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Predictive Maintenance of an Industrial Flow Control Loop

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Abstract: Process industries frequently employ industrial flow-control systems to maintain operational conditions and control fluid flow. The interplay of control valves, actuators, process instruments, and control equipment affects their performance. It is possible to create a benchmark for evaluating a system's performance over time by examining how it reacts to control commands.

The Forbes Marshall laboratory facility's flow-control loop is examined in this paper. Subject to controller compatibility, CODESYS is meant to serve as the programming environment for the Microcon ER 201 series programmable logic controller (PLC) used in the setup. Time-stamped command and flow measurements are used to evaluate the delay before a flow response is observed and the time taken for the measured flow to enter a specified target range. Comparing these parameters under similar operating conditions can help describe the consistency of the system's response. The paper lays the groundwork for future research on industrial monitoring of conditions and predictive maintenance and offers a useful technique for assessing command-to-flow behaviour. Keywords: Industrial Flow Control, Programmable Logic Controller, CODESYS, Control Valve, Electromagnetic Flow Meter, Response-Time Analysis, Condition Monitoring, Predictive Maintenance.

I. INTRODUCTION

Industrial flow-control systems are essential in process industries because they regulate fluid movement and help maintain required operating conditions. They are frequently discovered in uses including electricity generation, chemical processing, and water purification. A pump, control valve, actuator, positioner, flow meter, and programmable logic are all common components of a flow-control loop.controller (PLC). While the valve modifies the flow and the flow meter gages the process response, the PLC carries out the control logic.

The speed at which the measured flow reacts to a variation in the control command can be used to evaluate the behavior of a flow-control loop. The actuator, valve, process parameters, instrumentation, and data collection system could all have an impact on the reported delay. Establishing a baseline for upcoming performance evaluations is made easier by measuring this reaction under similar operating conditions.

The industrial flow-control loop at the Forbes Marshall laboratory premises is examined in this study. Subject to controller compatibility, CODESYS is the recommended programming environment for a Microcon ER 201 series PLC used for control implementation. Response latency and the amount of time needed for the flow to reach a predetermined target range are assessed using time-stamped control orders and electromagnetic flow-meter readings. Future monitoring of conditions and predictive-maintenance applications can be built upon the analysis that results.

II. LITERATURE REVIEW

Bacci di Capaci and Scali [1] examined various approaches to analysing control-valve stiction, including modelling, detection, and diagnostic techniques. Their review provides useful background for understanding valve abnormalities and their possible effects on control-loop behaviour.

The approaches used to identify and measure control-valve stiction were compared by Akavalappil and Radhakrishnan [2]. The variations between diagnostic techniques and the difficulties in implementing them in different operating systems are covered in their work.

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Choudhury et al. [3] used analytical techniques and process data to study the modelling and detection of control-valve stiction. Their work enhances our knowledge of how systematic analysis may be utilized to investigate anomalous valve behaviour.
Venkatasubramanian et al. [4] examined methods for diagnosing and detecting faults that make use of past process data. This study offers a framework for analysing time-series data to detect shifts in the behaviour of industrial processes.
In their discussion of data-driven methods for fault diagnosis and detection, Dai and Gao [5] emphasised how measured signals can be evaluated to provide valuable insights into system conditions. Their efforts aid in the expansion of data-driven condition-monitoring techniques.
These studies address valve stiction and general fault-diagnosis techniques, but the present study concentrates on measuring the response between a control command in PLC and the corresponding electromagnetic flow-meter output in an industrial flow control loop. It is looking at response delay and time to reach a defined target band for flow as base parameters for future surveillance.

III. PROBLEM STATEMENT

The performance of an industrial flow-control loop depends on the proper interaction of control valve, actuator and process instruments. changes in operating conditions or component behaviour can influence the response of the measured flow to a change in the control command. While process variables are routinely monitored. Looking at the timing of this response can give further knowledge about the behaviour of the system as a whole. Thus a systematic approach is needed to investigate the relationship between the control command and the corresponding output of the electromagnetic flow meter.

This study explores the command-to-flow response of the Forbes Marshall industrial flow-control set up with a Microcon ER 201 series PLC. response to appear, and the delay in the response, and the time it takes for the One of the key parameters is the measured flow entering a predefined target band. Studying these parameters under similar conditions can serve as a reference for future performance assessment and to develop condition monitoring and predictive maintenance techniques.

IV. OBJECTIVES

Our work has the following main objectives:

1. To study the operation and instrumentation of an industrial flow control loop.
2. To design the necessary control logic for the Microcon ER 201 series PLC, subject to “Verification of compatibility to CODESYS”.
3. To gather time-stamped data associated with PLC control commands and electromagnetic flow-meter readings.
4. To measure the delay between issuing a control command and detecting a corresponding change in the measured flow.
5. To determine the time required for the measured flow to enter a predefined target range.
6. To compare the flow-response characteristics under similar operating conditions.
7. To establish baseline response characteristics that can support future condition monitoring and predictive-maintenance development.

V. SYSTEM ARCHITECTURE

An industrial flow-control loop, associated process machinery, a pneumatic control valve, and a programmable logic controller (PLC) make up the experimental set. It is used to find out how the measured flow rate is affected by changes in the control instruction. The flow-control loop, the Piping and Instrumentation Diagram (P&ID), and the test setup are the three components that make up the system architecture.

- **Industrial Flow Control Loop Setup**

The study takes advantage of the Forbes Marshall industrial flow-control loop, which is composed of a PLC-based control system, an electromagnetic flow meter, an electro-pneumatic positioner, and a pneumatically operated control valve. The positioner, which changes the valve position to regulate fluid flow, gets a 4–20 mA analog data signal generated by the PLC. The process variable for response analysis is calculated by measuring the resulting flow rate with the flow meter. Process visualization and monitoring are provided through the SCADA interface, and the response characteristics of the loop are evaluated with time-stamped command and flow data.

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Fig. 1. Actual Forbes Marshall industrial flow and level control laboratory setup used for the experimental study.

- **Piping and Instrumentation Diagram (P&ID)**

The main procedure equipment, pipeline connections, and instruments in the flow-control loop are displayed in the Piping and Instrumentation Diagram (P&ID). It identifies the electrical and pneumatic signal pathways in addition to the control valve, pneumatic actuator, flow meter, and related equipment. The components and their functions are represented using standard instrument symbols and identification tags in compliance with the relevant instrumentation documentation standard [7]. The figure helps clarify the signal linkages between the process instruments and control equipment and provides a clear picture of the system configuration.[7]

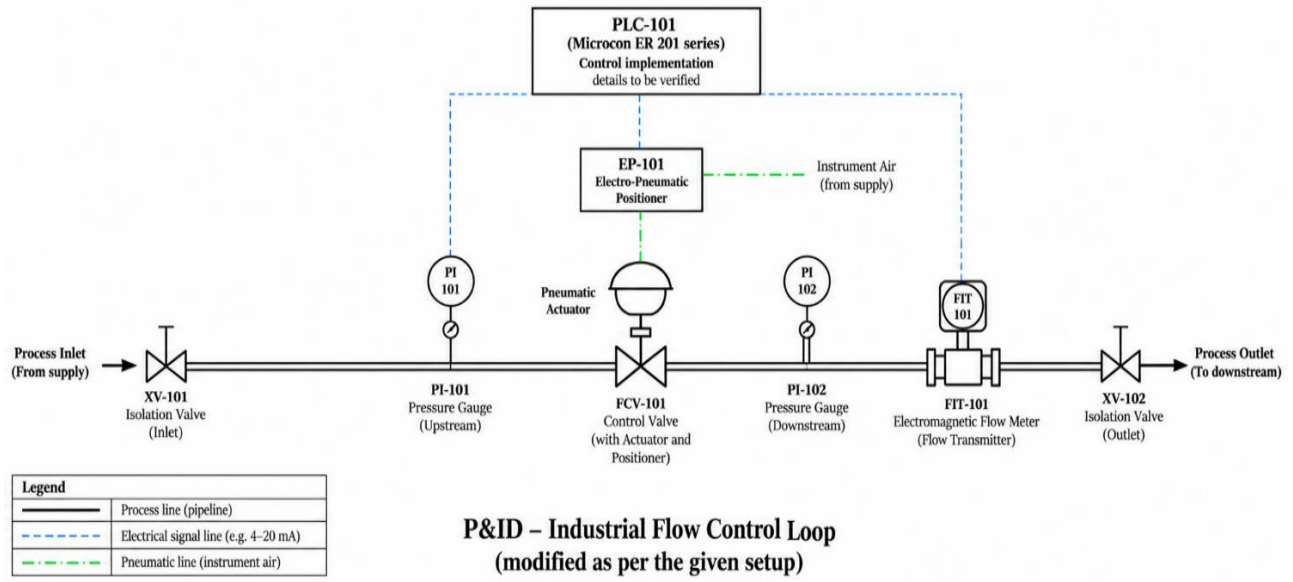


Fig. 2. Piping and Instrumentation Diagram of the industrial flow-control loop.

- **Experimental Setup**

Forbes Marshall's industrial flow-control facility is used for the experiment. A pneumatically controlled a control valve, an electro-pneumatic positioner, a differential pressure transmitter, pressure gauges, a temperature sensor, a flow meter,

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and isolation valves were all elements of the setup. In response to the control signal received by the positioner, the control valve changes the fluid flow through the pipeline. The flow meter provides the primary process variable for examining the control loop's response by determining the resulting flow rate.

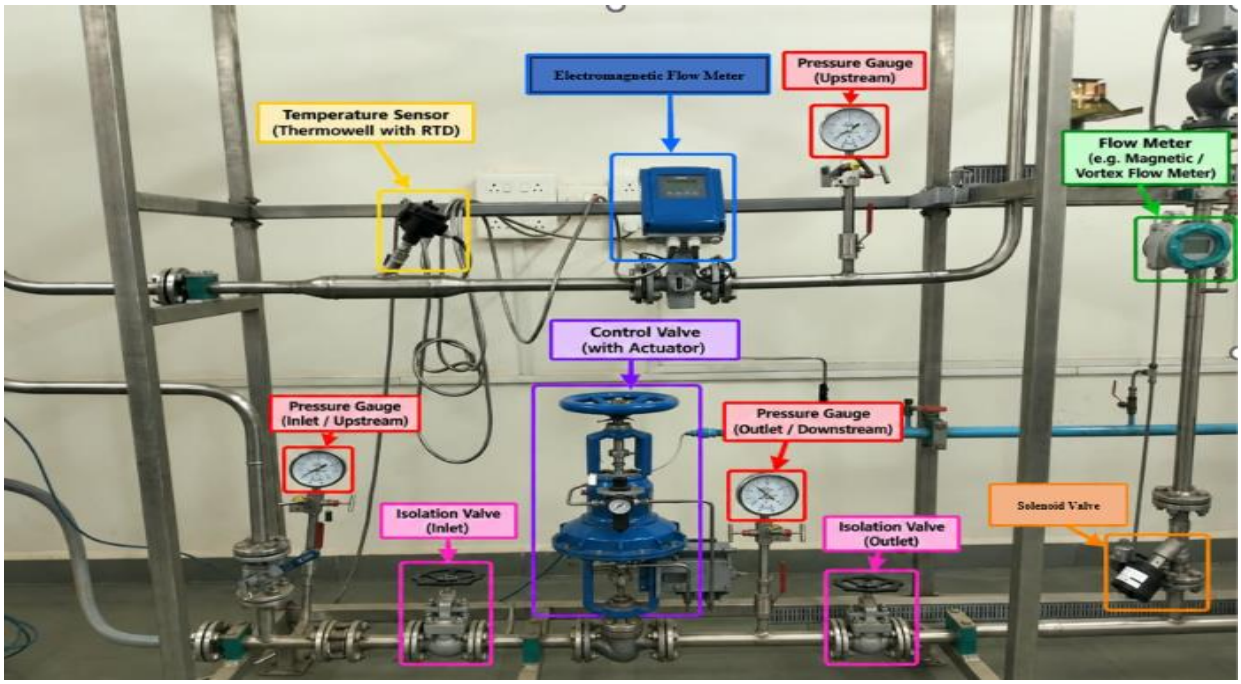


Fig. 3. Experimental setup of the industrial flow control loop.

VI. PROPOSED METHODOLOGY

Studying how the industrial flow-control loop responds to adjustments in the PLC control command are the primary objective of the methodology. The system's response is determined using the electromagnetic flow meter's corresponding output.

- **Test Procedure**

The flow loop runs under a fixed initial condition at the start of the experiment. After that, the PLC generates a control instruction and transmits it via an analog signal of 4–20 mA to the EP positioner. The positioner changes the flow rate by adjusting the pneumatic control valve. For analysis, the flow-meter readings that have been obtained are noted.

- **Data Acquisition**

Using a proper data-acquisition configuration, the control command and associated flow-rate measurements are recorded with timestamps. To accurately determine the response latency, a common time reference is needed. Once the final software choice has been verified, the SCADA platform will be determined. To catch flow changes and allow accurate response-time calculations, the sampling interval and timestamp resolution must be sufficient.

- **Response-Time Calculation**

The observed response delay is calculated as:

$$T_{\text{delay}} = t_{\text{onset}} - t_{\text{command}}$$

where t_{command} is the time at which the control command is issued, and t_{onset} is the time at which the measured flow satisfies a predefined response-onset criterion.

$$T_{\text{target}} = t_{\text{target}} - t_{\text{command}}$$

The time required to reach the target flow range is calculated separately.

where t_target is the time at which the measured flow first enters the predefined target band.

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These parameters define the overall system's command-to-flow responsiveness.
Measurement resolution, sample interval, process variability, and potential instrumentation and data acquisition delays are all taken into account in the analysis. When interpreting the computed reaction times, these constraints are taken into account.

VII. PLC LADDER LOGIC DESIGN

The industrial flow control loop's control logic is executed using the Microcon ER 201 series PLC. The electropneumatic (EP) positioner takes the 4–20 mA analog output signal that it produces. The positioner changes the control valve's position and regulates the fluid flow through the pipeline by transforming the electrical command into a pneumatic output.

Setting up the necessary PLC inputs and outputs, bringing the control sequence into practice, and confirming the analog output interface to the EP positioner are all part of the ladder logic structure. Subject to confirmation of compatibility with the particular Microcon ER 201 controller and its runtime, CODESYS is the proposed programming environment. The response of the whole control and measurement system can be characterized by analyzing the control command and associated flow measurements.

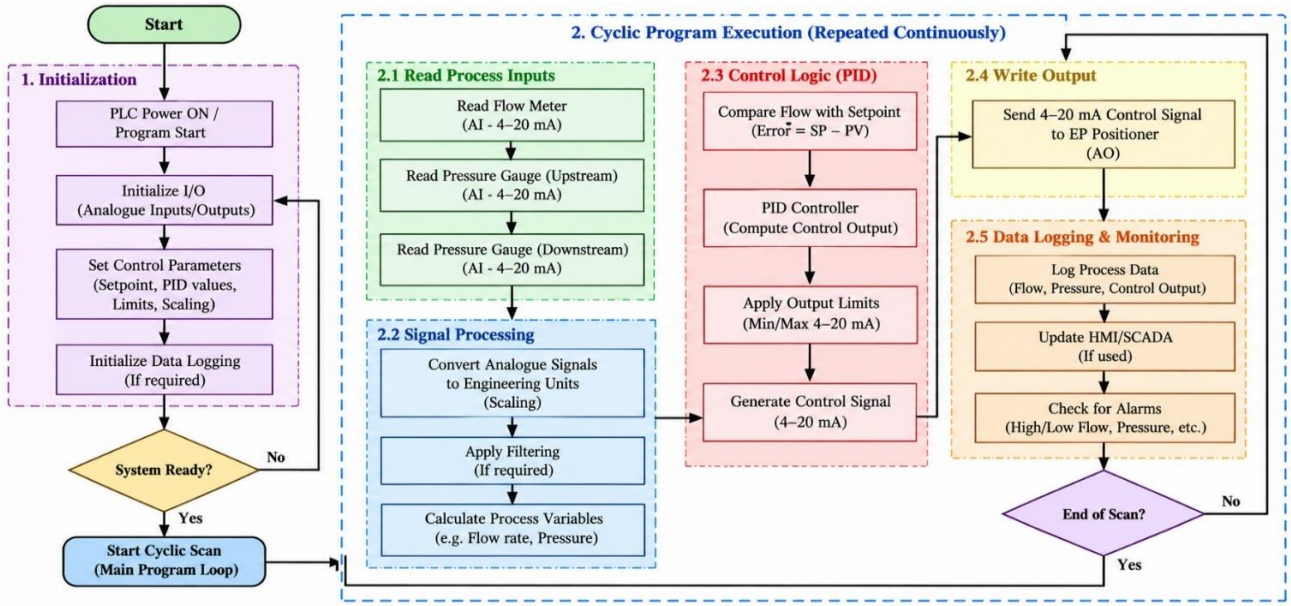


Fig. 4. PLC program flowchart illustrating system initialization, process-input acquisition, signal processing, control logic execution, 4–20 mA output generation, and process-data logging for the industrial flow-control loop.

VIII. SCADA IMPLEMENTATION AND DATA ACQUISITION

Operators can view process metrics and equipment status by using the SCADA interface, which offers a visual representation of the industrial flow-control system. A pump, storage tank, control valves, flow meters, a flow switch, a differential pressure transmitter, and a temperature transmitter are all included in the process configuration that is shown. The interface offers a simple way to view the process and its operating conditions by presenting instrument data and available valve operating modes.

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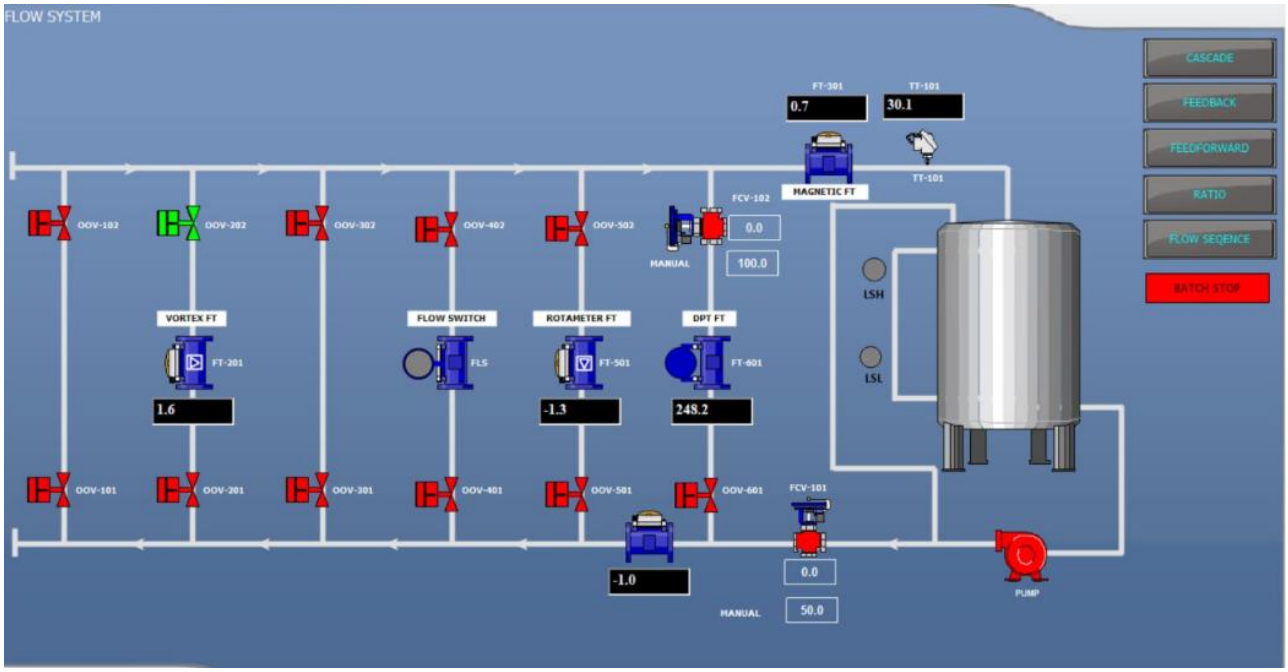


Fig. 5. SCADA graphical interface of the industrial flow system showing process instrumentation, control valves, pump, storage tank, measured process variables, and available operating modes.

IX. EXPECTED RESULTS AND DISCUSSION

- **Flow Response Characteristics**

The study focuses at how the PLC's order types affect the flow rate. The control valve is regulated by the 4–20 mA signal transmitted to the EP positioner, that modifies the pipeline's fluid flow. The dynamic reaction of the entire system can be characterized by comparing the control command with the equivalent electromagnetic flow-meter results [8].

- **Response-Time Analysis**

The delay before a noticeable change in flow is seen and the time required for the measured flow to enter an established target band are the two parameters that are the focus of the analysis. Time-stamped command and flow data are the source of these values. To assess response consistency and set reference values for upcoming performance monitoring, repeated trials carried out under similar operating conditions can be compared.

Table 1. Parameters for Flow-Response Analysis

Parameter	Symbol	Purpose
Command Time	t_command	Identifies when the control command is issued.
Response-Onset Time	t_onset	Identifies when the measured flow meets the response-onset criterion.
Response Delay	T_delay	Measures the delay before the observed flow response.
Target-Reaching Time	T_target	Measures the time required for the flow to enter the target band.
Measured Flow Rate	Q	Represents the process response.

T_delay = t_onset − t_command is used to determine the response delay, and T_target = t_target − t_command is utilized for determining the time to reach the target band. While they do not reflect what was observed from the experimental design, the illustrative response curves in Fig. 6 show how response characteristics can differ between normal and slower responses.

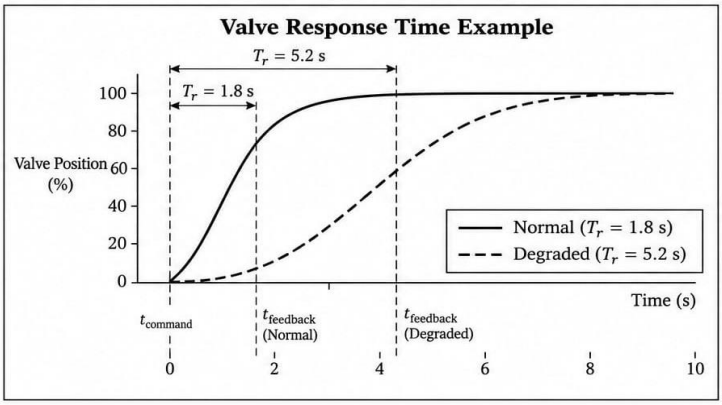
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Parameter	Unit	Normal (Healthy)	Warning (Moderate Degradation)	Degraded (Severe Degradation)	Observation
Valve response time (T_r)	s	≤ 2.0	2.0 – 4.0	> 4.0	Increase in response time indicates valve stiction.
Flow rate	L/min	Stable	Slight variation	Large variation	Flow deviation due to improper valve movement.
Pressure	bar	Within range	Slight deviation	High deviation	Pressure variation supports degradation detection.
AI/ML model output	–	Normal	Warning	Degraded	Model classifies valve health condition.



Response Time Calculation

$$T_r = t_{feedback} - t_{command}$$

Where,

T_r = Valve response time (s)

$t_{command}$ = Time when valve command is issued (s)

$t_{feedback}$ = Time when valve position reaches 90% of final value (s)

Key Result

Condition	Measured Response Time (Example)
Normal	1.8 s
Warning	3.1 s
Degraded	5.2 s

Fig. 6. Illustrative comparison of flow-response characteristics and response-time parameters under normal and slower-response conditions.

X. CONCLUSION

The response behavior of an industry flow-control loop containing a Microcon ER 201 series PLC, an electrical pneumatic positioner, a pneumatic control valve, and an electromagnetic flow meter is examined in this work. The positioner modifies the valve to control the fluid flow in reaction to a 4–20 mA analog signal from the PLC.

The study focuses on two parameters: the time required for the measured flow to approach a predetermined goal range and the time frame between executing a control procedure and detecting a significant change in flow.

Reference response characteristics can be defined to help identify changes in system behavior in future assessments. But an increase in response time doesn't necessarily mean valve degradation, because of the performance of actuators, process conditions, instrumentation and data-acquisition delays may also affect the measurements. The study lays a basis for further study of industrial flow-control performance and the development of methods for condition monitoring from process response data.

XI. FUTURE SCOPE

In order to facilitate constant surveillance and historical recording of control orders and flow data, future work may link the flow-control system with a SCADA platform. A more realistic baseline of system responsiveness could be developed with additional testing at various flow rates and operating circumstances. Deviations from this baseline could be examined in later analysis to find changes that need more research. Using accumulated process data, machine learning and artificial intelligence (AI/ML) strategies could be investigated to identify anomalous response patterns. These methods could aid in separating typical process variations from possible equipment-related issues and support maintenance prediction applications for industrial flow-control systems with enough data and experimental verification.

XII. ACKNOWLEDGMENT

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