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Industrial Fluid Power

Final Team Project

Automated Turning Machine

Submitted by:
Project Group 02

Name	Student No.
Akhil Binu	110147148
Aaditya Choudhary	110155763
Varun Vasudeo Haldankar	110157396
Lalaj Mukundan Lalasa	110151844
Gokulkrishna Unnikrishnan Nair	110142174
Abhishek Renjith	110153076

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Dr. Mohammed El Sayed

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1. Introduction

A hydraulic power system is a mechanical system that transmits energy through the controlled circulation of pressurized fluid, typically oil, to perform work. It consists of components such as a pump, actuators (like cylinders or motors), control valves, and a fluid reservoir. These systems are widely used in industrial automation, manufacturing machinery, construction equipment, and aerospace applications due to their ability to generate large forces and precise movements with compact components. In the context of this project, the hydraulic power system plays a critical role in automating a turning machine by controlling the sequential motion of a feeder, clamp, and cutting tool. The reliability, precision, and safety of the entire machining operation depend heavily on the correct design and sequencing of the hydraulic circuit. Through this project, the hydraulic system is designed not only to meet operational force and speed requirements but also to incorporate interlocks and fail-safes essential for machine safety and performance.

2. Problem Description

The objective of this project is to design a hydraulic circuit for an automated turning machine that performs three primary operations in sequence: feeding a workpiece into position, clamping the workpiece securely, and advancing a cutting tool to perform a machining operation. The system must be designed to control the motion of three hydraulic cylinders corresponding to each operation - feeder (200 mm stroke), clamp (150 mm stroke, 400 N clamping force), and cutter (250 mm stroke, 800 N cutting force at 500 mm/min speed). The project requires the implementation of logical constraints to ensure that the operations occur in the correct order: the feeder must not advance unless both the clamp and cutter are fully retracted, and the cutter must not begin its stroke unless the clamp has applied sufficient clamping force. Furthermore, the system must include protection against pump power loss to ensure safe machine operation in the event of failure. The final design is developed using Matlab Simscape, with appropriate assumptions made for any missing parameters. Given below is the schematic of the preliminary design.

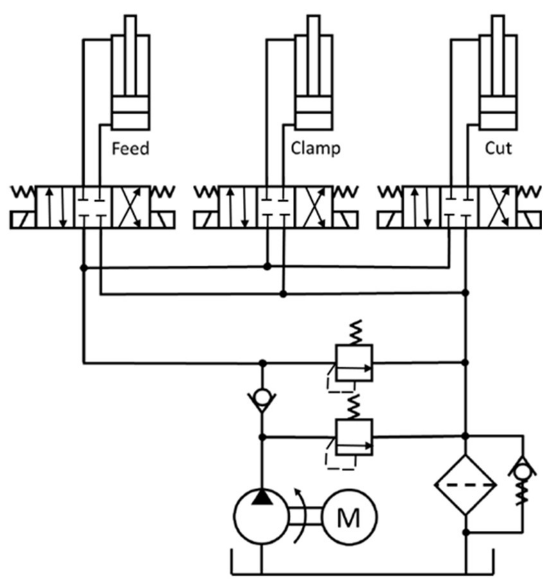

Fig. 1: Preliminary design layout of the hydraulic circuit

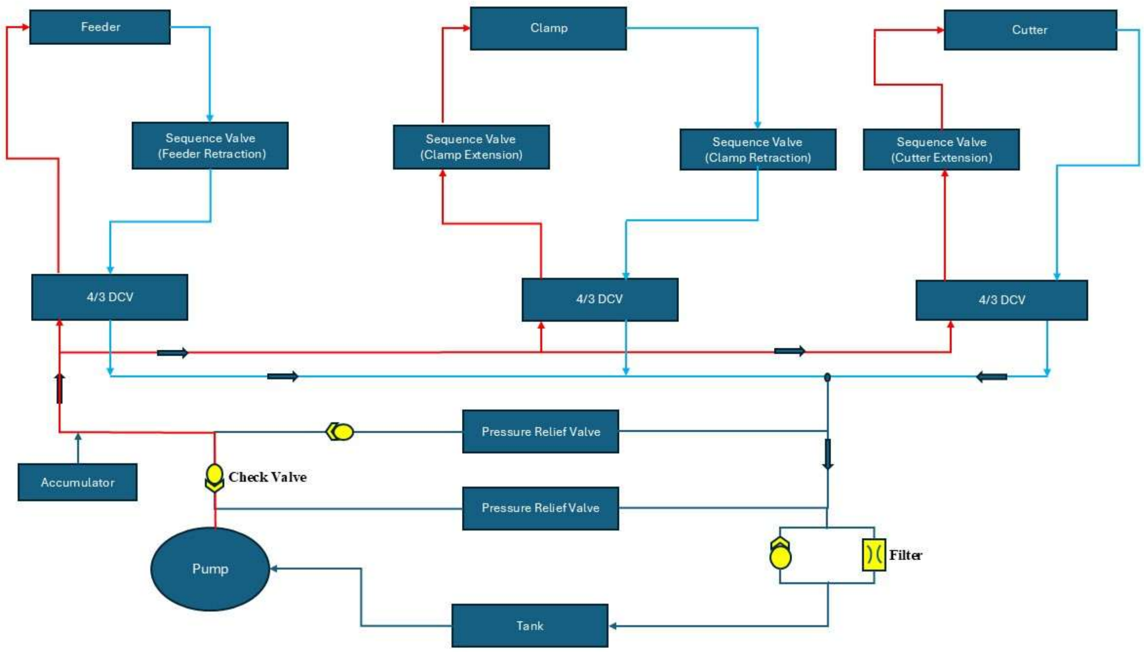

Fig. 2: Preliminary schematic for Simscape Modeling

3. Calculations

3.1. Selection of Hydraulic Cylinders

To standardize the system and ensure compatibility across all actuators, we selected the hydraulic cylinder size based on ISO standards provided in the CHSD Series catalog. The CHSD Series cylinders adhere to ISO 6020-2 standards and are designed for general-purpose industrial use [1]. Among the available options, we chose a cylinder with a **bore diameter of 40 mm** and a **rod diameter of 22 mm**. The 40 mm/22 mm sizing allows for practical stroke lengths and structural compactness while ensuring the reliability and durability of the actuators under repetitive cycling.

$$\text{Cap side area } (A_{Cap}) = \frac{\pi}{4} D^2 = 1256.64 \text{ mm}^2$$

$$\text{Rod side area } (A_{Rod}) = \frac{\pi}{4} (D^2 - d^2) = 876.90 \text{ mm}^2$$

3.2. Extension and Retraction Pressure

To ensure each actuator in the hydraulic system can deliver the required force, we calculated the theoretical operating pressure using the standard formula.

- Feeder cylinder extension pressure (PF1) = $\frac{120}{1256.6}$ N/mm^2 = 0.095496 MPa = **95.496 kPa**
- Clamp cylinder extension pressure (PC1) = $\frac{400}{1256.6}$ N/mm^2 = 0.318319 MPa = **318.32 kPa**
- Cutter cylinder extension pressure (PT1) = $\frac{800}{1256.6}$ N/mm^2 = 0.636638 MPa = **636.64 kPa**

- Feeder cylinder retraction pressure (PF2) = $\frac{120}{876.9}$ N/mm^2 = 0.136846 MPa = **136.846 kPa**
- Clamp cylinder retraction pressure (PC2) = $\frac{400}{876.9}$ N/mm^2 = 0.456152 MPa = **456.152 kPa**
- Cutter cylinder retraction pressure (PT2) = $\frac{800}{876.9}$ N/mm^2 = 0.912305 MPa = **912.305 kPa**

Theoretical cylinder pressure values were adjusted to prevent simultaneous motion, accounting for dynamic effects like pressure surges and flow sharing. Sequence valve pressures were increased accordingly. The clamp extension pressure was set to **400 kPa** to ensure the feeder fully extended before the clamp started moving. The cutter extension pressure was raised to **1100 kPa** to ensure the clamp fully engaged before cutter extension began.

Similarly, to ensure the correct retraction sequence—cutter first, followed by the clamp, and finally the feeder—the clamp and feeder retraction pressures were set significantly higher than their theoretical values. The clamp retraction pressure was adjusted to approximately twice the cutter's pressure **(1100 kPa**), while the feeder retraction pressure was set to roughly three times the cutter's pressure (**2700 kPa**). This multiplication created a sufficient pressure gap to account for system fluctuations, preventing premature movements and ensuring sequential operation.

3.3. Hydraulic Power Supply

It is given that the cutting tool cylinder must operate at a velocity of **500 mm/min**.

Therefore, Pump flow rate, $Q = Area \times Velocity = 1256.64 \times 500\ mm^3/min$

$$Q = 628320\ mm^3/min = 0.16597\ gpm = \mathbf{0.166}\ \boldsymbol{gpm}$$

3.4. Stroke Completion Time

To determine the efficiency and timing of each operation in the hydraulic system, the stroke completion time for each cylinder is calculated using the relation between stroke length and actuator velocity.

$$Time\ taken = \frac{Stroke\ Len}{Velocity}$$

- Time to reach 200 mm stroke of Feeder cylinder, t (F) = $\frac{200\ mm}{500\ mm/min}$ = 0.4 min = **24 sec**
- Time to reach 150 mm stroke of Clamp cylinder, t (C) = $\frac{150\ mm}{500\ mm/min}$ = 0.3 min = **18 sec**
- Time to reach 250 mm stroke of Cutter cylinder, t (T) = $\frac{250\ mm}{500\ mm/min}$ = 0.5 min = **30 sec**

3.5. Spring Stiffness and Damping Coefficient

To accurately simulate the dynamic response and force development in the hydraulic cylinders, it is essential to model the mechanical compliance and energy dissipation characteristics of the actuators. This is achieved by calculating the spring coefficient (which represents the elastic stiffness of the fluid column and cylinder components) and the damping coefficient (which accounts for energy losses due to fluid viscosity and flow restrictions).

- Feeder cylinder:
  - Spring stiffness, $k_{feed} = \frac{Force}{Stroke\ Len} = \frac{120}{200}$ *N/mm* = **600 N/m**
  - Damping Coefficient, $C_{feed} = \frac{Force}{velocity} = \frac{120}{0.00833}$ *Ns/m* = **14405.76 Ns/m**
- Clamp cylinder:
  - Spring stiffness, $k_{clamp} = \frac{400}{150}$ *N/mm* = **2666.66 N/m**
  - Damping Coefficient, $C_{clamp} = \frac{400}{0.00833}$ *Ns/m* = **48019.21 Ns/m**
- Cutter cylinder:
  - Spring stiffness, $k_{cutter} = \frac{800}{250}$ *N/mm* = **3200 N/m**
  - Damping Coefficient, $C_{cutter} = \frac{800}{0.00833}$ *Ns/m* = **96038.415 Ns/m**

4. Circuit Operation and Sequencing Logic

With the components in place, the hydraulic circuit is arranged as shown in the schematic. The pump draws fluid from the reservoir and feeds the pressure line, which branches to the three directional control valves parallel. The return ports of the DCVs join together back to the tank via the filter. The pressure relief valve is connected from the pressure line to tank to limit pressure. Below, describes the operation sequence and how the circuit logic ensures the required order of events:

1) **Initial State** (All Cylinders Retracted): At the start of a cycle, the feeder, clamp, and cutter cylinders are all fully retracted. In this state, all 3 DCVs are in their center neutral position.
2) **Workpiece Feeding:** The cycle begins with feeding a new workpiece. Feeder DCV is shifted to its forward position by energizing its solenoid using the pulse generator. This directs pump flow to the feeder cylinder, causing it to extend its 200 mm stroke and push a workpiece into the machining position. During this motion, the clamp and cutter remain retracted. Once the feeder extends and positions the workpiece, the feeder cylinder is held extended.
3) **Clamping the Workpiece:** Now the clamp cylinder is actuated via a sequence valve which open when it reaches the pressure of **400 kPa**. The clamp cylinder extends its 150 mm stroke and presses the workpiece, applying a clamping force. The clamp will stop moving when it contacts the workpiece and builds up pressure. The sequence valve in the cutter line is still closed at this time since it is set at a greater pressure that clamp, so all pump flow goes into clamping. The logic condition *"cutter should not advance unless clamping force is met"* is inherently satisfied by the sequence valve.
4) **Cutting Operation:** As soon as clamp force is achieved, pressure get build up and the sequence valve at the cutter cylinder gets open when it reaches the set pressure of **1100 kPa**, pushing the cutting tool forward for its 250 mm cutting stroke. The cutter cylinder extends at the desired feed rate (500 mm/min). If the cutting force turns out to require

higher pressure, then both clamp and cutter will simply be at that higher pressure – the clamp will clamp even harder, which is safe in our design as the structure can handle it.

5) **Cutter Retracts:** After the cutting operation is complete, the cutter must retract. During the negative pulse cycle, the DCVs will switch into the reverse position. This connects pressure to port B, which sends oil into the rod-ends of the cylinders, and opens port A to tank for their cap-ends. Since the retraction pressure is calculated as around 912 kPa, the sequence valve at Clamp and feeder are set at a higher value, increasing in the consequent order.
6) **Clamp Retraction:** Once the cutter is fully retracted, pressure will be fed to the rod side of the clamp cylinder in order to retract it. The pressure in the sequence valve to control the clamp cylinder retraction is kept higher than the cutter retraction pressure to keep the order of retraction proper. This prevents any collision or mis-timing, satisfying the condition that the workpiece unclamping will not begin unless the other cutter is retracted.
7) **Feeder Retraction:** The retraction of the feeder cylinder is triggered only after the clamp cylinder has completely retracted. This is achieved by routing hydraulic pressure to the rod side of the feeder cylinder once the clamp has returned to its initial position. A sequence valve is employed to regulate this action, with its cracking pressure deliberately set higher than that of the clamp's return pressure. This ensures that the feeder does not begin retracting until the clamp has fully disengaged the workpiece. This control method prevents early movement of the feeder, which could otherwise cause interference or damage during part unloading. By establishing this pressure-based sequence, a smooth and reliable transition between clamp release and feeder retraction is maintained. This approach also simplifies the circuit by removing the need for electronic control elements, making it well-suited for purely hydraulic systems.

Throughout the operating cycle, the pressure relief valve functions as a safety device to protect the system from excessive pressure by channeling surplus fluid back to the tank when pressure exceeds the predefined threshold. In addition, the accumulator and check valves serve a critical role in safeguarding the system during sudden power loss or pump failure. If the pump ceases operation, the **check valve positioned at the pump outlet** stops reverse flow, effectively separating the pump from the rest of the hydraulic circuit. At the same time, the **accumulator discharges stored energy**, allowing pressure to be maintained in essential areas of the system—particularly within the clamp cylinder, which is responsible for securely holding the workpiece, even in the absence of active pump pressure. This retained pressure ensures that **clamping force is not lost**, thereby preventing unintentional release or movement of the part during a power outage.

5. Component Specification and Functions

The hydraulic system designed for the automated turning machine consists of several key components, each selected to fulfill a specific function within the circuit while ensuring performance, reliability, and safety at a **nominal operating pressure of 3500 kPa**. Below is a detailed explanation of each major component used in the system.

5.1. Hydraulic Constant Flow Rate Source

For this system, we have chosen a hydraulic constant flow rate source to initiate fluid flow throughout the circuit. This source acts as a simplified representation of a real-world hydraulic power unit comprising a pump and electric motor. This block delivers a steady and predefined volumetric flow rate into the system, regardless of downstream pressure demands. It serves as an idealized representation of a hydraulic pump, simplifying the system for simulation purposes. This approach is beneficial for early-stage analysis or when the focus is on actuator dynamics and sequencing rather than detailed pump behavior. The source is configured to provide a continuous flow sufficient to drive the three cylinders according to their speed and stroke requirements — particularly ensuring that the cutter cylinder, which operates at 500 mm/min, receives adequate flow of **0.166 gpm.**

Fig. 3: Hydraulic Pump

5.2. Pressure Relief Valve (PRV)

A pressure relief valve is installed immediately downstream of the pump to protect the system from overpressure. This valve is set to open at **1000 kPa** (1 MPa) to safely divert excess fluid back to the tank in case of flow blockage or actuator end-stroke stalling. It ensures safe operation and protects sensitive components like valves and actuators from damage.

Fig. 4: Pressure Relief Valve

5.3. Double Acting Cylinder (Feeder, Clamp and Cutter)

The system uses three double-acting hydraulic cylinders to perform sequential operations: feeding the workpiece, clamping it in place, and cutting. All cylinders are designed with a **bore diameter of 40 mm** and a **rod diameter of 22 mm**, ensuring consistent design and interchangeability. The feeder cylinder has a stroke of 200 mm, the clamp cylinder 150 mm, and the cutter cylinder 250 mm. These cylinders are selected to meet the required forces: 400 N for clamping and 800 N for cutting.

5.4. Directional Control Valves (DCVs)

The hydraulic system employs three **4-way-3-position closed-center** directional control valves (DCVs), each dedicated to controlling one of the double-acting cylinders—feeder, clamp, and cutter. These valves are a critical component in the circuit, enabling precise and independent control of actuator movement. A 4-way valve includes four ports: pressure (P), tank (T), and two actuator ports (A and B), which are connected to the cap and rod sides of the cylinders. The 3-position design provides three spool states—extend, retract, and neutral—offering greater flexibility and safety. The neutral or center position in this case follows a closed-center configuration, meaning all four ports (P, T, A, and B) are blocked when the valve is in the center position. This effectively isolates each actuator when not in use, preventing unintended motion, hydraulic drift, or energy loss. The closed-center configuration is particularly advantageous in applications where actuators must hold their position under load, such as during the clamping or cutting phases of the machine cycle.

Fig. 5: Directional Control Valve

5.5. Pulse Generator

In this system, each DCV is operated via a controlled signal, typically **a pulse input**, which toggles the valve between the extend and retract positions. A positive pulse will switch the DCV in forward direction while a negative signal makes the valve in reverse direction. The valves return to their neutral (closed) position when not actuated, ensuring that no cylinder moves unless explicitly commanded. The use of separate closed-center DCVs for each actuator allows for structured sequencing and safe operation, aligning with the system's logic that requires the feeder to extend first, followed by the clamp, and then the cutter.

5.6. Check Valve

A check valve is designed to allow hydraulic fluid to move in only one direction, effectively blocking any reverse flow. This feature is essential in most hydraulic systems to preserve pressure and ensure controlled fluid movement. In the case of this turning machine project, the check valve is installed at the pump outlet to prevent backflow when the pump stops or during a power outage. This setup plays a vital role in maintaining pressure within the clamp cylinder, ensuring the workpiece remains firmly held even when the system is no longer actively pressurized. By retaining pressure within critical parts of the circuit, the check valve contributes significantly to the system's reliability and safety under emergency conditions.

Fig. 6: Check Valve

5.7. Translational Spring-Dampers and Mass Blocks

To realistically simulate the mechanical resistance and dynamic behavior of the pistons, translational dampers are applied to each cylinder with different damping coefficients based on their roles and physical interactions. Mass blocks representing the piston and rod assembly are connected to each actuator to reflect realistic inertia effects during simulation.

5.8. Accumulator

To fulfill the requirement of protecting the system against pump power loss, an accumulator is added to the circuit. It acts as a hydraulic energy backup, supplying pressurized fluid when the pump fails. The accumulator is sized based on the fluid volume needed during cylinder retraction (0.526 L) and pre-charged to 90% of the lowest system pressure, ensuring it stays inactive during normal operation but discharges when pressure drops [2]. This setup maintains clamping force during power failure, preventing accidental part release and ensuring safe system shutdown.

5.9. Pressure Sequence Valve

To enforce correct sequencing of operations, two pressure-sequence valves are integrated into the system for extension stroke and another two for retraction stroke. One is installed in the clamp cylinder's supply line and set to open at approximately 400 kPa. It ensures the clamp cylinder only receives flow once the feeder cylinder has fully extended and system pressure rises. The second sequence valve is installed in the cutter cylinder's line and opens at around 1100 kPa, ensuring the cutter only activates once the clamp has securely engaged the workpiece. Similarly, two other sequence valve is connected to the clamp and feeder, which will set open at pressures 1800 kPa and 2700 kPa respectively during the retraction stroke.

5.10. Hydraulic Reference and Working Fluid

In this project, Skydrol LD-4 was used as the default hydraulic fluid in the Simscape model. While it is not specifically selected for its real-world properties, it provides a reliable baseline for simulating fluid behavior within the system. At the system operating temperature of 60°C, it has a viscosity of 7.12 cSt, which supports stable simulation performance.

6. SIMSCAPE Simulation and Results

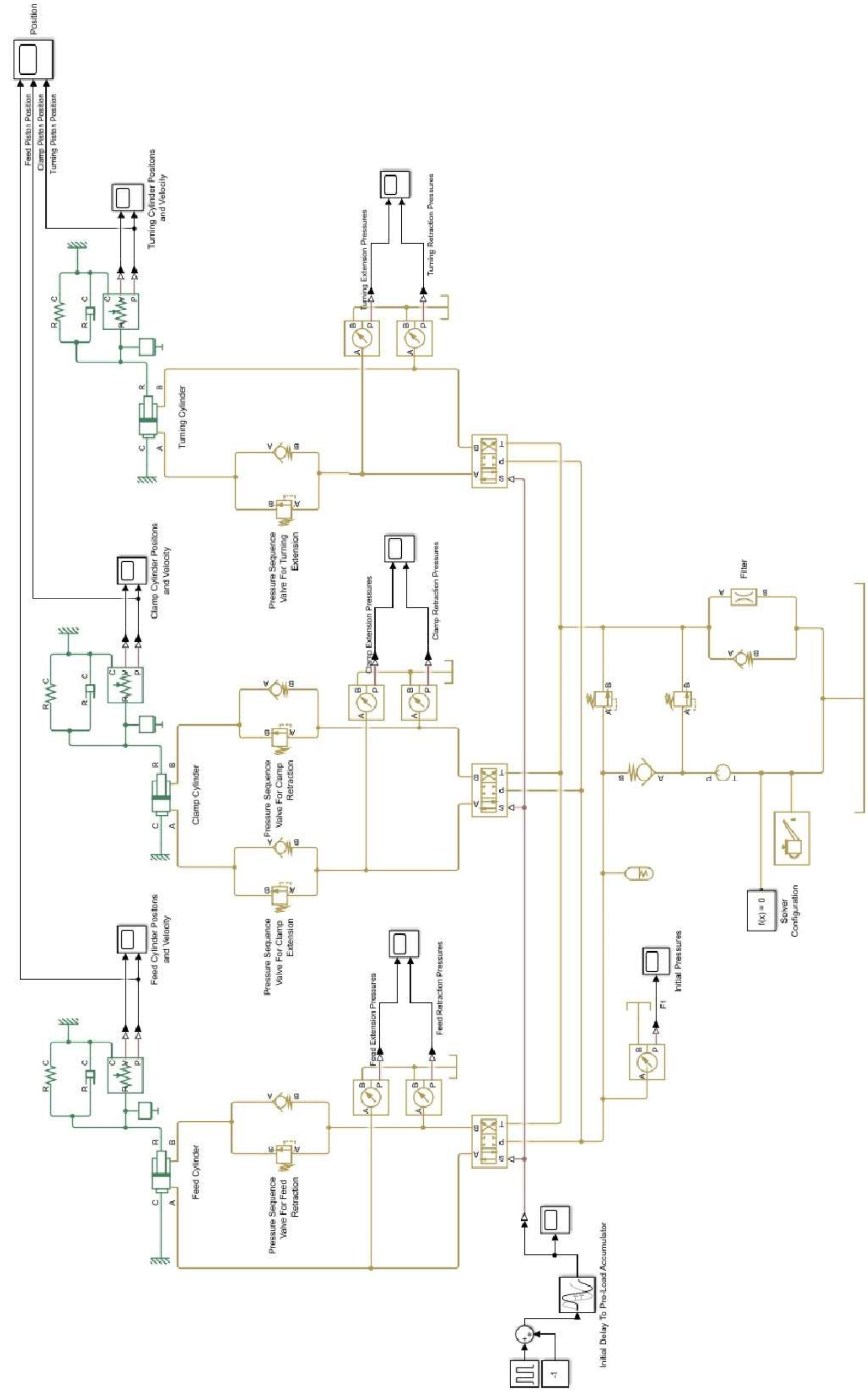

Fig. 7: Simscape Model of Automated Turning Machine

The diagram shows the Simscape hydraulic model for the automated turning machine. It includes three main actuators—feed, clamp, and cutting cylinders—each controlled by 4-way directional valves. Sequence valves ensure proper operation order: the cutter activates only after clamping, and the feeder retracts only after unclamping.

Pressure and position sensors monitor cylinder performance, while a check valve and accumulator provide protection during pump failure by maintaining clamp pressure. A relief valve limits overload, and a filter maintains fluid quality. The constant flow source represents the pump, enabling a complete simulation of system behavior and safety logic.

6.1. Graphical Results

6.1.1. Cylinder position vs time

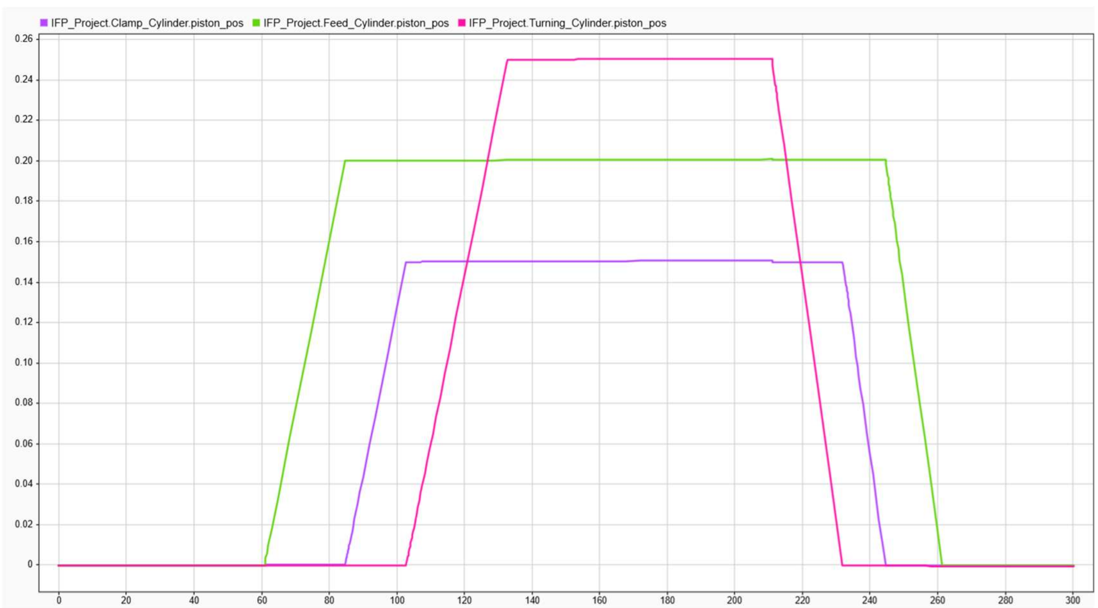

Fig. 8: Cylinder Position vs Time plot

The plot displays the simulated piston positions of the **feeder (Green)**, **clamp (Purple)**, and **cutter (Pink)** cylinders over time, highlighting the correct operation sequence.

- **Feeder Cylinder (Green):** Extends first to load the workpiece, then stays extended while clamping and cutting take place. It retracts only after both the clamp and cutter have returned—confirming proper interlocking in the control logic.
- **Clamp Cylinder (Purple):** Activates after the feeder, extends to secure the part, and holds position throughout the cutting operation. It retracts only once the cutter is fully retracted, ensuring safe part handling.
- **Cutter Cylinder (Pink):** Extends last, only after clamping is complete. It performs the cutting stroke, then retracts before the clamp releases—guaranteeing that cutting happens only when the part is securely held.

This sequence—**Feed → Clamp → Cut → Retract Cutter → Unclamp → Retract Feeder**—matches the project's functional requirements and confirms that the system behaves correctly and safely.

6.1.2. Feed cylinder behaviour

In the spring setup, the feed cylinder force increased smoothly, reaching approximately 120 N. The velocity profile was gradual and smooth without sharp spikes, and the displacement reached around 0.2 meters before returning.

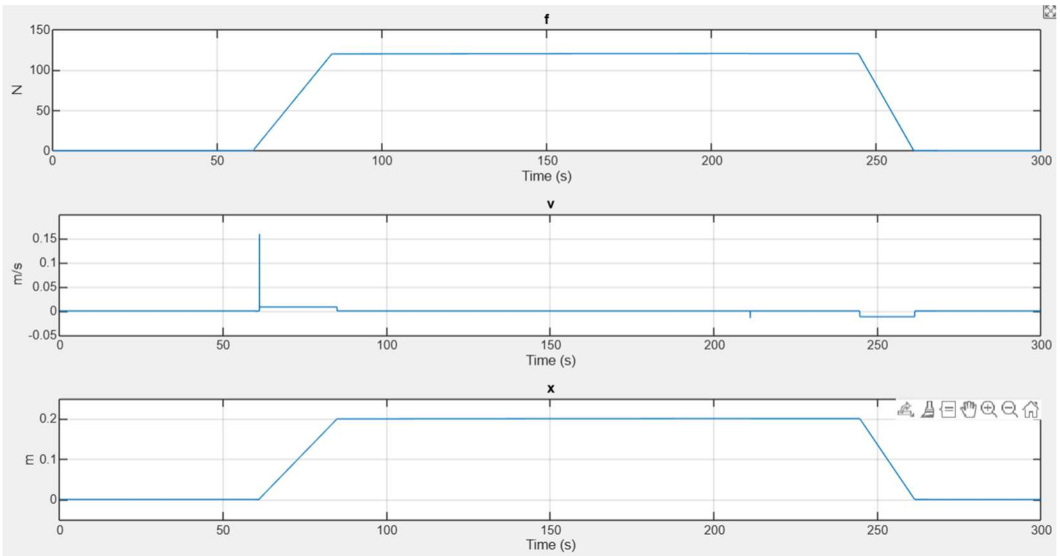

Fig. 9: Force, velocity & Displacement vs Time Plot of Feed Cylinder

6.1.2. Clamp cylinder behavior

In the spring configuration, the clamp cylinder exhibited a gradual force rise up to about 400 N. The velocity profile showed a steady and smooth motion during the clamping phase.

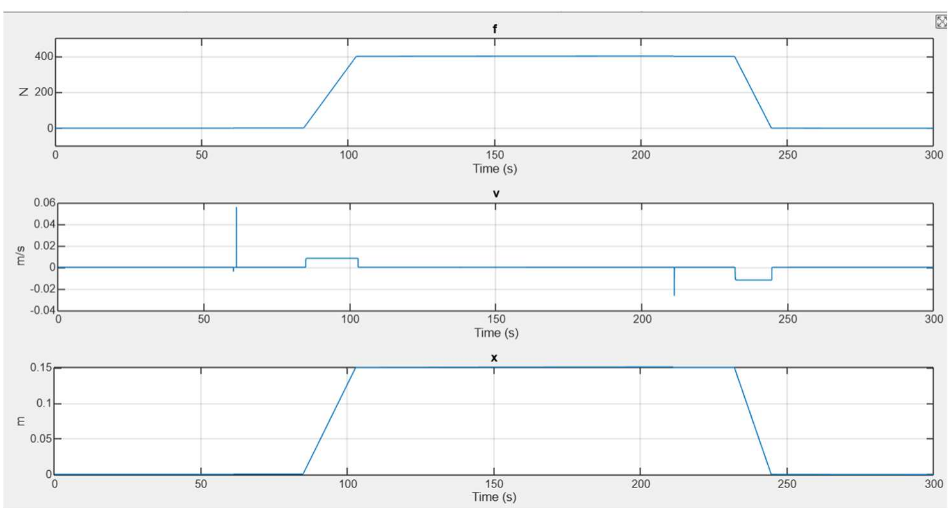

Fig. 10: Force, velocity & Displacement vs Time Plot of Clamp Cylinder

6.1.3. Turning cylinder (Cutter) behavior

Under the spring setup, the turning cylinder force increased gradually up to about 1000 N. The velocity stayed steady and low (~0.02 m/s) throughout the motion, and the displacement followed a smooth ramp-up and return.

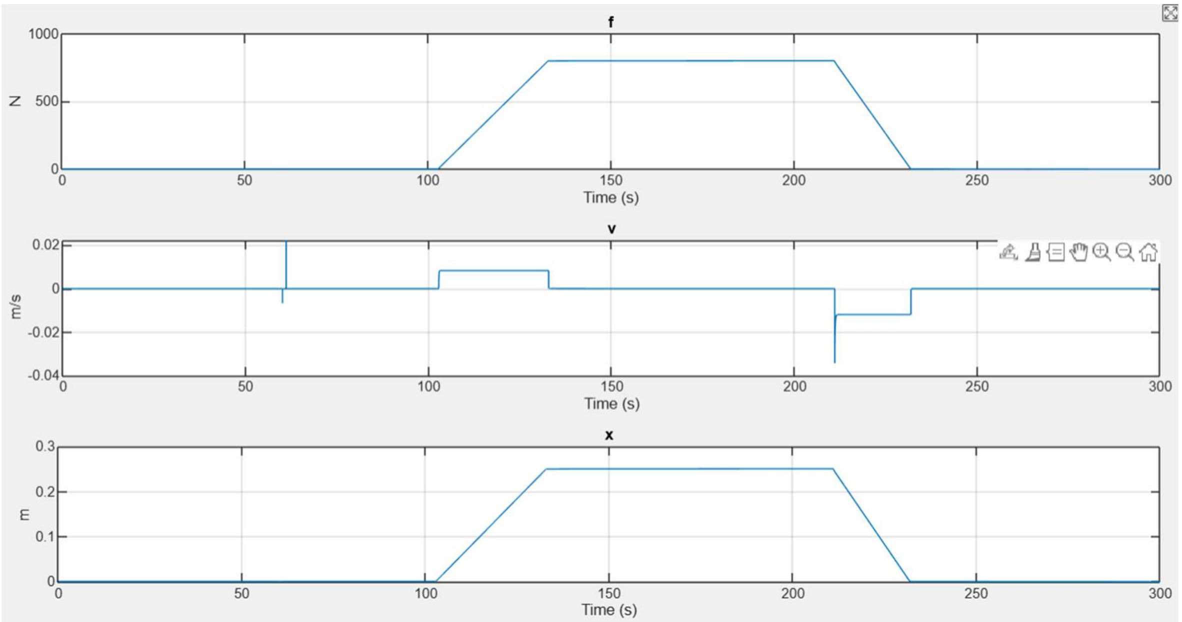

Fig. 11: Force, velocity & Displacement vs Time Plot of Turning Cylinder

6.1.4. Force vs Time Plot

The force versus time plot validates the correct operation and sequencing of the hydraulic actuators in the automated turning machine. Initially, all cylinders are inactive, with zero force. The feed cylinder (blue curve) activates first, gradually reaching a stable force of around 120 N, indicating the successful positioning of the workpiece.

Following this, the clamp cylinder (yellow curve) builds up force smoothly to approximately 400 N, confirming that clamping begins only after the feeder is extended, satisfying the required interlock. The clamp maintains this holding force steadily throughout the cutting phase.

Once the clamp is fully engaged, the turning (cutter) cylinder (red curve) engages, rising sharply to about 800 N. The cutter holds this force during its stroke, providing the necessary cutting load, and then retracts, with its force dropping back to zero. Subsequently, the clamp and feeder forces decrease sequentially, reflecting the correct and safe retraction order.

The smooth rise and fall of forces across all cylinders highlight the effectiveness of using spring elements, ensuring gradual force application and minimizing system shocks. The plot confirms that the sequence Feeding → Clamping → Cutting → Cutter Retraction → Clamp Retraction → Feeder Retraction is properly achieved, meeting all functional requirements set for the project.

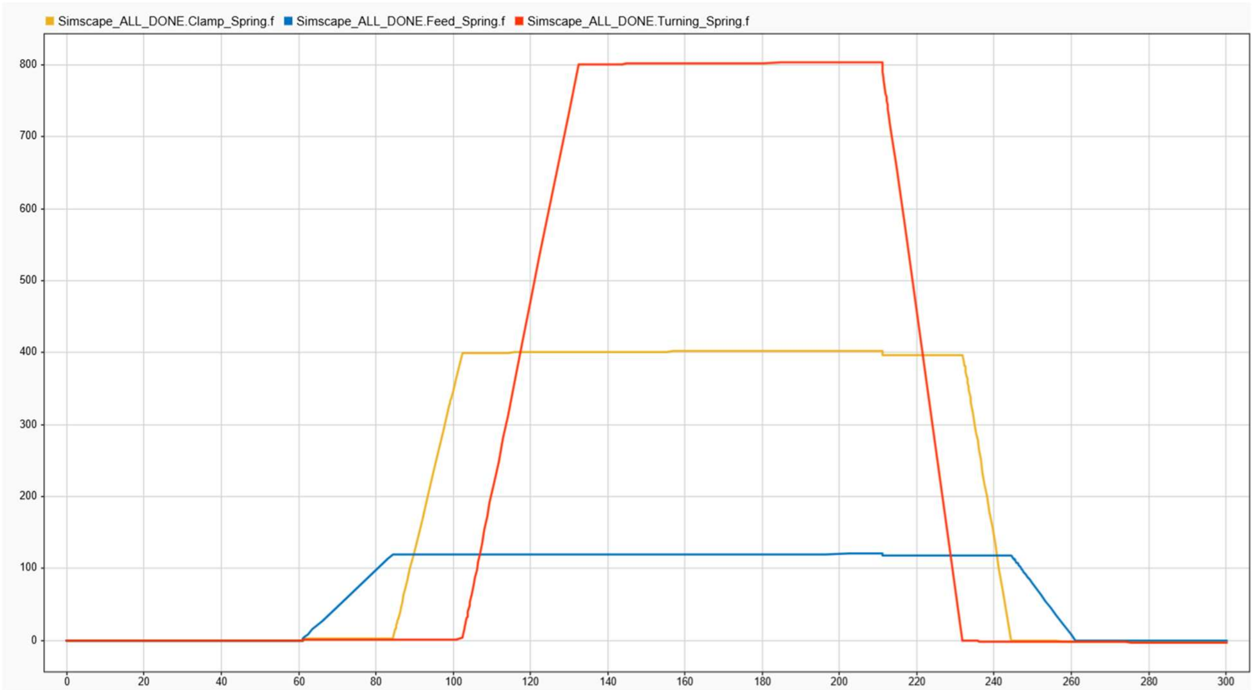

Fig. 12: Force vs Time plot for 3 Cylinders

7. Further Discussion and Analysis

The simulation outcomes verify that the hydraulic circuit effectively fulfilled the functional objectives set for the automated turning machine. The sequential movement of the feeder, clamp, and cutter cylinders occurred precisely as designed, ensuring both safe and reliable system behavior. The feeder cylinder extended first to position the workpiece, remained extended throughout the clamping and cutting stages, and retracted only after the clamp and cutter had fully returned to their initial positions. The clamp cylinder followed next, securing the workpiece during machining and retracting only after the cutter returned. The cutter cylinder extended strictly after clamping was completed and retracted before the clamp released, ensuring the workpiece was always held securely during the cutting process.

The behavior of force and velocity, as observed in the simulation graphs, further supports the circuit's correct operation. Under damping conditions, the actuators displayed fast, firm responses, while the spring-based configuration produced smoother and more stable motion, demonstrating controlled force buildup. These findings confirm that the implemented pressure sequencing, directional control, and safety components functioned as intended under simulated conditions.

Though the system performed as required, several areas offer scope for refinement. Adjusting the spring stiffness and damping values could lead to improved smoothness during transitions, especially under high-speed operations. Additionally, revisiting the accumulator size and pre-charge pressure could enhance performance under sudden pump loss. Incorporating adaptive or feedback-based control methods could further strengthen system reliability under dynamic load changes.

Thus, the simulation results confirm that the hydraulic circuit design meets all operational and safety requirements. It provides a reliable baseline solution with the flexibility for future improvements to boost performance and responsiveness.

7.1. Pressure Retention and System Protection during Pump Shutdown

The hydraulic system is equipped with an effective pressure retention and protection mechanism to maintain safe operation during a pump shutdown. The design incorporates a spring-loaded accumulator, a check valve, and a pressure relief valve to ensure that critical operations are preserved without interruption.

The accumulator stores hydraulic energy during normal machine operation and automatically supplies pressurized fluid when the pump is no longer active. This stored pressure keeps the clamp cylinder engaged, ensuring that the workpiece remains securely held in place throughout the shutdown period. The check valve installed at the pump outlet prevents backflow, isolating the system and maintaining pressure integrity within the critical circuits.

Additionally, the pressure relief valve safeguards the system by diverting excess pressure back to the reservoir during normal operation, protecting components from potential overpressure scenarios.

Together, these components enhance the system's robustness by preserving essential holding forces, preventing unintended movements, and ensuring operational safety even when the pump is not delivering flow. This design approach ensures that the hydraulic circuit remains reliable, safe, and aligned with the functional requirements of the automated turning machine.

8. Conclusion

The design and simulation of the hydraulic circuit for the automated turning machine successfully fulfilled the functional requirements and safety objectives outlined for the project. The circuit effectively coordinated the actions of the **feeder**, **clamp**, and **cutter cylinders**, maintaining the correct operational sequence through carefully configured **pressure sequencing** and **valve control logic**.

Essential mechanisms which were included as the **additional components**—such as the **check valves**, **accumulator**, **sequence valves** and **pressure relief valves**—were integrated into the system to enhance reliability. These components ensured **pressure retention**, safeguarded against overpressure, and maintained critical clamping force during power or pump failures, contributing to a stable and secure system response.

Simulation outputs confirmed that the actuators responded accurately, with well-regulated motion and force profiles. The use of **spring-damper elements** enabled smooth transitions and minimized system shocks, reflecting a realistic dynamic behavior suitable for industrial automation scenarios.

In summary, the hydraulic system meets all required performance criteria, ensuring precise motion control and safe operation. The design offers a solid and reliable foundation, with room for future refinements in responsiveness, efficiency, and advanced control if needed.

Reference

[1] SMC Corporation, "ISO standard hydraulic cylinder." [Online]. Available: https://www.smcpneumatics.com/pdfs/CHSD_CHSG.pdf (Accessed March 27 2025.)

[2] Flodraulic Group Inc., "Common terminology between fluid power and electronics," Apr. 29, 2024. [Online]. Available: https://flodraulic.com/resources/tech-tips/where-and-how-to-apply-hydraulic-accumulators/ (Accessed March 27 2025.)