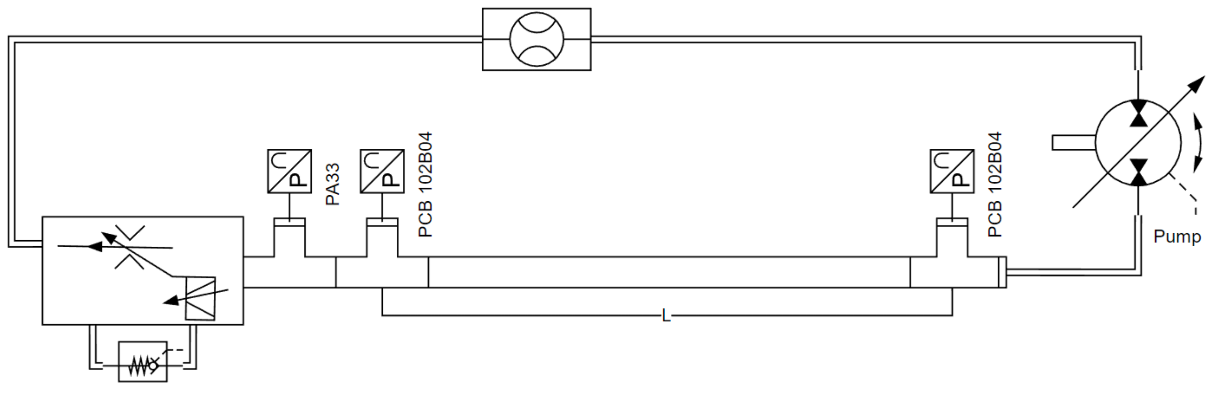


Figure 19: Test setup for measuring pressure ripples using absolute pressure sensors

In Figure 19, the thin pipes represent flexible tubes, while the big pipes represent steel pipes with an inner diameter of 12 mm. The pump unit used in the vehicles has a piece of flexible tube with a quick assembly coupling from Walther Präzision attached to provide a fast way to connect and disconnect the pump. This type of quick connector is shown in Figure 20, more information can be found in Appendix B.1.

Figure 20: Quick assembly coupling (Appendix B.1, p. 1)

On the left in Figure 20, the female part is shown (07-003-0-4M010-AADY-Y32), and on the right the male one (07-003-2-4M010-AADZ-Y32). The female part of this quick connector is attached to a first T-junction which also holds the first piezo-electric pressure transducer. The measuring tube is connected to the third terminal of the T-junction. At the opposite end of the testing tube, the second T-junction is connected to house the second piezo-electric pressure transducer and to connect the third T-junction. This third T-junction houses the absolute pressure sensor and connects to the needle valve that regulates the pressure in the testing tube by limiting the flowrate. To protect the components in the setup from pressures exceeding their operating ranges, a pressure relief valve is placed in parallel to the needle valve. From the needle valve, the flowmeter gets connected using a flexible tube and a final piece of flexible tubing is used to return the hydraulic oil to the reservoir in the pump unit. The pipes and T-junctions will be interconnected using a Tri-clamp system (following DIN 32676) as shown in Figure 21 and Figure 22. This system allows for quick adjustments during the research phase, while limiting flow restrictions. To attach the sensors and valves to the system, some custom components were made (Drawings in Appendix A.1 - A.7). Figure 23 shows the test setup as it is deployed at Tenneco.

Figure 21: Components Tri-clamp system [16]

Figure 22: Tri-clamp system mounted in the test setup

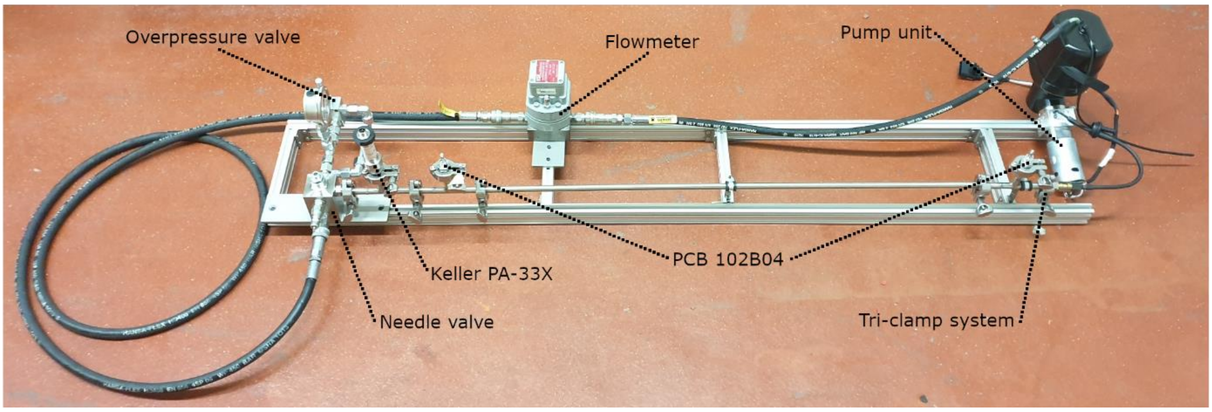


Figure 23: Test setup

As can be seen in Figure 23, the test pipe is held in place by two brackets with a rubber insert, one in the middle of the test pipe, and one at the T-junction at the pump side. At the needle valve side, the pipe is held in place by the mounting block for the needle valve. Table 1 gives an overview of all the parts used.

Table 1: Overview of used parts

Part	Model	Number
Connection pump unit	Quick assembly coupling, type 07-003-0-4M010-AADY-Y32	1
Mount for connection pump unit	Custom part: Appendix A.1	1
Connections test pipe	Tri-clamp system, micro clamps (DIN 32676)	14
T-junctions	12 mm internal diameter	3
Mounting brackets	Brackets with rubber inserts: diameter 15 mm	2
Piezoelectric pressure sensor	PCB Piezotronics 102B04	2
Mount for PCB 102B04	Custom part: Appendix A.2	2
Test pipe	12 mm internal diameter (Length between two sensors on T-junction)	1 m
Absolute pressure sensor	Keller PA-33X	1
Mount for Keller PA-33X	Custom part: Appendix A.3	1
Connection Tri-clamp system to mounting block FV102KV	Custom part: Appendix A.4	1
Mounting block for FV102KV	Custom part: Appendix A.5	1
Needle valve	Parker FV102KV	1
Mounting plate for FV102KV	Custom part: Appendix A.6	1
Pressure relief valve	VMP ¼” Light	1
Connections return pipe	Quick release couplings DNP PBV1 DN06-BG1-ISO6.3-BSP1/4	3 M 1 F
Hydraulic hose	Hose with connections: M – F	1
Flowmeter	VSE Flow VSI 0.02 High Definition Flow Meter	1
Mounting plate for flowmeter	Custom part: Appendix A.7	1
Hydraulic hose	Hose with connections: F – open ended	1
Frame	Bosch-profiles 20x40 mm (2x1,5 m + 4 cross members 250 mm)	4 m
	Sliding nuts M4	38
	Angle iron 20 mm x 20 mm x 2mm L=40 mm	8

3.2.2 Components of the test setup

- Absolute pressure sensor (PA-33)

In addition to measuring the pressure ripple in the system, the absolute pressure needs to be measured. The piezo-electric pressure sensors are not capable of measuring absolute pressure, so this can be achieved by using a Keller Series PA-33X pressure transmitter with a full-scale of 100 bar and a proof pressure up to 300 bar. The PA-33X is shown in Figure 24.

Figure 24: Keller PA-33X

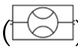
This sensor has an accuracy of 0.05 bar (0.05% FS). The readout of the sensor will happen through a measurement of a 0-10 V signal via a 3-wire connection. The datasheet for the Keller PA-33X is added in Appendix B.2. Additionally, this sensor contains a temperature probe that will be used instead of the separate temperature sensor from the first iteration of the setup. The readout of the built-in temperature probe happens through a digital signal following the RS485 protocol.

- Piezoelectric pressure sensor (PCB 102B04)

To measure the pressure ripple in the system, a piezoelectric pressure sensor will be used. The selected sensor is the PCB Piezotronics model 102B04 and is shown in Figure 25.

Figure 25: PCB 102B04

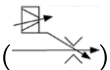
This sensor has a full scale of 69 bar and a useful overrange of 137.9 bar. The sensitivity of this sensor is 0.7 mV/kPa, the resolution is 0,14 mPa and the rise time of the sensor is less than 1 µs. The readout of the sensor will happen through the measurement of a current between 2 and 20 mA via a 2-wire connection. The datasheet for the PCB 102B04 is added in Appendix B.3.

- Flow meter ()

To measure the flow through the system, a VSE Flow VSI 0.02 High Definition Flow Meter will be used. Figure 26 shows the flowmeter installed in the test setup. The datasheet for the VSI 0.02 flowmeter is added in Appendix B.4.

Figure 26: Flowmeter

The version used has a measuring range from 0.02 to 2 l/min at an allowed working pressure of 315 bar, which leads to an accuracy of 0.02 l/min (given the current setup of the flowmeter) at the maximum flow that will be used in the tests (2 l/min). The read-out of the sensor will happen through a measurement of the frequency of a square wave via a 5-wire connection.

- Needle valve ()

To regulate the pressure in the system, a flow control valve will be used. By limiting the flow that passes through the valve, the pressure in the system can be increased. It is important that this valve does not introduce a pressure ripple or interferes with an existing pressure ripple. Therefore the selected valve is a Parker needle valve FV102KV, shown in Figure 27. The datasheet for the Parker FV102KV is added in Appendix B.5. This valve is manually adjustable from 0 to 23 l/min, resulting in a pressure regulating range of 0 to 204 bar. The use of a pressure relief valve in parallel as shown in Figure 28 is recommended to ensure the safety of the used sensors and other components. Later a stepper motor or servo can be attached to automate the flow control.

Figure 27: Needle valve Parker FV102KV [15]

Figure 28: Needle valve with pressure relief valve in parallel

As can be seen in Figure 28, the mounting block in which the FV102KV is installed is equipped with two quick release couplings of the type DNP PBV1 DN06-BG1-ISO6.3-BSP1/4, also shown in Figure 29. The datasheet for the DNP PBV1 quick release couplings can be found in Appendix B.6.

Figure 29: Quick release couplings DNP PBV1 DN06-BG1-ISO6.3-BSP1/4 [18]

- Pressure relief valve

To protect the system from higher pressures than it is intended for, a pressure relief valve will be used to limit the maximum pressure in the system. The selected pressure relief valve is a VMP ¼" Light and is shown in Figure 30. More information can be found in the datasheet in Appendix B.7.

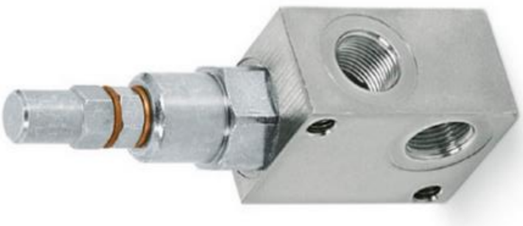


Figure 30: Pressure relief valve VMP ¼" L [19]

This valve has an adjustable pressure range from 10 to 180 bar and a maximum working pressure of 350 bar. The maximum flow of the pressure relief valve is 30 l/min, which is more than sufficient for application in this setup. The pressure relief valve is set to 80 bar in this test setup, because this is the rated pressure of the Tri-clamp system.

- Accelerometer

To measure the vibrations of different components of the test setup, accelerometers can be added to the setup. The model that is available at Tenneco is the PCB Piezotronics 356B21, a tri-axial ICP accelerometer. The sensitivity of this sensor is 10 mV/g and the sensor has a range of ±500 g. The readout of the sensor uses a 4-pin 8-36 connector. An important aspect of the accelerometer is its measuring frequency, which is up to 7000 Hz for the x-axis, and up to 10000 Hz for the y- and z-axes.

3.3 Data acquisition

To acquire the data, a National Instruments CompactDAQ is used. A cDAQ-9189 chassis [20] is used in combination with a NI-9220 analog input module with spring terminal connectors [21]. The analog module is shown in Figure 31.

Figure 31: Analog module NI 9220

The CompactDAQ is connected to a PC using an Ethernet cable and LabView is used to read the data from the CompactDAQ and convert the measured voltages to the suitable units for the different inputs. This conversion includes the sensitivity of each sensor individually as well as the setting of the signal conditioner if used. The data is also plotted in real-time on the PC screen to provide a means to monitor the test conditions. The sensors from PCB Piezotronics use a 482A20 ICP sensor signal conditioner, shown on the right in Figure 32, to convert the 4 to 20 mA signal into a 0 to 10 V signal that can be read by the CompactDAQ. The specifications of the 482A20 ICP sensor signal conditioner are shown in Appendix B.9.

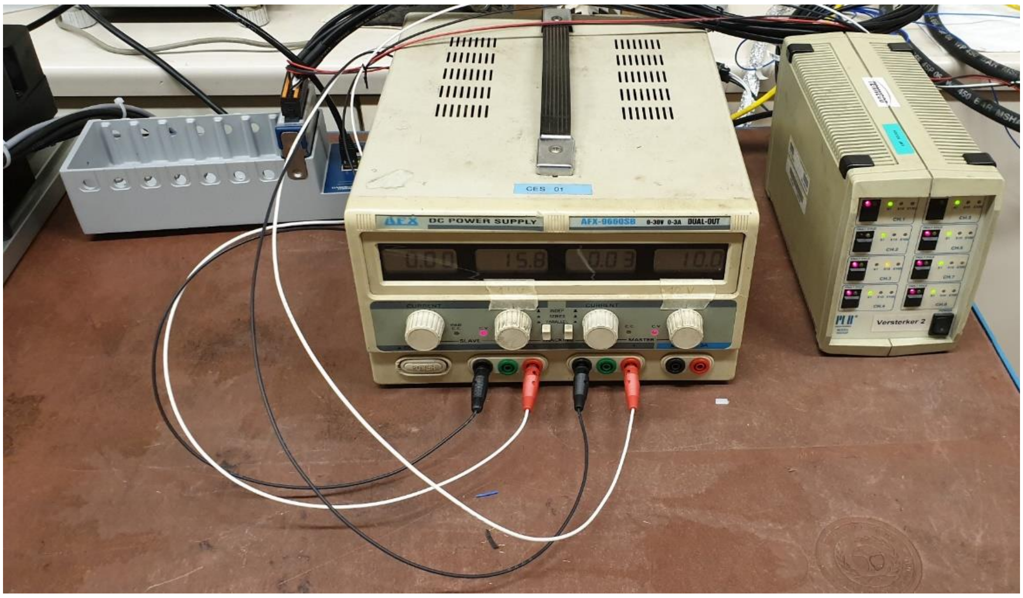


Figure 32: Setup of data acquisition

Figure 32 shows on the left the CompactDAQ with the analog module, in the center the AFX-9660SB power supply to provide power to the Keller pressure sensor and the VSE flowmeter and on the right the PCB signal conditioner. The sampling frequency of the CompactDAQ can be adjusted through LabView up to 100 kS/s/ch (kilosamples per second, per channel) (LabView program: Appendix C). At the end of the measurement, the data is saved. In the LabView program, there is also the possibility to connect and read three different accelerometers, but these are not used in this thesis because of time constraints.

The data saved from LabView is processed further using MATLAB R2021b (Matlab code: Appendices D.1-D.3). However, the code is made to be compatible with MATLAB R2018b, since this is the version used at Tenneco. In MATLAB, the CSV-files from LabView are read, and the timestamps are converted into a duration. Then, a lowpass filter is applied to the pressure signals. This way only the useful frequencies are visible when the pressure is plotted in function of time. After plotting the pressures and the flow, the signals from the PCB-sensors are processed using a single-ended frequency analysis. Finally, the amplitude of the harmonic distortion will be plotted in function of the frequencies.

The temperature of the hydraulic oil will be measured by the internal temperature probe of the Keller PA-33X. The readout of this probe is only possible through the digital readout of the sensor. To convert the digital signal to a signal that can be read by the PC, a Keller K-114B RS485 to USB converter is used. The digital readout happens through a proprietary program (CCS30) provided by Keller. The data converter is shown in Figure 33, more information is given in Appendix B.8.

Figure 33: RS485 to USB converter

To power the pump during testing, a three phase 380 V power supply is used. The model available at Tenneco is the Delta Elektronika SM 60-100 and is shown in Figure 34. This power supply has a voltage range from 0 to 60 V and a current range from 0 to 100 A and can be used either in constant voltage or constant current mode. During the tests, the constant voltage mode is used.

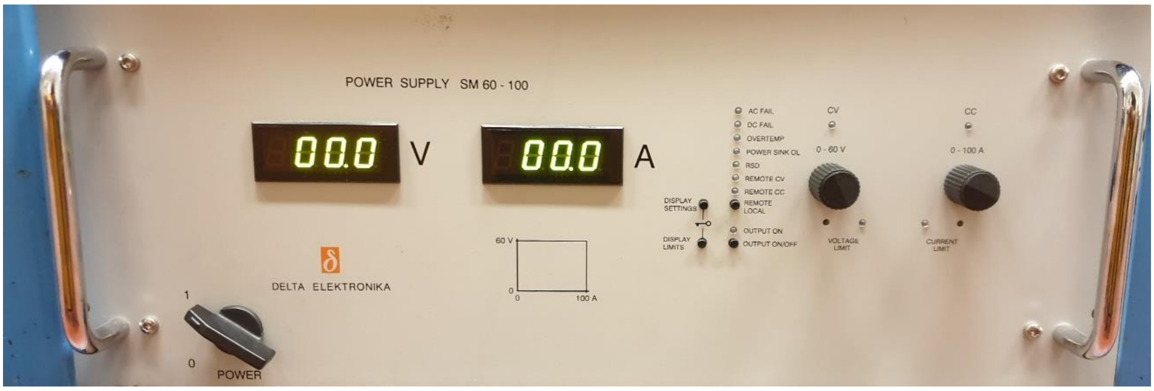


Figure 34: Power supply for the pump

3.4 Test procedure

The last part of the development of the test setup is composing a test procedure, so the measurements can be reproduced. The test procedure assumes that the test setup and the other components are placed on a level and dry surface. The test procedure uses the filling station for hydraulic systems that is widely used within Tenneco.

1. Check if all the Tri-clamp connections are lined up and tightened down properly. Secondly, check if all the threaded connections are screwed in properly and with use of a sealant (e.g. doughty washers).
2. Connect the filling station to the unused PBV1 quick release coupling and connect the filling station to a compressed air source (6 bar is used at Tenneco). Turn on the power of the filling station.
3. Use the filling station to pressurize the system with compressed air, to check for any leaks. Make sure that the flexible tube connecting the flowmeter to the tank of the pump is disconnected to close the system and prevent air or oil passing in/out the setup.
4. Turn off the compressed air on the filling station and open the valve of the atmospheric pressure.
5. When the system is at atmospheric pressure, this valve can be closed again and a vacuum can be applied to the system by opening the vacuum valve.
6. When a pressure of below 10 mbar is reached, close the vacuum valve. (Generally after 1 to 2 minutes)

7. To pressurize the oil in the filling station, open the compressed air valve. Make sure that the vacuum valve is closed.
8. To fill the system, open the filling valve on the filling station.
9. When the system is filled, disconnect the flexible hose from the test setup.
10. Close the pressurized air valve and open the valve for the atmospheric pressure. Then disconnect the pressurized air from the filling station and turn off the power of the filling station.
11. Connect the PCB 102B04 pressure sensors to two different inputs of the PCB signal conditioner and set the amplification value to 1. Then connect the corresponding outlet of the signal conditioner to the cDAQ.
12. Connect the $+V_s$ and the GND of the Keller PA-33X pressure sensor to the AFX-9660SB power supply and set the voltage between 15-30 V. Next connect the analog OUT and the GND to the cDAQ. Lastly, connect the two digital readouts and the GND to the RS485 to USB converter module.
13. Connect the $+V_s$ and the GND of the flowmeter to the AFX-9660SB power supply and set the voltage between 10-28 V. Then connect the analog OUT and the GND to the cDAQ.
14. Connect the cDAQ to a PC using an Ethernet cable, and the RS485 to USB converter module using the USB connector.
15. Connect the pump to the Delta Elektronika SM 60-100 power supply. Turn the main switch of the power supply on and set the settings to the desired voltage. Do not turn the output of the power supply on.
16. Start the proprietary Keller PC program (CCS30) for the digital readout of the Keller sensor. Make sure the correct drivers are installed on the PC.
17. Start the LabView file for the readout of the sensors.
18. Use a ¼" hex key to completely open the needle valve. Connect the flexible hose from the flowmeter to the reservoir of the pump.
19. Connect the cooling stand to the pressurized air terminal and slightly open the valve. Aim the nozzles at the pump motor.
20. Turn on the output of the SM 60-100 power supply. The pump will start.
21. Adjust the pressure by turning the hex key in the needle valve. The manometer installed on the system can be used as a reference. For a more accurate readout, check the CCS30 program for the digital readout of the Keller sensor.
22. Run the LabView program to start measuring and recording data. When the measurement is finished, press the SAVE&STOP button within the LabView program. A directory to save the data has to be specified twice (one for the flowmeter data, one for the pressure sensors data).
23. Turn off the output of the SM 60-100 power supply to turn off the pump. Close the valve of the cooling stand.
24. If the graphs are required for analysis of the data after the measurement, load the correct CSV-files (flowmeter data and pressure sensor data) into MATLAB and run the program.
    a. There is also a program 'comparing two measurements' to compare two measurements. To run this, four files need to be loaded into the program.
    b. A program to compare the results from the PCB sensor data from five measurements is also created. To run this, the files from five different measurements have to be loaded into the program 'comparing five measurements'.

4 Experiments and results

After the development of the test setup, the setup was built in partnership with AFMECH s.a.. The used hydraulic components can be found in paragraph 3.2. During the execution of the tests, some additional cooling using compressed air nozzles was provided to the pump motor since the motor is designed for short periodical use. Since the system is open to atmospheric pressure at the return line into the tank, the pressure drops quickly when the pump is shut down. As a result, the pump needed to run for longer intervals at a certain pressure to provide suitable measurement data. The regulation of the pressure in the system was carried out manually, which leads to longer run times and possible inaccuracies. The settling time of the pressure drop over the needle valve also contributed to longer run times. Figure 35 shows a graph that is acquired by the processing in MATLAB.

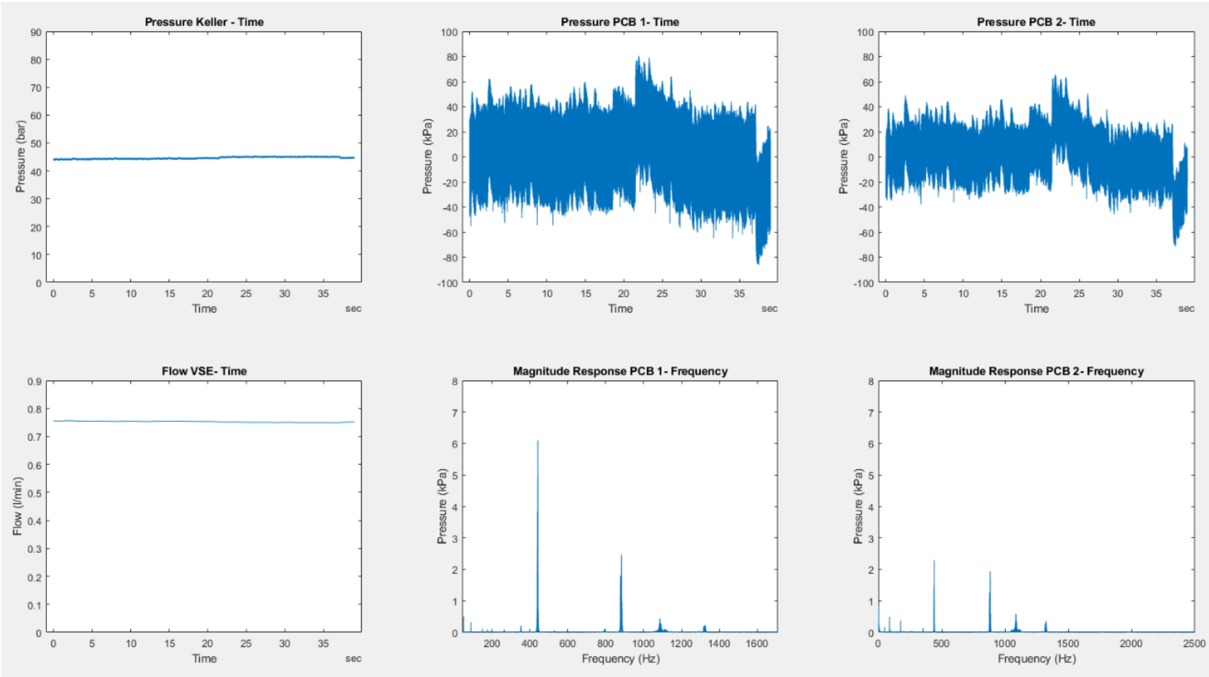


Figure 35: Results processing MATLAB

Figure 35 shows on the top left the absolute pressure measured by the Keller pressure sensor, and in the top center and right the results from the PCB- piezoelectric pressure sensors, all three in function of time. At the bottom left, the flow measured by the flowmeter is shown in function of the time. Lastly, on the bottom center and right, the FFTs from the PCB sensors are displayed. These FFTs show the amplitude of the pressure ripple in function of the frequency of the pressure ripple. A major disadvantage of this readout is that the pressure ripple cannot be seen clearly on any of the graphs. Because of this, from now on, all the graphs from the PCB pressure sensors will be zoomed in on the time scale to clearly visualize the pressure ripple.

4.1 Parameter diagram

To be able to perform meaningful measurements, the setup needs to have a certain level of repeatability and reproducibility. To help define all the parameters in the test setup and their influence on either the measurement itself or the collection of the data, a parameter diagram was composed. This parameter diagram is shown in Figure 36.

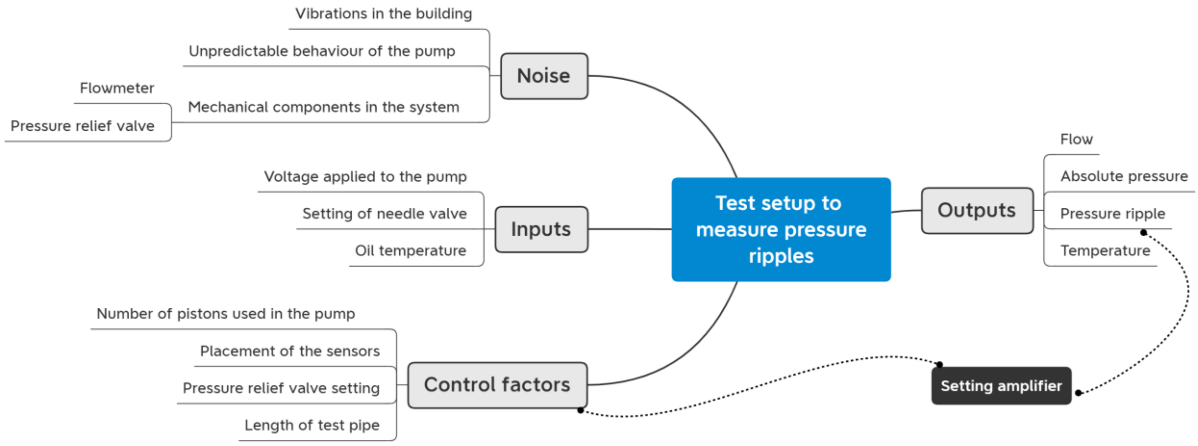


Figure 36: Parameter diagram

The parameter diagram in Figure 36 shows the different aspects that can influence the collected data from a measurement. In the top left corner the factors are shown that can possibly cause noise in the measurement. The flowmeter and the pressure relief valve are listed here because they include mechanical components. In the flowmeter, there are gears present that intermesh, which may cause noise in the measurement. The pressure relief valve contains a spring, so when the opening pressure of the valve is approached, this spring can be compressed slightly, which opens the valve unnecessarily. On the left, in the center, the direct inputs of the system are displayed. These are the factors that can be adjusted easily while performing the measurements. In the bottom left corner, the control factors are shown. These aspects of the measurement are adjustable, but to adjust these parameters, parts of the setup need to be disassembled. Therefore these are not classified as inputs. Lastly, on the right, the outputs of the system are shown. Here all the measured signals that are written into the CSV-file by LabView are listed. As can be seen in Figure 36, this output is also controlled by a control parameter. This control parameter does however not control the measurement, only the scale of the readout.

4.2 Reproduction of manufacturer test

The first measurement was performed to compare the data provided by the test setup with the data provided by the pump manufacturer. The test was carried out at a voltage of 13,2 V and a pressure of 45 bar. Figure 37 displays the data provided by the pump manufacturer, Figure 38 and Figure 39 display the data collected in the test setup.

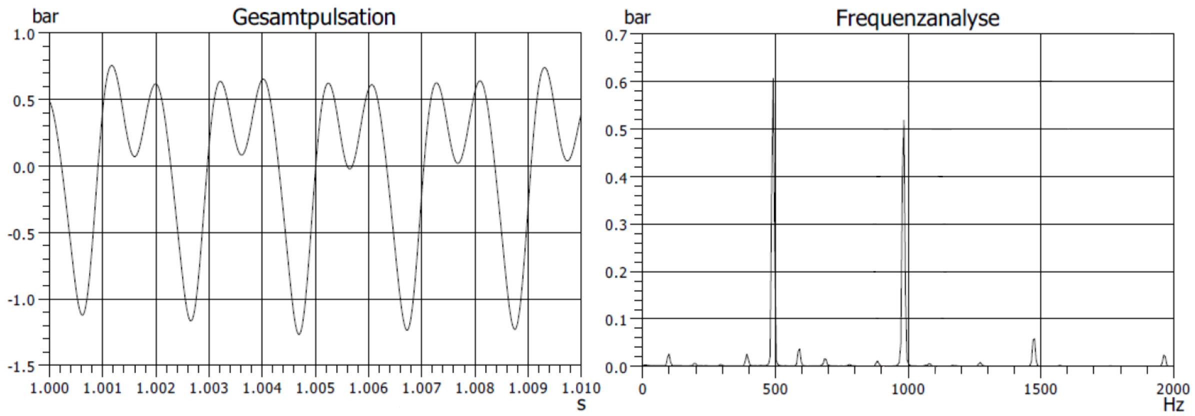


Figure 37: Manufacturer data [12, p. 9]

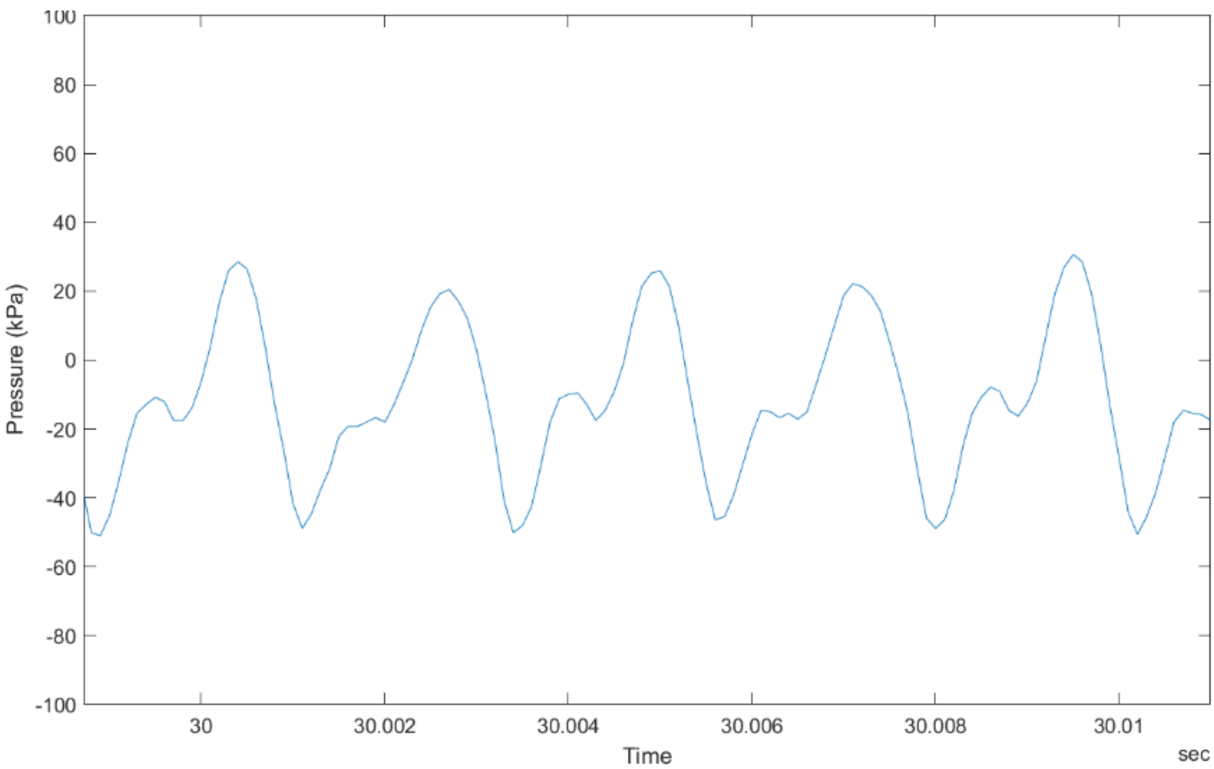


Figure 38: Measured pressure ripple at 45 bar

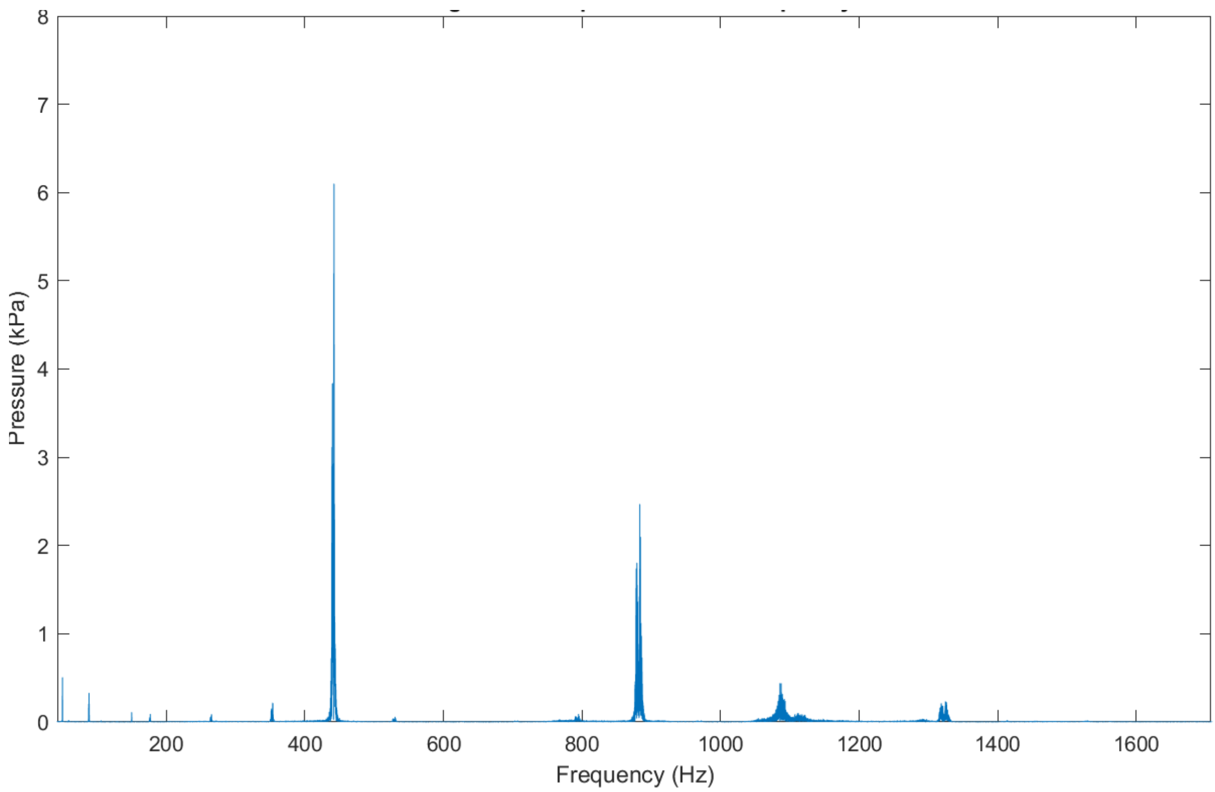


Figure 39: Magnitude response at 45 bar

If Figure 37 is compared to Figure 38 and Figure 39, it is clear that the peak-to-peak value of the pressure ripple is smaller in the experiments than in the manufacturer data. The peak-to-peak value provided by the manufacturer stands at 1,9 bar, while the value from the experiments amounts to 0,8 bar (80 kPa). When the FFTs are compared to each other, it is clear that they are very similar. However the peaks in the FFTs from the experiments tend to be about 20 to 30 Hz lower. Experience within Tenneco indicates that there is a variation of ± 10 % on the rotational speed of the pump motor, which is a possible reason for this deviation. Another reason for this difference might be that the measurements are performed on different temperatures. Since no temperature is provided by the manufacturer, this cannot be taken into account when performing the measurement.

4.3 Influence of flowmeter

To examine the influence of the flowmeter on the system, a reference measurement was executed to establish a baseline. After this, a measurement was executed without the flowmeter installed in the system. This way, the magnitude of the backpressure that the flowmeter adds to the system can be determined. Figure 40 displays the pressure measurement with and without the flowmeter in the hydraulic system.

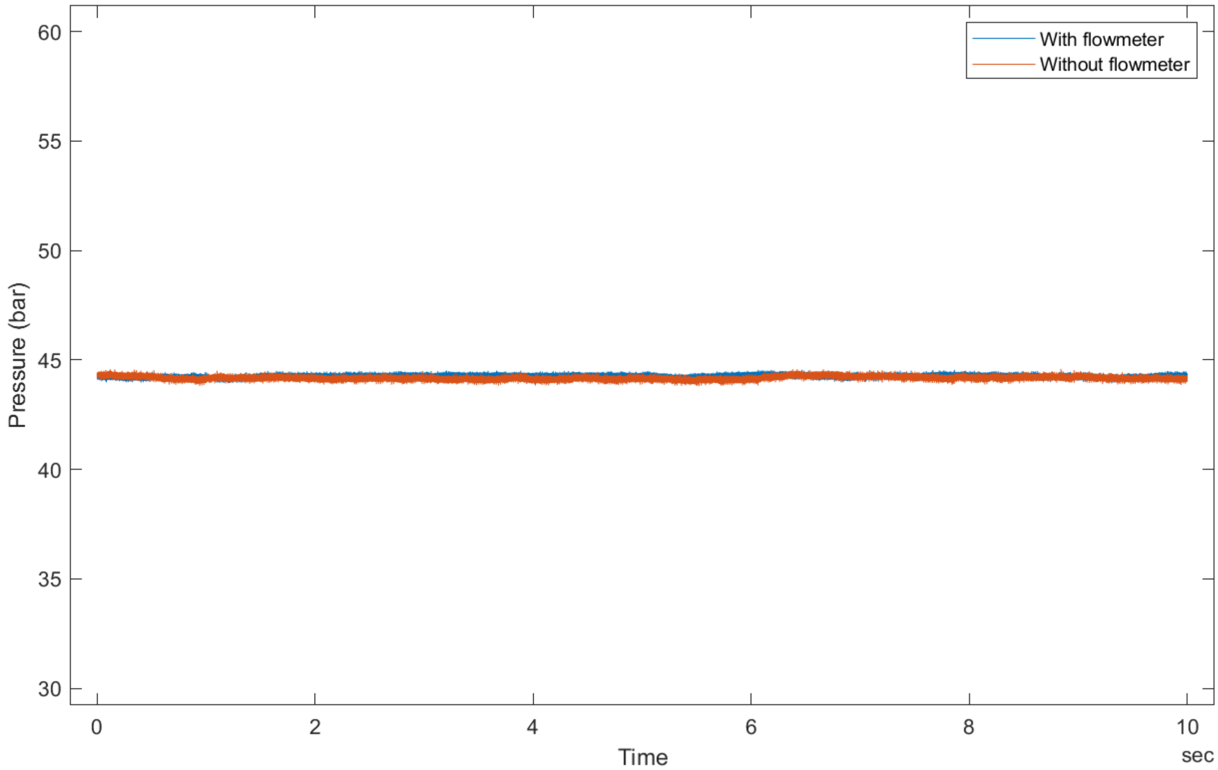


Figure 40: Pressure comparison to examine the influence of the flowmeter

Figure 40 shows that there is little to no difference between the pressure in the system with or without the flowmeter installed. In Figure 41, the graphs on the left side are from the PCB-sensor mounted closest to the pump and the right graphs are from the sensor mounted next to the needle valve. In the graphs, the blue data is with the flowmeter and the orange is without the flowmeter installed.

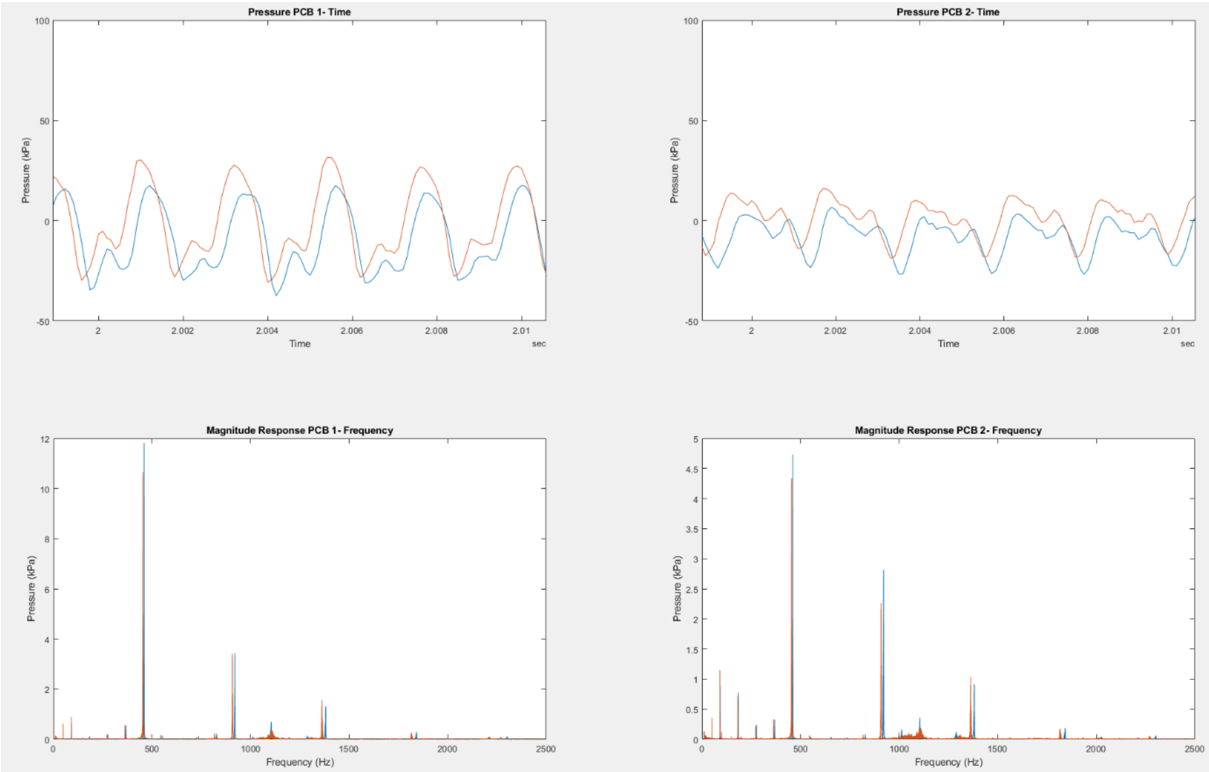


Figure 41: MATLAB-results at 45 bar (blue with flowmeter, orange without flowmeter)

To determine if the flowmeter has changed the pressure ripple, there are two parameters to look for in the top left graph of Figure 41. The first parameter is to look for additional peaks in the pressure ripple, which may be generated by the movement of the gears in the flowmeter. The second parameter is a drastic change in the magnitude of the ripple. Looking at the pressure response of PCB 1, it is clear that there are no additional peaks introduced into the ripple. Next, the difference between the magnitudes of the ripple with and without flowmeter is ± 5 kPa. This might also be slightly influenced by the different offset of the sensors. However this is only for the displayed peaks, and the difference between peaks in another time window from the same measurement could have another deviation. The same conclusion can be made with the top right graph of Figure 41. The FFTs shown at the bottom in Figure 41 indicate that there is no significant shift in frequency of the measured pressure ripple.

4.4 Influence of mounting brackets

To examine the influence of the mounting brackets, different measurements were done with different numbers of mounting brackets installed.

4.4.1 Influence of the central bracket

The first measurement, shown in blue in Figure 42, is the measurement with both brackets. The measurement shown in orange is the measurement where the central bracket is removed.

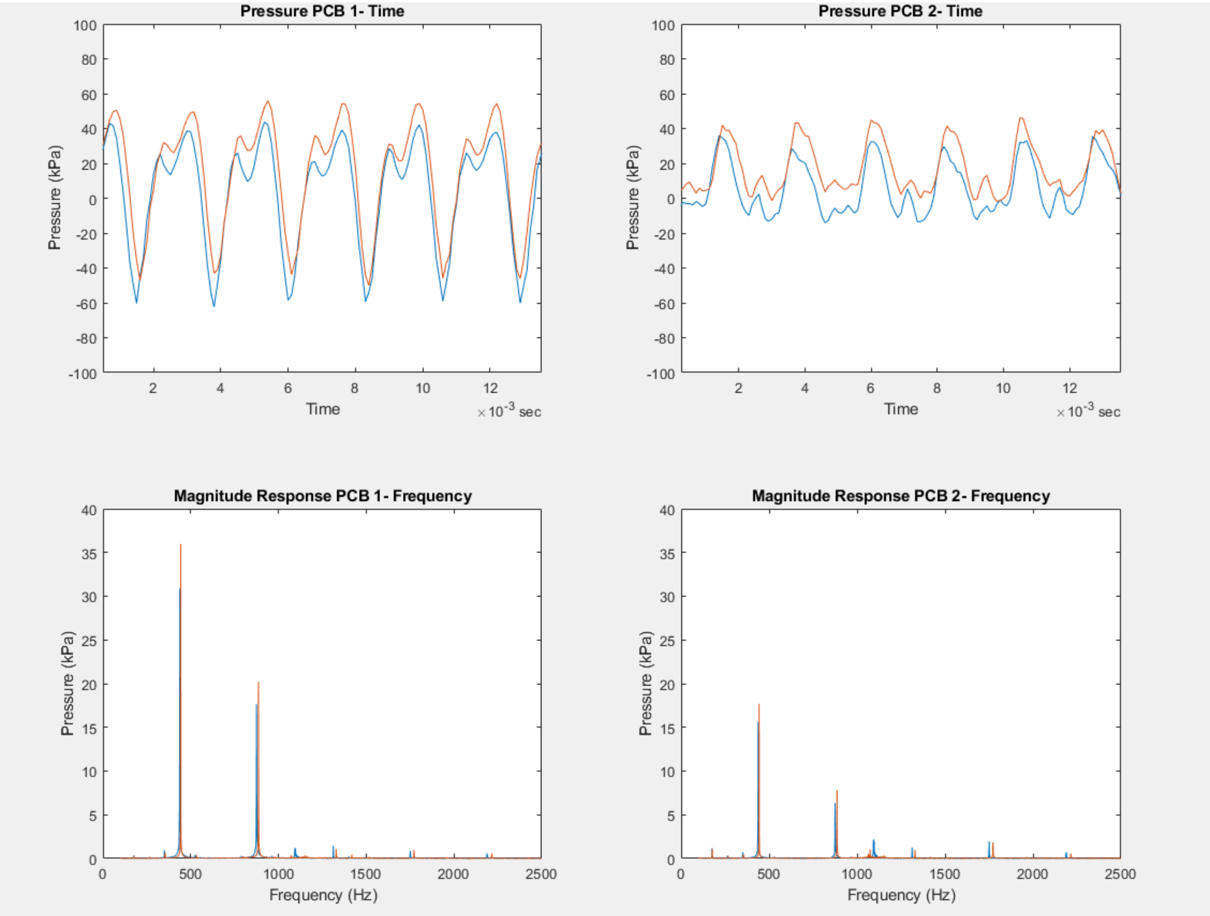


Figure 42: Measurement influence of central bracket

As can be seen in Figure 42, both measurement are very similar. The peak-to-peak values of both pressure measurement are nearly identical, and the FFTs of both measurements also show a lot of similarities. The small difference of 5 kPa between the two measurements could be caused by a small difference in the setting of the needle valve, since this is done manually during the tests.

4.4.2 Influence of removing both brackets

A third measurement is performed, this time with both brackets removed from the setup. The test pipe is now only connected to the mounting block for the needle valve, and to the pump with a flexible hose. The measurements with and without brackets are shown in Figure 43.

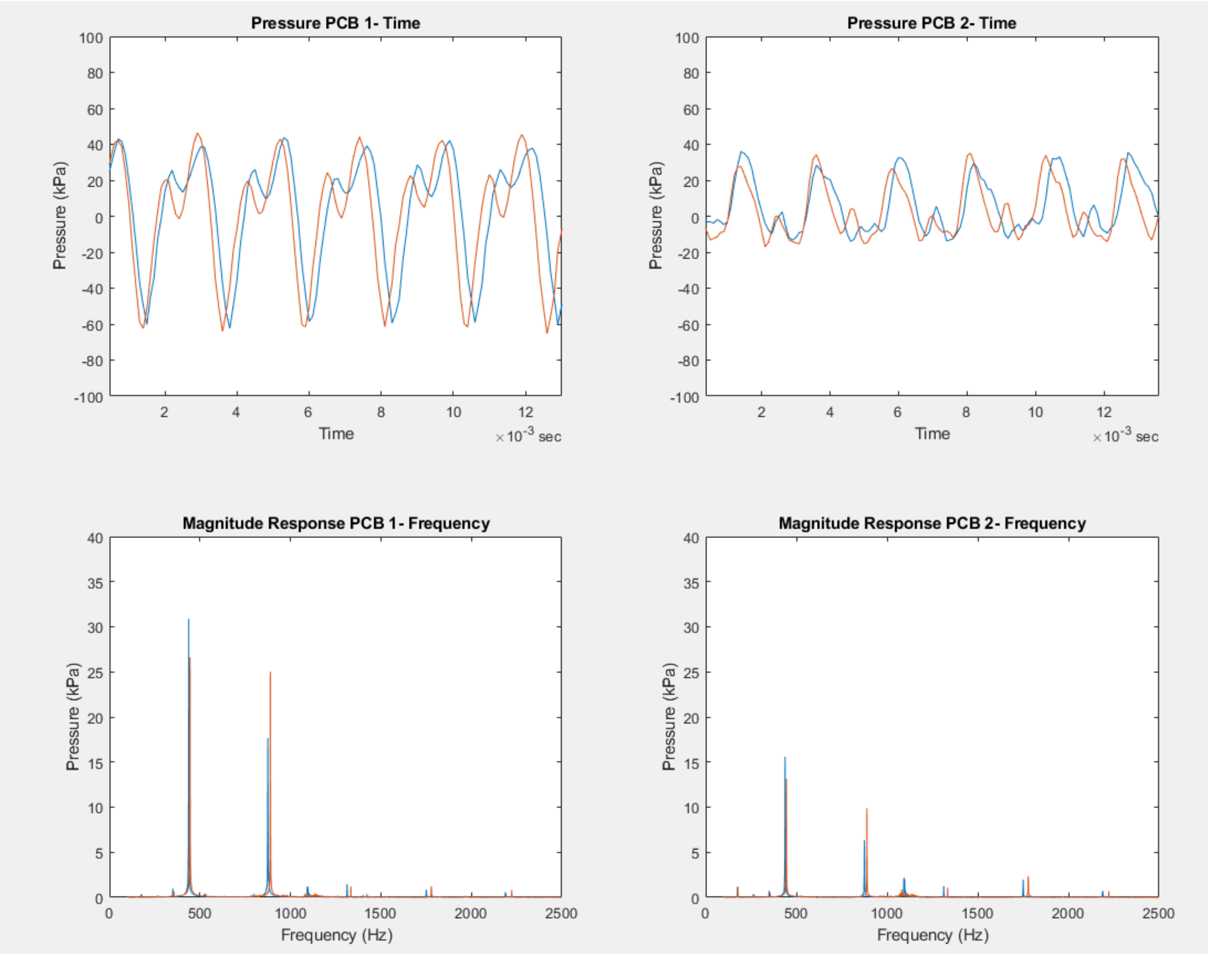


Figure 43: Measurement influence of brackets

In Figure 43, the measurement with the brackets installed is shown in blue, and the measurement without the brackets installed is shown in orange. As in paragraph 4.4.1, Figure 43 also shows very little difference between the measurements. The amplitude of the pressure ripple is nearly identical and the FFTs are very similar as well. A difference that is visible however, is that the second harmonic (at ±900 Hz) of the measurement without the brackets installed has a greater amplitude than when the brackets are installed. This might be caused by the free movements of the pipe system.

From the measurements in paragraph 4.4.1 and paragraph 4.4.2, it can be concluded that the influence of the mounting brackets on the setup are negligible, as they will not affect the measurements in a significant way.

4.5 Repeatability

4.5.1 No adjustments in between measurements

To check if the test setup records the same data when no parameters get changed in between the measurements, five measurements were executed with no changes in between. The results of these tests are shown in Figure 44 and Figure 45.

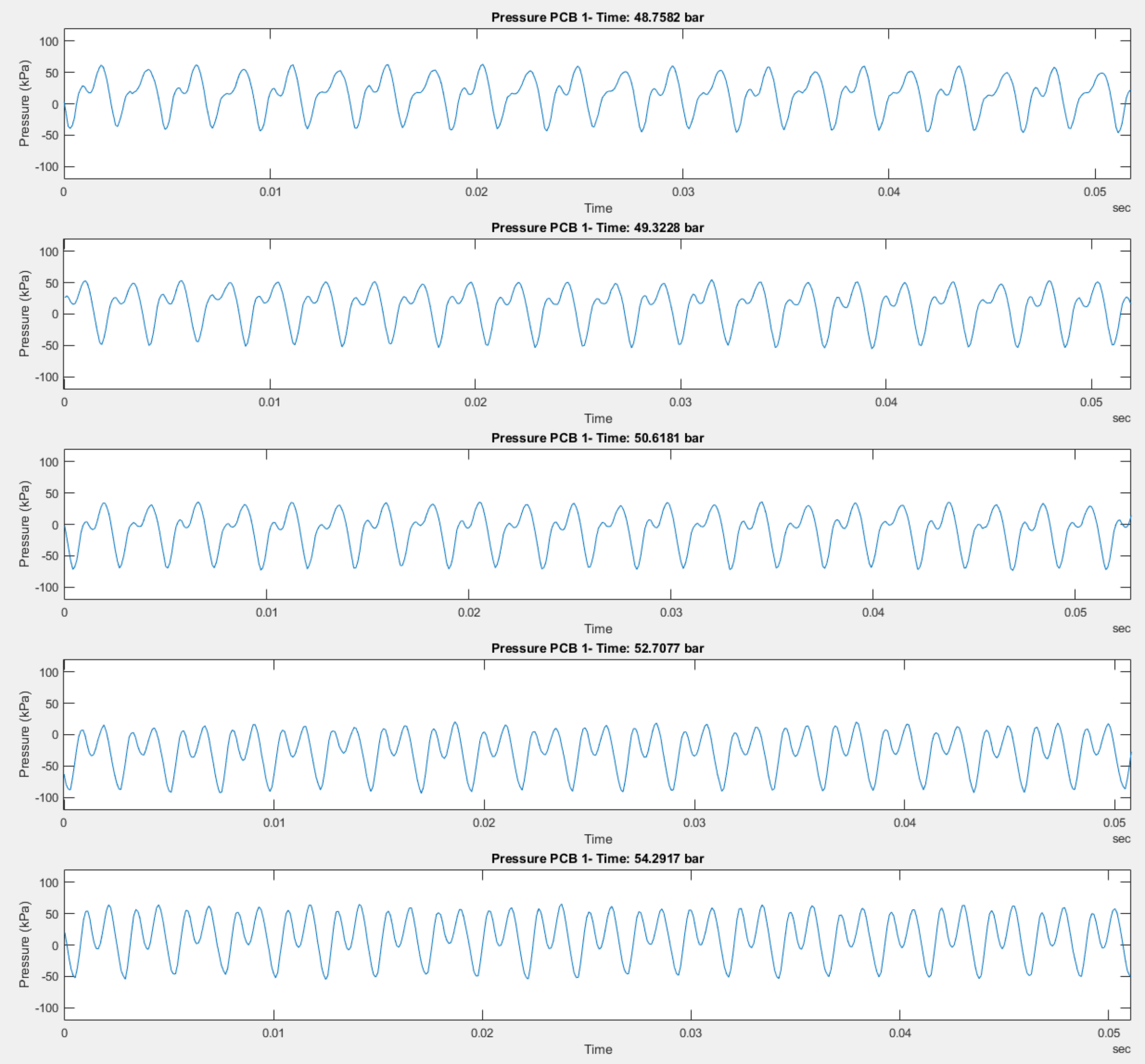


Figure 44: Repeatability results PCB 1

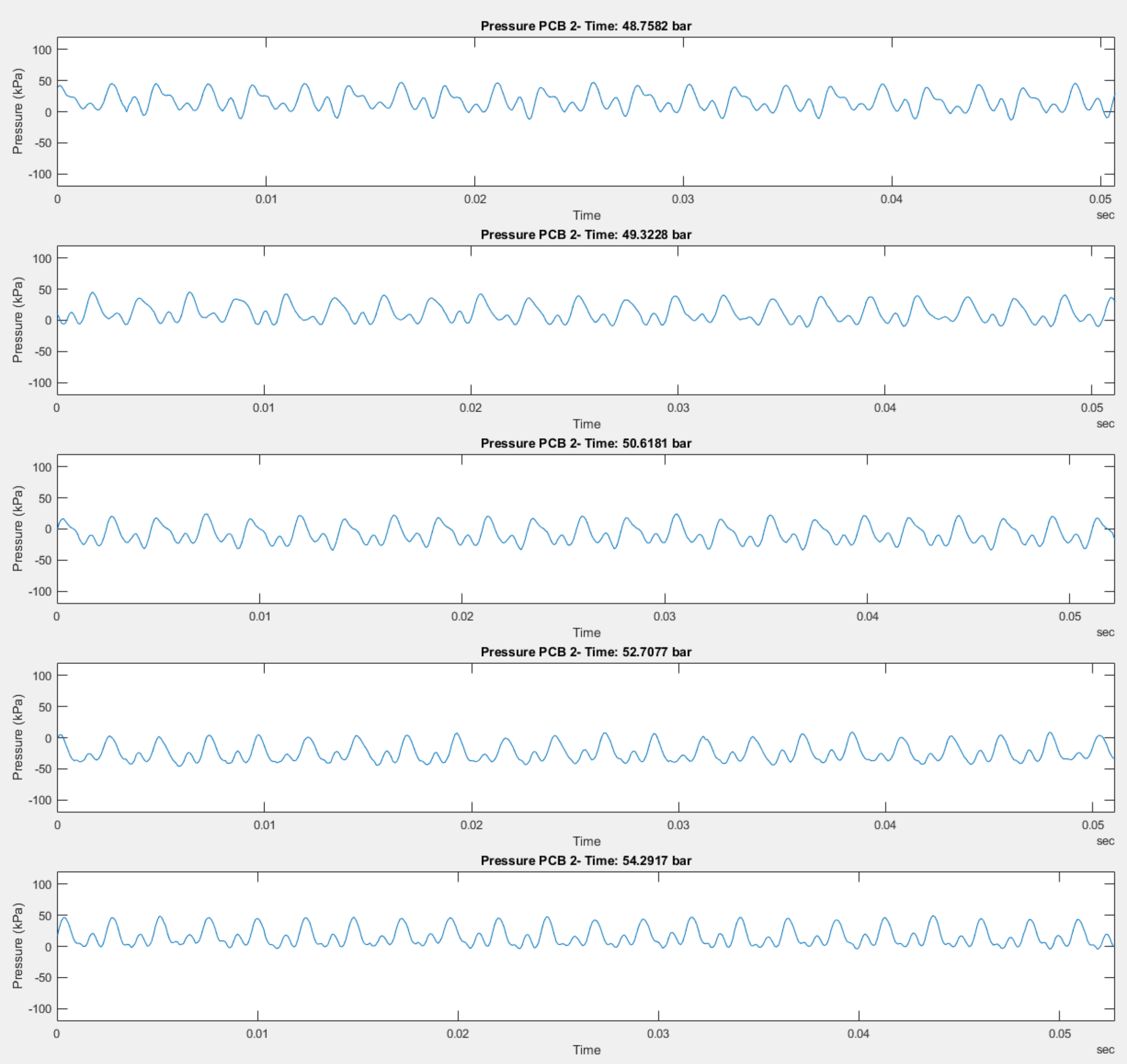


Figure 45: Repeatability results PCB 2

Figure 44 shows that when the absolute pressure varies between 48,8 bar and 54,3 bar, the pressure ripple measured by the PCB sensor closest to the pump unit (PCB1) has an amplitude of 100 kPa (± 5 kPa) or 0,10 bar. The pressure ripple measured by the second PCB sensor is shown in Figure 45 and has an amplitude of 50 kPa (± 8 kPa). This means that the amplitude of the pressure ripple has a variation across different measurements of 16 kPa.

4.5.2 Separate adjustments during every measurement

In contrast to the measurements without changing any settings in between, this time the needle valve is opened after every measurement and the same pressure is set separately during every measurement. These measurements were carried out multiple times but due to the similarities of the results, only two of the measurements are shown in Figure 46.

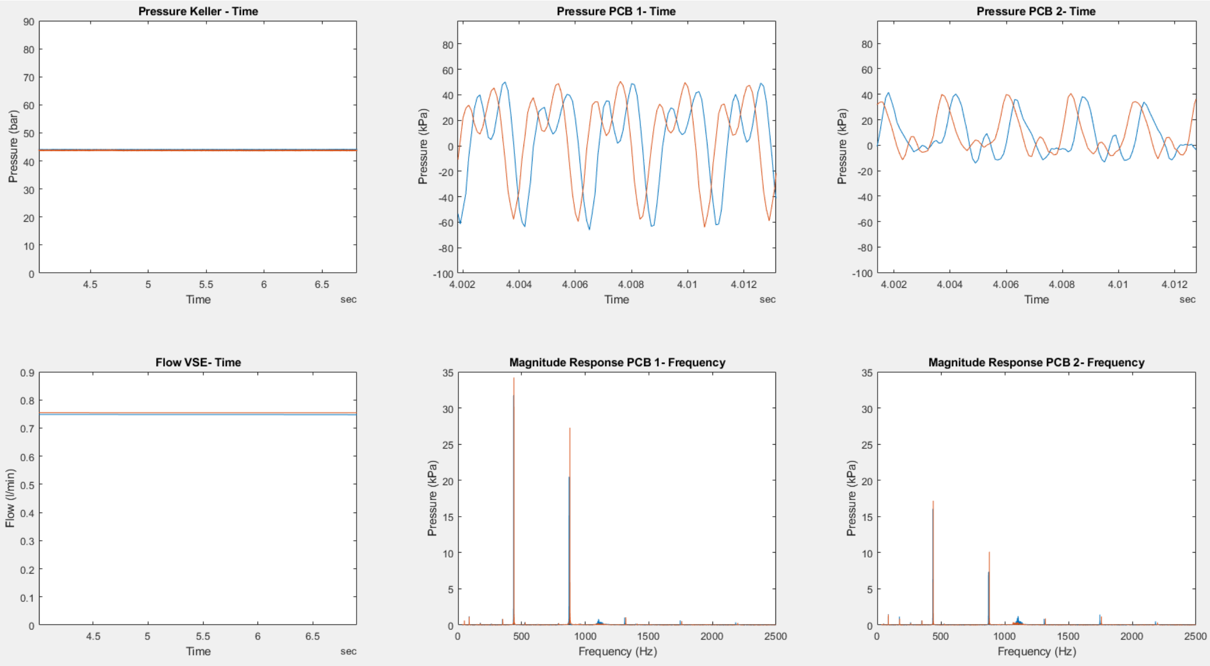


Figure 46: Repeatability results separate adjustments needle valve

Figure 46 shows that the absolute pressure for the first measurement is 43,7 bar, and for the second measurement 43,9 bar. This shows that when manually adjusting the needle valve, it is possible to achieve an accuracy of 0,2 bar. This is compared to not adjusting the needle valve in between the measurements as discussed in paragraph 4.5.1. In paragraph 4.5.1, it is visible that the difference in the absolute pressure in between the different measurements reaches up to 4,4 bar. From this can be concluded that manually adjusting the needle valve for every measurement separately gives more accurate results. When the pump is deployed in a vehicle, the system reacts to changes of 1 bar, so the 0,2 bar that can be achieved in the test setup is sufficient.

4.6 Difference between 5-piston and 7-piston pump

One of the improvements suggested in paragraph 2.4.1 to reduce the pressure ripple in hydraulic systems is to increase the amount of pistons. The influence of this adjustment will be measured. As mentioned in paragraph 2.1.3, most of the components of the pump stay the same. Only the piston housing, the number of pistons and the area of the piston heads have been changed. The results of the measurements are shown in Figure 47.

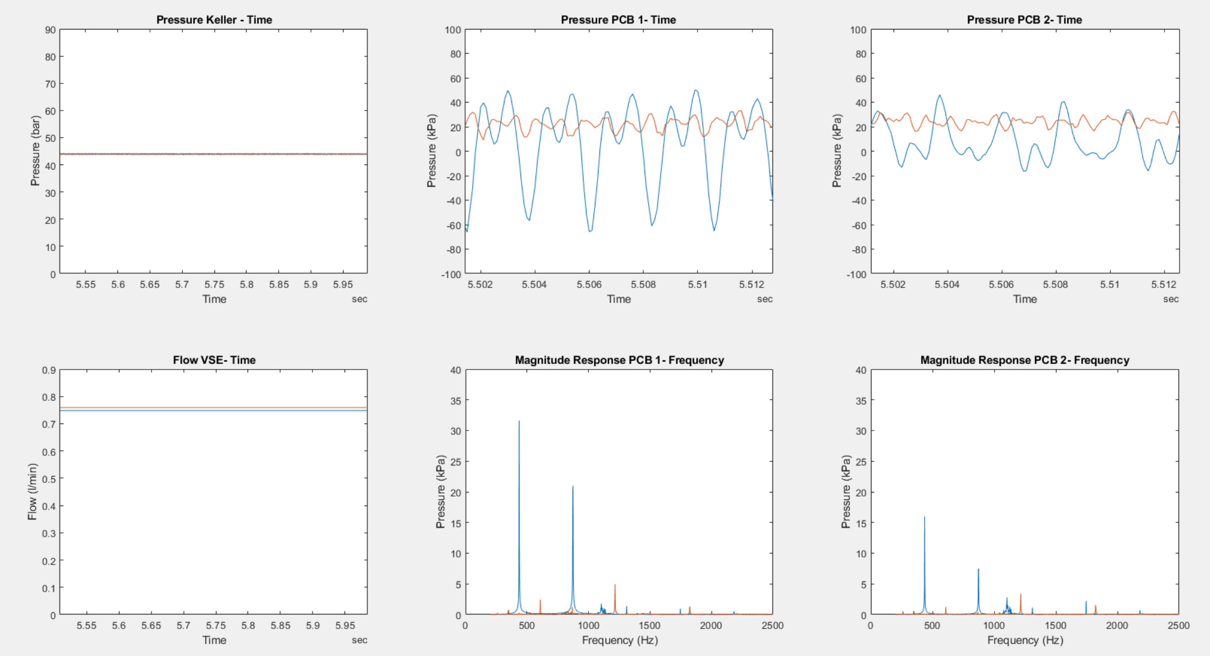


Figure 47: Measurements 5-piston and 7-piston pump

Figure 47 shows the measurement of the 5-piston pump in blue, and the measurements of the 7-piston pump in orange. It is clearly visible that the pressure ripple caused by the 7-piston pump has a significantly smaller amplitude than the pressure ripple from the 5-piston pump. The 5-piston pump introduces a pressure ripple of ±100 kPa into the system. The pressure ripple generated by the 7-piston pump has an amplitude of ±20 kPa. In the results of the FFT it is very clear that the frequency has shifted, as mentioned in paragraph 2.1.1. The 5-piston pump generates pressure ripples with a frequency of ±440 Hz, while the pressure ripples generated by the 7-piston pump have a frequency of ±600 Hz. This causes a second harmonic of ±870 Hz and ±1200 Hz respectively for the 5- and 7-piston pump.

5 Additions and limitations

5.1 Additions

5.1.1 In-line suppressor

An addition that can be made relatively easily, is the addition of an in-line nitrogen suppressor, as discussed in the literature study. To add this, two custom parts with the correct thread need to be made to be able to fit the silencer onto the Tri-clamp system, similar to the parts needed to mount the sensors into the setup.

5.1.2 Modular system

To comply with some of the required specifications, a modular system using Tri-clamps (DIN 32676) was implemented into the setup. Due to the limited size of the climate chamber at Tenneco, the setup cannot fit entirely in the climate chamber. The use of this modular system allows certain parts to be replaced or removed from the setup. This way, the most essential sensors can be used for testing in the climate chamber. Doing this would require research on the influence of the components that were replaced or removed.

5.1.3 Influence of the length of the hydraulic hose attached to the pump unit

Another possible addition that can be made to the setup is the examination of the length of the hydraulic hose that is attached to the pump unit. Some of the pumps use a piece of flexible hose of ± 25 cm, while others use ± 80 cm. Another possibility to examine the influence of the hydraulic hose is to replace the hydraulic hose with a piece of metal tubing. Currently, Tenneco considers this piece of hose as a part of the pump unit. In the future it might be possible to examine the influence of it separately.

5.1.4 Implementation digital readout pressure sensor in LabView

Since the temperature probe is embedded in the Keller PA-33X, the temperature readout happens through a separate program provided by Keller. A possible addition is to log the temperature readout in LabView. This way, all the readouts are grouped together and a better overview is provided.

5.1.5 Accelerometers

Additionally, it is possible to add accelerometers to the setup. This way, the vibrations of the pump and the test pipe can be measured. The implementation for the readout of the accelerometers is already programmed in the LabView program, so this makes the process "plug-and-play". Furthermore, the vibrations of the frame can be measured to take the influence of the mounting hardware into account. By comparing the vibrations produced by the pump and the piping system with the vibrations in the frame, it can be calculated how much of the vibrations are damped.

5.1.6 Surface plot

An addition that can be made to clearly visualize the relation between the different parameters is a surface plot. This is a three-dimensional plot that includes three parameters, namely the absolute pressure, the pressure ripple amplitude and the rotational speed of the pump. The rotational speed of the pump is proportional to the flow created by the pump. The implementation of this addition takes a lot of time, because of all the required measurement, so this is not possible within this thesis.

5.2 Limitations

5.2.1 Manual adjustment needle valve

One of the major limitations of the setup is the manual adjustment of the needle valve. This makes the measurements difficult to be reproduced within a certain margin. If the adjustment of the needle valve could be electronically controlled, preferably while introducing as few moving parts as possible into the system itself, more consistent results could be acquired. An example to improve the setup is adding a servo motor which controls the needle valve either directly, but since this might be difficult, indirectly by using a transmission mechanism.

5.2.2 Temperature control

Another limitation of the setup is the lack of temperature control. If the measurements need to be carried out at equal temperatures, a long waiting period is required while the hydraulic oil cools passively to the surrounding air. This could be sped up by adding a cooler (or a heater, depending on the desired temperature) into the return line of the setup. By placing it in the return line of the setup, the influence of the component on the pressure ripple is minimized, as demonstrated with the flowmeter in paragraph 4.3.

5.2.3 Power supply

The power supply provided by Tenneco uses voltage control to control the motor of the pump. This is different from the implementation in the vehicles, where the power of the pump is controlled by a PWM-signal. Since the measurement took place at a constant voltage of 13,2 V, this is not very influential for the measurement. Related to this different power supply is the lack of a readout for the rotational speed of the motor. This leads to differences in the frequency spectrum of the pressure ripple, which cannot be adjusted accurately.

6 Conclusion

The main objective of this thesis's project was to develop a method to quantify the pressure ripple caused by a hydraulic pump for a hydraulic roll-control system in vehicles. Firstly, a literature study was carried out to determine the main causes of pressure ripples. After this, the literature study continued to search for examples of test setups. This part resulted in a hydraulic scheme with sections from different sources, including ISO 10767-2 and other setups used in the industry. In the final part of the literature study, solutions were searched to reduce pressure ripples and noise in hydraulic systems. A limited number of these solutions were later tested in this thesis.

After the literature study, the test setup was further developed with pressure sensors for the absolute pressure in the system as well as pressure sensors to measure the smaller pressure ripple. In the setup, the flow of the hydraulic oil is also measured to completely identify the hydraulic behavior.

The setup complies with most of the requirements from the requirements package composed by Tenneco. Thanks to the modular system using the Tri-clamp system, the setup can be used inside the climate chamber, after making some adjustments. Because of the frame that supports all the hydraulic components of the test setup, it is easily transportable. All components in the system are compatible with the Fuchs Titan CHF-202 hydraulic oil used in the setup and in the vehicles.

The power supplies for the pump unit and the sensors are provided by Tenneco, and are easily configurable to produce the desired voltages and currents. By disconnecting a limited number of wires, the power supplies and data acquisition setup can be transported separately from the hydraulic part of the test setup.

During the initial phase of testing, the pressure relief valve was not installed in the system. In this period, the maximum pressure of the test setup was checked. The working pressure of 120 bar is achievable, but to protect the components in the setup, the pressure relief valve was added and adjusted to open at a pressure of 80 bar. All the sensors have a sufficient temperature range and resolution, except the flowmeter. The resolution of the flowmeter is 0,02 l/min, while the required resolution was 0,01 l/min. Since the flow measurement is not the primary target of this setup, this was not detrimental to the setup.

To carry out the tests on the setup in a repeatable way, a test procedure was composed, describing all the steps in the process. It was found to measure at an identical pressure level in different measurements, it is more accurate to adjust the needle valve for every measurement separately than to leave the valve in the same position. Additional testing revealed that the flowmeter and mounting brackets have an insignificant influence on the system. Finally a seven piston pump was tested which resulted in a noticeable decrease in the amplitude of the pressure ripple.

Finally, the possible additions and the limitations of the setup are examined. A possible research topic for the future is the addition of an in-line nitrogen suppressor, which can reduce the pressure ripple in the system, as explained in the literature study. An addition that is already used in the setup is the use of a modular system of piping. This allows for relatively an easy removal or replacement of certain parts. Another topic that can be researched in the future, is the influence of the hydraulic hose that is attached to the pump. For the time being, Tenneco considers this piece of hose as a part of the pump unit. A smaller possible addition is to log the temperature through LabView, together with all the other sensors. Currently, the readout of the temperature happens through a separate program. The addition of the accelerometers is already implemented in LabView, so it is relatively easy to add these to the setup in the future.

The most important limitation of the setup is the manual setting of the needle valve. This leads to a reduced accuracy for the tests. This limitation can be resolved by adding for example a servo motor attached to a few gears to the setup. Another limitation of the setup is the lack of temperature control, which leads to long waiting times when measurements have to be carried out at equal temperatures. A final limitation, which Tenneco considers to be a minor limitation, is that the used power supply for the pump does not use a PWM-signal, as is used in the vehicles. Instead of the PWM-signal, it is possible to control the voltage and the current through the power supply.

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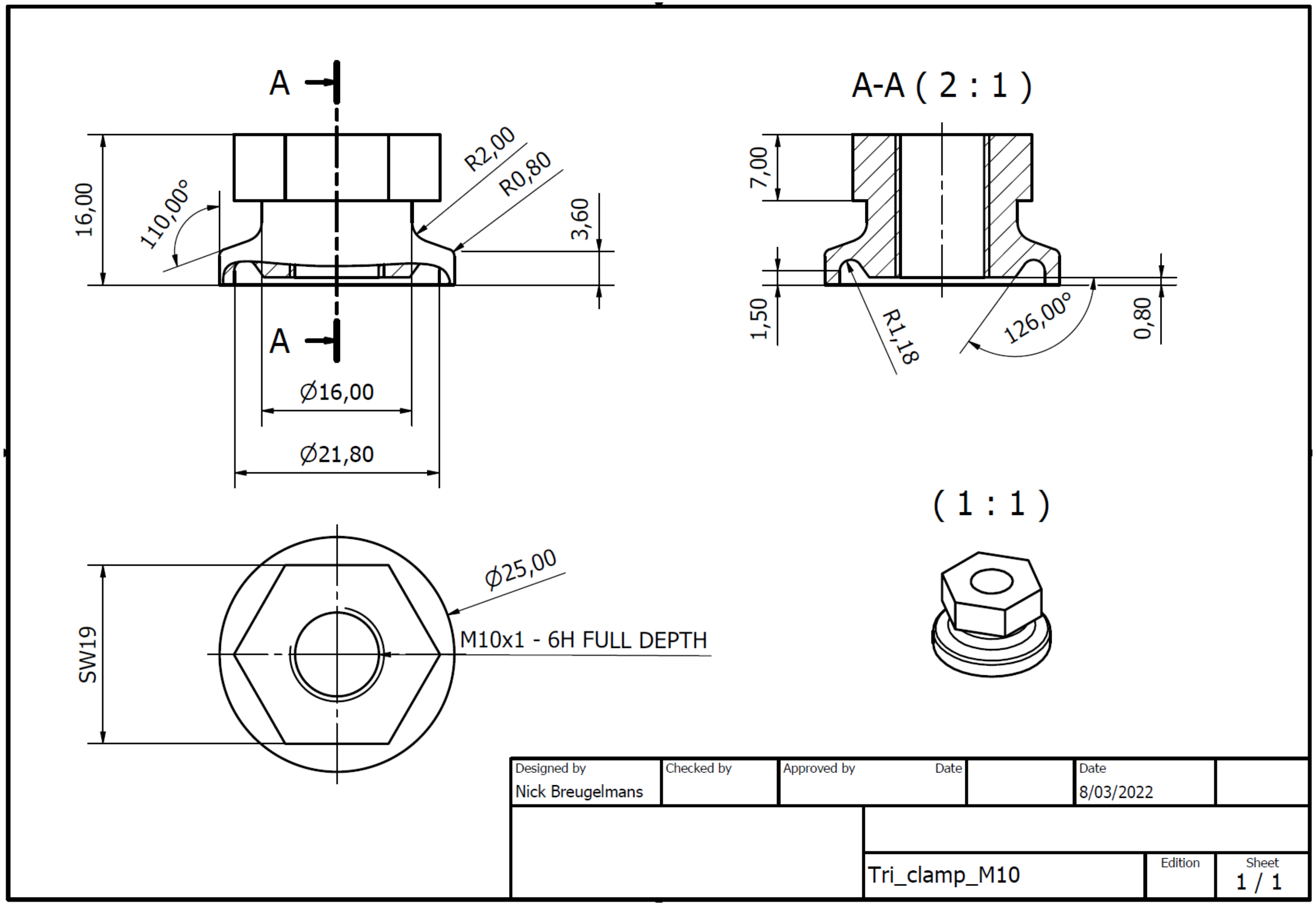
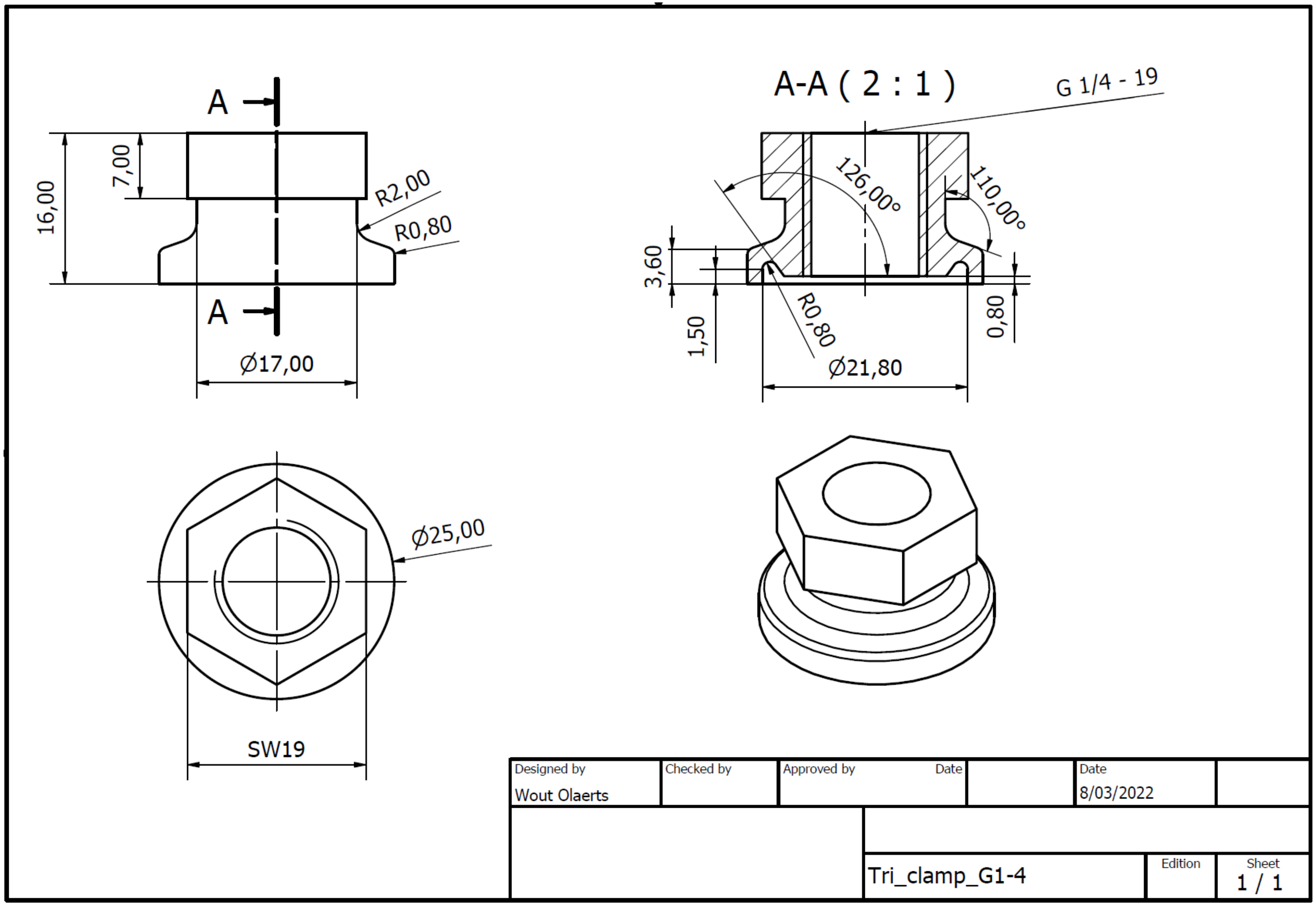
Appendices

A. Drawings of custom made parts

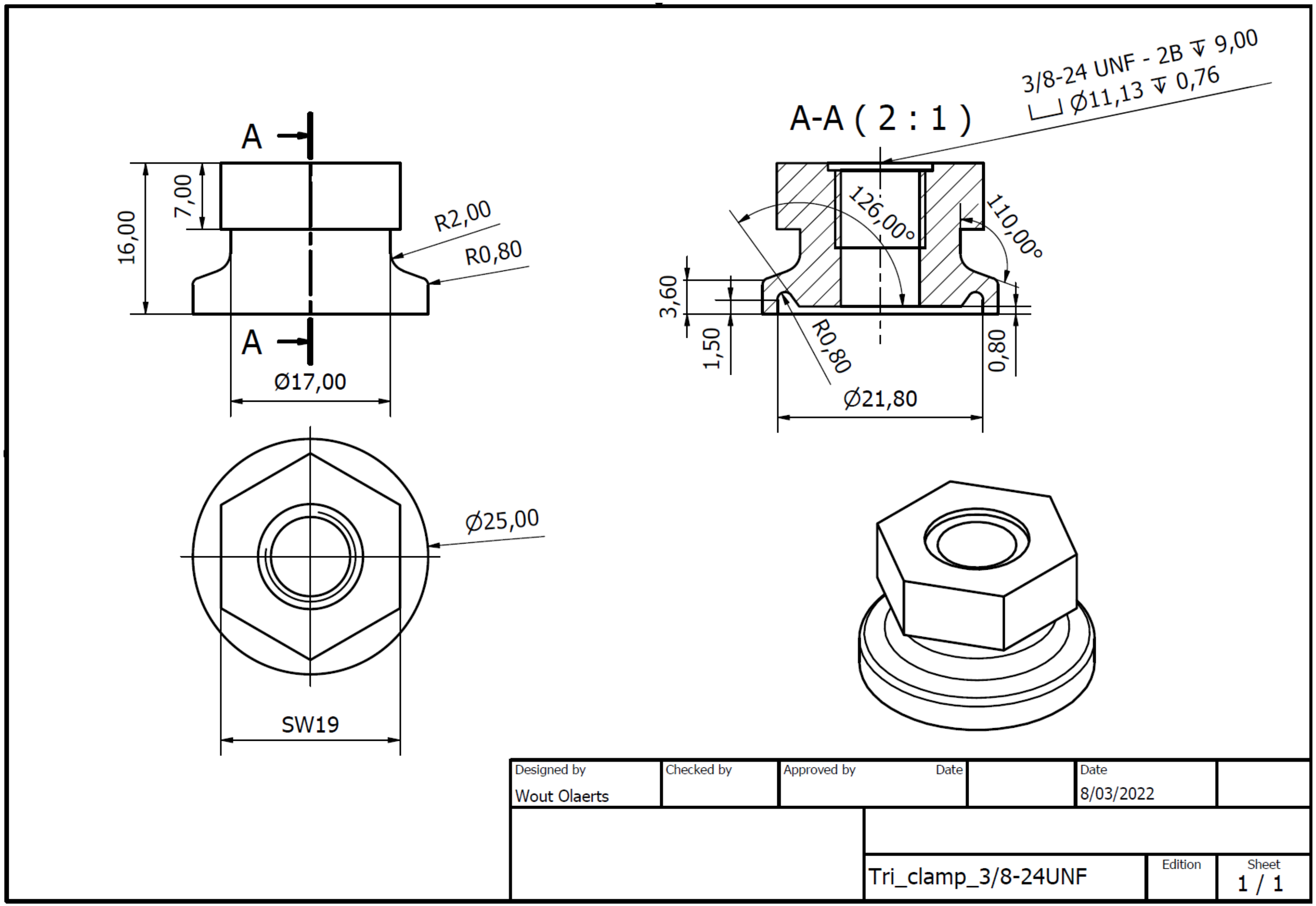
A.1 Mount for connection pump unit



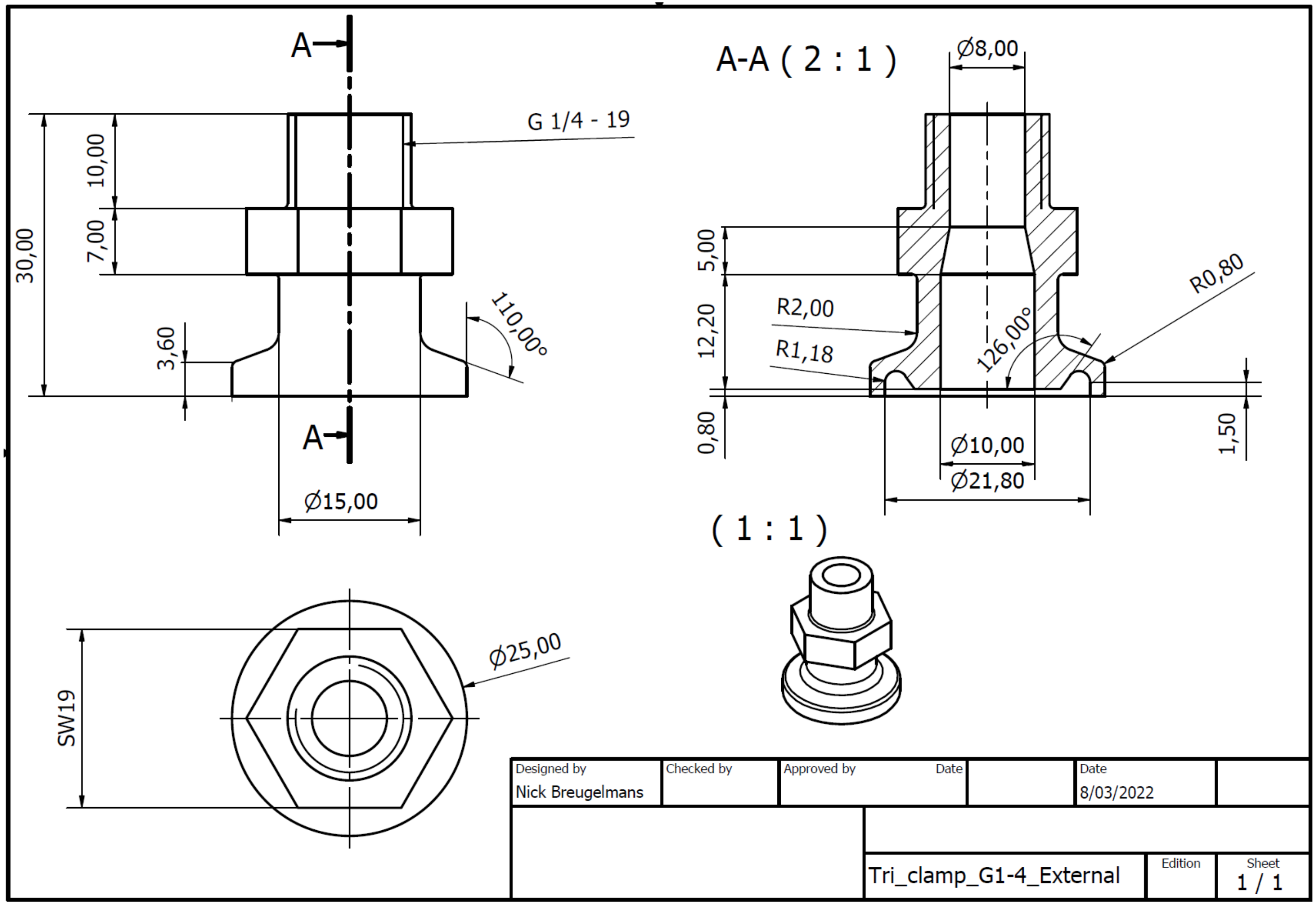
A.2 Mount for connection PCB 102B04



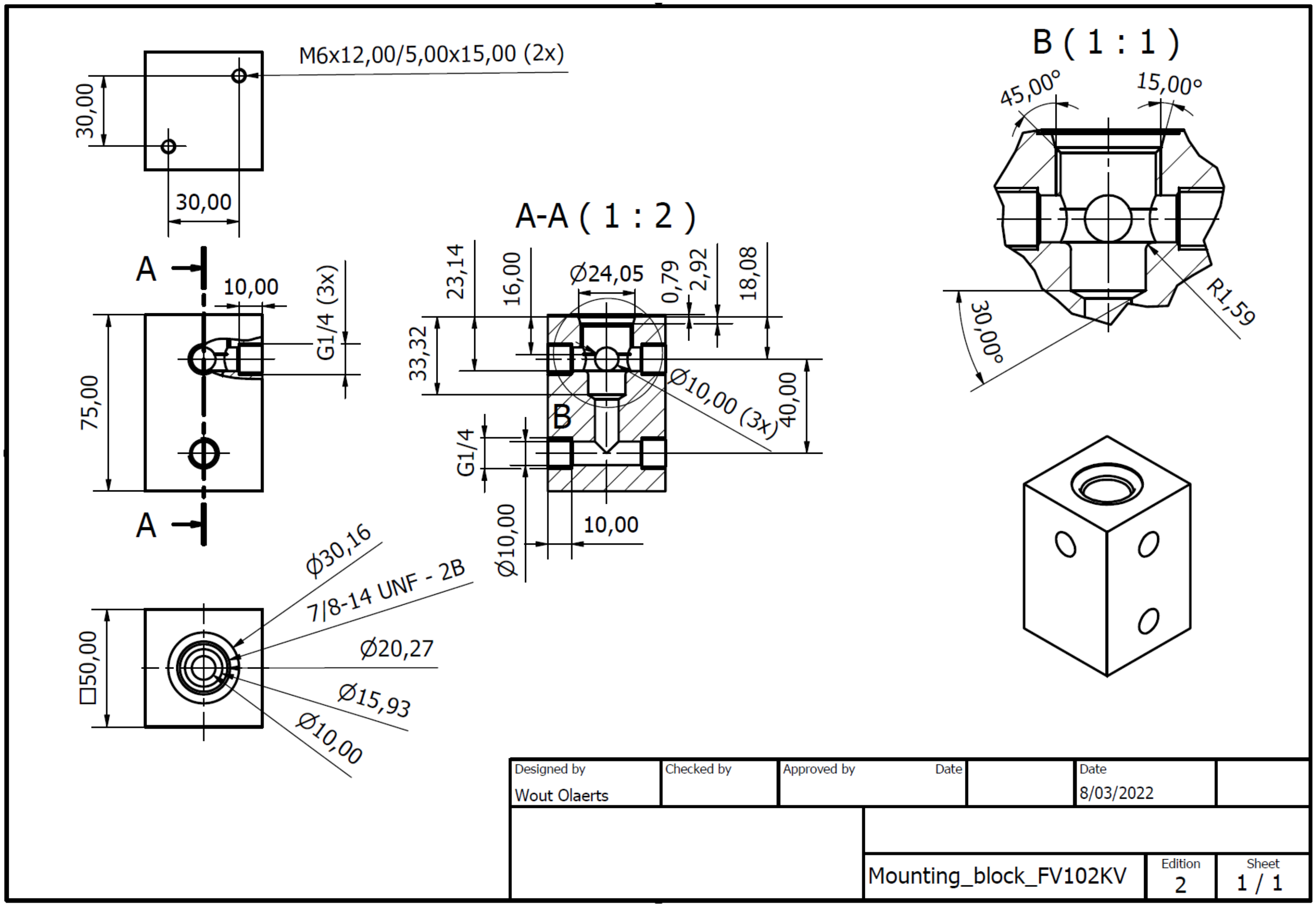
A.3 Mount for connection Keller PA-33X



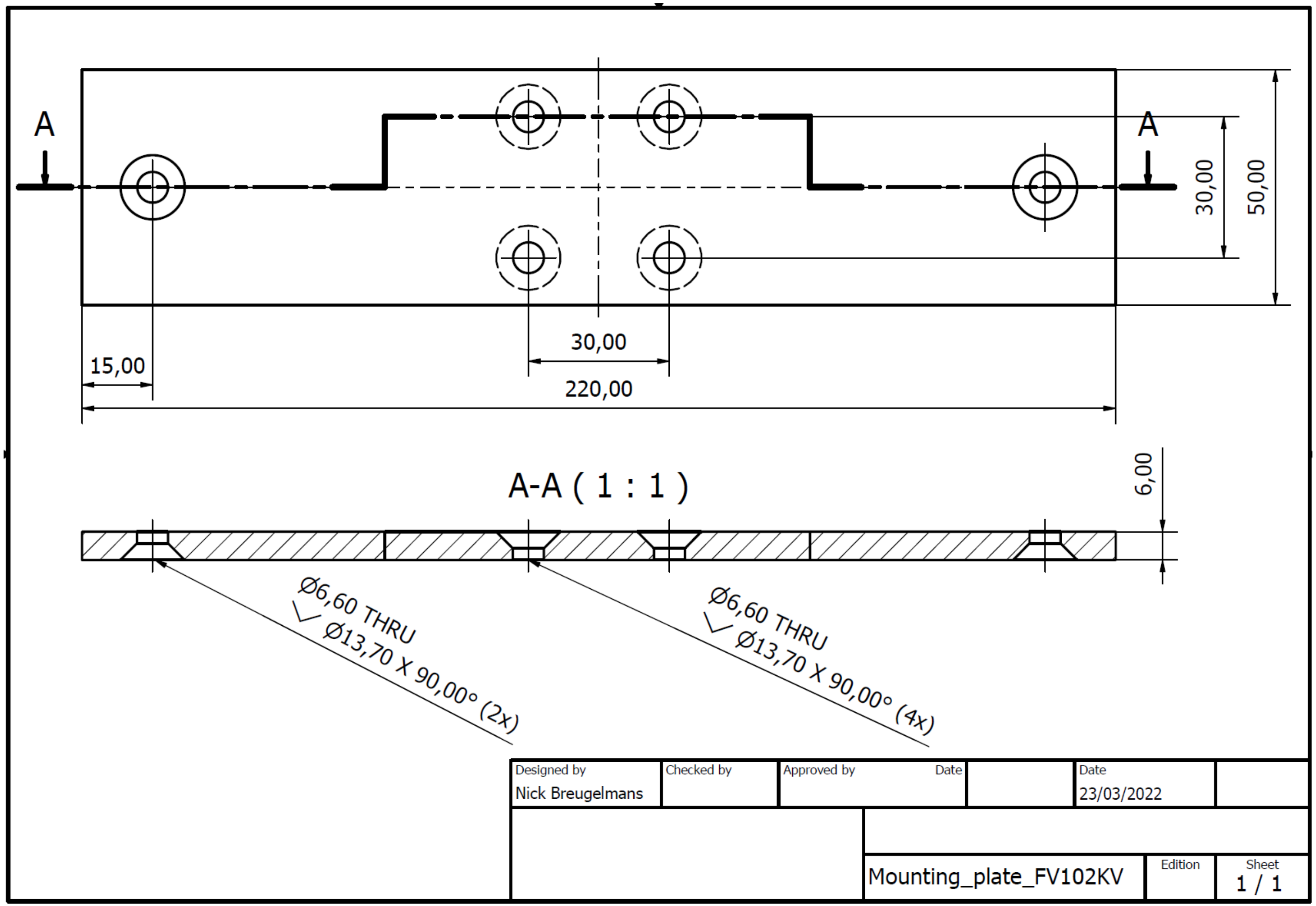
A.4 Mount for connection to mounting block FV102KV



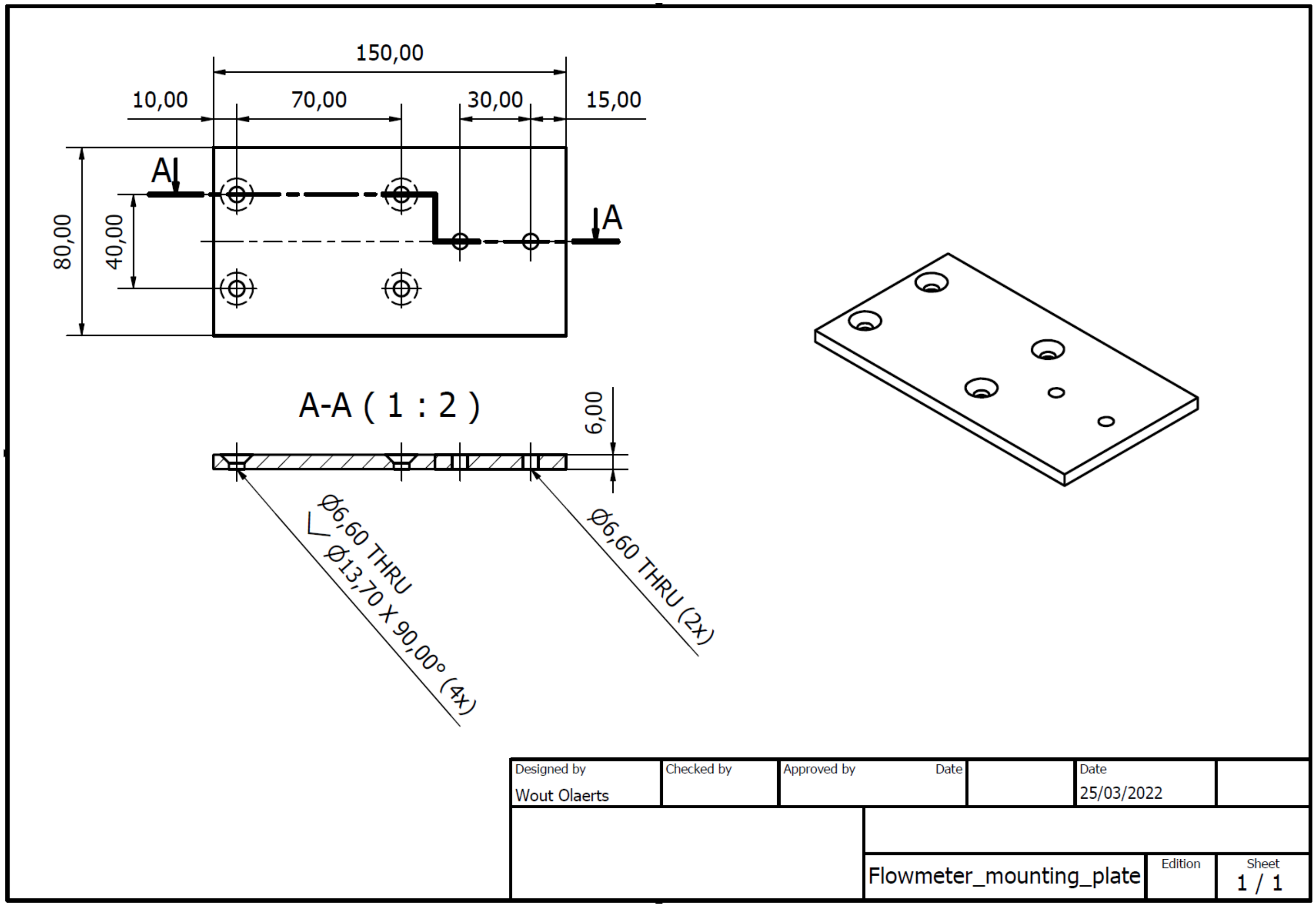
A.5 Mounting block for FV102KV



A.6 Mounting plate for FV102KV



A.7 Mounting plate flowmeter



B. Datasheets used components

B.1 Datasheet Quick assembly coupling Walther Präzision (Selected pages)

Source: [1] Carl Kurt Walther GmbH & Co. KG, “Schnellmontagekupplung für Kompakthydraulik von Walther.” https://www.walther-praezision.de/de/produkte/monokupplungen/sonderprogramm/schnellmontagekupplungen/index.html (Accessed May 29, 2022).

walther präzision

WalCoDo®

WALTHER CONNECTING & DOCKING

Basic Specification

Quick assembly coupling, type 07-003-0/2-4M010-….-Y32

(FKM version)

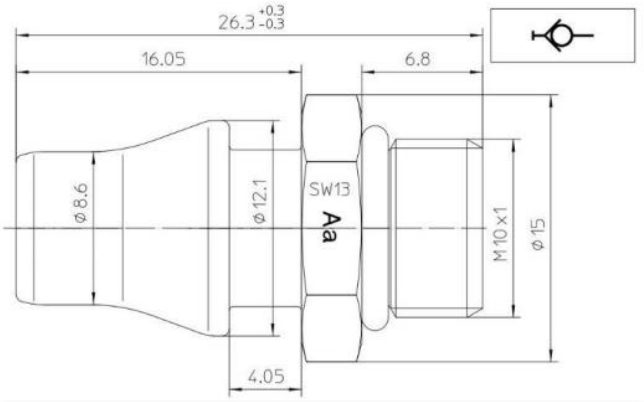
Status document:	Released, REV00, 24.11.2021
Applications:	In automotive and mobile hydraulic systems, preferably in indoor protected areas
Customer segment:	OEM's
Part no./Ident no.:	**Version FKM with ZAMAK valve (100° C)** 07-003-0-4M010-AAEB-Y32, ID 237662 07-003-2-4M010-AAEC-Y32, ID 237663 **Version FKM with Brass valve (120°C)** 07-003-0-4M010-AADY-Y32, ID 237548 07-003-2-4M010-AADZ-Y32, ID 237549
Date:	17.12.2021
Author:	JK

Internal releases

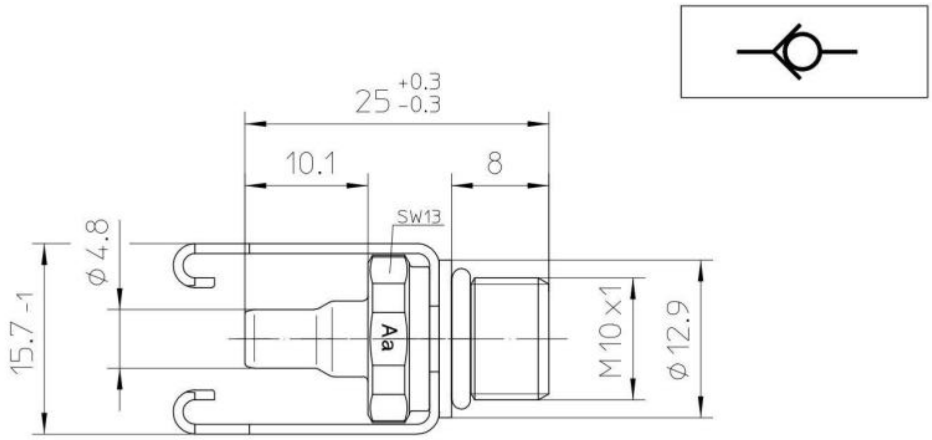
Technology	: D. Heinrich	**Quality**	: L. Lennartz
Manufacturing	: A. Sturm	**Procurement**	: J. Lennertz
Logistics	: D. Merten	**Sales**	: J. Kortmann

1

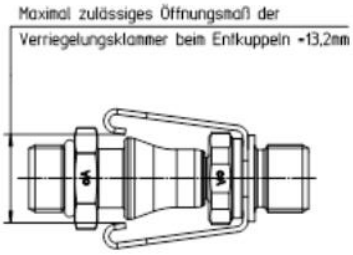
Self-sealing coupling



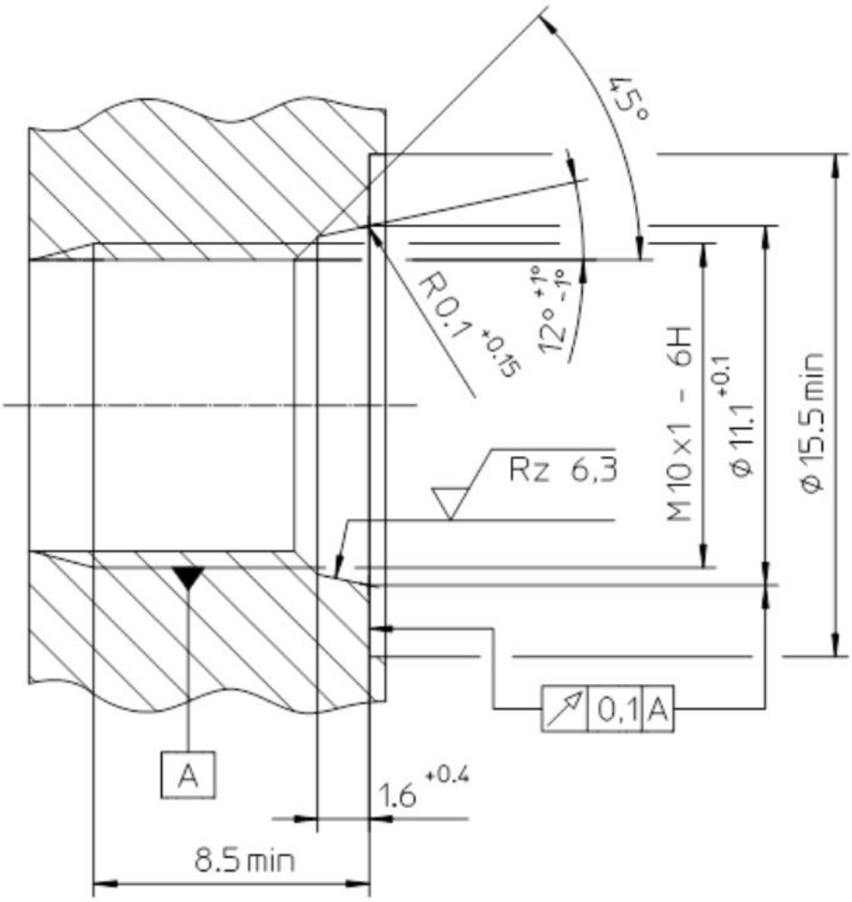
Self-sealing adaptor



The following instruction for opening the locking clamp with a suitable tool of an adjustable circlip pliers, e. g. manufacturer Knipex. Opening dimension max. 13.2 mm.



Connection recommendation, customer-side cavity / installation space / tightening



Torque moment: **M10 x 1: 6 $^{+1}$ Nm, additional thread locking, e. g. by glueing, if necessary**

2.2 Product requirements

2.2.1 Coupling frequency and coupling force

Low, only for initial filling and servicing, up to 100 coupling and uncoupling cycles.

For higher coupling cycles please inquire separately.

Coupling force, unpressurized: < 60 N.

2.2.2 Operating teperatures

Walther Order No.	Walther ID#	part	O-Ring	valve	operating temp. min/max		protected application
1-07-003-0-4M010-AADY-Y32	**237548**	**Female**	**FKM**	**Brass**	**-40°C**	**+120°C**	**Connected and disconnected**
1-07-003-2-4M010-AADZ-Y32	**237549**	**Male**	**FKM**	**Brass**	**-40°C**	**+120°C**	**Connected and disconnected**
1-07-003-0-4M010-AAEB-Y32	**237662**	**Female**	**FKM**	**ZAMAK**	**-40°C**	**+100°C**	**Only connected**
1-07-003-0-4M010-AAEC-Y32	**237663**	**Male**	**FKM**	**ZAMAK**	**-40°C**	**+100°C**	**Only connected**

Recoating temperature, briefly

FKM/ZAMAK valve : max. + 110° C (3 x 15 min.)

FKM/Brass valve : max. + 130° C (3 x 15 min.)

Storage temperature : - 40° C bis + 50° C

Test temperature (strength) : 23° C +/- 5° C

Flow rate and flow velocity

Flow rate : 1 – 2 l / min; fluid: hydraulic oil

Max. flow velocity : 8 m/s

2.2.3 Pressure drop

At room temperature in both flow directions, e. g. with Aero Shell Fluid 41:
Q= 1 l/min. delta p < 1 bar
Q= 2 l/min. delta p < 3 bar

2.2.4 Operating media

The compatibility of the materials used and the sealing compound (FKM) must always be tested and validated by the customer. Our experience shows a good compatibility with e. g. Castrol Hyspin 4004, or ZHM or Aero Shell Fluid 41 (ASF41) or Pentosin

B.2 Datasheet Keller PA-33X (Selected pages)

Source: "Serie 33X | KELLER Pressure," 2022. https://keller-druck.com/en/products/pressure-transmitters/standard-pressure-transmitters/serie-33x (accessed February 15, 2022).

KELLER

Series 33X

Piezoresistive pressure transmitters with maximum accuracy of 0,01 %FS

Features

- Maximum accuracy/precision down to 0,01 %FS
- RS485 interface can be combined with analog interface
- Analog interface rangeable by RS485 interface (turn-down)
- Modbus RTU protocol for process values and configuration
- Highest long-term stability

Technology

- Insulated and encapsulated piezoresistive pressure sensor
- High-quality pressure transducers and tried-and-tested mathematical compensation

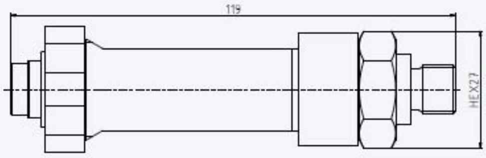
Typical applications

- Laboratory use
- Test benches
- Gauge standard
- Precision measurements
- Industrial applications

Accuracy
± 0,05 %FS
Total error band
± 0,1 %FS @ -10…80 °C
Pressure ranges
0…0,3 to 0…1000 bar

Modbus RTU CE

Series 33X



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KELLER

Series 33X – Specifications

Standard pressure ranges

Relative pressure PR		Proof pressure
0…0,3	-0,3…0,3	3
0…1	-1…1	
0…3	-1…3	9
0…6	-1…6	18
0…10	-1…10	30
0…16	-1…16	48
0…30	-1…30	90
bar rel.		bar
Reference pressure at ambient pressure		based on reference pressure

Absolute pressure PAA	Absolute pressure PA	Proof pressure
0,8…1,2		3
0…1	0…1	
0…3	0…3	9
0…6	0…6	18
0…10	0…10	30
0…16	0…16	48
0…30	0…30	90
0…60	0…60	180
0…100	0…100	300
0…300	0…300	600
0…700	0…700	1100
0…1000	0…1000	1100
bar abs.	bar	bar
Reference pressure at 0 bar abs. (vacuum)	Reference pressure at 1 bar abs.	based on reference pressure

All intermediate ranges for the analog interface can be ranged (turn-down) from the standard ranges without surcharge.
Smallest range: 0,1 bar. Negative and further +/- ranges also possible. Optionally: adjust directly to intermediate ranges

Performance

Pressure

Digital nonlinearity	≤ ± 0,02 %FS	Best fitted straight line (BFSL)
Accuracy @ RT (20…25 °C)	≤ ± 0,05 %FS	Nonlinearity (best fitted straight line BFSL), pressure hysteresis, non-repeatability, zero point deviation and amplification deviation
Total error band (10…40 °C)	≤ ± 0,05 %FS	Max. deviation within the compensated pressure and temperature range
Total error band (-10…80 °C)	≤ ± 0,1 %FS	Max. deviation within the compensated pressure and temperature range Experience shows that, outside the compensated temperature range, the total error band in the ambient temperature range is expanded by 0,1 %FS
Compensated temperature range	10…40 °C	Extended room temperature range RT
	-10…80 °C	Other, optional temperature ranges within -40…125 °C possible
Analog interface additional deviation	≤ ± 0,05 %FS	Based on accuracy @ RT and the total error band
Long-term stability	typ. ± 0,05 %FS	Per year under reference conditions, yearly recalibration recommended
	max. ± 0,10 %FS	
Position dependency	≤ ± 2 mbar	Calibrated in vertical installation position with pressure connection facing downwards
Resolution	0,0005 %FS	Digital
Signal stability	0,0025 %FS	Digital noise-free
Internal measurement rate	≥ 1800 Hz	For version «3-wire + digital (0…10 V, 0…5 V)» > 6000 Hz
Pressure range reserve	±10 %	Outside the pressure range reserve, +Inf/-Inf is displayed. If there is an error in the device, NaN is displayed
Vacuum resistance	For operating pressures ≤ 0,1 bar abs., a vacuum-optimised version is recommended	
Note	For pressure ranges < 1 bar, all data apply with reference to a full-range signal (FS) of 1 bar	

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KELLER

Series 33X – Specifications

Electrical data

Connectivity	digital	2-wire + digital	3-wire + digital		
Analog interface		4…20 mA	0…10 V	0…5 V	0,1…2,5 V
Digital interface	RS485	RS485	RS485	RS485	RS485
Power supply	3,2…32 VDC	8…32 VDC	13…32 VDC	8…32 VDC	3,2…32 VDC
Power consumption (without communication)	< 8 mA	3,5…22,5 mA	< 8 mA	< 8 mA	< 8 mA
RS485 voltage insulation	± 32 VDC	± 18 VDC	± 32 VDC	± 32 VDC	± 32 VDC
Note	Disturbance of the 4...20 mA signal occurs during communication via the digital interface 3-wire types are suitable for simultaneous operation of the analog and digital interface				

Start-up time (power supply ON)	< 250 ms
Overvoltage protection and reverse polarity	± 32 VDC
GND case insulation	> 10 MΩ @ 300 VDC

Analog interface

Load resistance	< (U - 8 V)/25 mA	2-wire
	> 5 kΩ	3-wire
Limiting frequency	≥ 300 Hz	2-wire
		3-wire (0,1…2,5 V)
	≥ 1000 Hz	3-wire (0…10 V, 0…5 V)
Note	Filter properties can be adjusted by the customer	

Digital interface

Type	RS485	Half-duplex
Communication protocols	Modbus RTU	
	KELLER bus protocol	Proprietary
Identification	Class.Group: 5.24	Standard settings: bus address 1, baud rate 9600 bit/s Other default settings available on request. Can be reconfigured via software by the customer later
Unit of pressure	bar	
Unit of temperature	°C	
Data type	Float32 and Int32	
Baud rates	9600 and 115'200 bit/s	
Lines	up to 1,2 km	

Electrical connection

Plug type	Binder series 723	DIN EN 61076-2-106, 5-pin
	M12	DIN EN 61076-2-101, A-coded, 5-pin
	Souriau series 8525	MIL-STD-1669
	GSP (without RS485)	EN 175301-803-A (DIN 43650)
Cable	ø 5,8 mm, PE sheath	5-wire, cable gland

Electromagnetic compatibility

CE-conformity as per 2014/30/EU (EMC)	EN 61326-1/EN 61326-2-3/EN 61000-6-1/EN 61000-6-2/EN 61000-6-3/EN 61000-6-4

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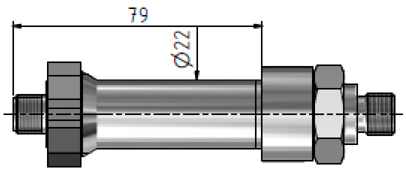
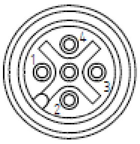
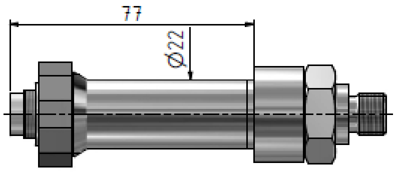
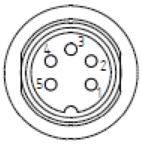
Series 33X – Dimensions and options

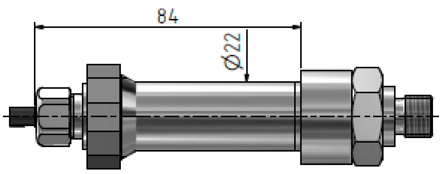
Electrical connections

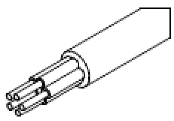


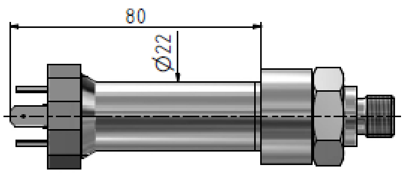
M12	2-wire		3-wire	
M12 × 1	4…20 mA		0…max. 10 V	
	1	OUT/GND	1	GND
	2	n.c.	2	+OUT
	3	+Vs	3	+Vs
	4	RS485A	4	RS485A
	5	RS485B	5	RS485B

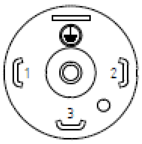


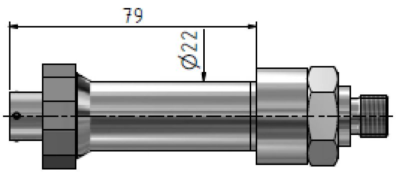
Binder series 723	2-wire		3-wire	
M16 × 0,75	4…20 mA		0…max. 10 V	
	1	OUT/GND	1	GND
	2	n.c.	2	+OUT
	3	+Vs	3	+Vs
	4	RS485A	4	RS485A
	5	RS485B	5	RS485B

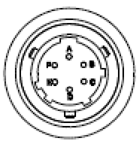


Cable gland	2-wire		3-wire	
Cable ø 5,8	4…20 mA		0…max. 10 V	
	WH	OUT/GND	WH	GND
	RD	n.c.	RD	+OUT
	BK	+Vs	BK	+Vs
	BU	RS485A	BU	RS485A
	YE	RS485B	YE	RS485B
	Shield on CASE		Shield on CASE	



GSP EN 175301-803-A	2-wire		3-wire	
□ 18	4…20 mA		0…max. 10 V	
	1	OUT/GND	1	GND
	2	n.c.	2	+OUT
	3	+Vs	3	+Vs
	⏚	CASE	⏚	CASE



Sourlau series 8525	2-wire		3-wire	
	4…20 mA		0…max. 10 V	
	C	OUT/GND	C	GND
	B	n.c.	B	+OUT
	A	+Vs	A	+Vs
	D	RS485A	D	RS485A
	F	RS485B	F	RS485B
	Shield on CASE		Shield on CASE	

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B.3 Datasheet PCB 102B04

Source: "PCB Model 102B04." https://www.pcb.com/products?m=102b04 (accessed February 24, 2022).

Model Number 102B04	ICP® PRESSURE SENSOR			Revision: C ECN #: 34651
Performance	**ENGLISH**	**SI**		
Measurement Range(for ±5V output)	1 kpsi	6900 kPa		
Useful Overrange(for ± 10V output)	2 kpsi	13,790 kPa	[2]	
Sensitivity(± 10 %)	5.0 mV/psi	0.7 mV/kPa		
Maximum Pressure(static)	10 kpsi	69,000 kPa		
Resolution	20 mpsi	0.14 kPa	[1]	
Resonant Frequency	≥ 500 kHz	≥ 500 kHz		
Rise Time(Reflected)	≤ 1.0 μ sec	≤ 1.0 μ sec		
Low Frequency Response(-5 %)	0.005 Hz	0.005 Hz		
Non-Linearity	≤ 1.0 % FS	≤ 1.0 % FS	[3]	
Environmental				
Acceleration Sensitivity	≤ 0.002 psi/g	≤ 0.0014 kPa/(m/s^2)		
Temperature Range(Operating)	-100 to +275 °F	-73 to +135 °C		
Temperature Coefficient of Sensitivity	≤ 0.03 %/°F	≤ 0.054 %/°C	[1]	
Maximum Flash Temperature	3000 °F	1650 °C		
Maximum Shock	20,000 g pk	196,140 m/s^2 pk		
Electrical				
Output Polarity(Positive Pressure)	Positive	Positive		
Discharge Time Constant(at room temp)	≥ 100 sec	≥ 100 sec		
Excitation Voltage	20 to 30 VDC	20 to 30 VDC		
Constant Current Excitation	2 to 20 mA	2 to 20 mA		
Output Impedance	<100 ohm	<100 ohm		
Output Bias Voltage	8 to 14 VDC	8 to 14 VDC		
Electrical Isolation	10^8 ohm	10^8 ohm		
Physical				
Sensing Geometry	Compression	Compression		
Sensing Element	Quartz	Quartz		
Housing Material	Stainless Steel	Stainless Steel		
Diaphragm	Invar	Invar		
Sealing	Welded Hermetic	Welded Hermetic		
Electrical Connector	10-32 Coaxial Jack	10-32 Coaxial Jack		
Weight	0.41 oz	11.6 gm		

CE [4]

All specifications are at room temperature unless otherwise specified.
In the interest of constant product improvement, we reserve the right to change specifications without notice.

ICP® is a registered trademark of PCB Group, Inc.

OPTIONAL VERSIONS

Optional versions have identical specifications and accessories as listed for the standard model except where noted below. More than one option may be used.

CA - Ablative Coating

H - Hermetic Seal

Sealing	Welded Hermetic	Welded Hermetic

M - Metric Mount

Supplied Accessory : Model 065A40 Seal ring 0.435" OD x 0.397" ID x 0.030" thk brass (3) replaces Model 065A03

N - Negative Output Polarity

S - Stainless Steel Diaphragm

Diaphragm	316L Stainless Steel	316L Stainless Steel

W - Water Resistant Cable

NOTES:

[1] Typical.
[2] For +10 volt output, minimum 24 VDC supply voltage required. Negative 10 volt output may be limited by output bias.
[3] Zero-based, least-squares, straight line method.
[4] See PCB Declaration of Conformance PS023 for details.

SUPPLIED ACCESSORIES:

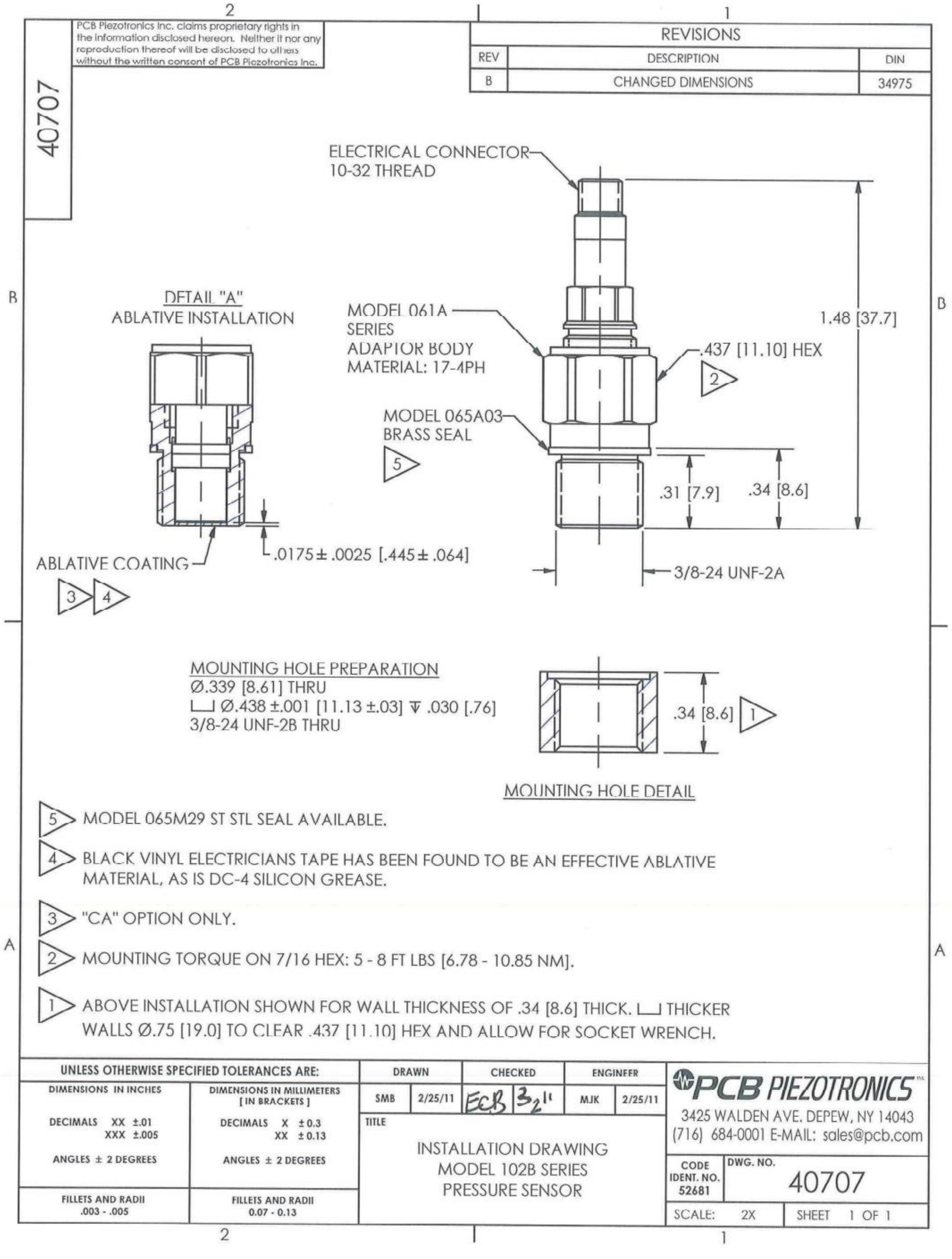
Model 065A03 Seal ring 0.435" OD x 0.377" ID x 0.030" thk brass (3)

Entered: YOMW	Engineer: NGX	Sales: BWM	Approved: EB	Spec Number:
Date: 12/21/10	Date: 12/21/10	Date: 12/21/10	Date: 12/21/10	40730

PCB PIEZOTRONICS™ PRESSURE DIVISION

3425 Walden Avenue, Depew, NY 14043

Phone: 716-684-0001
Fax: 716-686-9129
E-Mail: pressure@pcb.com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40707
REVISIONS
REV | DESCRIPTION | DIN
B | CHANGED DIMENSIONS | 34975
ELECTRICAL CONNECTOR 10-32 THREAD
DETAIL "A" ABLATIVE INSTALLATION
MODEL 061A SERIES ADAPTOR BODY MATERIAL: 17-4PH
.437 [11.10] HEX
1.48 [37.7]
MODEL 065A03 BRASS SEAL
.31 [7.9]
.34 [8.6]
ABLATIVE COATING
.0175± .0025 [.445± .064]
3/8-24 UNF-2A
MOUNTING HOLE PREPARATION
Ø.339 [8.61] THRU
⌴ Ø.438 ±.001 [11.13 ±.03] ↧ .030 [.76]
3/8-24 UNF-2B THRU
.34 [8.6]
MOUNTING HOLE DETAIL
5 MODEL 065M29 ST STL SEAL AVAILABLE.
4 BLACK VINYL ELECTRICIANS TAPE HAS BEEN FOUND TO BE AN EFFECTIVE ABLATIVE MATERIAL, AS IS DC-4 SILICON GREASE.
3 "CA" OPTION ONLY.
2 MOUNTING TORQUE ON 7/16 HEX: 5 - 8 FT LBS [6.78 - 10.85 NM].
1 ABOVE INSTALLATION SHOWN FOR WALL THICKNESS OF .34 [8.6] THICK. ⌴ THICKER WALLS Ø.75 [19.0] TO CLEAR .437 [11.10] HEX AND ALLOW FOR SOCKET WRENCH.
UNLESS OTHERWISE SPECIFIED TOLERANCES ARE:
DIMENSIONS IN INCHES
DECIMALS XX ±.01 XXX ±.005
ANGLES ± 2 DEGREES
FILLETS AND RADII .003 - .005
DIMENSIONS IN MILLIMETERS [IN BRACKETS]
DECIMALS X ±0.3 XX ±0.13
ANGLES ± 2 DEGREES
FILLETS AND RADII 0.07 - 0.13
DRAWN SMB 2/25/11
CHECKED ECB 3/2/11
ENGINEER MJK 2/25/11
TITLE
INSTALLATION DRAWING MODEL 102B SERIES PRESSURE SENSOR
PCB PIEZOTRONICS
3425 WALDEN AVE. DEPEW, NY 14043
(716) 684-0001 E-MAIL: sales@pcb.com
CODE IDENT. NO. 52681
DWG. NO. 40707
SCALE: 2X
SHEET 1 OF 1

B.4 Datasheet flowmeter (Selected pages)

Source: VSE Volumentechnik GmbH, *Solutions for Fluid Technology for flow meters of the product line " VSI High Definition Flow Meter "*. 2022.

STORAGE, RETURN AND DISPOSAL

Temporary storage

All VSE flow meters are supplied with sealing plugs and in suitable packaging for all destinations and modes of transport to ensure optimum protection. The flow meters should always be stored in their original foam packaging or transport box.
The units must not be exposed to temperatures below -20°C or above +60°C and must be protected from moisture and its effects.

Return

1. The flow meter must be properly cleaned by the customer before being returned to prevent the risk of poisoning/contamination by harmful, explosive and other high-risk pumped media for humans and the environment.
2. If media have been conveyed whose residues with atmospheric humidity lead to corrosion damage or ignite on contact with oxygen, the flow meter must be additionally neutralised and thoroughly cleaned with anhydrous, inert gas to dry.
3. The return of the flow meter must always be accompanied by a fully completed declaration of no objection (see page 26). All applied safety and decontamination measures must be indicated.
4. When returning the flow meter, it must be packed in accordance with the applicable logistics standards and sealed with sealing plugs.

Disposal

VSE actively promotes environmental awareness and has an operational management system that meets the requirements of ISO 9001:2015. The impact on the environment and people should be minimised during the production, storage, transport, use and disposal of our products and solutions.

- Collect rinsing liquid as well as residual liquid and dispose of it in accordance with the statutory provisions and regulations.
- Wear protective clothing and protective mask/+ goggles if necessary.

Materials must be disposed of properly as follows:

- Metal
- Plastics
- Electronic components
- etc.

When disposing of the materials, ensure that the waste-relevant rules and regulations of the respective country of destination are observed!

TECHNICAL SPECIFICATIONS VSI 0.02 / IPF – VSI 4 / IPF

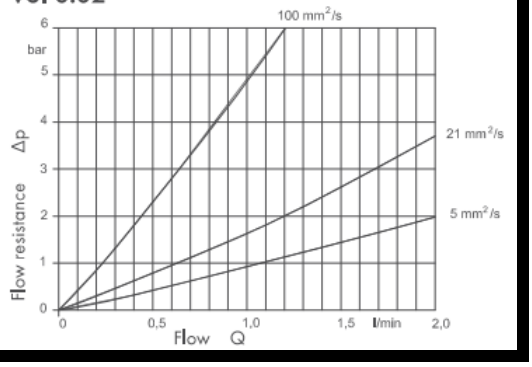
Size	Measuring range l/min	Frequency Hz	Pulse value cm³/pulse	K-factor pulse/litre
VSI 0.02	0.002 ... 2	1.667 * IPF ... 1666.67 * IPF	0.02 / IPF	50 000 * IPF
VSI 0.04	0.004 ... 4	1.667 * IPF ... 1666.67 * IPF	0.04 / IPF	25 000 * IPF
VSI 0.1	0.01 ... 10	1.667 * IPF ... 1666.67 * IPF	0.1 / IPF	10 000 * IPF
VSI 0.2	0.02 ... 18	1.667 * IPF ... 1500.00 * IPF	0.2 / IPF	5 000 * IPF
VSI 0.4	0.03 ... 40	1.250 * IPF ... 1666.67 * IPF	0.4 / IPF	2 500 * IPF
VSI 1	0.05 ... 80	0.833 * IPF ... 1333.33 * IPF	1 / IPF	1 000 * IPF
VSI 2	0.1 ... 120	0.833 * IPF ... 1000.00 * IPF	2 / IPF	500 * IPF
VSI 4	1.0 ... 250	4.167 * IPF ... 1041.67 * IPF	4 / IPF	250 * IPF

Adjustable interpolation factors IPF: 1; 2; 3; 4; 5; 8; 10; 12; 16

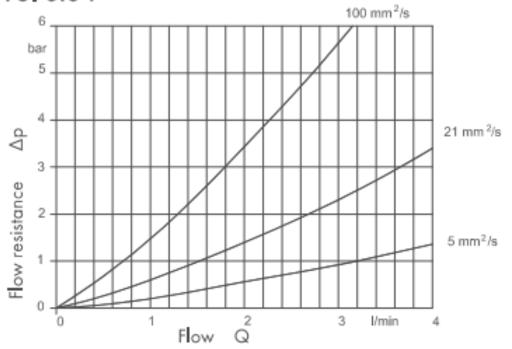
Measurement accuracy	up to 0.3% of measurement value (with viscosity > 20 mm²/s)
Repetition accuracy	± 0.05% under the same operating conditions
Material	Cast iron EN-GJS-400-15 (EN 1563) or Stainless steel 1.4305
Meter bearing	Ball bearings or steel plain bearings (medium-dependent)
Seals	FPM (standard), NBR, PTFE, EPDM or silicone
Max. operating pressure	Cast iron EN-GJS-400-15 (EN 1563) 315 bar / 4500 psi Stainless steel 1.4305 450 bar / 6500 psi
Medium temperature	–40°C ... + 120°C (–40°F ... 248°F)
Ambient temperature	–20°C ... + 50°C (–4°F ... 122°F)
Viscosity range	1 ... 100 000 mm²/s
Installation position	any
Flow direction	any
Running noise	max. 72 db(A)
Power supply version	10 to 28 volts/DC
Pulse output	3 current limiting and short-circuit-proof output stages low signal: 0 = GND; high signal: 1 = U_b -1
Channel offset	90° ± 30° max.
Pulse-width repetition rate	1/1 ± 15° max.
Preamplifier housing	Aluminium
Protection type	IP 65

FLOW RESPONSE CURVES VSI 0.02 – VSI 4

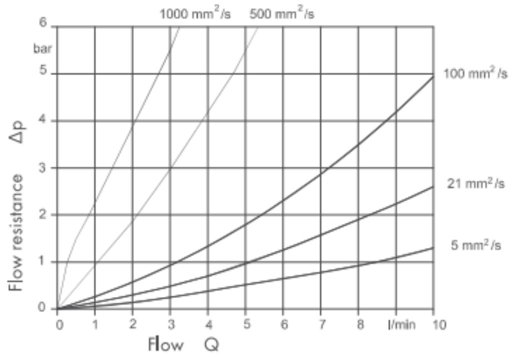
VSI 0.02



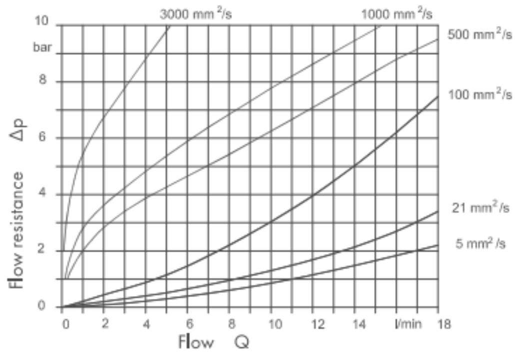
VSI 0.04



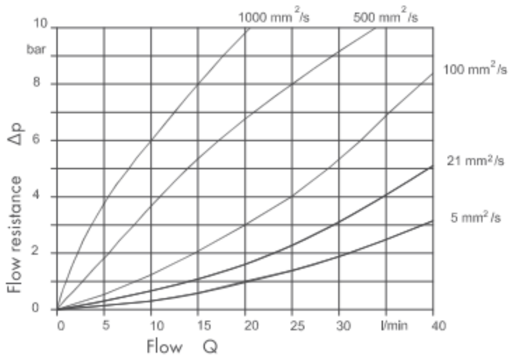
VSI 0.1



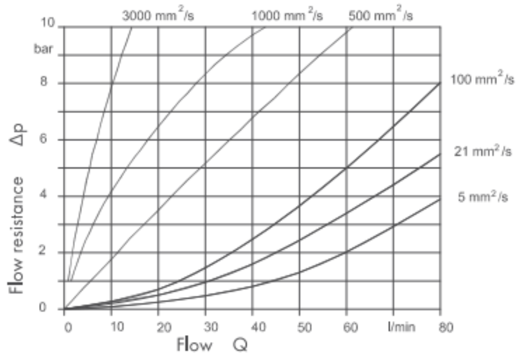
VSI 0.2



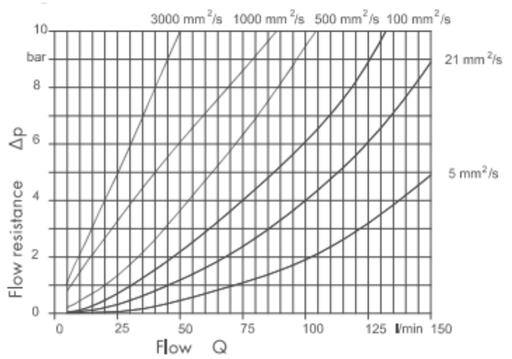
VSI 0.4



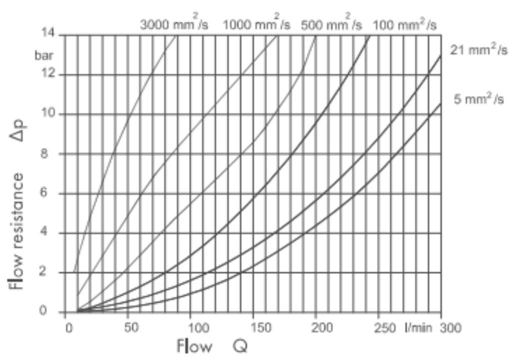
VSI 1



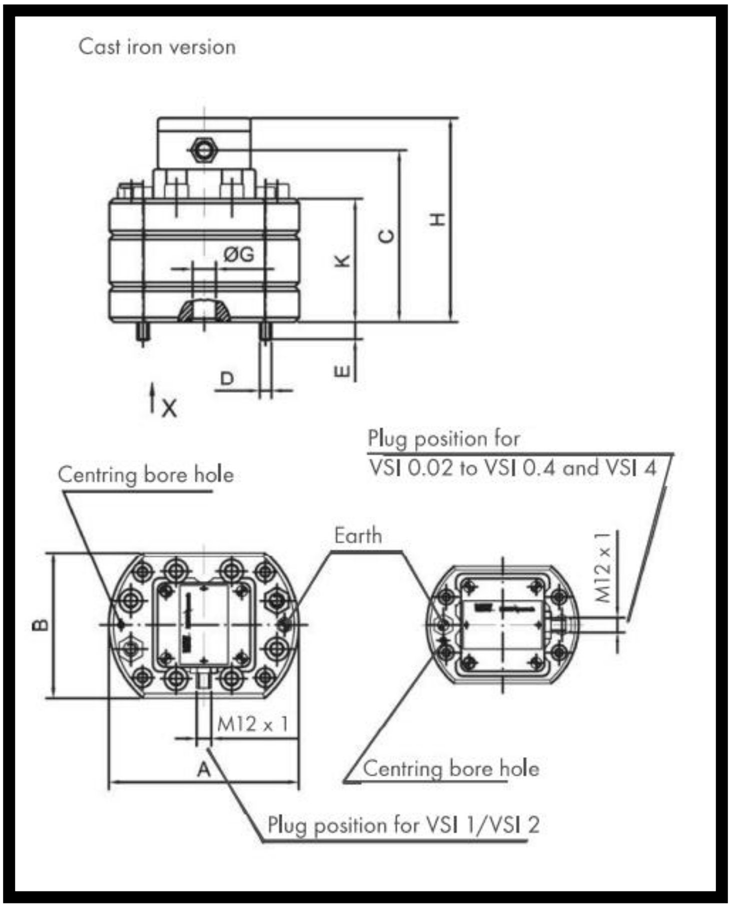
VSI 2

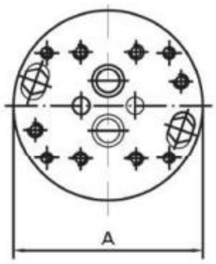


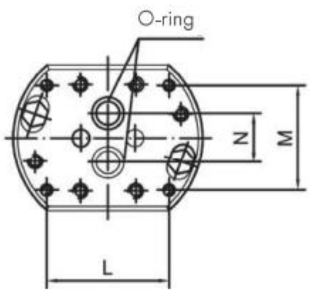
VSI 4



DIMENSIONS VSI 0.02 – VSI 4





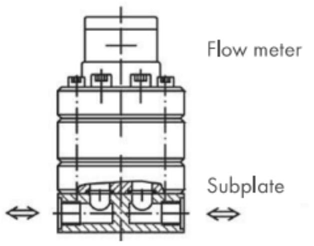


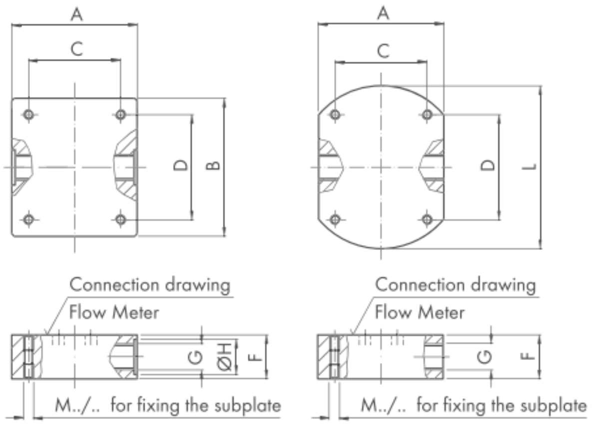
Size VSI	A	B	C	D	E	ø G	H	K	L	M	N	O-ring	Weight GCI kg	SS kg
0.02	100	80	91	M6	12.0	9	114	58	70	40	20	11 x 2	2.8	3.4
0.04	100	80	92	M6	11.5	9	115	59	70	40	20	11 x 2	2.8	3.4
0.1	100	80	94	M6	9	9	117	61	70	40	20	11 x 2	2.8	3.4
0.2	100	80	94	M6	9.5	9	117	61	70	40	20	11 x 2	3.0	3.7
0.4	115	90	96.5	M8	11.5	16	120	63.5	80	38	34	17.96 x 2.62	4.0	5.0
1	130	100	101	M8	12.5	16	124	68	84	72	34	17.96 x 2.62	5.3	6.8
2	130	100	118	M8	15	16	141	85	84	72	34	17.96 x 2.62	6.7	8.4
4	180	140	143	M12	20	30	166	110	46	95	45	36.17 x 2.62	14.7	18.4

Dimensions in mm

DIMENSIONS, SUBPLATES AP.0.2 – 4

Connection position, side

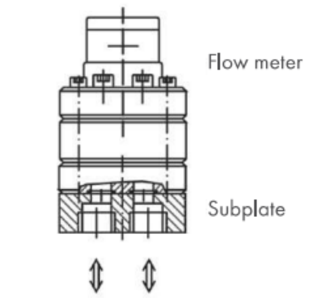


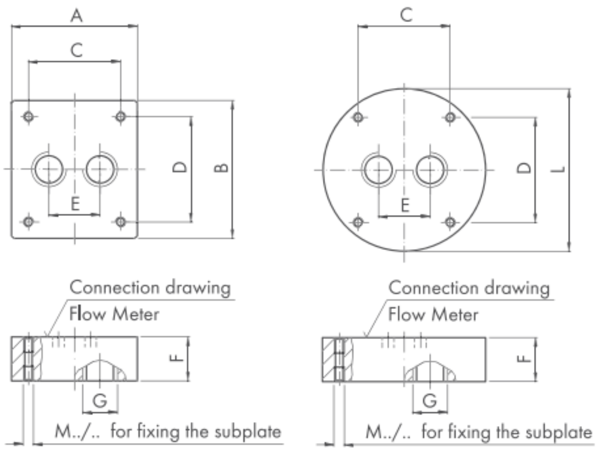


Size VSI	Connection thread G	F	øH	A	B	C	D	E	L	Thread / depth M	Weight kg
0.02 0.04 0.1 0.2	G 1/4"	35	20	80	90	40	70	26	100	M6/12	1.8
	G 3/8"		23					30			
	G 1/2"		28					38			
0.4	G 1/2"	35	28	90	100	38	80	46	115	M8/15	2.7
	G 3/4"	40	33					52			
1 2	G 1/2"	35	28	100	110	72	84	46	130	M8/15	3.6
	G 3/4"	40	33					52			
	G 1"	55	41					55			
4	G 1 1/4"	70	51	120	130	100	110	60		M8/15	7.4
	*G 1 1/2"	70	56				120	72			
	G 1 1/2"	80		140			110		180		12.0

only for AP . 4 U...

Connection position below



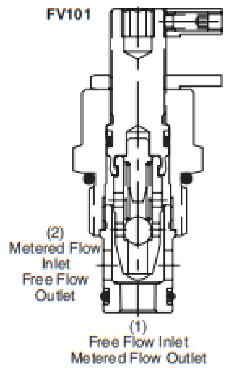


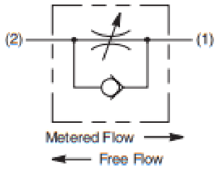
B.5 Datasheet Parker FV102KV

Source: Parker Hannifin, “Hydraulic Cartridge Systems Threaded Cartridge Valves and Integrated Hydraulic Products,” pp. 88–89.

General Description

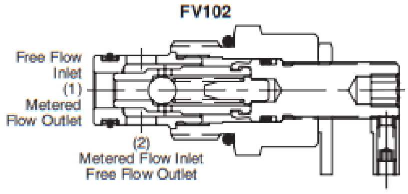
Needle Valve with a Reverse Check. Also known as a Flow Control Valve. For additional information see Technical Tips on pages FC1-FC4.





Features

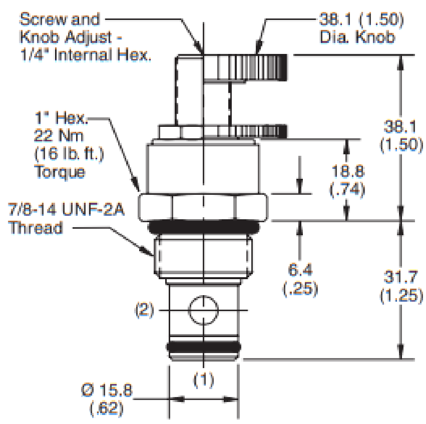
- Hardened, precision ground parts for durability
- Compact size for reduced space requirements
- Fine thread needle option available for precise adjustment
- All external parts zinc plated



Specifications

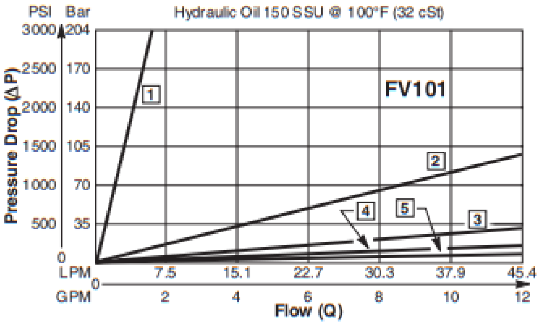
Rated Flow	FV101 45 LPM (12 GPM) FV102 23 LPM (6 GPM)
Maximum Inlet Pressure	210 Bar (3000 PSI)
Cartridge Material	All parts steel. All operating parts hardened steel.
Operating Temp. Range/Seals	-34°C to +121°C (Nitrile) (-30°F to +250°F) -26°C to +204°C (Fluorocarbon) (-15°F to +400°F)
Fluid Compatibility/ Viscosity	Mineral-based or synthetic with lubricating properties at viscosities of 45 to 2000 SSU (6 to 420 cSt)
Filtration	ISO-4406 18/16/13, SAE Class 4
Approx. Weight	0.23 kg (0.50 lbs.)
Cavity	C10-2 (See BC Section for more details)
Form Tool	Rougher None Finisher NFT10-2F

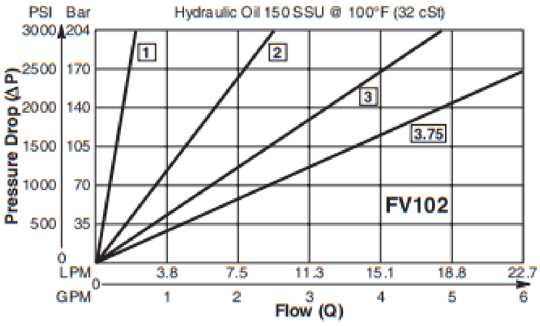
Dimensions Millimeters (Inches)



Performance Curves

Metered Flow vs. Pressure Drop (Through cartridge only)





☐ **= No. of Turns CCW From Fully Closed.**

The number on each curve indicates the number of complete turns of the knob or screw adjustment from fully closed. When the metered flow is 22.5 LPM (6 GPM) and the adjustment is two complete turns from closed, the pressure drop will be 13.8 Bar (200 PSI). When the metered flow is 22.5 LPM (6 GPM) and the adjustment is five complete turns from closed, the pressure drop will be 3.5 Bar (50 PSI).

☐ **= No. of Turns CCW From Fully Closed.**

The number on each curve indicates the number of complete turns of the knob or screw adjustment from fully closed (non-metered flow). When the metered flow is 7.5 LPM (2 GPM) and the adjustment is two complete turns from closed, the pressure drop will be 156.9 Bar (2275 PSI). When the metered flow is 7.5 LPM (2 GPM) and the adjustment is 3.75 turns from closed, the pressure drop will be 56.6 Bar (820 PSI).

Ordering Information

FV10	☐	☐	☐
10 Size Flow Control Valve	Style	Adjustment Style	Seals

Highlighted represents preferred options that offer the shortest lead times. Other options may be available, but at extended lead times.

Code	Style
1	**Coarse Flow**
2	Fine Flow

Code	Adjustment Style / Kit No.
K	**Knob Adjust (840208K)**
S	Screw Adjust

Code	Seals / Kit No.
Omit	**Nitrile / (SK10-2)**
V	Fluorocarbon / (SK10-2V)

Order Bodies Separately
See section BC

B10	–	2	–	☐
10 size		2-Way Cavity		Port Size

Code	Porting / Body Material
8T	SAE-8 / Steel (5000 PSI)
A8T	SAE-8 / Aluminium (3000 PSI)

B.6 Datasheet Quick release couplings DNP PBV1 DN06 (Selected pages)

Source: "DNP Catalogue 2022 PBV1," in *DNP Catalogue 2022*, 2022, pp. 1–2.

PBV1

ISO B/STEEL

ACCIAIO
STEEL
STAHL
ACIER

Caratteristiche tecniche I

- Norma: ISO 7241 B
- Occlusione: valvola
- Aggancio: sfere radiali
- Materiale: acciaio
- Finitura: Zn-Fe (Cr III)
- Filettature: BSP-NPT-SAE
- Guarnizioni standard: NBR
- Temperatura d'esercizio: -25°C +100°C
- Guarnizioni opzionali: FKM, FFKM, EPDM o altro.
- Pressioni di esercizio: 100-500 bar
- Connessione in pressione residua: non consentita

Technical data E

- Standard: ISO 7241 B
- Occlusion: poppet
- Locking: radial balls
- Material: steel
- Finishing: Zn-Fe (Cr III)
- Threads: BSP-NPT-SAE
- Standard seals: NBR
- Working temperature: -25°C +100°C
- Optional seals: FKM, FFKM, EPDM or more.
- Working pressure: 100-500 bar
- Connection under resdual pressure: not allowed

Technische Merkmale D

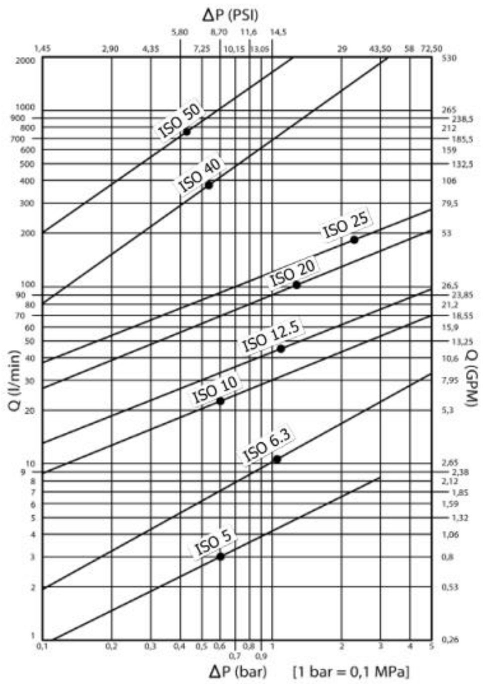
- Norm: ISO 7241 B
- Verschluss: ventil
- Verriegelung: Stahlkugeln
- Werkstoff: Stahl
- Ausführung: Zn-Fe (Cr III)
- Gewinde: BSP-NPT-SAE
- Standard-Dichtungen: NBR
- Betriebstemperatur: -25°C +100°C
- Dichtungen nach Wahl: FKM, FFKM, EPDM, usw.
- Betriebsdruck: 100-500 bar

Caracteristiques techniques F

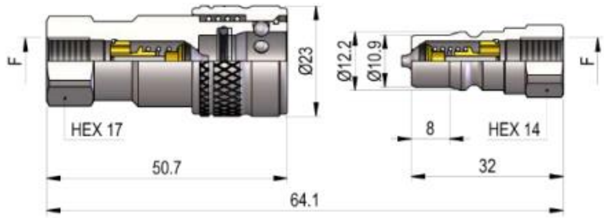
- Norme: ISO 7241 B
- Obturation: clapet
- Accrochage: billes radiales
- Matériel: acier
- Traitement: Zn-Fe (Cr III)
- Taraudage: BSP-NPT-SAE
- Joints standard: NBR
- Température de service: -25°C +100°C
- Joints facultatifs: FKM, FFKM, EPDM, ect.
- Pression de service: 100-500 bar
- Connexion sous pression résiduelle: pas possible

Nominal size				Max working pressure	Rated flow	Max flow rate	Min burst pressure Male	Min burst pressure Female	Min burst pressure Coupled	Fluid spillage
DNP	BG	ISO	mm	MPa	l/min	l/min	MPa	MPa	MPa	cc
04	0	5	4.2	50	3	9	240	230	270	0.5
06	1	6.3	6.5	25	12	24	110	180	100	1
10	2	10	8.5	25	23	46	140	140	130	2.4
13	3	12.5	10.5	25	45	90	110	140	110	3.9
20	4	20	15.8	25	106	220	100	130	120	11
25	5	25	17.3	25	189	260	100	110	100	19
39	7	40	36	20	379	757	80	80	80	95
50	8	50	50	10	757	1000	40	40	40	170

1 MPa = 145.04 psi • 1 l = 0.264 gal

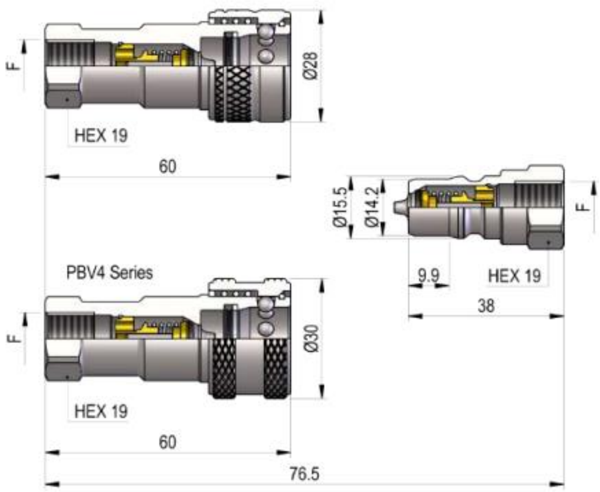


PBV1 DN04 - BG 0 - ISO 5



F	STANDARD	FEMMINA - FEMALE - MUFFE - FEMELLE			MASCHIO - MALE - STECKER - MALE		
		COD. F	Weight (g)	Packaging (pcs)	COD. M	Weight (g)	Packaging (pcs)
BSP 1/8"	DIN 3852-2-X	PBV1.0404.002	89	160	PBV1.0404.003	20	500
NPT 1/8"	ANSI B1.20.3	PBV1.0404.012	89	160	PBV1.0404.013	20	500

PBV1 DN06 - BG 1 - ISO 6.3



F	STANDARD	FEMMINA - FEMALE - MUFFE - FEMELLE			MASCHIO - MALE - STECKER - MALE		
		COD. F	Weight (g)	Packaging (pcs)	COD. M	Weight (g)	Packaging (pcs)
BSP 1/4"	DIN 3852-2-X	PBV1.0606.002	123	100	PBV1.0606.003	39	300
NPT 1/4"	ANSI B1.20.3	PBV1.0606.012	124	100	PBV1.0606.013	40	300
BSP 1/4"	DIN 3852-2-X	PBV4.0606.002	133	80			
NPT 1/4"	ANSI B1.20.3	PBV4.0606.012	134	80			

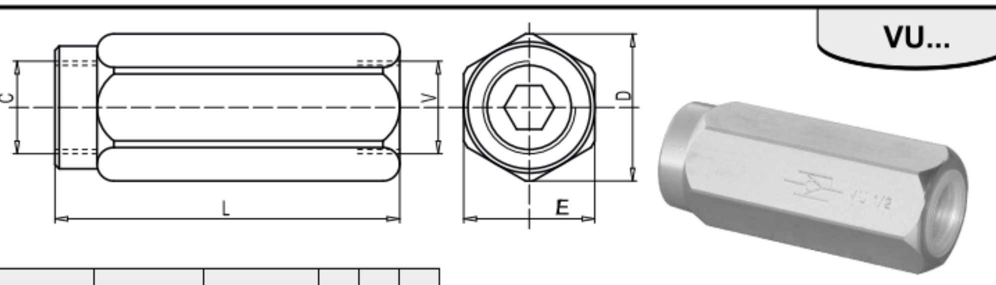
B.7 Datasheet pressure relief valve VMP ¼"L

Source: "Veiligheidsventiel VMP 1/4" Light | VMP 1/4" Light| Hydrauliek24.nl." https://www.hydrauliek24.nl/veiligheidsventiel-vmp-1-4-light (Accessed May 01, 2022).

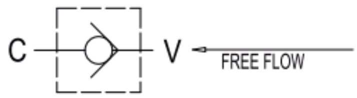
HYDRAULIEK 24 — COMPONENTEN | SYSTEMEN | SLANGEN — HYDRAULIC VALVES

VU...

Check Valve

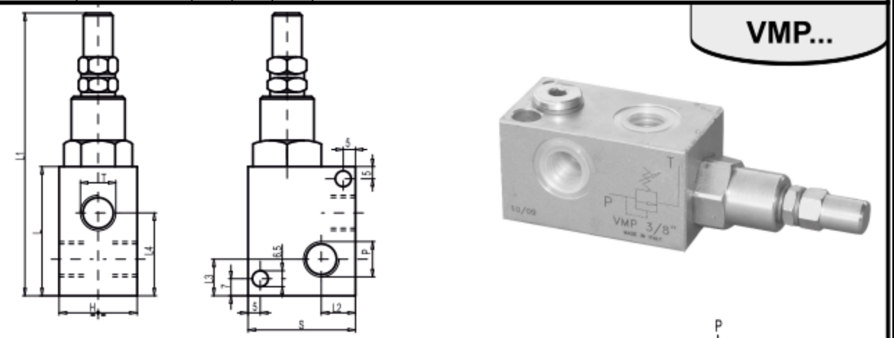


Code Number	Type	Max. Flow	Max. Pressure	L	E	D
		Lt./min	Bar	mm	mm	mm
V0592	VU 1/8	3	350	44	14	16
V0590	VU 1/4	20	350	62	19	21
V0600	VU 3/8	45	350	68	24	26,5
V0610	VU 1/2	70	350	77	30	34

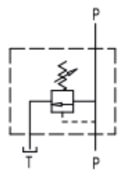


VMP...

Crossover Relief Valve

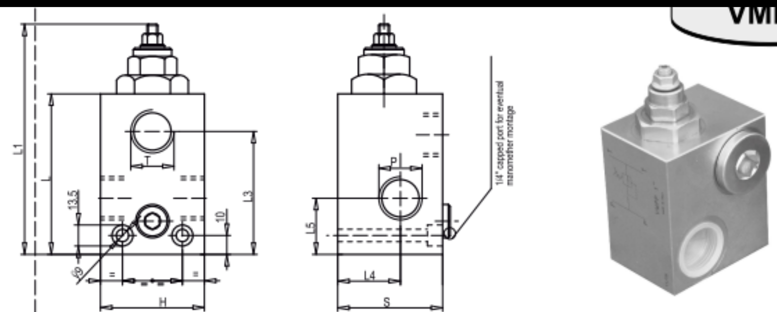


Code Number	Type	Max. Flow	Max. Pressure	L	L1	L2	L3	L4	H	S
		Lt./min	Bar	mm	mm	mm	mm	mm	mm	mm
V0689	VMP 1/4 L	30	350	52	114	12	13	34	30	40
V0690	VMP 3/8 L	40	350	55	117	12	15	35,5	30	40

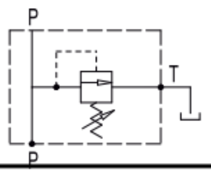


VMPP...

Differential Type Relief Valve



Code Number	Type	Max. Flow	Max. Pressure	L	L1	L2	L3	L4	L5	H	S
		Lt./min	Bar	mm	mm	mm	mm	mm	mm	mm	mm
V0725	VMPP 3/4	120	350	94	135	32	72	35	32	60	60
V0735	VMPP 1	180	350	94	135	30	69	34	23	60	60



+31 (0)53 711 38 61 | HYDRAULIEK24.NL 164

B.8 Datasheet RS485 to USB converter: Keller K-114

Source: KELLER Druckmesstechnik AG, "K-114 | KELLER Pressure," 2022. https://keller-druck.com/en/products/software-accessoires/converters/k-114 (Accessed May 22, 2022).

KELLER

INTERFACE CONVERTER

K-114

COMMUNICATION USB – RS485

The K-114 interface converter is recommended for use with KELLER products and enables communication between a device and computer via a USB interface.

K-114

Description

The interface converter communicates with the connected devices via an RS485 bus. Power is supplied to the connected devices via the computer's USB interface or an external power supply.

Bias or termination resistors may be activated if necessary in order to improve communication via the RS485. An echo function is also available.

Multimeter/measuring analog signals

The K-114 converter measures the power consumption of the connected devices and an arbitrary voltage signal. These signals can be evaluated and displayed using the supplied software. If only one external device is connected, a functional check can be performed or the analog pressure signal can be displayed.

The K-114 interface converter enables

- ✓ Communication USB – RS485 (half-duplex)
- ✓ Power supply to connected devices (12 VDC)
- ✓ Measurement of applied signal voltage (0…12 VDC)
- ✓ Measurement of the power consumption of end consumers (0…40 mA)
- ✓ Optical status and configuration display (LED)
- ✓ Galvanic isolation between computer and converter
- ✓ Selective activation of echo, bias resistors or a termination resistor
- ✓ Software and drivers included in scope of delivery

Technical specifications

Power supply to end consumer (without power adapter)		12 VDC / max. 40 mA
External power supply (with power adapter)		12…20 VDC / < 150 mA
Voltage input		0…12 VDC / Accuracy 0,3 %FS (RI ≥ 30 kΩ)
Resolution of voltage input		< 0,016 V
Current measurement		0…40 mA / Accuracy 0,3 %FS
Resolution of current measurement		< 0,05 mA
Interface / plug type		USB 2.0 / Mini USB-B
RS485 configuration parameters		ECHO / BIAS (2 x 560 Ω) / Termination (120 Ω)
RS485 transmission rate	(slow)	up to 250 kbps
RS485 transmission rate	(high)	up to 3 Mbps
RS485 bus devices		up to 128 bus devices (1/4 unit load)
RS485 cable length		0,75 m
Storage / operating temperature		-10…50 °C
H × W × D		56 × 31 × 24 mm
Weight		approx. 90 g
Protection		IP40

CE

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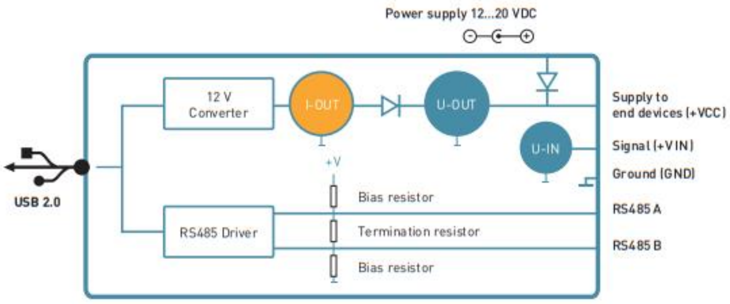
www.keller-druck.com

Functions



The K-114 converter shows the connection status and the selected configuration parameters, which are displayed via status LEDs.

The digital multimeter enables measurement of the supply voltage U-OUT [VDC] and the power consumption of the connected devices I-OUT [mA], as well as measurement of the voltage signal U-IN [VDC] of the connected device.

The K-114 interface converter generates a virtual COM port via which the RS485 interface can be accessed. The converter can be configured via address 253.

Communication can be established with the connected devices via an RS485 (half-duplex mode) bus at 9600 baud (default) or 115200 baud, 8 data bits, 1 stop bit and no parity.

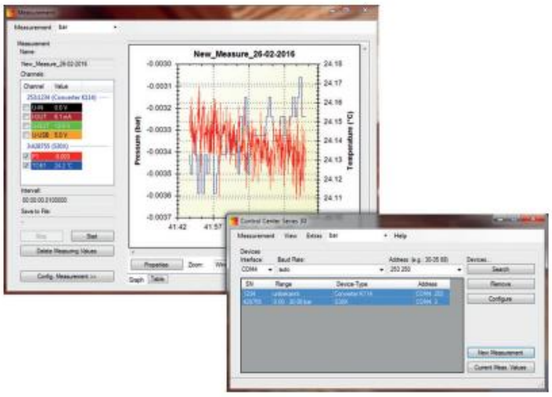
Power is supplied to the connected devices via the USB interface or an external power supply. KELLER products operate with fail-safe drivers, which output a logical high at the receiver outlet in the event of short-circuited, open or non-terminated inputs in order to avoid invalid signal states. The RS485 drivers are also slew-rate limited, which limits the edge steepness of the driver output and thus suppresses reflections, even when the RS485 interface is not complete.

Software

ControlCenterSeries30

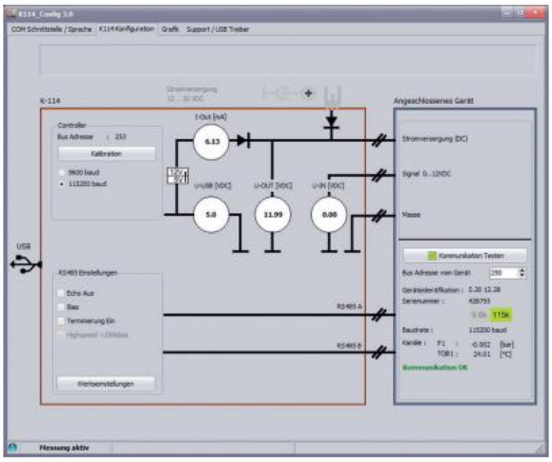
ControlCenterSeries30 makes it easy to record and visualise pressure and temperature data, as well as the power consumption or the voltage signal pattern.

✓ Visualise measurement data for several devices via RS485
✓ Analog output signal for 1 device (4…20 mA or 0…10 V)



K-114_Config

A configuration and diagnostic tool and the status display for the interface converter simplify handling.



Product overview

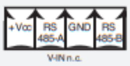
The various versions of the K-114 interface converter use different, product-specific interface plugs. The product overview shows the compatibility between the product and the interface converters. The converter can also be expanded using additional cable options. For a complete product overview and a detailed technical description of the interface converter and operating instructions, visit www.keller-druck.com.

USB

K-114	K-114-A	K-114-B	K-114-V
Product no. 309010.0074	Product no. 309010.0075	Product no. 309010.0076	Product no. 309010.0132
X-Line with cable	DCX-16 DCX-22 DCX-25PVDF DCX-38 LEO-Record LEX1 ARC1/GSM2 LPX, MPX, HPX	X-Linie with Binder plug LEO3 dV22-PP	Customised, ready to use X-Line

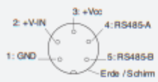
Pin assignment of the converters

K-114
Plug-in screw terminal
MC 1,5 / 4-ST-3,81



K-114-A
Fischer plug-in connector
S 103 A054-130 [male]

K-114-B
Binder cable connector
Series 680 [female] 5-pin



K-114-V
with open
cable head

WH:	GND
GN:	+V-IN
YE:	+Vcc
BN:	RS485-A
GY:	RS485-B
Shield:	Ground / Shield

Scope of delivery

The product is supplied in a box, and includes:

- Manual K-114
- Converter K-114 (in accordance with product no. 309010.00XX)
- Software CD
- USB cable 1 m (A Mini / B)

Accessories

Compatible adapter cables available e.g to K-114-B:

Cable option 1

Binder plug to strand clips

Cable option 3

Binder plug to 6-pin Molex socket

Plug-in adapter 15 V

- Incl. adapter: PLUG-EU, PLUG-GB, PLUG-US/JP
- Input: 100…240 VAC / 50…60 Hz
- Output: 15 VDC / 500 mA
- Cable length: 1,8 m
- Product no.: 309010.0144

B.9 Datasheet PCB signal conditioner

Source: PCB Piezotronics, "PCB Piezotronics Vibration Div Product Catalog," p. 172 (3.4).

Line-Powered Signal Conditioners

MULTI-CHANNEL, LINE-POWERED ICP® SENSOR SIGNAL CONDITIONERS WITH GAIN

These full-featured, multi-channel, line-powered signal conditioners offer push-button, selectable gain for each channel and optional output switching to simplify data acquisition. Each features a bank of LED's on each channel to indicate gain setting, input overload, and input fault due to open or short circuit connections. In addition to the channel specific BNC's, the optional switched output units offer additional output BNC's that carry the signals of the switch-selected channel.

Model 482A16
4 channel,
gain x1, x10, x100

Model 482A18
8 channel
gain x1, x10, x100
8 to 1 output
switching

Full-Featured, Line-Powered Signal Conditioners with Gain

Model Numbers	482A16	482A20
Style	Full Feature with gain	Full Feature with gain
Channels	4 channels	8 channels
Sensor excitation [1]	24 volt, 2 to 20 mA	24 volt, 2 to 20 mA
Gain (each channel)	×1, ×10, ×100	×1, ×10, ×100
Low frequency response (-5%)	0.225 Hz [2]	0.225 Hz [2]
High frequency response (-5%)	100 kHz	100 kHz
Broadband noise (at unity gain)	9.1 µV rms	9.1 µV rms
Power required	90 to 130 VAC 50 to 400 Hz	90 to 130 VAC 50 to 400 Hz
Input/output connectors	BNC/BNC	BNC/BNC
Size (height × width × depth)	6.3 × 2.9 × 9.7 in 160 × 73.7 × 246.4 mm	6.3 × 4.0 × 9.7 in 160 × 101.6 × 246.4 mm
Weight	32 oz (907.2 gm)	97.6 oz (2767 gm)
Optional Models		
4 to 1 output switching	482A17	482A19 [3]
8 to 1 output switching	N/A	482A18
210 to 250 VAC powerable	F482A16	F482A20

NOTES: [1] Current is factory set at 4 mA but is user adjustable between 2 and 20 mA.
[2] Achieved with readout device having a 1 megohm input impedance.
[3] Model 482A19 offers dual 4 to 1 output switching and is ideally suited for use with two channel analyzers.

DC POWER CONDITIONERS

Models 485B and **485B12** serve to regulate available current from any conventional DC power supply or battery source to a constant value between 2 and 20 mA as required by ICP® sensors. In addition, the units decouple the sensor's output bias voltage from the measurement signal to enable zero based measurements with any readout device.

Model 485B features a 10-32 coaxial jack input connector, while Model 485B12 features a BNC jack input connector. Both units feature BNC jack output connectors.

Model 485B

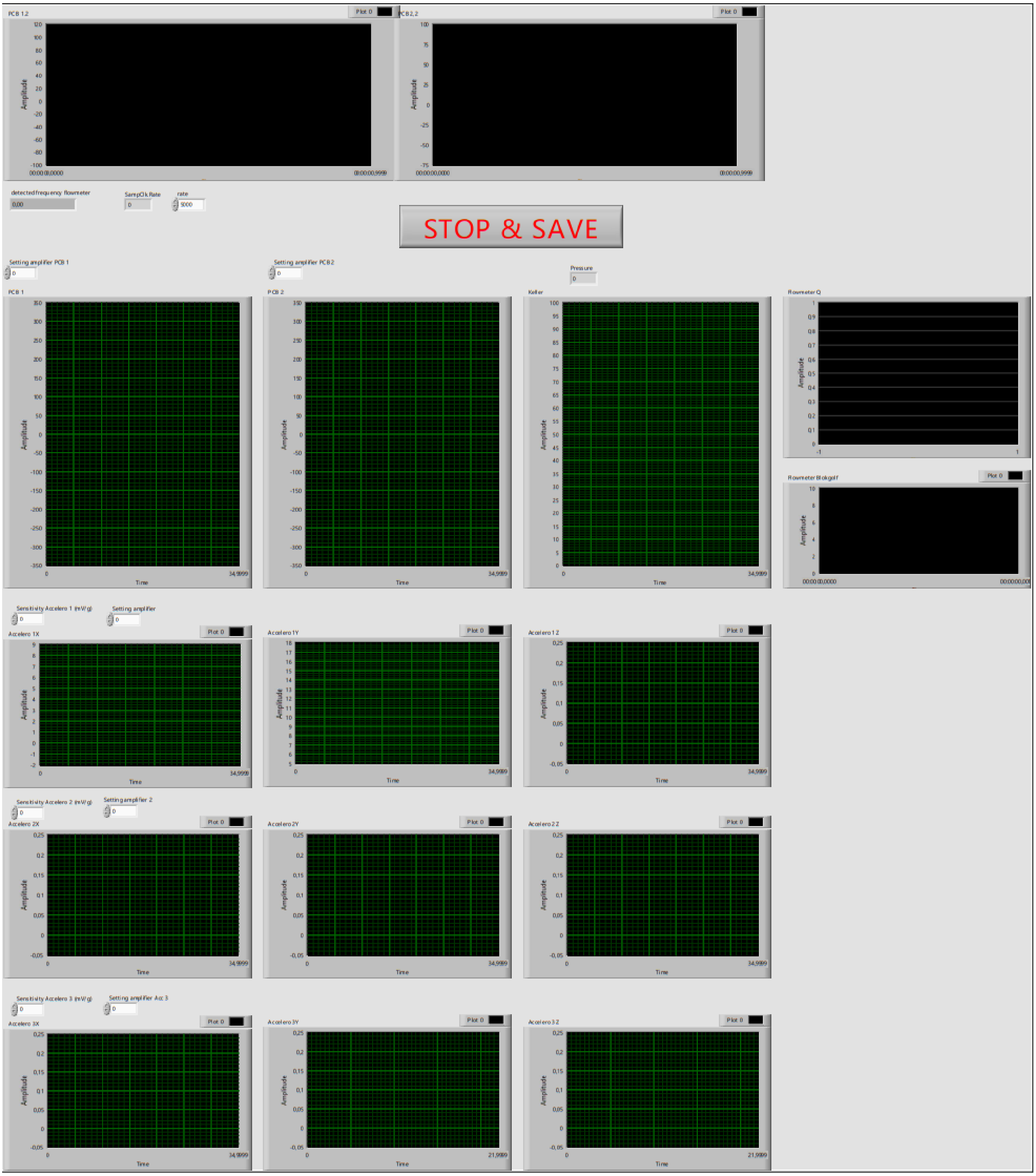
Model 485B12

Dimensions shown are in inches (millimeters).

C. LabView program:

Page 1

SensorReadoutMasterThesisTenneco.vi
C:\Users\Gebruiker\Documents\TestData_NI\SensorReadoutMasterThesisTenneco.vi
Last modified on 1/05/2022 at 11:44
Printed on 22/05/2022 at 11:46



SensorReadoutMasterThesisTenneco.vi
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Last modified on 1/05/2022 at 11:44
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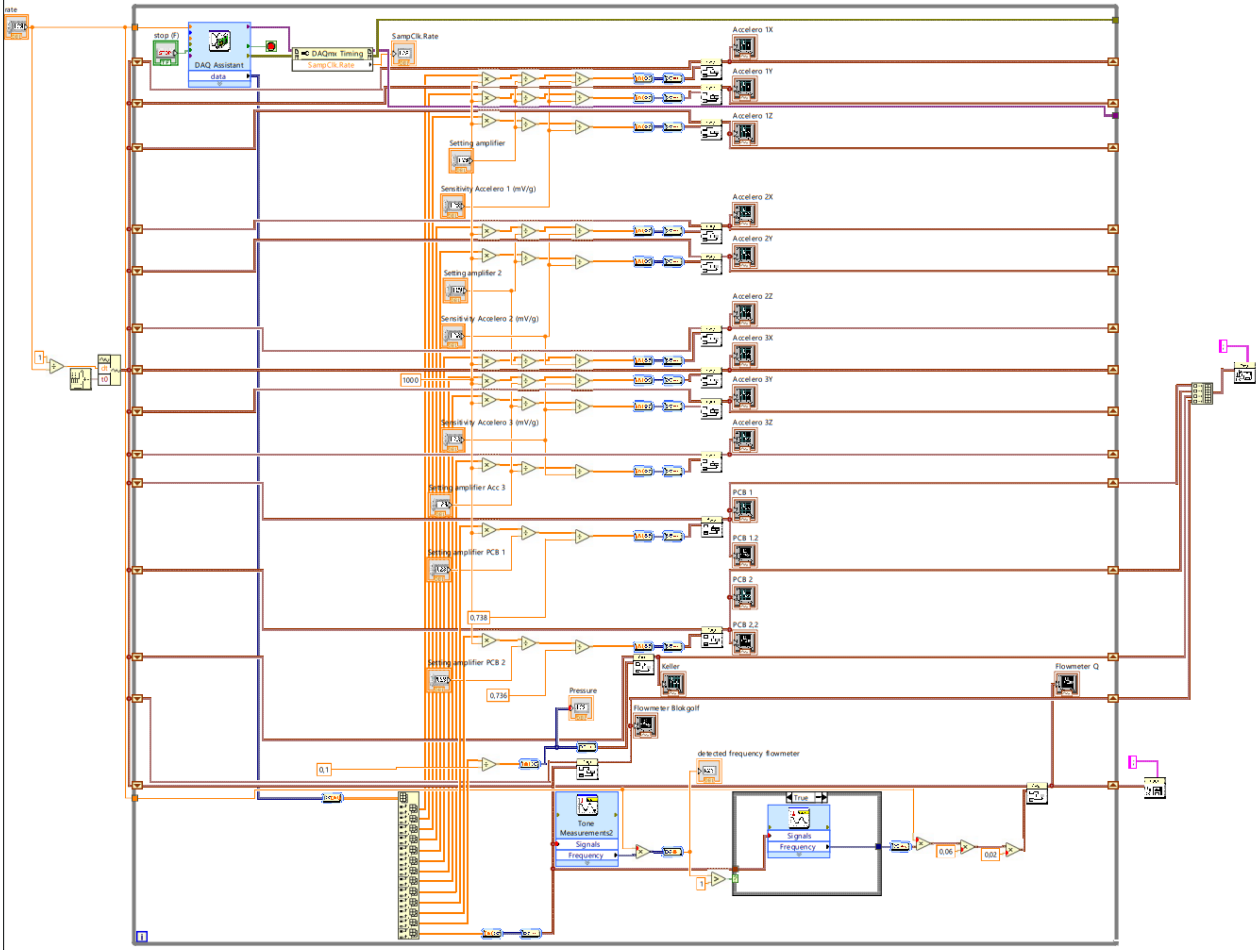

D. MATLAB code

D.1 Plotting one measurement

```
clear, clc;

M = readmatrix("G:\Gedeelde drives\Wout-Nick\MP\Meetresultaten\11-05-2022\Meting68b.csv",'Range',[6 2],'Delimiter',";",'DecimalSeparator',',');

F = readmatrix("G:\Gedeelde drives\Wout-Nick\MP\Meetresultaten\11-05-2022\Meting68.csv",'Range',[5 2],'Delimiter',";",'DecimalSeparator',',');

T = readmatrix("G:\Gedeelde drives\Wout-Nick\MP\Meetresultaten\11-05-2022\Meting68b.csv",'Range','A6','Delimiter',";",'DecimalSeparator',',','OutputType','string');

% Reading out the time and converting it to a time difference

Fs = 10000;                    % samplerate

T2 = T(:,1);

T3 = datetime(T2,'Format','MM/dd/yyyy  HH:mm:ss,SSSSSS');

T4 = T3(:,1)-T3(1,1);

Time = duration(T4,'Format','mm:ss.SSSSSS');

Time.Format = 's';

% Plotting the pressure measured by the Keller sensor

y=lowpass(M(:,3),Fs/2-1,Fs);

figure;

subplot(2,3,1);

plot(Time,y,Time(1,1),0,Time(1,1),90);

xlabel('Time');

ylabel('Pressure (bar)');

title('Pressure Keller - Time');

% Plotting of the pressure ripple measured on the pump side

y2=lowpass(M(:,1),Fs/2-1,Fs);

subplot(2,3,2);

plot(Time,y2,Time(1,1),-100,Time(1,1),100);

xlabel('Time');
```

```
ylabel('Pressure (kPa)');

title('Pressure PCB 1- Time');

% Plotting of the pressure ripple measured on the throttle side

y3=lowpass(M(:,2),Fs/2-1,Fs);

subplot(2,3,3);

plot(Time,y3,Time(1,1),-100,Time(1,1),100);

xlabel('Time');

ylabel('Pressure (kPa)');

title('Pressure PCB 2- Time');

% Plotting of the flow

sizeF = size(F);

sizeT = size(Time);

TimeFlow = linspace(Time(1,1),Time(sizeT(1,1),1),sizeF(1,1));

subplot(2,3,4);

plot(TimeFlow,F(:,1),TimeFlow(1,1),0,TimeFlow(1,1),0.85);

ylabel('Flow (l/min)')

xlabel('Time');

title('Flow VSE- Time');

% Frequency analyses of the pressure ripples

A1 = M(:,1);

n1 = length(A1);

y4 = fft(A1);

f1 = (0:(n1/2))*Fs/n1;

Amp1 = abs(2*y4/n1);

subplot(2,3,5);

plot(f1(100:floor(n1/4)),Amp1(100:floor(n1/4)),f1(1,1),7.5);

xlabel('Frequency (Hz)');

ylabel('Pressure (kPa)');
```

```
title('Magnitude Response PCB 1- Frequency');

A2 = M(:,2);

n2 = length(A2);

y5 = fft(A2);

f2 = (0:(n2/2))*Fs/n2;

Amp2 = abs(2*y5/n2);

subplot(2,3,6);

plot(f2(100:floor(n2/4)),Amp2(100:floor(n2/4)),f2(1,1),7.5);

xlabel('Frequency (Hz)');

ylabel('Pressure (kPa)');

title('Magnitude Response PCB 2- Frequency');
```

D.2 Comparing two measurements

- **Loading the files is identical to the code for one graph, to compare two graphs, just repeat two times.**
- **Converting the timestamps to a time difference also need to be repeated identically to the conversion used to plot one graph.**

```
% Plotting the pressure measured by the Keller sensor

y1_1=lowpass(M1(:,3),Fs/2-1,Fs);

y2_1=lowpass(M2(:,3),Fs/2-1,Fs);

t_end = 1*Fs; %gives desired length of graphs: length = t/Fs

t_start = 0*Fs+1;

t_plot = t_start/Fs;

figure;

subplot(2,3,1);

plot(Time1(t_start:t_end),y1_1(t_start:t_end,1),Time2(t_start:t_end),y2_1(t_start:t_end,1), ...

   Time1(1,1),0,Time1(1,1),90);

xlabel('Time');

ylabel('Pressure (bar)');

title('Pressure Keller - Time');
```

- **Plotting the data from the PCB sensors happens similar to plotting the Keller sensor, just select a different array to plot.**
- **Plotting the flow follows the same principle as plotting one graph. It is needed to create a second pair of arrays and linspaces to correct the time.**
- **Plotting two frequency analyses of the pressure ripples is done identically to plotting one. A second instance of every variable need to be created and both need to be plotted simultaneously.**

D.3 Comparing five measurements

- **Loading the files is identical to the code for one graph, to compare two graphs, just repeat two times.**
- **Converting the timestamps to a time difference also need to be repeated identically to the conversion used to plot one graph.**
- **Plotting the pressure from the Keller and PCB sensors follows the same principle as comparing two graphs. To compare five graphs, five instances of every variable have to be created and subsequently plotted.**
- **Plotting the flow follows the same principle as comparing two graphs. This time, it is needed to create five pairs of arrays and linspaces to correct the time.**
- **To compare the pressure ripples from five different measurements, it is easiest to create a new figure and plot them all underneath each other. The average absolute pressure is added to every graph to be able to distinguish the different measurements.**

```
% Plotting the pcb sensors in different graphs

gem1=string(mean(y1_1));

gem2=string(mean(y2_1));

gem3=string(mean(y3_1));

gem4=string(mean(y4_1));

gem5=string(mean(y5_1));

figure;

subplot(5,2,1);

plot(Time1(1:t),y1_2(1:t,1));

title('Pressure PCB 1- Time: '+ gem1 +' bar');

xlabel('Time');

ylabel('Pressure (kPa)');

…
```