DESIGN AND DEVELOPMENT OF DIGITAL HYDRAULIC VALVE SYSTEM IN A HYDROSTATIC SYSTEM

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For the partial fulfillment of the degree of

BACHELOR OF TECHNOLOGY

Supervisor: Prof. Jayanta Das

CERTIFICATE

This is to certify that the thesis titled "Design & development of digital hydraulic valve system in a hydrostatic system" being submitted by Ms. Muskan (Admission no: 20JE0593), Mr. Prashant (Admission no: 20JE0712), and Mr. T Sharath Chandrahas Reddy (Admission no: 20JE 1011) for the award of the degree of Bachelor of Technology in the Department of Mechanical Engineering of Indian Institute of Technology (Indian School of Mines), Dhanbad is a record of bonafide research work carried out by they/them under my supervision. In my opinion, the thesis is worthy of consideration for the award of the degree of Bachelor of Technology in accordance with the regulations of the institute. The results presented in the thesis have not been submitted to any other university or institute for the award of any degree.

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Date:

DECLARATION

We hereby declare that the work being presented in this dissertation entitled "Design & development of digital hydraulic valve system in a hydrostatic system," in partial fulfillment of the requirements for the award of the degree of B.Tech in Mining Machinery Engineering, is an authentic record of our own work carried out during the period from August 2023 to May 2024 under the supervision of Prof. Jayanta Das, Department of Mechanical Engineering, Indian Institute of Technology (ISM) Dhanbad, Jharkhand, India.

We acknowledge that we have read and understood the UGC (Promotion of Academic Integrity and Prevention of Plagiarism in Higher Educational Institutions) Regulations, 2018. These Regulations were published in the Indian Official Gazette on 31st July 2018.

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We further declare that no portion of the dissertation or its data will be published without the Institute's or Guide's permission. We have not previously applied for any other degree or award using the topics and findings described in my dissertation.

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Date: 8 May 2024

Abstract

This thesis investigates a novel approach in hydraulic systems termed ***digital hydraulics***. Unlike traditional proportional valves, digital hydraulics employ multiple, readily available, on/off solenoid valves connected in parallel. These solenoid valves, often referred to as ***digital valves*** exhibit fast switching times and minimal leakage due to their poppet design. This design eliminates the need for continuous pump operation, leading to a significant reduction in energy consumption.

Furthermore, digital hydraulics utilizes a smaller hydraulic power unit (HPU) situated on the machine floor, eliminating the requirement for extensive piping installations from remote basements. This not only reduces initial investment costs but also simplifies system maintenance. Additionally, the mass production of digital valves makes them considerably cheaper than proportional valves, further lowering initial and spare part costs.

Digital hydraulics boasts an inherent fault tolerance mechanism. In the event of a single digital valve failure, the remaining valves can automatically reconfigure their operation, ensuring minimal performance degradation. This stands in stark contrast to proportional valve failure, which typically brings the entire process to a halt and can potentially cause damage to roll covers due to uncontrolled pressure surges.

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Chapter 1: Introduction

This thesis investigates the potential of digital hydraulics, a promising alternative to traditional proportional directional control valves (DCVs). Proportional DCVs are widely used across industries for precise flow control in hydraulic systems, enabling tasks like:

- *Machine tool control*: Regulating cutting force and speed for accurate machining in the automotive and aerospace industries.
- *Construction equipment operation*: Smoothly actuating booms and buckets on excavators and cranes.
- *Robotic arm movements*: Mimicking human motion for intricate tasks in manufacturing and assembly lines.

However, proportional DCVs suffer from limitations like complexity, high energy consumption due to continuous pump operation, and potential leakage. Digital hydraulics offers a compelling solution by replacing them with multiple, readily available, on/off solenoid valves. These "*digital valves*" boast faster switching times, minimal leakage, and inherent fault tolerance, leading to significant advantages:

- *Enhanced reliability*: Automatic reconfiguration upon digital valve failure minimizes downtime and maintenance needs.
- *Reduced energy consumption*: The elimination of continuous pump operation leads to substantial energy savings.
- *Lower costs*: Smaller on-machine HPUs, simpler piping, and mass-produced digital valves drastically reduce initial investment and ongoing maintenance expenses.
- *Potential for improved precision*: In some applications, digital hydraulics might even surpass proportional DCVs in terms of control accuracy.

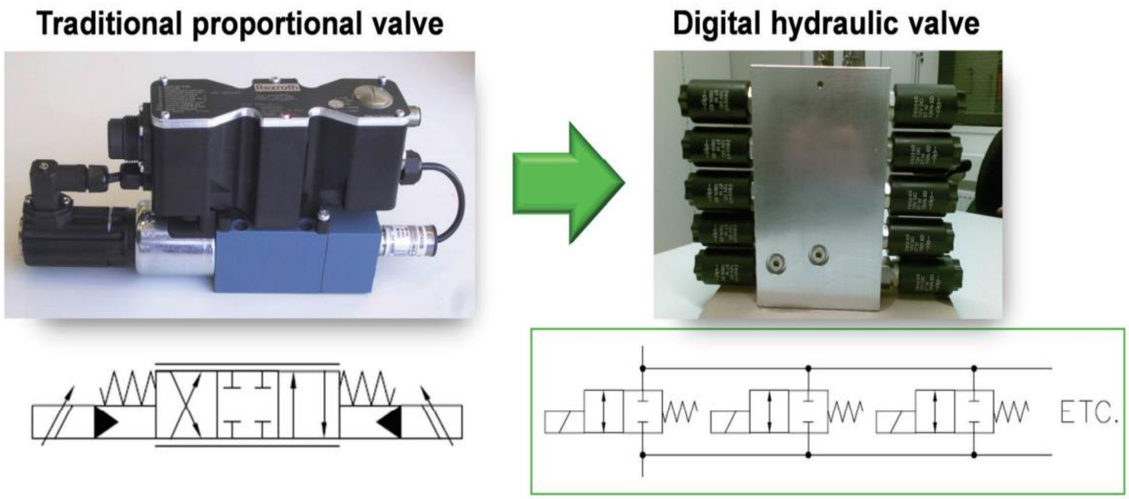

fig. 1.a. Photo and hydraulic symbol of a traditional proportional DCV (left) and a digital hydraulic valve (right)

1.1 Introduction to Proportional DCV

A proportional solenoid control valve is utilized to regulate fluid flow by altering the size of the flow passage via a restrictor. This controlled flow rate subsequently adjusts crucial parameters affecting the system's process, such as level, pressure, and temperature. Additional minor parameters encompass weight, thickness, humidity, density, pH, color, and viscosity.

In an automated control valve configuration, the restrictor is governed by a signal from an actuator controller. In the instance of a proportional control solenoid valve, a solenoid acts as the actuator, facilitating variable positioning of the valve.

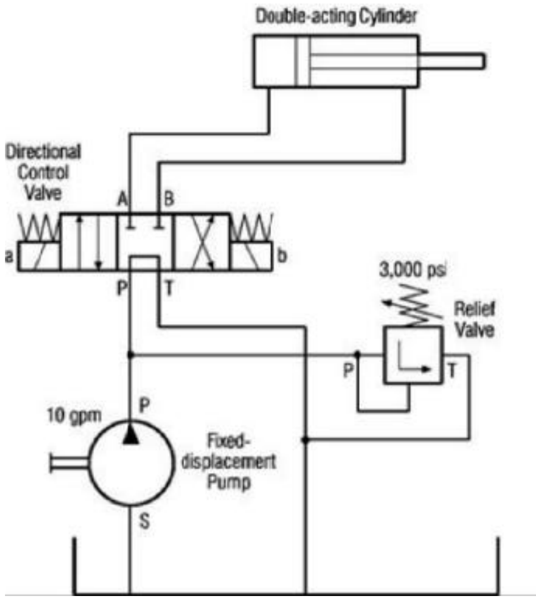

fig. 1.b. Hydraulic circuit with proportional DCV

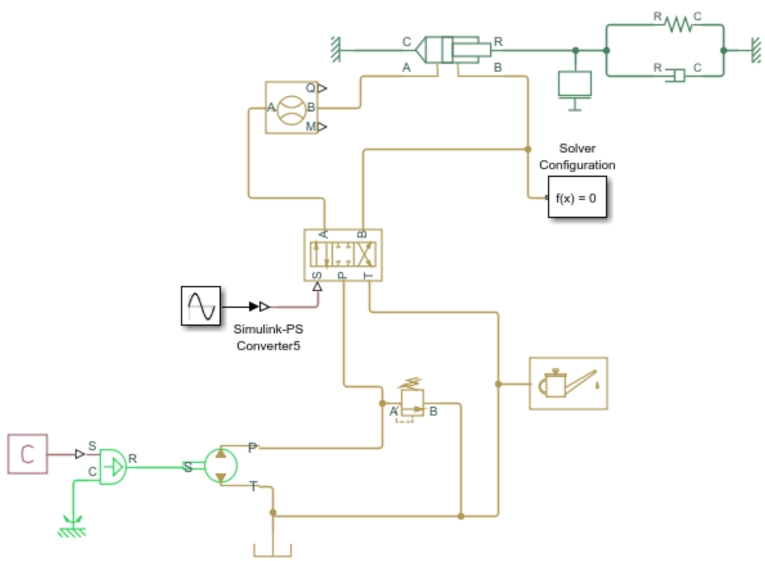

fig. 1.c. Hydraulic circuit with proportional DCV in MATLAB Simulink

1.2 Introduction to Digital Hydraulic Valves

Digital hydraulic valves differ from traditional ones in that they control fluid flow using binary logic—entirely on or off—instead of continuously modulating it. This allows them to create various flow patterns by combining multiple valves. They're managed by electronic signals that can be customized to suit system needs.

These valves open or close small orifices using solenoids or piezoelectric actuators. By arranging these orifices in different configurations, the valve can control flow rates and pressures precisely and swiftly. Electronic signals generated by microcontrollers or digital signal processors dictate the switching process, optimizing system performance.

Digital hydraulic valves offer enhanced efficiency, accuracy, reliability, and adaptability compared to conventional valves. They minimize energy losses and provide finer resolution and quicker responses. With fewer moving parts, they require less maintenance and boast longer lifespans. Moreover, their flexibility allows them to adapt to diverse applications and conditions and can be integrated with other components to form intelligent hydraulic systems.

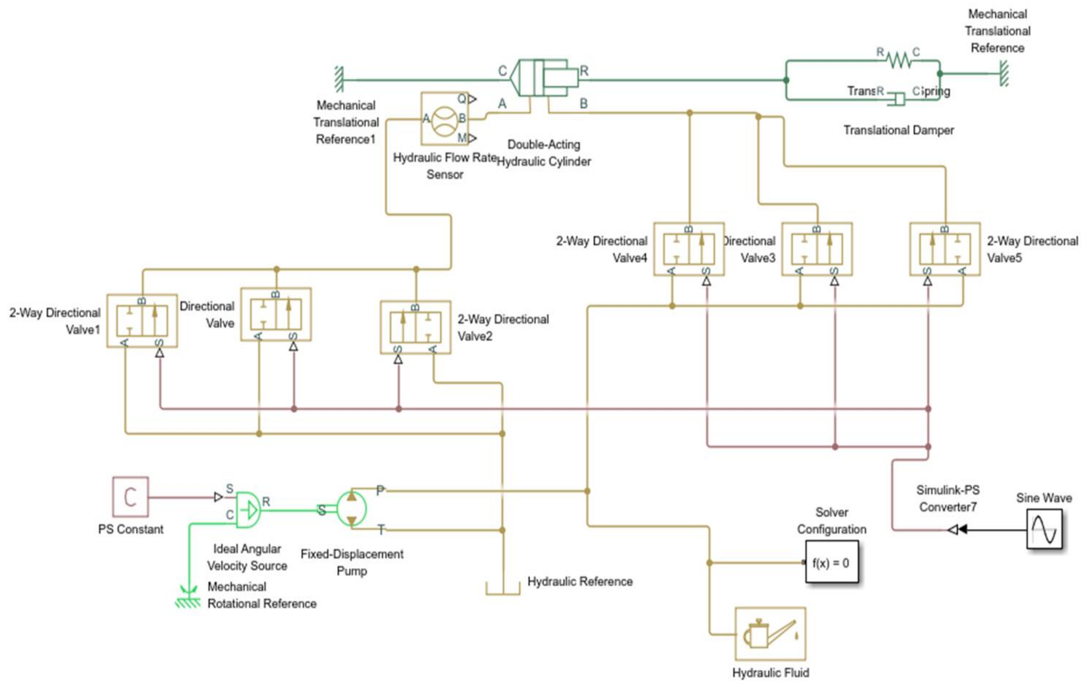

fig. 1.d. Hydraulic circuit containing 6 digital valves

Chapter 2: PID-controlled DCV

2.1. Proportional Integral Derivative (PID) Controller

Proportional Integral Derivative (PID) controller is a widely used and versatile feedback control method that plays a significant role in hydraulic systems. It offers a robust and effective way to manage the behavior of actuators or other controlled variables. Here's a breakdown of its core principles:

- *Proportional (P) Control:* Responds directly to the current error (difference between desired and actual value). Larger errors lead to larger control signals to correct the behavior.
- *Integral (I) Control:* Addresses steady-state errors by accumulating the error over time. This ensures the system eventually reaches the desired setpoint even if the P term alone cannot completely eliminate the error.
- Derivative (D) Control: It forecasts future errors by examining the error signal's rate of change. This aids in reducing overshoot and enhancing response time.

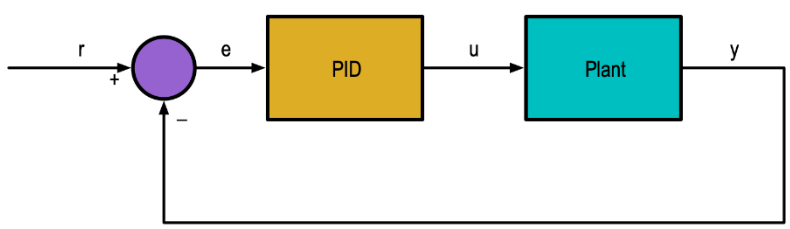

fig. 2.a. Block diagram of PID

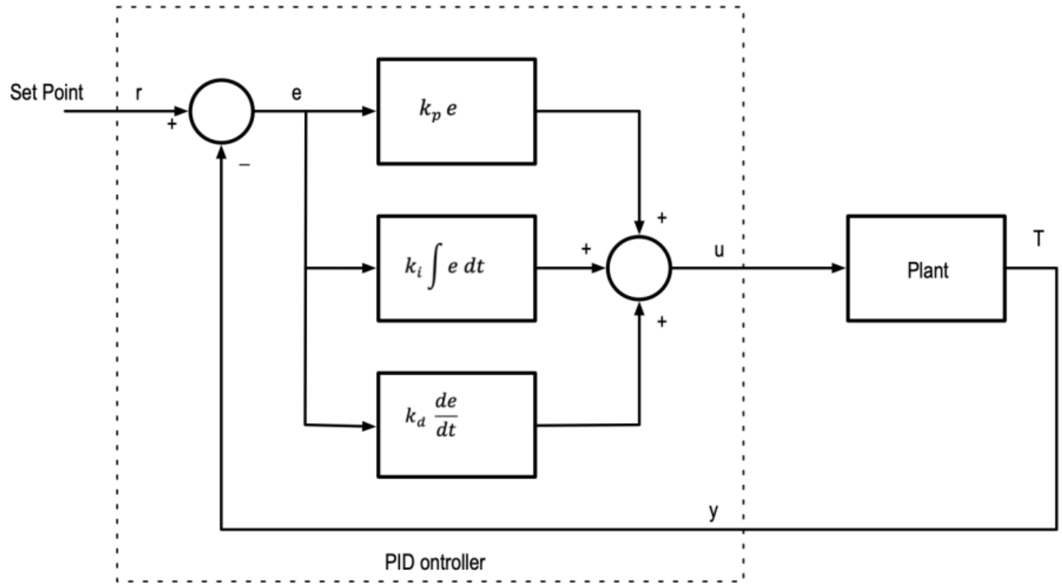

fig. 2.b. Detailed block diagram of PID. The proportional, integral and derivative terms are calculated separately and added together to create the output signal.

Benefits of PID Control in Hydraulics:

- *Versatility:* Applicable to a wide range of hydraulic systems and control tasks.
- *Simplicity:* Relatively simple to implement and understand compared to more complex control algorithms.
- *Effectiveness:* Provides good control performance with minimal tuning effort in many cases.
- *Robustness:* Handles variations in system parameters and external disturbances effectively.

The effectiveness of PID control relies on proper tuning of its three parameters (P, I, D). Tuning involves adjusting these parameters to achieve the desired system response characteristics, such as:

- Rise time: Time taken by system's output to reach the desired set point.

- Settling time: Time taken for system's output to reach and stay within a specific range of the desired value.
- Overshoot: The amount by which the system output exceeds the desired value.

2.2. Method used for tuning PID

In this project, we used the Ziegler-Nichols Method to tune our PID controller. It is a widely used technique for obtaining initial tuning parameters for proportional-integral-derivative (PID) controllers. This method leverages the concept of the system's ultimate gain (Ku) and ultimate period (Pu) to determine the PID controller coefficients (Kp, Ti, and Td).

2.3. DCV controlled by PID for constant demand

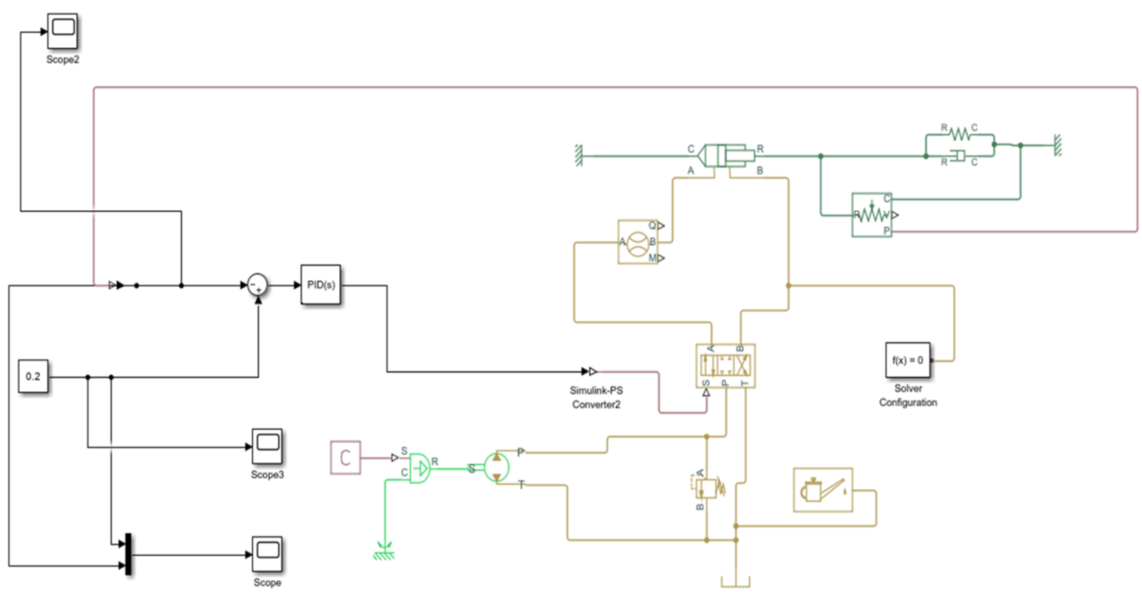

fig. 2.c. Hydraulic circuit with DCV controlled by a PID

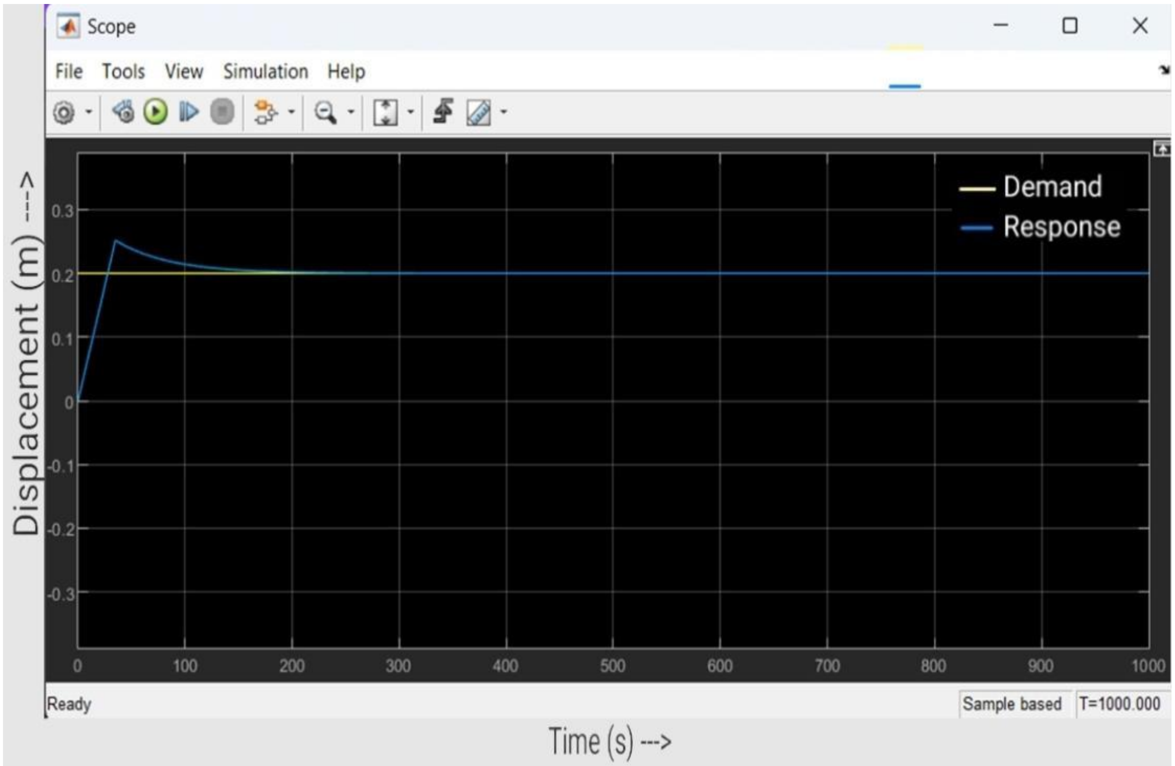

fig. 2.d. Displacement v/s time graph of the actuator, where the yellow curve denotes demand, and the blue curve denotes the response

This scenario exhibits an initial overshoot in the system's response. The actuator position momentarily exceeds the target value (0.2 m) before settling at the desired setpoint. This overshoot can be attributed to factors such as the dynamics of the hydraulic system and the control strategy employed.

2.4. DCV controlled by PID controller at sine wave demand

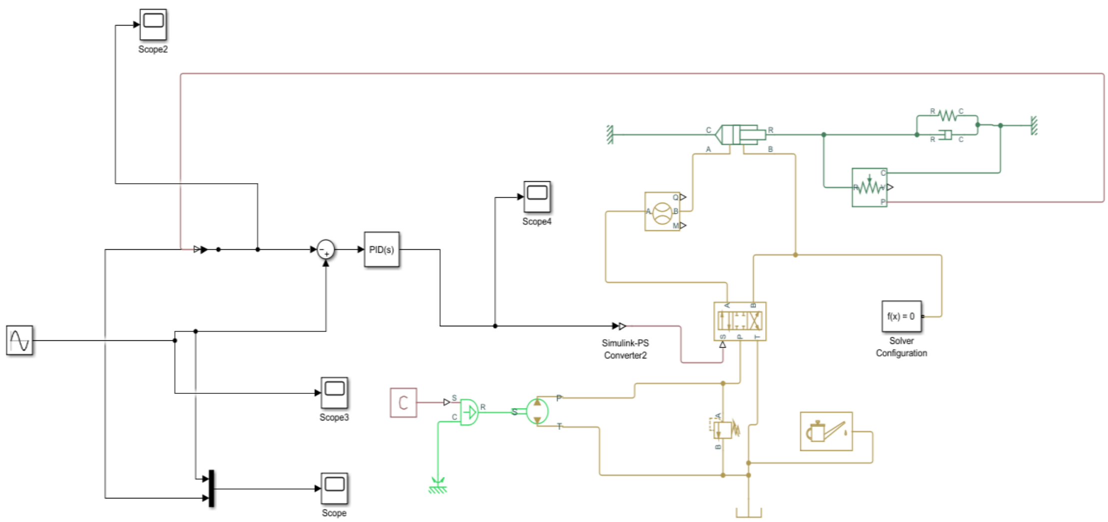

fig. 2.e. Hydraulic circuit with DCV, PID and sine wave demand

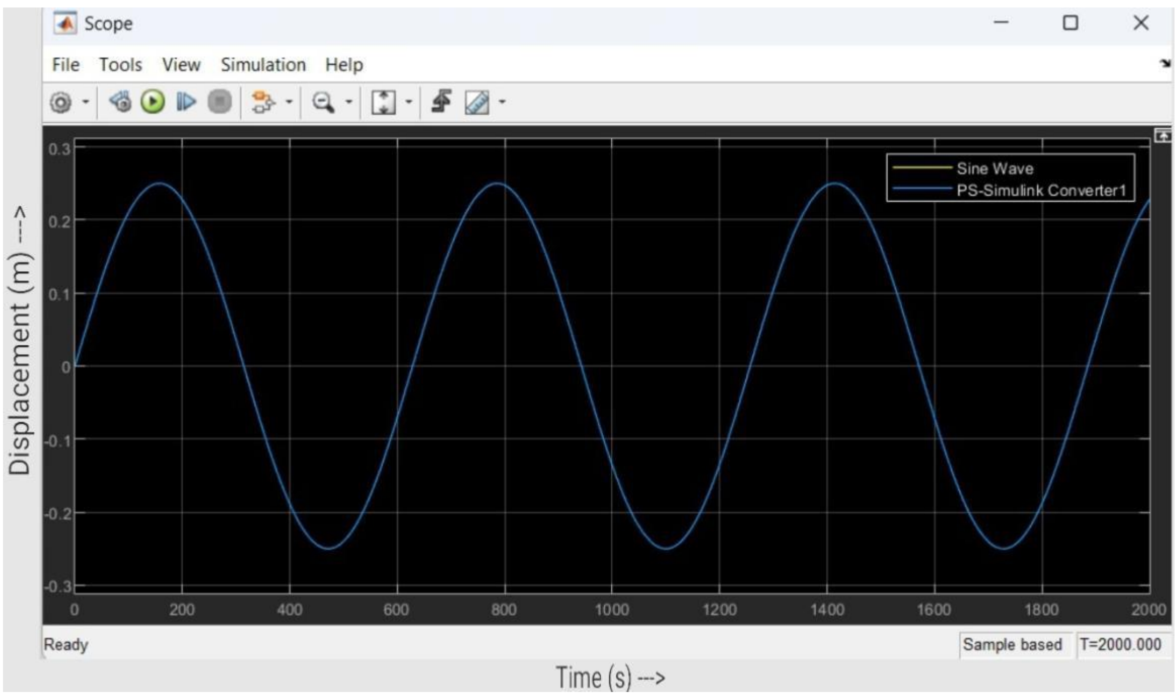

fig. 2.f. Displacement v/s time graph (yellow curve for demand; blue curve for response)

Chapter 3: Control strategies for digital valves

3.1. Digital valve control with look-up tables

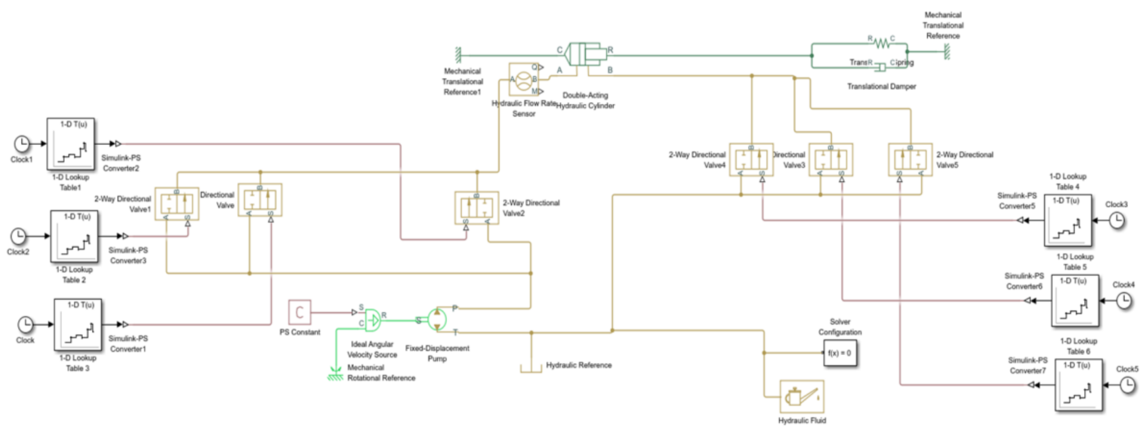

fig. 3.a. Hydraulic circuit containing 6 digital valves along with 6 look-up tables

This chapter explores a control strategy for individual valves within the Simulink environment. This method utilizes lookup tables and pre-defined datasets that map desired valve opening and closing times to corresponding control signals.

Within Simulink, these lookup tables are integrated into the control logic for each valve. This allows for precise control over valve behavior based on the pre-defined time profiles.

Three distinct control scenarios are investigated. The corresponding lookup tables and the resulting graphical representations of valve behavior obtained from Simulink simulations are presented in the following sections.

Case: 1

The initial system configuration is established with all inlet valves closed and all return valves open. This configuration minimizes any potential fluid flow except for a minimal leakage that may occur across closed valves. This approach ensures the system starts in a predictable, controlled state with minimal leakage flow.

Inlet Valve	Inlet Valve Opening Time (s)	Return Valve	Return Valve Closing Time (s)
Valve 1	remains closed	Valve 4	remains open
Valve 2	remains closed	Valve 5	remains open
Valve 3	remains closed	Valve 6	remains open

(table 1)

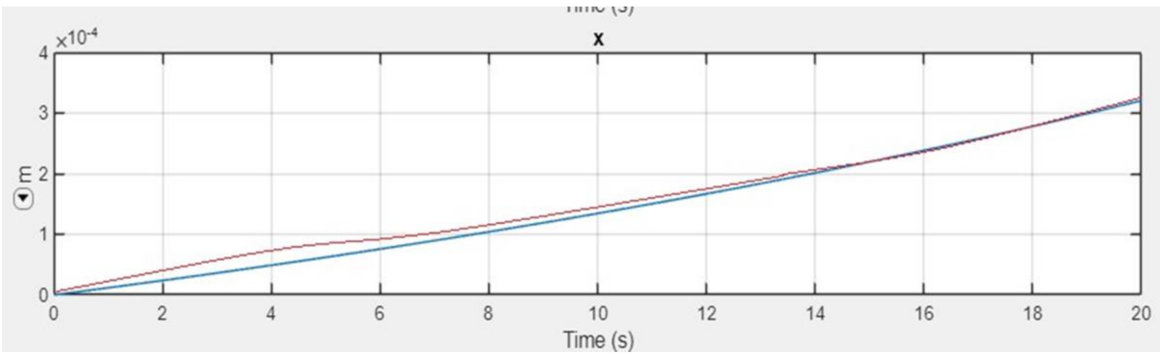

fig. 3.b. Displacement-time graph

The displacement-time graph depicts two curves: the red curve represents the characteristics of a proportional DCV, while the blue curve illustrates the characteristics observed using multiple digital valves.

Case: 2

Inlet Valve	Inlet Valve Opening Time (s)	Return Valve	Return Valve Closing Time (s)
Valve 1	5 s	Valve 4	remains open
Valve 2	10 s	Valve 5	remains open
Valve 3	15 s	Valve 6	remains open

(table 2)

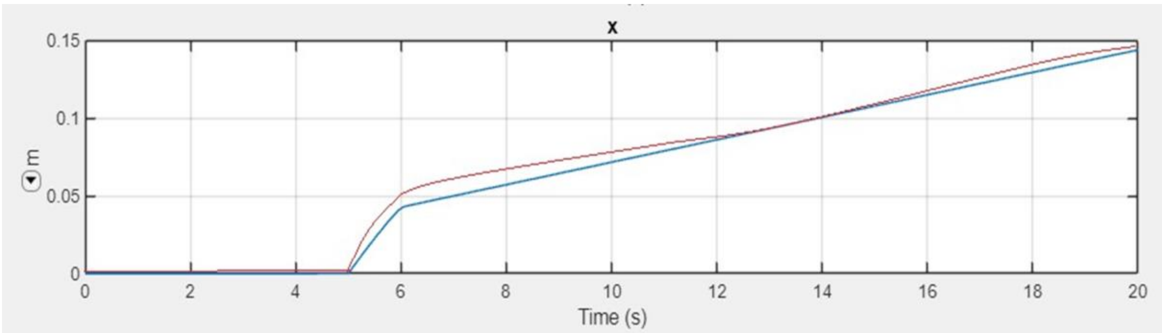

fig. 3.c. Displacement-time graph

Case: 3

Inlet Valve	**Inlet Valve Opening Time (s)**	**Return Valve**	**Return Valve Closing Time (s)**
Valve 1	5 s	Valve 4	5 s
Valve 2	10 s	Valve 5	10 s
Valve 3	15 s	Valve 6	15 s

(table 3)

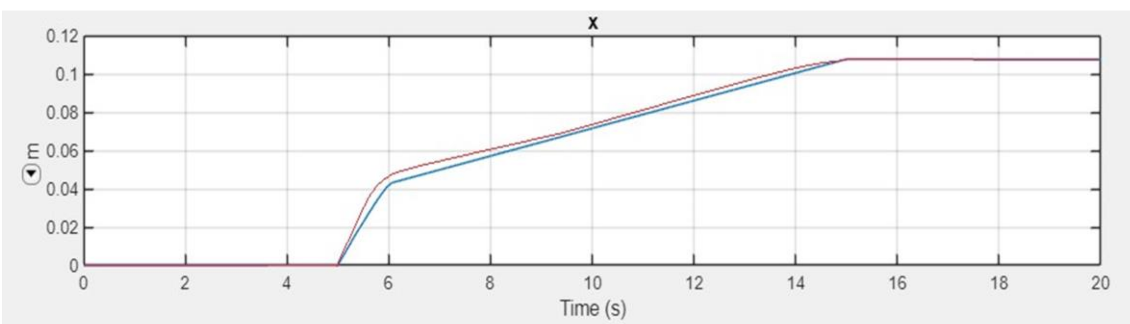

fig. 3.d. Displacement-time graph

By adjusting the opening and closing times of individual digital valves, we can effectively modulate the overall flow signal (*blue curve*) delivered to the actuator. This approach allows us to achieve control characteristics similar to those of a proportional DCV (*red curve*). Notably, the accuracy can be further refined by increasing the number of digital valves employed within the circuit. This offers a crucial advantage – the ability to tailor the level of precision to the specific needs of the application. With more valves, we can achieve finer control over the flow profile.

This finding highlights the potential of digital valves to replicate the functionality of proportional DCVs while offering additional benefits like simpler design and potentially lower costs.

3.2. Digital valve control using S-function

While the previous method achieved the desired results, it relied on controlling each valve individually. This approach can become tedious and cumbersome for complex systems with numerous valves. To address this limitation and introduce a more intelligent control strategy, we have transitioned to utilizing an S-function within Simulink.

An S-function is a powerful tool that allows us to integrate custom code directly into the Simulink environment. In this case, the S-function acts as an automated control module. It receives a single demand value as input and calculates the appropriate opening and closing signals for all the valves within the system. This eliminates the need for manual individual valve control, streamlining the process and making it more scalable. For our purpose, we are using the "*level-2 S-function*" feature of Matlab Simulink.

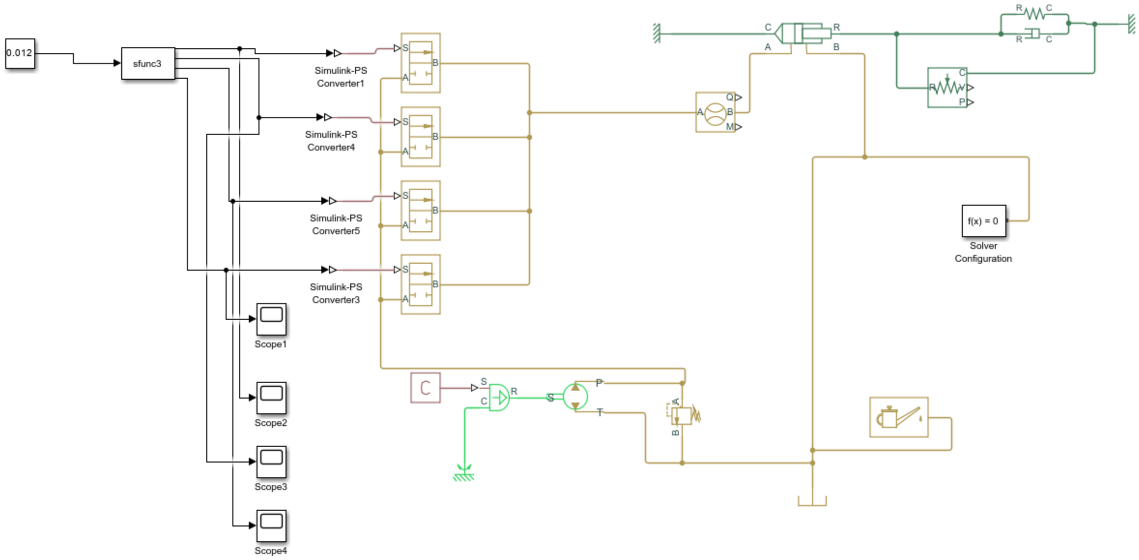

fig. 3.e. Hydraulic circuit containing 4 digital valves and level 2 S-function

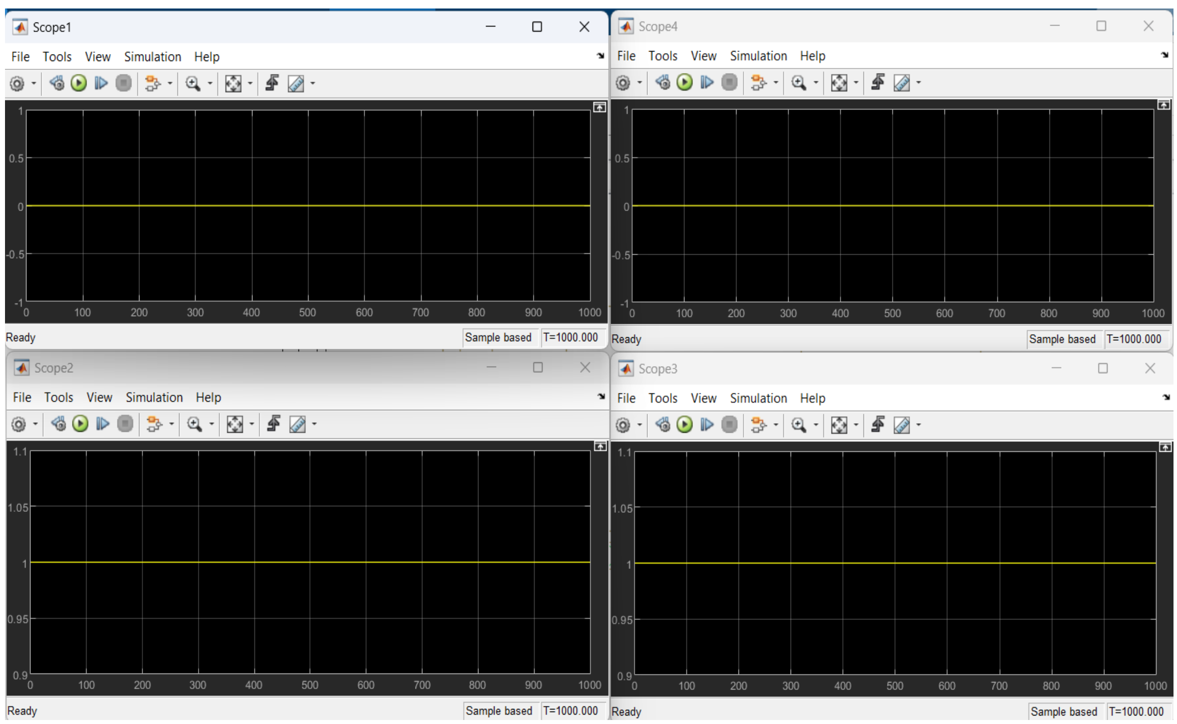

fig. 3.f. Opening and closing statuses of all 4 valves at a given demand

sfunc3.m

```
function myFunction_sfun(block)
    setup(block);
end

function setup(block)
    % Register number of input and output ports
    block.NumInputPorts  = 1;
    block.NumOutputPorts = 4;

    % Set up input port
    block.InputPort(1).Dimensions        = 1;
    block.InputPort(1).DirectFeedthrough = true;
    block.InputPort(1).SamplingMode      = 'sample';

    % Set up output ports
    for i = 1:4
        block.OutputPort(i).DimensionsMode = 'Fixed';
        block.OutputPort(i).SamplingMode = 'sample';
    end

    % Set sample time
    block.SampleTimes = [-1, 0];

    % Register functions for initialization and output
    block.RegBlockMethod('InitializeConditions', @InitializeConditions);
    block.RegBlockMethod('Outputs', @Outputs);
end

function InitializeConditions(block)
    % Initialize the S-function block
end

function Outputs(block)
    % Calculate the outputs of the S-function block

    % Get the input value
    x = block.InputPort(1).Data;

    % Call the external C function and get the output values
    [a, b, c, d] = myFunction(x);

    % Set the output values
    block.OutputPort(1).Data = a;
    block.OutputPort(2).Data = b;
    block.OutputPort(3).Data = c;
    block.OutputPort(4).Data = d;
end

function [a, b, c, d] = myFunction(x)
    % The logic from your C code
    if(x < 0.006)
        a = 0;
        b = 0;
        c = 0;
        d = 0;
    elseif(x >= 0.012 && x < 0.018)
        a = 1;
        b = 1;
        c = 0;
        d = 0;
    elseif(x >= 0.018 && x < 0.024)
        a = 1;
        b = 1;
        c = 1;
        d = 0;
    else
        a = 1;
        b = 1;
        c = 1;
        d = 1;
    end
end
```

fig. 3.g. Code for S-function used here

Based on the desired demand value, the S-function calculates and outputs binary signals (0 or 1) to each individual digital valve. These binary signals directly correspond to the valve state:

0: Valve Closed (minimal flow)

1: Valve Open (full flow)

By strategically controlling the number of open valves at any given time, the S-function allows us to effectively modulate the overall flow delivered to the actuator.

3.3. Digital valve control with S-function and PID

While S-functions offer a powerful tool for implementing custom control logic in Simulink, they also have some limitations that can be addressed by incorporating PID control into our digital hydraulic system.

Limitations of S-Functions:

- *Debugging Challenges:* Debugging issues within an S-function can be complex, as isolating the source of errors within custom code can be time-consuming.
- *Potential Performance Overhead:* Depending on the complexity of the S-function code, it may introduce some computational overhead during simulation compared to using standard Simulink blocks.

By combining S-functions with PID control, you can leverage the strengths of both approaches:

- S-functions provide the flexibility to implement complex control logic specific to our digital hydraulic system. For example, the S-function can handle the core logic of translating demand values into valve opening/closing sequences.
- PID control can then be used with the S-function or as a separate control loop to refine the overall system response. By continuously monitoring the difference between the desired and actual actuator position (error), the PID controller can adjust the valve opening sequences calculated by the S-function, mitigating issues

like overshoot or settling time.

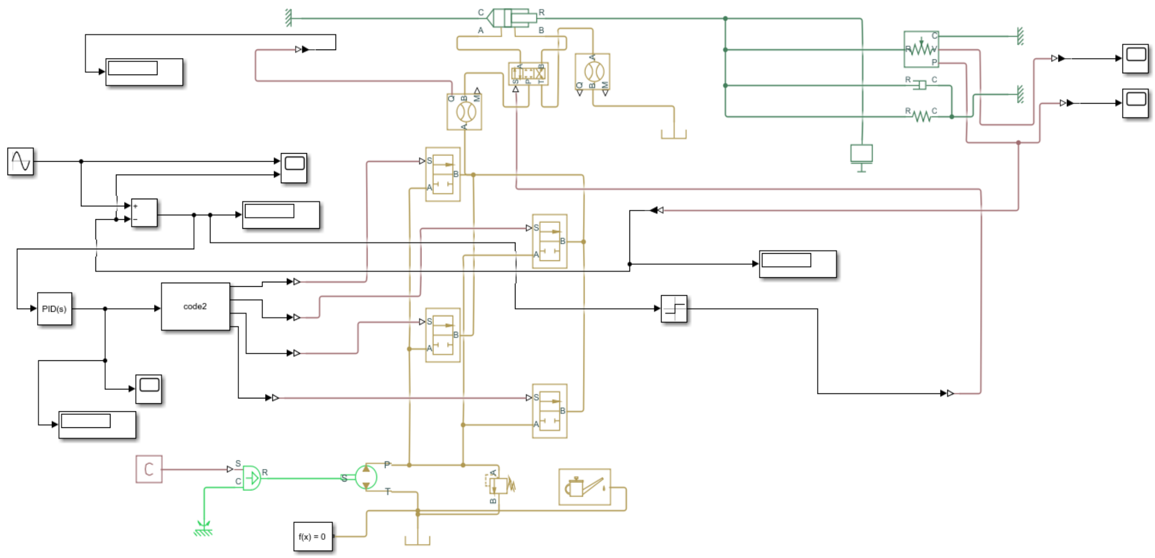

fig. 3.h. Hydraulic circuit containing level 2 S-function, PID 4 digital valves

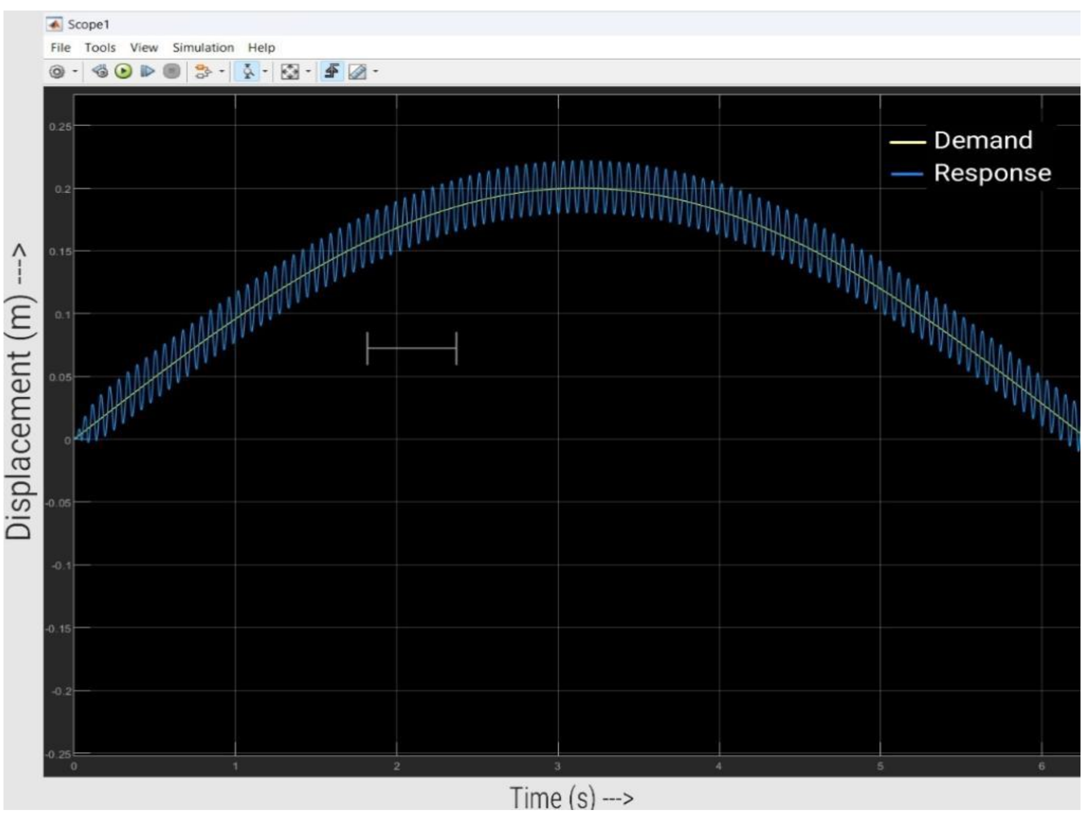

fig. 3.i. Displacement v/s time demand (yellow curve) v/s response (blue curve)

code2.m

```matlab
function code2(block)
    setup(block);
end

function setup(block)
    % Register number of input and output ports
    block.NumInputPorts  = 1;
    block.NumOutputPorts = 4;

    % Set up input port
    block.InputPort(1).Dimensions       = 1;
    block.InputPort(1).DirectFeedthrough = true;
    block.InputPort(1).SamplingMode      = 'sample';

    % Set up output ports
    for i = 1:4
        block.OutputPort(i).DimensionsMode = 'Fixed';
        block.OutputPort(i).SamplingMode = 'sample';
    end

    % Set sample time
    block.SampleTimes = [-1, 0];

    % Register functions for initialization and output
    block.RegBlockMethod('InitializeConditions', @InitializeConditions);
    block.RegBlockMethod('Outputs', @Outputs);
end

function InitializeConditions(~)
    % Initialize the S-function block
end

function Outputs(block)
    % Calculate the outputs of the S-function block

    % Get the input value
    x = block.InputPort(1).Data;

    % Call the external C function and get the output values
    [a, b, c, d] = myFunction(x);

    % Set the output values
    block.OutputPort(1).Data = a;
    block.OutputPort(2).Data = b;
    block.OutputPort(3).Data = c;
    block.OutputPort(4).Data = d;
end

function [a, b, c, d] = myFunction(x)
    % The logic from your C code
    if(x<0)
        a = 1;
        b = 0;
        c = 0;
        d = 0;
    elseif(x>=0 && x<=0.00002);
        a = 1;
        b = 1;
        c = 0;
        d = 0;
    elseif(x>=0.00002 && x<0.00008);
        a = 1;
        b = 1;
        c = 1;
        d = 0;
    elseif(x>=0.00008 && x<0.00032);
        a = 1;
        b = 1;
        c = 1;
        d = 1;
    else(x >=0.00032);
        a = 1;
        b = 1;
        c = 1;
        d = 1;
    end
end
```

fig. 3. j. Code used with S-function in this case

The graph in fig. 3.i depicts the demand signal (yellow curve), represented as a sine wave, and the corresponding system response (blue curve) achieved using digital hydraulics. While the response curve attempts to follow the desired sine wave, we observe the presence of oscillations.

These oscillations are a consequence of the inherent on/off nature of digital valves. Unlike proportional DCVs that can modulate flow continuously, digital valves operate in discrete steps, opening and closing completely. This discrete control can lead to imperfections in replicating the smooth, continuous flow profile of a sine wave, resulting in the observed oscillations.

The key takeaway from this figure lies in the relationship between the number of digital valves and the level of oscillation. By increasing the number of digital valves employed in the system, these oscillations can be further reduced. With more digital valves, we can achieve finer granularity in controlling the overall flow. By strategically switching multiple valves on and off in rapid succession, we can create a more nuanced flow profile that better approximates the smooth, continuous flow of the desired sine wave without using the proportional DCV.

Chapter 4: Conclusion

This thesis investigated the potential of digital hydraulics, a novel approach employing multiple on/off solenoid valves, as a transformative alternative to traditional proportional directional control valves (DCVs).

Digital hydraulics exhibits demonstrably superior performance metrics:

- Enhanced Fault Tolerance: Automatic valve reconfiguration minimizes system downtime.
- Reduced Energy Consumption: Elimination of continuous pump operation leads to significant improvements in energy efficiency.
- Lower Lifecycle Cost: Smaller HPUs, simplified piping, and mass-produced valves significantly decrease initial capital expenditure (CAPEX) and ongoing operational expenditure (OPEX).
- Potential for Superior Control Accuracy: Digital hydraulics offers the potential to surpass proportional DCVs in specific applications through high-frequency valve switching, enabling finer flow granularity.

Control strategies explored within this thesis:

- Individual Valve Control with Look-Up Tables: Offers precise individual valve control but can become cumbersome for complex systems.
- S-Function Control: Utilizes a custom Simulink code block to calculate valve opening/closing sequences based on a single demand value, simplifying control logic and improving scalability.
- The integration of PID control with S-function

Chapter 5: Future Work and References

5.1. Future Work

Building upon the established advantages of digital hydraulics, some key areas for future research and development are as follows:

1. Advanced Valve Optimization:

- Optimal Valve Count: Develop algorithms to determine the optimal number of digital valves needed for a specific application. This will balance control accuracy with system complexity and cost.
- Hybrid Valve Configurations: Explore the potential of combining digital on/off valves with proportional valves for scenarios requiring both high flow precision and rapid response.

2. Enhanced Control Strategies:

- Adaptive Control Algorithms: Develop control algorithms that can adapt to varying operating conditions and automatically adjust valve sequences for optimal performance.
- Integration with Advanced Techniques: Investigate the seamless integration of digital hydraulics with control techniques like Model Predictive Control (MPC) for even more precise and efficient system operation.

3. System-Level Design Optimization:

- Digital Hydraulic System Modeling: Develop comprehensive simulation tools to model and predict the behavior of entire digital hydraulic systems, facilitating design optimization and troubleshooting.
- Energy Harvesting and Regeneration: Explore strategies to capture and reuse energy dissipated during system operation, further enhancing the overall energy efficiency of digital hydraulics.

By addressing these areas of future work, digital hydraulics can solidify its position as a revolutionary technology, offering unmatched performance, reliability, and efficiency across a wide range of industrial applications.

5.2. References

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