

Article

Bridging the Field Gap in Compressor Surge Testing: A Semi-Automated Supervisory Framework for Surge Limit Verification

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Abstract

Reliable determination of the surge limit of an installed centrifugal compressor cannot rely solely on OEM performance maps, theoretical predictions, or previously configured surge lines. The actual field boundary is influenced by installation-specific characteristics, including piping volumes, recycle-system dynamics, valve response, and instrumentation, all of which affect compressor behavior as surge is approached. At the same time, field surge testing is inherently demanding, because it is a safety-critical procedure that requires careful execution and often depends on the experience of specialist personnel. This paper presents a semi-automated supervisory framework for field surge limit verification intended for use by trained site engineers under operator supervision. The framework guides the testing process through readiness checks, instrumentation verification, recycle-valve assessment, gradual reduction of surge margin, real-time monitoring, surge-event identification, recovery actions, and structured data logging. Because early surge precursors are not consistently visible using standard plant instrumentation, the proposed approach relies on a practical signal-based event-recognition method derived from installed measurements and referenced to a pre-event baseline. The paper also introduces a structured method for tuning staged Recycle Trip[®] recovery actions following surge limit verification using a limited number of field tests. The field evaluation included seven industrial compressor records: five independently confirmed surge cases, one shutdown/non-surge transient, and one confirmed no-surge case. Using a record-specific baseline threshold, all five confirmed surge events were recognized, with reported detection delays of 0–0.1 s. The supporting dynamic simulation environment was used for logic development and qualitative assessment of the supervisory and recovery-tuning concepts. Overall, the proposed approach provides a more structured and repeatable basis for supervised field surge limit verification while preserving operator authority.



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1. Introduction

Centrifugal compressors are indispensable in the oil and gas, petrochemical, power generation, refrigeration, and many other process industries, where reliable operation is

essential for maintaining production continuity and protecting high-value equipment [1–3]. Among the operating limitations of these machines, surge remains one of the most severe aerodynamic instabilities. It occurs when stable compression breaks down, leading to large oscillations in pressure and flow that can rapidly develop into damaging transient events [4–7]. If not arrested promptly, surge can impose significant mechanical and thermal loads on the compressor, bearings, seals, couplings, and connected piping. Consequently, modern compressor trains rely on dedicated anti-surge control systems to preserve an adequate operating margin and to initiate rapid recovery whenever unstable operation is detected [3,8–11]. A longstanding challenge in anti-surge control is that the true surge limit of an installed compressor rarely coincides exactly with the surge line supplied by the original equipment manufacturer or predicted during design. Once installed in a process plant, compressor behavior is influenced by numerous installation-specific factors, including suction and discharge piping volumes, recycle-system dynamics, valve performance, instrumentation characteristics, signal filtering, and controller execution timing [9,12–15]. The effective surge boundary may also shift throughout the equipment lifetime as a result of fouling, wear, internal leakage, or process modifications [16]. These factors make periodic field verification of the surge limit an important aspect of maintaining both compressor protection and operating efficiency. Excessively conservative settings increase recycle losses and reduce plant performance, whereas aggressive settings decrease the available stability margin and increase the likelihood of surge [2,9,11,17].

Although the importance of field surge testing is widely recognized, routine implementation remains uncommon. Conducting these tests requires careful planning, controlled operation near the stability boundary, rapid interpretation of transient process behavior, and close coordination among operations, process, machinery, and control engineers [18–20]. Such expertise is not always available, particularly during offshore commissioning campaigns, at remote installations, or during startup and shutdown periods where testing time is limited. As a result, many compressor trains continue to operate using surge settings established during commissioning, while subsequent changes in machine condition or system dynamics remain unverified.

The work presented in this paper was motivated by this practical gap between industrial need and field execution. Rather than proposing a new anti-surge controller or a universal surge-prediction algorithm, this study introduces a semi-automated supervisory framework that assists trained field engineers during surge limit verification. The framework structures the test into a repeatable sequence that verifies system readiness, confirms instrumentation and recycle-valve performance, guides the compressor toward the stability boundary in a controlled manner, recognizes surge events using standard plant measurements, executes predefined recovery actions, and records the results for subsequent engineering review. In this sense, the proposed methodology provides supervised automation that supports field personnel while preserving human authority over all safety-critical decisions [21,22].

An important design objective was to avoid relying on incipient-surge prediction as the primary trigger during field verification. Although considerable research has been devoted to identifying early surge precursors, these signatures are not always observable using the measurement quality, sensor placement, and sampling rates typically available in industrial control systems. For practical field deployment, reliable recognition of an actual surge event is often more valuable than attempting to predict its onset from weak or inconsistent precursor signals. Consequently, the proposed framework emphasizes robust event recognition based on routinely available plant measurements rather than early-warning indicators that may not be consistently detectable under industrial conditions [23–25].

The framework was developed using representative field operating records, practical engineering experience, practitioner input, and a supporting dynamic simulation environ-

ment. The simulation model was used to develop and qualitatively assess the supervisory sequence, recovery behavior, and event-recognition logic under controlled operating conditions. It was not intended to serve as a high-fidelity digital twin of a particular compressor installation, but rather as an engineering platform for evaluating supervisory concepts before field deployment.

The remainder of this paper is organized as follows. Section 2 defines the industrial problem and establishes the scope of the work. Section 3 describes the evidence base, introduces the supervisory surge-testing framework, presents the proposed baseline-referenced surge-event recognition method, details the post-verification recovery-tuning concept, and describes the supporting simulation environment together with the field-verification basis. Section 4 discusses the experimental and simulation results. The principal limitations of the study are summarized in Section 5, followed by recommendations for future research in Section 6. Finally, Section 7 presents the main conclusions of the work.

2. Industrial Problem Definition and Scope

2.1. Field Gap in Surge Testing

Surge testing is widely regarded as an important part of compressor commissioning and lifecycle validation, and its value is recognized in both industry standards and operating practice [3,9,18]. Despite this, field execution remains inconsistent. In many facilities, surge testing is postponed, reduced in scope, or omitted entirely because it is operationally disruptive, safety-critical, and often dependent on the availability of specialist personnel [19,20]. As a result, there is often a mismatch between the need for verified surge protection and the practical ability of site teams to carry out surge verification in a consistent, repeatable, and safe manner. This challenge is particularly evident in:

- Offshore or remote installations where access to turbomachinery specialists is limited;
- Facilities operating within short startup or shutdown windows that allow little time for controlled surge verification.

Under these conditions, operators frequently maintain conservative anti-surge settings rather than approach the stability limit without structured procedures or expert support. While this approach preserves protection margin, it can also increase recycle losses and reduce operating efficiency [9,17].

2.2. Objective of the Present Work

This study develops a practical supervisory framework for field surge limit verification that supports controlled testing, event recognition, recovery, and documentation. The goal is to improve the repeatability of field verification activities while maintaining engineering oversight during a safety-critical test [9,20]. Two supporting features are included. The first is a signal-based surge-event recognition method that uses standard field measurements. The second is a structured post-verification tuning approach for staged open-loop recycle-valve recovery action. In Compressor Controls Corporation terminology, this recovery action is referred to as Recycle Trip® (Recycle Trip is a registered trademark of Compressor Controls Corporation).

2.3. Scope and Boundaries

The methodology presented in this paper is intended for supervised surge testing in the field and is not intended for autonomous operation during normal plant running conditions. The supervisory philosophy follows established procedural-automation principles in which readiness checks, execution support, and operational guidance are automated, while responsibility for engineering decisions remains with qualified personnel [21,22]. The supporting simulation environment serves as a development and assessment platform

rather than a predictive model of a specific compressor installation. Accordingly, the paper focuses on the supervisory testing framework, the signal-based surge-event recognition method, and the proposed post-verification recovery-tuning concept.

3. Materials and Methods

3.1. Evidence Basis of the Study

The methodology presented in this work was developed from practical field needs, representative field records, practitioner input, and a supporting dynamic simulation environment. To provide complementary evidence regarding industrial relevance and deployment context, a separate 2024 practitioner study evaluated advanced compressor-control solutions using Maximum Difference (MaxDiff) scaling [26]. The study included 84 qualified respondents after data cleaning and quality control. Respondents were drawn from oil and gas, chemical production, air separation, mining and quarrying, and steel production, and they included compressor-control, rotating-equipment, instrumentation, maintenance, process, operations, and plant-management roles.

Of the respondents, 99% reported that they currently oversee or work with compressor controls or turbomachinery trains, 97% described themselves as very or extremely knowledgeable in this area, and 65% had more than 10 years of professional experience. The regional sample included North America, EMEA, APAC, South America, and other regions, while the industry distribution included oil and gas (37%), mining and quarrying (20%), steel production (18%), chemical production (15%), and air separation (10%).

Within the MaxDiff exercise, Surge Limit Verification obtained an overall scaled preference score of 5.50. Directionally higher scores were observed among respondents from South America (8.93) and within air-separation (8.86) and chemical-production (7.65) applications. These subgroup results are interpreted with caution, because several regional and industry segments contained fewer than 30 respondents. Accordingly, the practitioner-derived findings are used in this paper only as directional evidence of perceived industrial relevance and potential deployment interest. They are not used as technical validation of the proposed surge-event detector or supervisory framework.

The technical evaluation presented in this work is instead based on the field-recorded compressor cases and the supporting dynamic simulation environment described in the following sections. This separation between practitioner-perception evidence and technical evaluation is maintained throughout the manuscript. The use of field-oriented evidence is consistent with the industrial emphasis on validation of anti-surge systems and installed compressor behavior under real operating conditions [9,18,27].

3.2. Semi-Automated Surge Test Concept

The central concept of the present work is a semi-automated, engineer-supervised surge-test procedure intended to support field surge limit verification in a structured and repeatable manner. The framework does not replace the anti-surge controller and is not intended for unsupervised operation. Instead, it organizes surge testing into a supervisory sequence that verifies readiness, guides a controlled approach toward the stability boundary, identifies surge events from installed measurements, executes recovery actions, and records the resulting test data for engineering review. This approach is consistent with procedural-automation concepts in which workflow execution is standardized, while human supervision and decision authority are retained [21,22].

At a high level, the proposed concept consists of four functional layers:

1. Readiness verification;
2. Controlled approach toward surge;
3. Surge-event recognition;

4. Recovery and logging.

The concept also establishes the relationship between surge limit verification and post-verification recovery tuning. The field surge limit must first be verified before a suitable operating target to the right of the surge control line can be defined for subsequent recovery optimization.

3.3. *Semi-Automated Supervisory Framework for Surge Testing*

3.3.1. Framework Design Philosophy

The proposed methodology is implemented as an engineer-supervised state machine composed of clearly defined stages. Progression through the sequence requires satisfaction of the relevant permissives, while the engineer retains authority to pause, abort, or terminate the test at any stage. This approach was selected because field surge testing is a safety-critical activity requiring both automation and engineering judgement. Accordingly, the framework is intentionally semi-automated rather than fully autonomous, following established supervisory-control and procedure-automation principles used in safety-critical industrial applications [21,22,28].

3.3.2. Overview of the Supervisory Sequence

The principal stages of the framework are:

1. Engineer authorization and test permissives;
2. Instrumentation verification;
3. Process stability qualification;
4. Controller preparation;
5. Recycle-valve readiness verification;
6. Staged reduction of surge margin or equivalent surge limit setting;
7. Surge detection or verification-point recognition;
8. Recovery and restoration.

The proposed sequence reflects common field surge-testing practices while expressing the decision process in a more explicit and repeatable form. It incorporates readiness checks, controlled advancement through the test, recovery preparedness, and operator oversight in a manner consistent with published guidance for anti-surge systems and compressor commissioning activities [9,19,20]. Figure 1 shows the overall supervisory workflow and the principal decision paths used during field surge limit verification.

3.3.3. Instrumentation Verification

Before process stability is assessed, the framework verifies the health and availability of the instrumentation used by the anti-surge system. This step is performed first because stability qualification, surge recognition, and recovery assessment all depend on reliable measurements. Using invalid or degraded signals may lead to incorrect qualification of the operating condition and reduce test repeatability. The verification procedure includes signal-quality and plausibility checks for the measurements used directly by the anti-surge system, with particular focus on pressure, temperature, and flow-related signals. Where available, transmitter diagnostics and device-status information are also reviewed. Instrumentation characteristics such as transmitter response, filtering, signal damping, and control-system scan time can influence both surge recognition and interpretation of the transient response. Therefore, signal quality and availability must be confirmed before the test proceeds. If a fault, communication problem, bad-quality indication, or implausible measurement is detected, the sequence is paused, and the engineer is notified. Testing does not continue until the affected signals have been restored and validated. This approach is consistent with industrial guidance, which recognizes instrumentation quality as a key

element of anti-surge system performance [8,20]. It is also consistent with earlier surge-control practice that treated surge-related measurements as integral parts of the protection system and of field calibration activities [10].

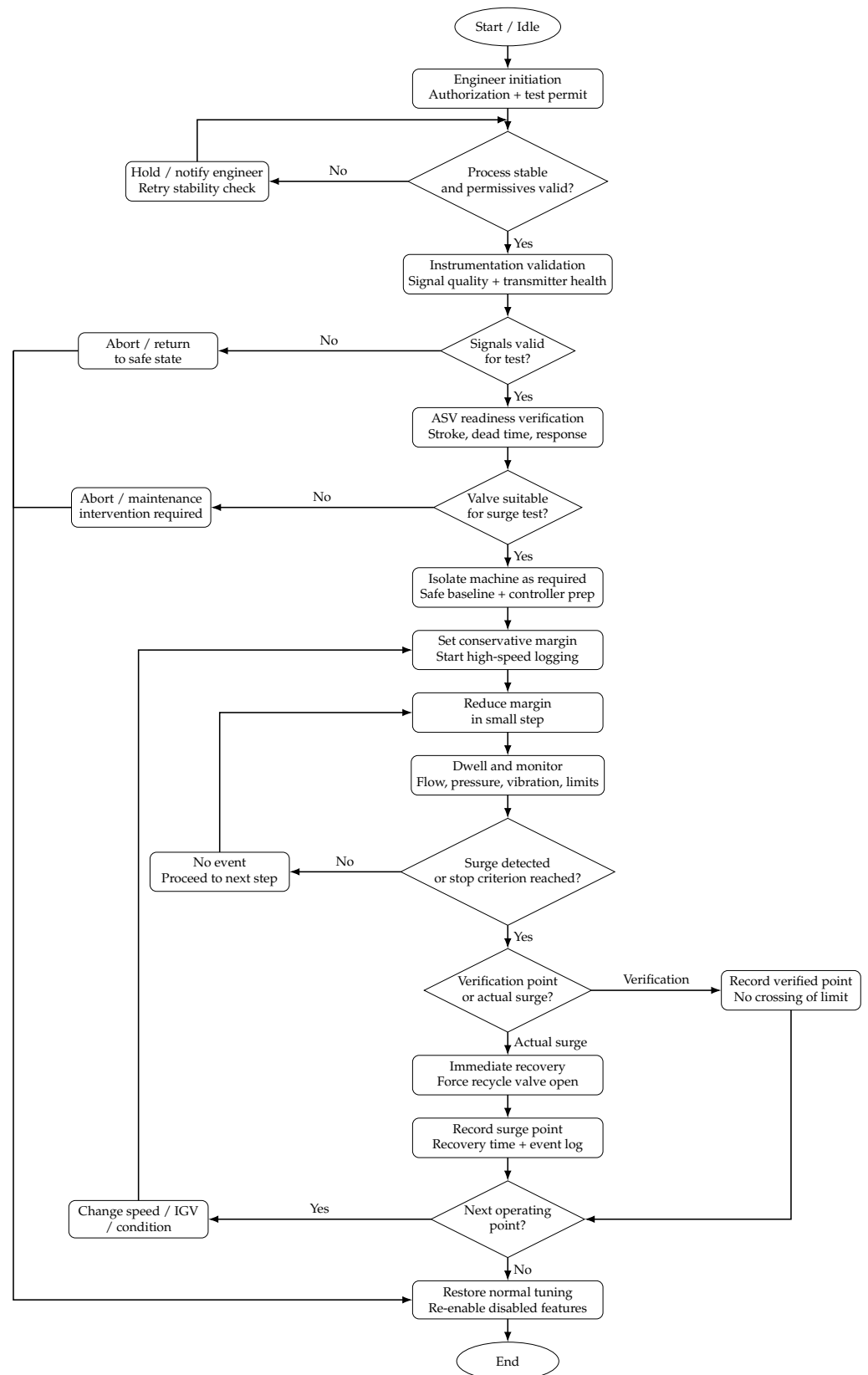


Figure 1. Proposed semi-automated supervisory framework for field surge limit verification.

3.3.4. Preconditions and Stability Qualification

Before approaching the surge boundary, the framework verifies that the compressor is operating under sufficiently stable conditions. This avoids reducing the surge margin during process disturbances, unresolved transients, or shifts in the operating point that could affect test repeatability. The qualification procedure uses the flow-related differential-pressure signal employed by the anti-surge system. The signal is first filtered and then evaluated using a configurable rolling window of duration T_w . At each evaluation instant t_k , a linear regression model is fitted to the historical data contained within the interval $[t_k - T_w, t_k - \Delta t]$, where Δt is the sampling period. The resulting regression model is

$$x_r(t) = a_k + b_k t \quad (1)$$

and is evaluated at the current instant to estimate the expected signal value,

$$\hat{x}(t_k) = a_k + b_k t_k. \quad (2)$$

A prediction envelope is then constructed around the estimated value:

$$U(t_k) = \hat{x}(t_k)(1 + \delta) \quad (3)$$

$$L(t_k) = \hat{x}(t_k)(1 - \delta) \quad (4)$$

where δ represents the allowable deviation fraction. In the present implementation, a tolerance of $\pm 5\%$ is used. The instantaneous stability criterion is therefore defined as

$$L(t_k) \leq x_f(t_k) \leq U(t_k), \quad (5)$$

where $x_f(t_k)$ denotes the filtered process signal. Equation (5) checks whether the current operating condition remains consistent with the trend established during the previous evaluation window while remaining tolerant of normal measurement noise. To avoid rapid switching between stable and unstable states, a requalification mechanism is included. After an instability event, satisfying the instantaneous stability criterion alone is not sufficient to restore the stable state. Instead, the signal must satisfy the stability criterion continuously over a defined verification period:

$$T_q = N_q T_w \quad (6)$$

where N_q is the required number of consecutive qualification windows, and T_q is the resulting requalification interval. In the implementation presented here, $N_q = 2$, which results in a requalification period of $T_q = 10$ s for a 5 s evaluation window. The operating condition is considered stable again only after the instantaneous criterion has remained satisfied throughout the entire requalification period. Figure 2 illustrates the qualification procedure. The upper panel shows the measured and filtered signals, the middle panel presents the rolling prediction envelope used for stability assessment, and the lower panel compares the instantaneous stability result with the final confirmed stability state obtained after applying the requalification logic.

3.3.5. Controller Preparation and Configuration Management

Before the controlled approach to surge, the compressor is brought into a test-ready operating configuration. In practical terms, this may involve isolating the compressor from parts of the process, redirecting flow toward recycle, placing the relevant performance controller in the required mode, and preparing the anti-surge controller for test execution.

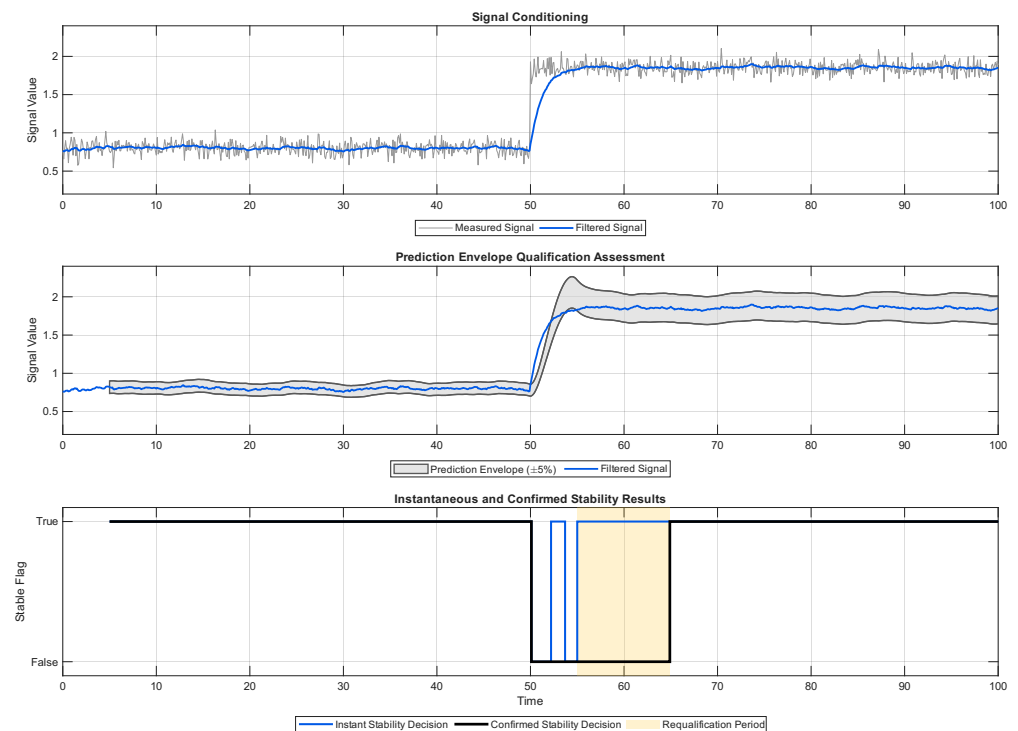


Figure 2. Trend-based stability qualification using a rolling prediction envelope. A regression model is fitted using the previous T_w seconds of filtered data and evaluated at the current instant to estimate the expected operating point. Instantaneous stability is determined from the deviation between the filtered signal and the prediction envelope, while the final qualification state additionally includes the requalification interval following instability events. Shaded regions indicate active requalification periods.

To improve fidelity during the test, certain auxiliary controller features may be temporarily disabled or detuned, depending on site configuration. These may include derivative actions, fallback handling, decoupling logic, and limit-management features that would otherwise interfere with controlled surge approach. The anti-surge proportional–integral controller may also be detuned according to the test objective. The framework records these temporary configuration changes and ensures that normal settings are restored once the test is complete. Formal management of temporary control-system modifications is consistent with procedure-based execution practices intended to maintain traceability and reduce commissioning risk during nonroutine operating activities [21,28].

3.3.6. Recycle Valve Readiness Verification

Before approaching the stability limit, the recycle valve is tested through commanded movement across its operating range. The objective is to confirm that the valve can respond quickly enough to support surge recovery. Problems such as insufficient travel, sluggish actuation, excessive dead time, or stiction must be identified before active testing begins. Because valve response is critical to anti-surge performance, valve readiness is treated as a mandatory supervisory checkpoint rather than an optional pretest check. This approach is consistent with industrial guidance emphasizing that the anti-surge valve must respond rapidly enough to restore the operating point during severe disturbances and, if necessary, during the first surge cycle [9,10,20].

3.3.7. Controlled Reduction of Surge Margin

Following instrumentation verification, process stability qualification, controller preparation, and recycle-valve readiness verification, the framework enters the active test phase.

The anti-surge controller remains in automatic mode, while the effective surge margin is reduced in controlled increments. The reduction is performed in stages rather than continuously. After each step, the operating point is allowed to settle while process conditions are monitored over a defined dwell period. This approach improves repeatability by standardizing the path toward the surge boundary and reduces the likelihood of an abrupt uncontrolled surge by maintaining a gradual, supervised approach to the stability limit [9,10,29].

3.3.8. Surge Detection and Verification Logic

The framework identifies either a verification point or an actual surge event using observable changes in standard process measurements. Event recognition is supported by the baseline-referenced S^+ method described in Section 3.4.1. Once the selected event criterion is satisfied, the surge event is declared, latched, and recorded for engineering review.

The framework distinguishes between two possible outcomes of a test step:

- A verification point, where the planned boundary condition is reached without entering actual surge;
- An actual surge event, where the event criteria are satisfied and immediate recovery is required.

Earlier industrial observations support this emphasis on rapid flow-related changes. Staroselsky and Ladin reported that flow typically falls very rapidly immediately before and during surge and may reverse once the surge cycle develops, making rapid recognition and recovery essential in field protection practice [10].

3.3.9. Recovery Actions

When a surge event is detected, the framework commands the recycle valve to a predefined safe open position and maintains the recovery condition for a specified period to re-establish stable forward flow. The event and corresponding surge point are recorded for later review. Once recovery is complete, the sequence either returns to a safe idle state or proceeds according to the engineer's selected next action. The recovery strategy is designed to minimize both the number and duration of surge cycles. Rapid recycle-valve response remains essential, since successful recovery depends on both the selected recovery action and the dynamic performance of the installed valve system [9,10,19].

3.3.10. Engineer Oversight and Abort Capability

At all stages of the supervisory sequence, the engineer retains authority to pause, abort, or terminate the test and return the compressor to a safe operating condition. The framework supports execution and documentation but does not replace engineering judgement. This approach follows established supervisory-automation principles in which automation assists task execution, while responsibility for high-consequence operational decisions remains with qualified personnel [21,22].

3.4. Surge-Assist Features

3.4.1. Baseline-Referenced S^+ Surge Event Detection

To support surge recognition during supervised field testing, a signal-based detection method was developed using measurements commonly available within industrial anti-surge systems. Existing surge-recognition approaches have employed pressure derivatives, flow-related derivatives, vibration and acoustic features, spectral analysis, machine-learning-based features, and multivariable operating-point parameters derived from pressure- and flow-related measurements. The present method adopts a different approach by evaluating the temporal evolution of a directly measured discharge-

pressure/flow-differential quotient. The S^+ indicator itself is calculated from compressor discharge pressure P_d and the flow-related differential-pressure signal ΔP_o . Recycle-valve output u is used separately to delimit the baseline-learning interval and to support the subsequent valve-transient comparison.

The starting point is the discharge-pressure/flow-differential quotient

$$R(t) = \frac{P_d(t)}{\Delta P_o(t)}, \quad (7)$$

which combines discharge-pressure and flow-related measurements available to the anti-surge system. Rather than evaluating the quotient directly, the proposed indicator is defined as its time derivative,

$$S(t) = \frac{d}{dt} \left(\frac{P_d(t)}{\Delta P_o(t)} \right). \quad (8)$$

This formulation responds to rapid changes in the relationship between discharge pressure and the flow-related signal and therefore emphasizes the transient behavior associated with surge development. Applying the quotient rule yields

$$S(t) = \frac{\dot{P}_d(t)\Delta P_o(t) - P_d(t)\dot{\Delta P}_o(t)}{\Delta P_o(t)^2}. \quad (9)$$

Earlier anti-surge and surge-recognition methods have considered derivatives of individual pressure and flow-related measurements, combinations of multiple derivative channels, and derivatives of normalized compressor operating-point parameters [30]. The proposed S -indicator is narrower in scope. It evaluates the derivative of the directly measured quotient $P_d/\Delta P_o$, producing a single detector signal in which pressure and flow-related dynamics are algebraically coupled through the quotient rule. In the literature and prior-art sources reviewed for this work, this exact raw-measurement quotient derivative was not identified as a centrifugal-compressor surge-event detector. The contribution therefore lies in the formulation and evaluation of $d(P_d/\Delta P_o)/dt$ as a practical field-deployable surge-event recognition metric rather than in pressure–flow coupling as a general concept.

Because the flow-related signal may approach small values near the stability boundary, a protected form of the differential-pressure signal is defined as

$$\Delta P_{o,\text{clip}}(k) = \begin{cases} \Delta P_o(k), & |\Delta P_o(k)| \geq \Delta P_{\min}, \\ \Delta P_{\min}, & 0 \leq \Delta P_o(k) < \Delta P_{\min}, \\ -\Delta P_{\min}, & -\Delta P_{\min} < \Delta P_o(k) < 0. \end{cases} \quad (10)$$

where $\Delta P_{\min}$ is a small lower bound introduced to avoid numerical instability as the denominator approaches zero. For the field-record analysis, the protected lower bound was set to $\Delta P_{\min} = 10^{-3}$ in the native differential-pressure units of each record.

For practical implementation, the derivatives were evaluated over a finite window T_w . Because industrial control-system measurements may be affected by scan-to-scan noise and signal quantization, a finite-window derivative estimate was adopted to improve robustness while preserving the rapid transient behavior associated with surge events. Let

$$N_d = \text{round} \left(\frac{T_w}{\Delta t} \right). \quad (11)$$

The field-record calculations and associated data analysis were performed using MATLAB R2026a (The MathWorks, Inc., Natick, MA, USA). For the field-record characterization presented in this work, $T_w = 0.1$ s. Because all records were sampled at 10 Hz ($\Delta t = 0.1$ s),

this corresponds to $N_d = 1$, so the implemented derivative is a one-sample finite difference evaluated over 0.1 s.

The windowed derivatives are approximated as

$$\dot{P}_d(k) = \frac{P_d(k) - P_d(k - N_d)}{N_d \Delta t}, \quad \Delta \dot{P}_o(k) = \frac{\Delta P_o(k) - \Delta P_o(k - N_d)}{N_d \Delta t}. \quad (12)$$

The resulting indicator is

$$S(k) = \frac{\dot{P}_d(k) \Delta P_{o,clip}(k) - P_d(k) \Delta \dot{P}_o(k)}{\Delta P_{o,clip}(k)^2}. \quad (13)$$

Its positive component is defined as

$$S^+(k) = \max(S(k), 0), \quad (14)$$

To avoid dependence on a fixed universal threshold, the decision threshold is referenced to a baseline segment obtained from the early portion of each test record. The first 10 s of each record are excluded from threshold estimation. The initial recycle-valve reference is defined as the median output over the first 50 samples. A candidate baseline end is identified at the first sample for which the recycle-valve output differs from this reference by more than 20 percentage points. If no such deviation occurs, the candidate baseline end is set to 120 s or to the end of the available record, whichever occurs first. A minimum baseline end of 30 s from the start of the record is enforced. The baseline used for threshold estimation therefore extends from 10 s to the resulting baseline endpoint. The recycle-valve signal is used only to delimit the baseline-learning interval and is not an input to the S^+ indicator.

Defining

$$\mathcal{B} = \{S^+(k) \mid k \in \text{baseline interval}\}, \quad (15)$$

the surge-detection threshold is calculated as

$$S_{thr} = \max(S_{min}, \alpha Q_p(\mathcal{B})), \quad (16)$$

where $Q_p(\mathcal{B})$ denotes the p th percentile of the baseline detected values, α is a threshold scaling factor, and S_{min} is a lower threshold bound. In the field-data implementation presented in this work, $p = 95$ and $\alpha = 50$. Accordingly, the principal adaptive threshold used for the field-record characterization is

$$S_{thr} = 50 Q_{95}(\mathcal{B}), \quad (17)$$

subject to the lower bound S_{min} defined above.

This baseline-referenced formulation allows the detector threshold to adapt to the normal signal behavior of the individual compressor record rather than require a single universal threshold applicable to all machines and operating conditions. Importantly, once the baseline threshold has been established, subsequent process transients, including recycle-valve movements, remain visible to the detector and are not incorporated into the learned baseline.

The instantaneous threshold-exceedance condition is

$$A_{raw}(k) = \begin{cases} 1, & S^+(k) > S_{thr}, \\ 0, & \text{otherwise.} \end{cases} \quad (18)$$

A surge event is identified when $S^+(k)$ first exceeds the baseline-referenced threshold. Because a physical surge episode may contain multiple oscillatory cycles and consequently multiple threshold exceedances, closely spaced exceedances associated with the same oscillatory episode are grouped and treated as a single physical surge event. The first threshold crossing within the grouped episode defines the reported detection time.

To provide an independent time reference for detector evaluation, the physical surge onset in each field record was manually identified from the characteristic coupled pressure and flow-related oscillations observed in the recorded signals. Because the records were sampled at 10 Hz, and the manual onset annotation is subject to finite temporal resolution and engineering interpretation, threshold crossings occurring up to 0.5 s before the manually identified onset were treated as belonging to the same physical surge episode. The event-association interval therefore begins at

$$t_{\text{search,start}} = t_{\text{surge}} - 0.5 \text{ s}. \quad (19)$$

A threshold crossing occurring within this 0.5 s pre-onset tolerance is not interpreted as surge prediction; instead, it is treated as coincident with the manually identified event and assigned a reported detection delay of zero. Accordingly,

$$T_{\text{det}} = \max(0, t_{\text{det}} - t_{\text{surge}}), \quad (20)$$

where t_{surge} is the manually identified surge-onset time, and t_{det} is the first S^+ threshold crossing associated with the same physical surge episode. For the present evaluation, associated crossings were searched from 0.5 s before the manual onset to 10 s after it.

A separate comparison was performed using manually selected recycle-valve transient windows. This comparison was introduced because recycle-valve movement can generate substantial pressure and flow-related transients without representing compressor surge.

For records containing both an independently confirmed surge episode and a retained recycle-valve transient, the valve-induced response was compared directly with the corresponding surge response from the same record. This within-record comparison avoids comparing raw derivative magnitudes between compressors having different engineering units, operating conditions, and instrument scaling.

For the coupled S^+ indicator, the valve-to-surge peak ratio is defined as

$$R_{S,v/s} = \frac{S_{\text{peak,valve}}^+}{S_{\text{peak,surge}}^+}. \quad (21)$$

Similarly, the individual pressure- and flow-related derivative responses are compared according to

$$R_{\dot{P},v/s} = \frac{\max |\dot{P}_d|_{\text{valve}}}{\max |\dot{P}_d|_{\text{surge}}}, \quad (22)$$

and

$$R_{\Delta \dot{P},v/s} = \frac{\max |\Delta \dot{P}_o|_{\text{valve}}}{\max |\Delta \dot{P}_o|_{\text{surge}}}. \quad (23)$$

These ratios quantify how strongly the selected valve transient excites each signal relative to a confirmed surge event observed in the same compressor record. Values approaching unity indicate that the valve transient produces a peak response comparable in magnitude to that observed during surge.

For the S^+ indicator, a second comparison is retained because it is directly related to the detector decision:

$$F_{S,v} = \frac{S_{\text{peak, valve}}^+}{S_{\text{thr}}}. \quad (24)$$

A value $F_{S,v} < 1$ indicates that the selected valve transient remained below the active surge-event threshold.

Records containing shutdown or other confirmed non-surge behavior but no independently confirmed surge episode are treated separately. For such records, a within-record valve-to-surge ratio is not defined; instead, the transient response is assessed relative to the active S^+ threshold and its observed process behavior. This distinction prevents non-surge shutdown behavior from being used as a surrogate surge reference.

The method is intended as a surge-event recognition tool within the supervisory testing workflow rather than as an incipient-surge predictor or standalone compressor-protection law.

Figure 3 summarizes the baseline-referenced S^+ surge-event detection process.

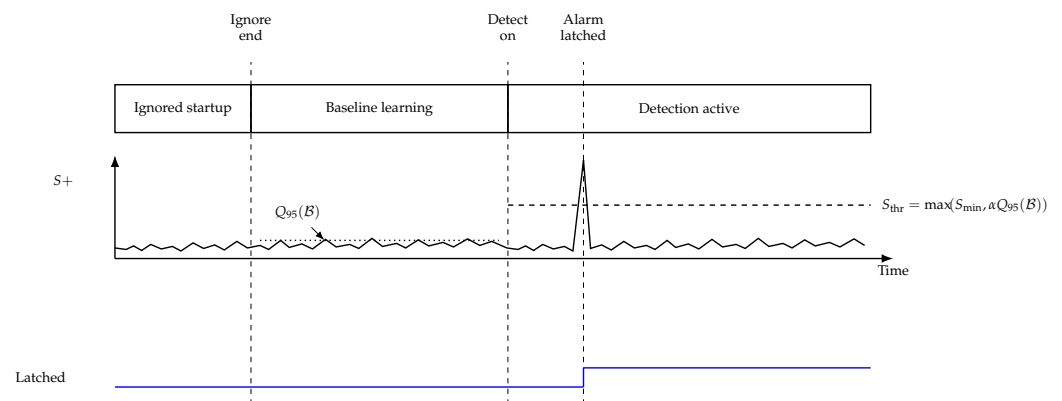


Figure 3. Conceptual illustration of the baseline-referenced S^+ event-recognition method. The detector learns baseline behavior, establishes a threshold from the baseline interval, and latches the event when the threshold is exceeded.

3.4.2. Post-Verification Recovery-Tuning Concept

Once the actual field surge limit has been identified through supervised surge testing, a second practical task becomes possible: selection of a suitable open-loop recycle-valve recovery opening. In industrial anti-surge systems, recovery actions are typically designed to restore adequate operating margin as rapidly as possible while limiting unnecessary recycle flow and associated process disturbance [9,10,17]. In Compressor Controls Corporation terminology, this recovery response is referred to as Recycle Trip® (Recycle Trip is a registered trademark of Compressor Controls Corporation). In many industrial implementations, this action is triggered when the operating point crosses a protective line located between the surge control line and the verified surge limit.

Fixed recovery openings are often selected conservatively. Large opening steps provide stronger protection but may increase recycle losses and process disturbance, whereas smaller openings may fail to restore adequate surge margin. This tradeoff between protection performance and process efficiency has motivated continuing research into improved anti-surge and recycle-control strategies [11,17,31]. The present work therefore formulates recovery selection as a post-verification activity aimed at identifying a suitable single-step opening within the explored candidate range that satisfies a user-defined recovery criterion while avoiding unnecessarily large recycle action. The response associated with the selected opening is subsequently used to define a physically meaningful repeat time.

Let the signed operating-point deviation from the surge control line be denoted by $D(t)$, where increasing positive deviation represents movement toward the desired recovery region. For each recovery test, the pre-action operating condition is used as a local reference. The incremental recovery response is therefore defined as

$$\Delta D(t) = D(t) - D_0, \quad (25)$$

where D_0 is the mean deviation immediately before application of the recovery action. This baseline-referenced quantity represents the operating-point movement produced by the commanded recycle-valve opening and is the response variable used for recovery tuning.

The peak baseline-referenced recovery response is defined as

$$\Delta D_{\text{peak}} = \max_{t \in [t_0, t_{\text{end}}]} \Delta D(t), \quad (26)$$

where t_0 is the recovery-action initiation time, and t_{end} is the end of the evaluation interval.

The recovery objective is to achieve

$$\Delta D_{\text{peak}} \geq \Delta D_{\text{target}}, \quad (27)$$

where $\Delta D_{\text{target}} > 0$ is the prescribed minimum baseline-referenced recovery response. In the representative simulation presented in this work, $\Delta D_{\text{target}} = 0.10$.

A candidate recovery policy is parameterized by the magnitude of the open-loop recycle-valve opening,

$$\Pi = \{\Delta u\}, \quad (28)$$

where Δu is the commanded additional recycle-valve opening applied at the instant the recovery action begins. For each candidate, the recovery command follows a predefined execution profile consisting of an initial opening step, a fixed hold interval, and a subsequent gradual release. The hold and release characteristics are maintained unchanged between candidate tests; therefore, the opening magnitude Δu is the only parameter varied during the tuning procedure. In the representative implementation, the recovery-opening search is initialized from a selected initial guess, $\Delta u_{\text{start}} = 5\%$. If this initial candidate does not satisfy the prescribed recovery criterion, the opening is increased in increments of $\Delta u_{\text{step}} = 10$ percentage points until the first successful recovery opening is identified. The focus on the initial recovery-opening magnitude is consistent with the practical behavior of many industrial anti-surge systems, where rapid valve opening is used to move the operating point away from the surge region before more gradual stabilization takes place [9,10]. The commanded valve position after the recovery step may be written as

$$u_{\text{cmd}} = u_0 + \Delta u, \quad (29)$$

where u_0 is the recycle-valve opening at the instant the recovery sequence begins.

Although the recovery-opening selection is based on the magnitude of the initial opening step, the time required for the resulting operating-point response to develop remains of practical interest. Once the final candidate opening Δu has been selected and applied at time t_0 , the process response time, denoted by T_{process} , is defined as the elapsed time between application of the recovery action and the peak of the resulting baseline-referenced recovery response. Accordingly,

$$T_{\text{process}} = t_{\text{peak}} - t_0, \quad (30)$$

where

$$t_{\text{peak}} = \arg \max_{t \in [t_0, t_{\text{end}}]} \Delta D(t). \quad (31)$$

This definition provides a directly observable timing measure associated with the development of the recovery response. The explicit consideration of response time reflects the fact that surge recovery depends not only on the nominal recovery opening but also on the dynamic interaction between the recycle valve, compressor, and connected process volumes [9,20].

The repeat time is not tuned independently. Once the final candidate has been confirmed and T_{process} has been determined from the measured response, the repeat time is assigned as

$$T_{\text{repeat}} = \beta T_{\text{process}}, \quad 0.7 \leq \beta \leq 0.9, \quad (32)$$

where β is a configurable factor selected by the engineer or supervisory logic. This formulation provides a practical link between the observed process response and the repeat-action timing rather than treating repeat timing as an independent tuning parameter.

For each tested recovery opening, the primary criterion is whether the baseline-referenced recovery target is achieved. A binary success variable is defined as

$$S(\Pi) = \begin{cases} 1, & \Delta D_{\text{peak}} \geq \Delta D_{\text{target}}, \\ 0, & \text{otherwise.} \end{cases} \quad (33)$$

Among the candidates evaluated by the staged search, the preferred recovery opening is the successful opening resolved after bracketing and refinement. The search therefore seeks a sufficiently small recycle-valve opening within the explored candidate range for which

$$\Delta D_{\text{peak}} \geq \Delta D_{\text{target}}. \quad (34)$$

The selection rule is therefore intentionally simple. Rather than seeking a mathematically optimal recovery policy, the objective is to identify a successful recovery action within the explored candidate range that satisfies the prescribed recovery-response target while avoiding unnecessary recycle opening. This emphasis on practical and interpretable tuning is consistent with industrial anti-surge practice, where robustness and transparency are often favored over highly optimized but difficult-to-validate solutions [9,11].

Because the number of practical recovery trials should remain limited, the opening search is performed in two stages. First, the candidate opening is increased by the prescribed coarse increment until the first successful opening is identified. The last unsuccessful candidate defines the lower bracket, Δu_{low} , while the first successful candidate defines the upper bracket, Δu_{high} .

The resulting interval is then refined by bisection. At each iteration, the midpoint candidate is calculated as

$$\Delta u_{\text{mid}} = \frac{\Delta u_{\text{low}} + \Delta u_{\text{high}}}{2}. \quad (35)$$

If the midpoint satisfies the prescribed recovery criterion, the upper bracket is updated according to

$$\Delta u_{\text{high}} = \Delta u_{\text{mid}}, \quad (36)$$

whereas an unsuccessful midpoint updates the lower bracket according to

$$\Delta u_{\text{low}} = \Delta u_{\text{mid}}. \quad (37)$$

The refinement continues until the opening interval satisfies

$$\Delta u_{\text{high}} - \Delta u_{\text{low}} \leq \varepsilon_u. \quad (38)$$

The successful upper bracket is then selected as the final recovery opening,

$$\Delta u_{\text{final}} = \Delta u_{\text{high}}. \quad (39)$$

In this way, the procedure refines the successful recovery opening within the established search bracket, rather than simply selecting a conservatively large recycle opening.

Figure 4 summarizes the proposed post-verification recovery-tuning workflow. The search begins with a selected initial recovery-opening guess and, if the recovery criterion is not satisfied, increases the candidate opening until the first successful upper bracket is identified. The resulting interval is then refined by bisection until the prescribed opening tolerance is satisfied. The selected recovery case is subsequently re-run to determine T_{process} and the corresponding repeat time $T_{\text{repeat}} = \beta T_{\text{process}}$.

3.5. Supporting Dynamic Simulation Environment

A supporting dynamic simulation environment was developed in Simulink R2026a (The MathWorks, Inc., Natick, MA, USA) to assist the development and qualitative assessment of the proposed semi-automated surge-testing framework. The model was used to exercise the supervisory sequence, evaluate the behavior of the proposed surge-event recognition logic, and examine recovery actions following a controlled approach to surge.

The simulation environment is a reduced-order engineering development and qualitative-assessment platform rather than a validated high-fidelity digital twin of a specific compressor installation. It was not calibrated to any of the field compressors and is not intended to predict installation-specific transient amplitudes, frequencies, or time constants. This positioning is consistent with the use of reduced-order compression-system models for understanding surge behavior, testing control concepts, and evaluating system-level interactions without attempting full installation-specific prediction [32–35].

Figure 5 shows the overall Simulink implementation used in this work. The model represents a centrifugal compressor system together with the principal process elements that influence surge behavior, including suction and discharge volumes, suction and discharge throttling elements, a recycle loop, recycle-valve dynamics, a simplified recycle cooler, and supervisory control logic. The structure was selected to capture the dominant dynamic interactions required for surge-testing studies while maintaining a level of complexity suitable for control development and qualitative analysis.

The simulated process begins at the suction boundary and suction throttle valve, which regulate the flow entering the upstream process volume. The upstream volume represents the principal gas capacitance on the suction side and provides the compressor inlet pressure and temperature. The compressor block determines the operating point from the interaction between the compressor performance characteristic and the surrounding system dynamics. Downstream of the compressor, a discharge volume represents the discharge-side gas capacitance and captures the transient pressure response between the compressor outlet and the downstream restriction.

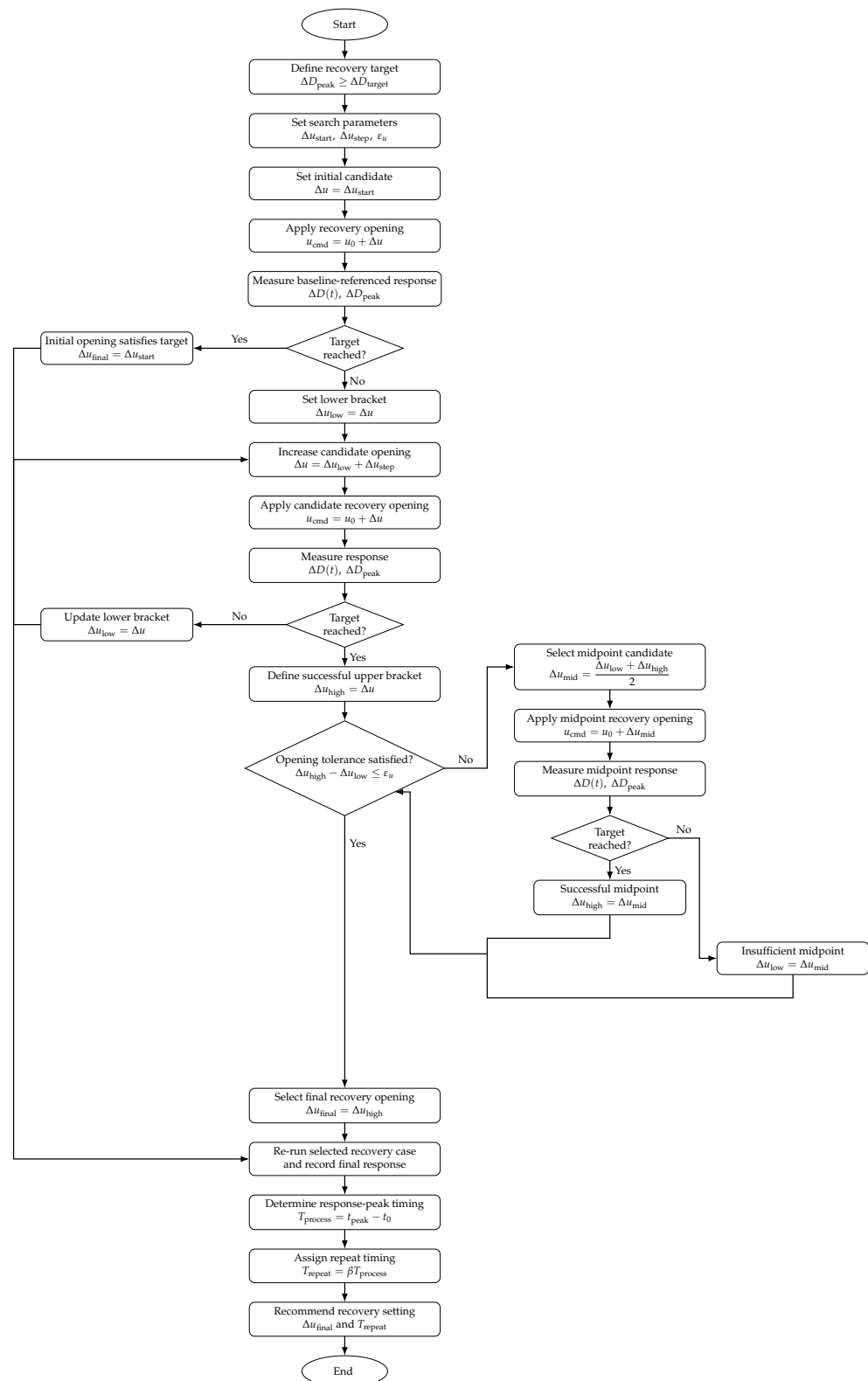


Figure 4. Post-verification recovery-tuning workflow used in the representative implementation. The search begins with an initial recycle-valve opening and increases the candidate opening until the baseline-referenced recovery target is bracketed. The opening interval is considered converged when $\Delta u_{\text{high}} - \Delta u_{\text{low}} \leq \epsilon_u$. If this tolerance is not yet satisfied, midpoint testing is repeated to refine the successful upper and unsuccessful lower brackets. Once the opening tolerance is satisfied, the successful upper bracket is selected as the final recovery opening, and the case is re-run to determine T_{process} and $T_{\text{repeat}} = \beta T_{\text{process}}$.

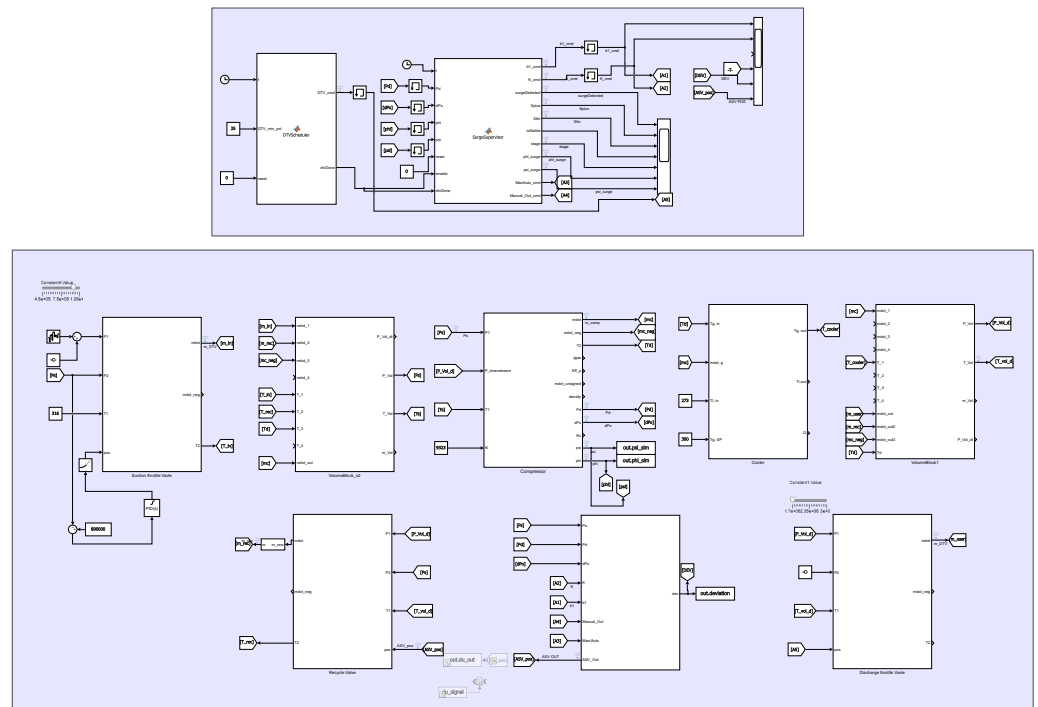


Figure 5. Simulink implementation used to support development and assessment of the proposed surge-testing framework.

The compressor-flow dynamics are represented using a lumped gas-inertia formulation derived from the one-dimensional momentum balance commonly used in compression-system models [4,33,34,36,37]. The rate of change of compressor mass flow is driven by the pressure-force imbalance acting on an equivalent gas column representing the compressor and its associated piping inertia. The governing equation is

$$L_{\text{eff}} \frac{d\dot{m}_c}{dt} = A_{\text{eff}} [P_s + \Delta P_c(\dot{m}_c, N, P_s, T_s) - P_d], \quad (40)$$

where $\dot{m}_c$ is the compressor mass flow rate, L_{eff} is the effective flow-path length, A_{eff} is the effective flow area, P_s is suction pressure, P_d is discharge pressure, and ΔP_c is the compressor pressure rise determined from the compressor characteristic as a function of mass flow rate, rotational speed, and inlet conditions.

Equation (40) represents the inertia of the gas column between the compressor and the surrounding process volumes. Similar compressor-duct inertia formulations form the foundation of Greitzer-type compression-system models, where mass-flow acceleration is governed by the pressure imbalance between the compressor and the downstream system [33,36,37]. When the compressor-generated discharge pressure exceeds the downstream system pressure, the mass flow accelerates; conversely, when the downstream pressure exceeds the compressor-generated pressure, the mass flow decelerates. This formulation provides the principal dynamic coupling between the compressor characteristic and the surrounding system volumes and enables the simulation of surge-related flow oscillations and temporary flow reversal.

The compressor pressure rise appearing in Equation (40) is obtained from a compressor performance characteristic derived from representative compressor map data, as described below.

The compressor characteristic used in the model was obtained from representative centrifugal-compressor performance data expressed in terms of the non-dimensional flow

coefficient ϕ and pressure coefficient ψ . The use of non-dimensional flow and pressure coefficients follows established compressor-modeling practice and facilitates comparison between measured compressor characteristics and dynamic simulation models [33,37]. The available compressor map points were first converted into ordered (ϕ, ψ) pairs and subsequently fitted using a cubic polynomial representation suitable for dynamic simulation. The resulting workflow used to construct the compressor characteristic is illustrated in Figure 6.

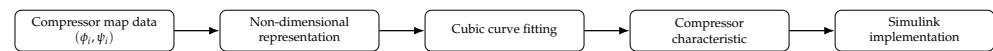


Figure 6. Workflow used to generate the compressor characteristic implemented in the simulation model.

The compressor characteristic is represented by

$$\psi(\phi) = a\phi^3 + b\phi^2 + c\phi + d, \quad (41)$$

where the coefficients implemented in the compressor model are

$$a = -0.4036, \quad b = -0.0283, \quad c = 0.4440, \quad d = 0.9857. \quad (42)$$

To avoid numerical instability during dynamic simulations, the flow coefficient is bounded before evaluation of the polynomial according to

$$-2 \leq \phi \leq 1.4. \quad (43)$$

The available compressor performance data cover the range

$$0.703 \leq \phi \leq 1.266, \quad (44)$$

which is referred to here as the validation region. Within this interval, the polynomial coefficients were selected to reproduce the measured compressor characteristic. Outside this interval, the polynomial is used solely to preserve continuity of the compressor characteristic during surge and flow-reversal simulation. Consequently, the interval

$$-2 \leq \phi < 0.703 \quad (45)$$

is referred to as the simulation region and should be interpreted as a numerical extension rather than a direct representation of measured compressor performance. Similar extensions are commonly employed in dynamic compressor simulations to preserve continuity during surge-cycle and flow-reversal studies when measured compressor data are unavailable in the extended operating range [37,38].

Figure 7 shows both the measured compressor map points and the characteristic implemented in the simulation environment. The measured points define the validation region, while the extended portion of the cubic curve provides a continuous mathematical representation for dynamic simulation when the operating point moves toward surge or flow reversal.

Figure 8 presents the compressor subsystem implemented within the simulation environment. The subsystem receives suction pressure, inlet temperature, gas properties, rotational speed, impeller diameter, and flow-related inputs. It then calculates the compressor pressure coefficient, pressure ratio, polytropic head, pressure rise, discharge temperature, efficiency, and gas power. These outputs provide the main dynamic link between the compressor characteristic and the surrounding suction and discharge volumes.

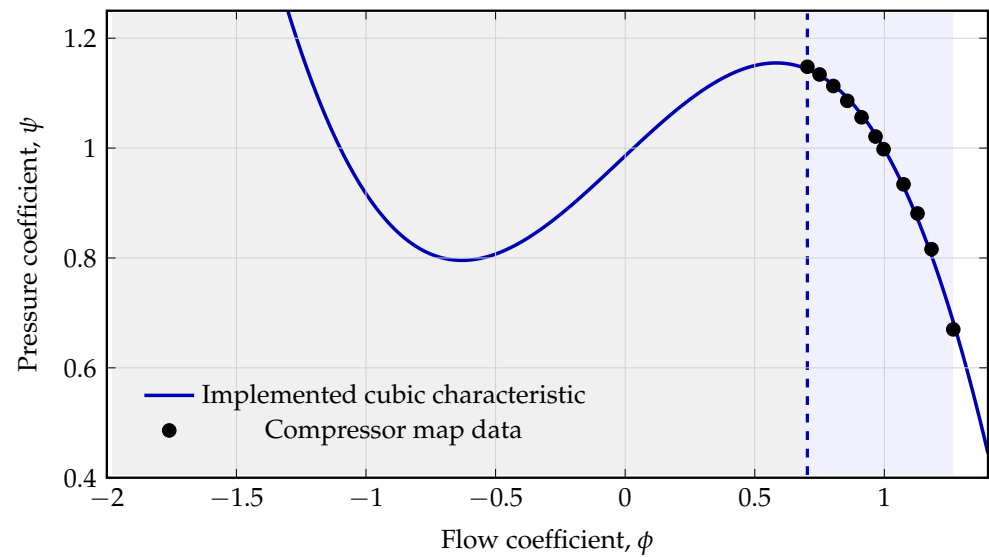


Figure 7. Compressor characteristic implemented in the simulation environment. The measured compressor-map points define the validation region, while the negative-flow portion of the characteristic is retained as a continuous mathematical extension for surge and flow-reversal simulations. The blue-shaded region indicates the validation region, while the gray-shaded region indicates the simulation-extension region.

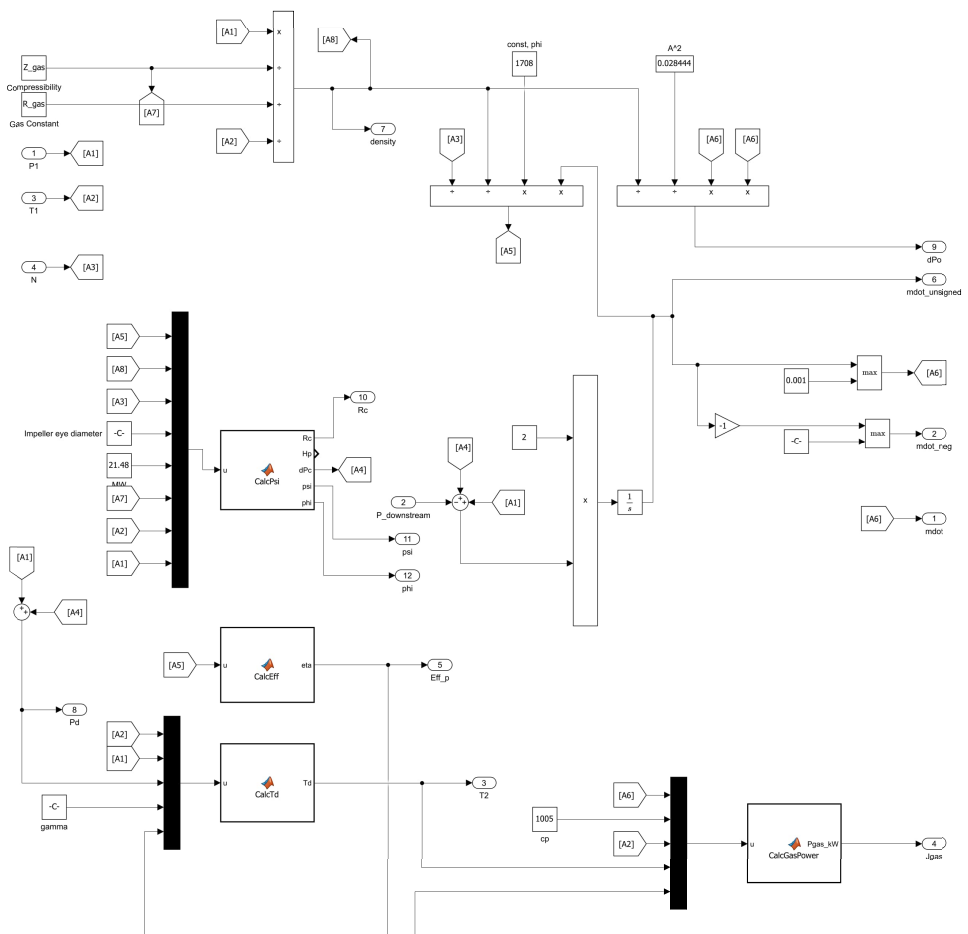


Figure 8. Compressor subsystem used within the dynamic simulation environment. The subsystem calculates compressor pressure coefficient, flow coefficient, pressure ratio, polytropic head, discharge temperature, efficiency, and gas power from the compressor characteristic and operating conditions.

The upstream and downstream process volumes are represented using lumped-parameter mass and energy balances, following the general structure of reduced-order compressor-system models in which gas storage and gas inertia are represented by a small number of dynamic states [33,36,39]. For a generic well-mixed control volume, the mass balance is expressed as

$$\frac{dm}{dt} = \sum \dot{m}_{in} - \sum \dot{m}_{out}, \quad (46)$$

where m is the gas mass contained in the volume, $\dot{m}_{in}$ denotes incoming mass-flow rates, and $\dot{m}_{out}$ denotes outgoing mass-flow rates. Assuming ideal-gas behavior and spatially uniform properties within each volume, the pressure dynamics may be expressed in simplified form as

$$\frac{dp}{dt} = \frac{\kappa R}{V} (\sum T_{in} \dot{m}_{in} - T \sum \dot{m}_{out}), \quad (47)$$

where p is the volume pressure, V is the volume, R is the gas constant, κ is the specific heat ratio, T_{in} is the temperature of the incoming stream, and T is the well-mixed volume temperature. This lumped representation captures the dominant suction- and discharge-pressure transients relevant to surge approach and recycle recovery. Although simplified, this representation captures the principal storage effects responsible for the interaction between compressor flow dynamics and process-volume pressure dynamics during surge development [36,37,40].

The compressor head is calculated from the pressure coefficient using a reference-head scaling,

$$H_p = \psi H_{p,o}, \quad (48)$$

where H_p is the compressor polytropic head, and $H_{p,o}$ is the reference head used for scaling. In the present implementation,

$$H_{p,o} = 145,000 \text{ J kg}^{-1}. \quad (49)$$

The compressor pressure ratio is then calculated from the polytropic head relation,

$$R_c = \left[1 + \frac{H_p MW \sigma}{Z R_u T_s} \right]^{1/\sigma}, \quad (50)$$

where R_c is the compressor pressure ratio, MW is the molecular weight, Z is the gas compressibility factor, R_u is the universal gas constant, T_s is the suction temperature, and σ is the polytropic volume coefficient. In the present implementation, $\sigma = 0.22$. The compressor pressure rise is obtained from

$$\Delta P_c = P_s (R_c - 1), \quad (51)$$

and the discharge pressure is therefore

$$P_d = P_s + \Delta P_c. \quad (52)$$

The compressor outlet temperature is estimated using the pressure ratio and polytropic efficiency,

$$T_2 = T_1 (R_c)^{\frac{\kappa-1}{\kappa \eta_p}}, \quad (53)$$

where T_1 and T_2 are the compressor inlet and outlet temperatures, respectively, η_p is the polytropic efficiency, and κ is the specific heat ratio. The efficiency is calculated in the compressor subsystem using a separate efficiency relation, while the gas power is computed from the resulting head and compressor mass flow.

A recycle path connects the compressor discharge side back to the suction side through a recycle valve and cooling element. This recycle loop provides the primary surge-recovery mechanism within the model. When the recycle valve opens, a portion of the compressed gas is returned to the compressor inlet, increasing compressor flow and moving the operating point away from the surge region. The recycle subsystem is shown in Figure 9.

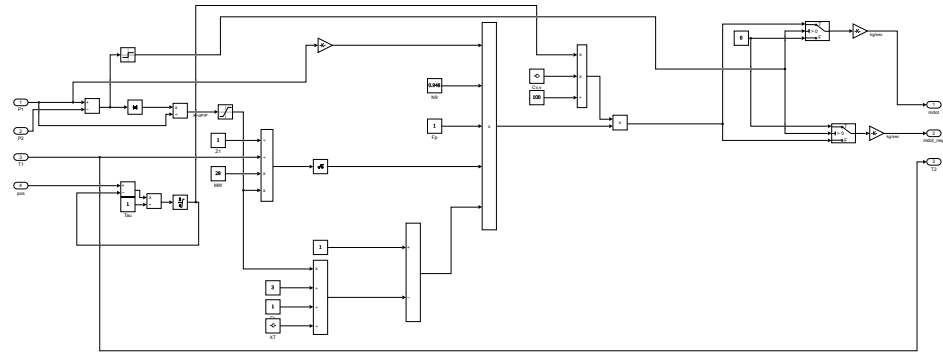


Figure 9. Recycle subsystem used for surge-recovery studies. The subsystem returns a portion of the compressor discharge flow to the suction side through a dynamic recycle valve and associated flow calculation, providing the primary anti-surge recovery mechanism.

The recycle-valve flow is represented using a simplified compressible-flow relation based on valve coefficient, pressure drop ratio, gas properties, and valve position. In compact form, the recycle-valve mass flow may be written as

$$\dot{m}_{rv} = C_v(u) f(P_1, P_2, T_1, Z_1, MW, X), \quad (54)$$

where $\dot{m}_{rv}$ is the recycle-valve mass flow, $C_v(u)$ is the valve coefficient as a function of valve opening u , P_1 and P_2 are the upstream and downstream valve pressures, T_1 is the upstream gas temperature, Z_1 is the upstream compressibility factor, MW is the gas molecular weight, and

$$X = \frac{P_1 - P_2}{P_1} \quad (55)$$

is the pressure drop ratio. The valve subsystem distinguishes between subcritical and limited-flow behavior through the pressure-drop-ratio calculation and associated valve constants. The actuator response is represented by a first-order dynamic element,

$$\tau_v \frac{du}{dt} + u = u_{cmd}, \quad (56)$$

where τ_v is the actuator time constant, u is the valve position, and u_{cmd} is the commanded valve opening. This representation allows the model to capture the finite response speed of the recycle valve during surge recovery.

The supervisory logic uses the simulated process signals to reproduce the principal stages of the proposed surge-testing workflow. These signals include suction pressure, discharge pressure, flow-related differential pressure, compressor flow, recycle-valve position, and the derived variables used by the surge-event recognition method.

Several simplifying assumptions were adopted to maintain computational efficiency and to keep the model suitable for control-logic development. The gas inside each process volume is assumed to be well mixed. Piping acoustics and distributed wave propagation are not explicitly modeled—despite their known influence on some compressor-system transients [14,40]—gas properties are treated in simplified form, and the compressor is represented using a single-speed cubic characteristic. installation-specific surge transients with

full quantitative accuracy. Instead, it serves as a qualitative development and assessment tool for the proposed framework, consistent with the use of reduced-order compression-system models for surge studies, controller development, and system-level interpretation [32,34,41].

3.6. Surge Limit Representation and Field Verification Basis

The industrial guidance considered in this study recommends representing the surge limit in reduced-head or pressure-ratio versus reduced-flow coordinates because this form reduces sensitivity to gas-composition changes and improves surge-prediction accuracy [9]. Earlier industrial work likewise emphasized the need to construct surge limit and surge control lines in a way that reflects changing operating conditions rather than relying on overly simplified representations [10]. The guidance further recommends selecting surge margins that account for both surge limit uncertainty and the dynamic behavior of the installed system, with a typical range of 6–10% of the actual surge flow limit, although plant-specific requirements may differ [9]. Field verification is particularly relevant because it evaluates the surge limit model under the compressor's actual operating conditions and installed configuration. The same guidance recommends that such testing be conducted with extreme caution. Initial verification is preferably performed under relatively low pressure-differential and operating-pressure conditions, often referred to as “low-energy” conditions. If verification is later required at higher-head conditions, lower-energy tests should be completed first to characterize compressor behavior and instrumentation response near surge [9].

The framework does not prescribe a universal numerical threshold for escalation from lower-energy to higher-head testing. This progression is intentionally retained under qualified engineering authority because the acceptable test condition depends on compressor configuration, process conditions, and site-specific operating limits. The supervisory implementation may provide guidance messages to support this decision, but final authorization remains with the responsible engineer. This retained decision authority is one of the reasons the proposed framework is semi-automated rather than fully autonomous.

The supervisory methodology is not restricted to single-stage compressors or to linear surge-limit representations. For multi-stage or multi-cylinder configurations, the framework is applied to the stage protected by the corresponding anti-surge system using the relevant stage measurements and surge-limit representation. Where multiple stages are represented by a common overall anti-surge system, the same supervisory methodology is applied to the corresponding overall surge representation. The surge-limit representation may therefore be linear or nonlinear without changing the general supervisory sequence.

The guidance also highlights several practical benefits of field surge testing. These include confirming correct instrumentation installation and operation, verifying control-system functionality, validating surge-detection systems where used, confirming that the actual surge point does not lie to the right of the predicted surge point, and observing vibration behavior near the surge boundary [9]. Together, these considerations support the use of a structured field-verification process rather than relying solely on factory test results or static OEM surge models.

4. Results and Discussion

4.1. Multi-Case Surge Signature and Event Detection

The proposed surge-event recognition method was evaluated using seven field-recorded cases obtained from industrial centrifugal compressors. Samples 1–5 contain independently confirmed surge events and are used for quantitative surge-event detection evaluation. Sample 6 contains a shutdown transient with substantial recycle-valve and

process movement but is not classified as a surge event. Sample 7 is a confirmed no-surge record and is used as an additional non-surge reference.

The seven cases include compressors from MAN Diesel & Turbo (now Everllence), GHH-BORSIG (now Everllence), Baker Hughes, and Siemens AG, covering high-pressure gas compression, recycle-gas service, gas-compression-plant applications, and refrigeration service. The working fluids include sour hydrocarbon gas, a hydrogen/hydrocarbon mixture, lean natural gas, and propane. The dataset also spans different compressor configurations, driver types, rotational speeds, and flow-measurement arrangements.

All seven field records were sampled at 10 Hz, corresponding to a sampling interval of 0.1 s. The recorded signals were retained in their native engineering units rather than converted to a common unit system. For Sample 1, P_s and P_d are expressed in barg and ΔP_o in mbar. For Sample 2, P_s and P_d are expressed in kg/cm²g and ΔP_o in mmWC. For Samples 3–7, P_s and P_d are expressed in psig and ΔP_o in inH₂O. Recycle-valve output is expressed as percent opening in all records.

Consequently, the dimensional units of S^+ are record dependent. Cross-record comparisons are therefore based on dimensionless normalized quantities such as S^+ / S_{thr} or $S^+ / Q_{95}(\mathcal{B})$, rather than direct comparison of absolute S^+ magnitudes.

For quantitative detector evaluation, the physical surge onset in each record was manually identified from the characteristic coupled pressure and flow-related oscillations. The automatic detection time reported in the following analysis corresponds to the first S^+ threshold crossing associated with that manually identified surge episode. This distinction is important because it evaluates detector response relative to the physical surge event rather than simply reporting the first threshold excursion anywhere in the complete record.

Table 1 summarizes the available machine, operating, and measurement characteristics of the seven field records.

The available field records span different compressor services, driver arrangements, operating speeds, gas compositions, and flow-measurement configurations. Molecular weight ranges from 7.85 to 44.08 kg/kmol, while the assessed rotational speed ranges from 8291 to 14,427 rpm. The dataset includes five independently confirmed surge records, one shutdown record containing substantial recycle-valve and process transients without confirmed surge, and one confirmed no-surge record. Samples 1–5 are therefore used for quantitative surge-event recognition, while Samples 6 and 7 provide complementary evidence for interpretation of non-surge transient behavior. Although the dataset remains limited in size, it provides useful variation in the installed conditions under which the proposed event-recognition method is evaluated.

For each manually annotated physical surge episode, the first baseline-referenced S^+ threshold crossing associated with that episode was identified together with the maximum S^+ response reached during the developed transient. The detection delay was evaluated relative to the manually identified surge onset, while the peak detector response was referenced to the record-specific pre-event baseline.

To provide a common normalized measure between records, the maximum surge-associated S^+ response was compared with the 95th percentile of the corresponding baseline,

$$R_{S^+} = \frac{S_{\text{peak,surge}}^+}{Q_{95}(S_{\text{baseline}}^+)}. \quad (57)$$

This normalization expresses the magnitude of the developed surge response relative to the normal upper-range variation of the same record and avoids direct comparison of absolute S^+ magnitudes between installations having different pressure levels, flow-signal scaling, and background noise.

Table 1. Summary of the seven field-recorded centrifugal-compressor records used in the field evaluation.

Parameter	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7
Record classification	Confirmed surge	Confirmed surge	Confirmed surge	Confirmed surge	Confirmed surge	Shutdown/non-surge transient	Confirmed no surge
OEM/model	MAN Diesel & Turbo ^a /RB 28-5	GHH-BORSIG ^a /RV050/06	Baker Hughes/2BCL608	Baker Hughes/2BCL607	Baker Hughes/2BCL607	Siemens AG/STC-SV (08-6-A)	Siemens AG/STC-SV (08-6-A)
Service	HP gas compressor	Recycle gas	Gas compression plant	Gas compression plant	Gas compression plant	Refrigeration	Refrigeration
Configuration/stages	Single stage	Single stage	Two stages ^b	Two stages ^b	Two stages ^b	Two stages ^b	Two stages ^b
Driver	Variable-speed electric motor	Steam turbine	Fixed-speed synchronous motor	Fixed-speed synchronous motor	Fixed-speed synchronous motor	Fixed-speed electric motor	Fixed-speed electric motor
Working fluid	Sour hydrocarbon	H ₂ /hydrocarbon mixture	Lean natural gas	Lean natural gas	Lean natural gas	Propane	Propane
Molecular weight (kg/kmol)	26.64	7.85	20.54	19.41	21.99	44.08	44.08
Speed at assessed condition (rpm)	14,427	9027	9232	9371	8291	8700	8700
Flow-measuring device	Orifice, corner tapping	Long-pattern Venturi	Venturi, welded 15° cone, D and d/2 taps	Venturi, welded 15° cone, D and d/2 taps	Venturi, welded 15° cone, D and d/2 taps	Venturi, welded 15° cone, D and d/2 taps	Venturi, welded 15° cone, D and d/2 taps
Signal units	P_s, P_d : barg; ΔP_o : mbar; OUT: %	P_s, P_d : kg/cm ² g; ΔP_o : mmWC; OUT: %	P_s, P_d : psig; ΔP_o : inH ₂ O; OUT: %	P_s, P_d : psig; ΔP_o : inH ₂ O; OUT: %	P_s, P_d : psig; ΔP_o : inH ₂ O; OUT: %	P_s, P_d : psig; ΔP_o : inH ₂ O; OUT: %	P_s, P_d : psig; ΔP_o : inH ₂ O; OUT: %
Sampling frequency (Hz)	10	10	10	10	10	10	10

^a MAN Diesel & Turbo and GHH-BORSIG are now part of Everllence. ^b Two-stage compressor; only one stage was assessed in the corresponding field record. All flow-measuring devices were located on the compressor suction side. OUT denotes recycle-valve output.

Table 2 combines the independently referenced detection timing with the baseline- and threshold-normalized S^+ response for the five independently confirmed surge records. Absolute S^+ quantities retain the native engineering units of the corresponding record, whereas the normalized ratios are dimensionless.

Table 2. Surge-associated detection timing and baseline-referenced S^+ characterization for the five independently confirmed surge records.

Quantity	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Manual surge onset, t_{surge} (s)	9082.6	887.6	722.3	558.2	1020.4
Associated threshold crossing, t_{det} (s)	9082.3	887.6	722.4	558.2	1020.5
Raw crossing offset, $t_{\text{det}} - t_{\text{surge}}$ (s)	−0.3	0.0	0.1	0.0	0.1
Reported detection delay, T_{det} (s)	0.0	0.0	0.1	0.0	0.1
Baseline S^+ , $Q_{95}(\mathcal{B})$	0.01339	0.28284	0.45151	1.0965	0.69064
Detection threshold, $50Q_{95}(\mathcal{B})$	0.66949	14.1422	22.5756	54.8259	34.532
S^+ at manual surge onset	0	139.53	11.252	57.917	0
$S^+_{\text{onset}}/S_{\text{thr}}$	0	9.8665	0.4984	1.0564	0
Peak S^+ time (s)	9085.5	887.6	722.6	559.1	1021.8
Peak S^+	12,233	139.53	1875.1	6.134×10^9	3351.9
$S^+_{\text{peak}}/Q_{95}(\mathcal{B})$	9.1364×10^5	493.33	4153	5.5941×10^9	4853.3
$S^+_{\text{peak}}/S_{\text{thr}}$	18,273	9.8665	83.06	1.1188×10^8	97.065

Absolute S^+ values use the native engineering units listed in Table 1. Normalized ratios are dimensionless. A threshold crossing occurring within 0.5 s before the manually identified surge onset is associated with the same physical event and reported with $T_{\text{det}} = 0$.

Across the five independently confirmed surge records, an associated S^+ threshold crossing was identified in every case. The raw crossing offset relative to the manually identified surge onset ranged from −0.3 to 0.1 s. After application of the 0.5 s pre-onset association tolerance described in Section 3.4.1, the reported detection delay ranged from 0 to 0.1 s, with a median value of 0 s. Thus, five out of five confirmed surge episodes were recognized within the prescribed event association interval.

The corresponding detector responses for the five confirmed surge cases are shown in Figure 10.

The negative raw offset observed in Sample 1 is not interpreted as prediction of surge onset. Rather, it reflects the finite 0.1 s sampling resolution together with uncertainty in manual identification of the physical onset from the recorded pressure and flow-related oscillations. The result is therefore reported as a zero-delay associated detection in accordance with the predefined evaluation rule.

The relationship between the manually identified onset and the detector threshold varied between the five confirmed surge records. At the exact manually annotated onset sample, S^+ remained below threshold in Samples 1, 3, and 5, with onset-to-threshold ratios of 0, 0.4984, and 0, respectively. In Samples 2 and 4, the detector had already reached or exceeded the active threshold at the manually identified onset, with corresponding ratios of 9.8665 and 1.0564.

These differences should be interpreted in the context of the 10 Hz sampling rate, the oscillatory nature of the developed surge transient, and the finite uncertainty associated with manual onset annotation. The detector is therefore evaluated using the predefined event-association interval rather than requiring the threshold crossing to occur strictly after the manually selected onset sample. This treatment is consistent with the intended role of S^+ as a surge-event recognition metric rather than as an incipient-surge predictor.

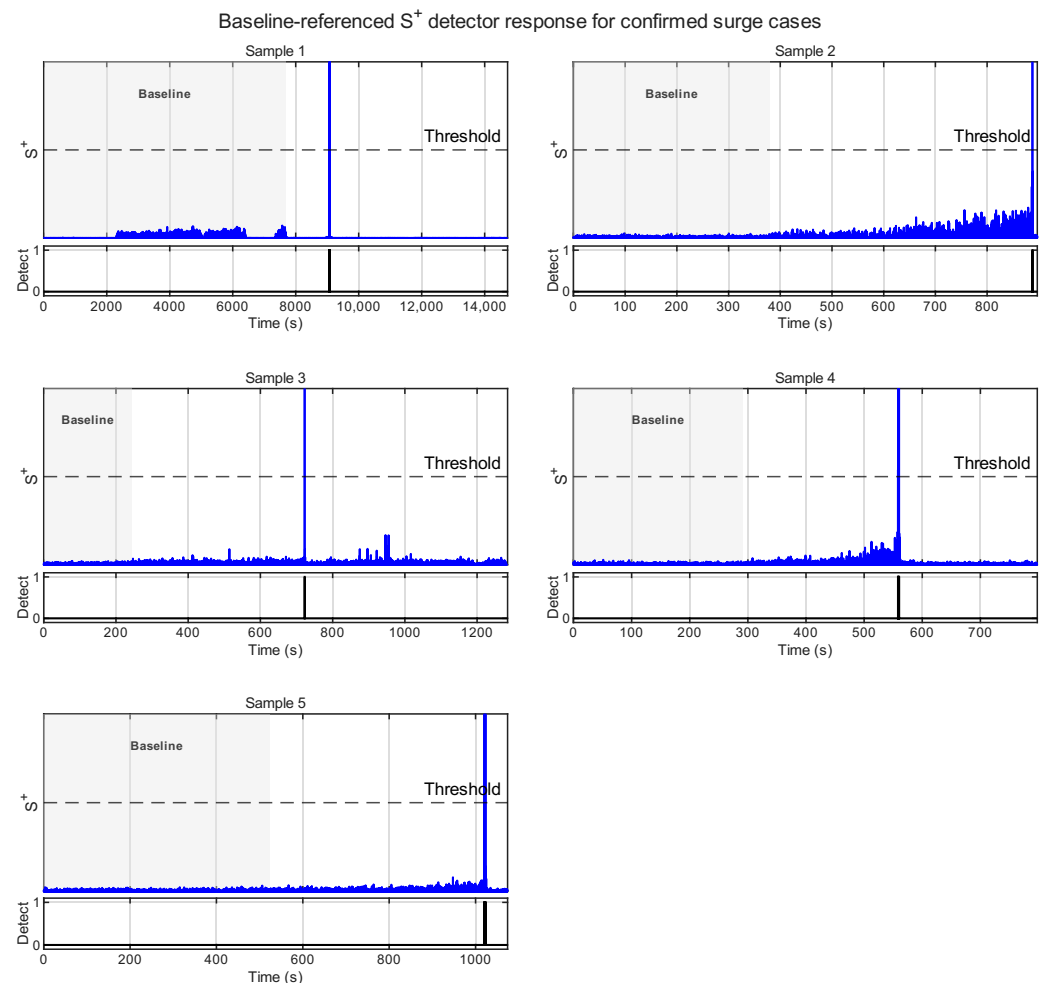


Figure 10. Baseline-referenced S^+ detector response for the five confirmed surge cases. The blue trace represents the S^+ detector response. The shaded region indicates the baseline interval used for threshold estimation, the dashed line denotes the active record-specific threshold S_{thr} , and the lower trace in each panel shows the resulting detection state. All five independently confirmed surge events produced a detector response exceeding the corresponding threshold.

Following surge development, all five confirmed surge records produced peak S^+ values above their respective record-specific detection thresholds. The normalized peak response,

$$R_{thr} = \frac{S_{peak}^+}{S_{thr}}, \quad (58)$$

ranged from 9.8665 in Sample 2 to 1.1188×10^8 in Sample 4. Thus, even the least-separated confirmed surge case produced a peak S^+ response nearly one order of magnitude above its active record-specific threshold.

Relative to the pre-event baseline, the peak S^+ response ranged from 493.33 times $Q_{95}(\mathcal{B})$ in Sample 2 to 5.5941×10^9 times $Q_{95}(\mathcal{B})$ in Sample 4. The wide variation reflects differences in compressor operating condition, native signal units and scaling, flow-measurement configuration, and the degree to which the flow-related differential-pressure signal approaches zero during the developed transient.

Because the field records retain their native engineering units, absolute S^+ magnitudes are not directly comparable between installations. Cross-record interpretation therefore relies primarily on dimensionless quantities such as S^+ / S_{thr} and $S^+ / Q_{95}(\mathcal{B})$. Furthermore, neither the absolute nor normalized peak magnitude should be interpreted as a direct measure of physical surge severity.

The behavior of the detector can be interpreted from its defining expression,

$$S(t) = \frac{\dot{P}_d(t)\Delta P_o(t) - P_d(t)\Delta \dot{P}_o(t)}{\Delta P_o(t)^2}. \quad (59)$$

The indicator responds to the simultaneous evolution of discharge pressure and the flow-related differential-pressure signal. In particular, a rapid decrease in ΔP_o while P_d remains appreciable can generate a large positive S^+ response. This coupled behavior is representative of the developed surge transient, in which compressor flow falls rapidly while the pressure field undergoes substantial dynamic variation.

The exceptionally large normalized peak observed in Sample 4 requires particular caution in interpretation. During the developed surge transient, the measured flow-related differential pressure ΔP_o approaches the protected lower-denominator region used in the computation of

$$R = \frac{P_d}{\Delta P_o}. \quad (60)$$

Consequently, a rapid change in $P_d/\Delta P_o$ can produce a very large value of S^+ , even though this does not imply that Sample 4 experienced a physically more severe surge than the other records. The denominator protection prevents numerical singularity, but the resulting peak magnitude remains sensitive to very small values of ΔP_o .

Accordingly, the extreme Sample 4 peak is interpreted only as a strong surge-associated detector response. It is not used as a quantitative measure of surge severity or for direct comparison of physical surge intensity between compressors.

The record-specific baseline normalization is therefore important to the proposed method. Rather than relying on a universal absolute value of S^+ , the detector evaluates the transient relative to the normal upper-range behavior observed in the same record. This permits the same recognition structure to be applied across compressors having substantially different pressure levels, flow-signal magnitudes, and background noise.

The results also motivate comparison with individual process derivatives. Large values of $|\dot{P}_d|$ or $|\Delta \dot{P}_o|$ are not unique to surge and may also occur during recycle-valve movement and other rapid process transients. The valve-transient comparison presented subsequently therefore examines whether the coupled S^+ formulation provides useful additional discrimination against this field-relevant disturbance.

The dimensionless peak-to-threshold ratios reported in Table 2 provide the most appropriate basis for comparing detector response across the five confirmed surge records. All five events exceeded their corresponding adaptive thresholds, while the magnitude of the normalized response varied substantially between records. This variation is expected because the detector response depends on the local pressure and flow-related signal dynamics and should not be interpreted as a measure of relative surge severity.

Figures 11 and 12 present two representative field records in full signal form, including discharge pressure P_d , flow-related differential pressure ΔP_o , recycle-valve output, the derived S^+ indicator, the baseline-derived threshold, and the resulting detection signal.

The results demonstrate response to independently identified positive surge episodes and quantify the corresponding detection delay. They do not, however, by themselves establish false-alarm performance against non-surge disturbances. This distinction is important because rapid process transients can also generate large individual pressure or flow-related derivatives. Accordingly, the next analysis examines manually identified recycle-valve transients as a specific field-relevant non-surge disturbance and compares their response with the confirmed surge episodes.

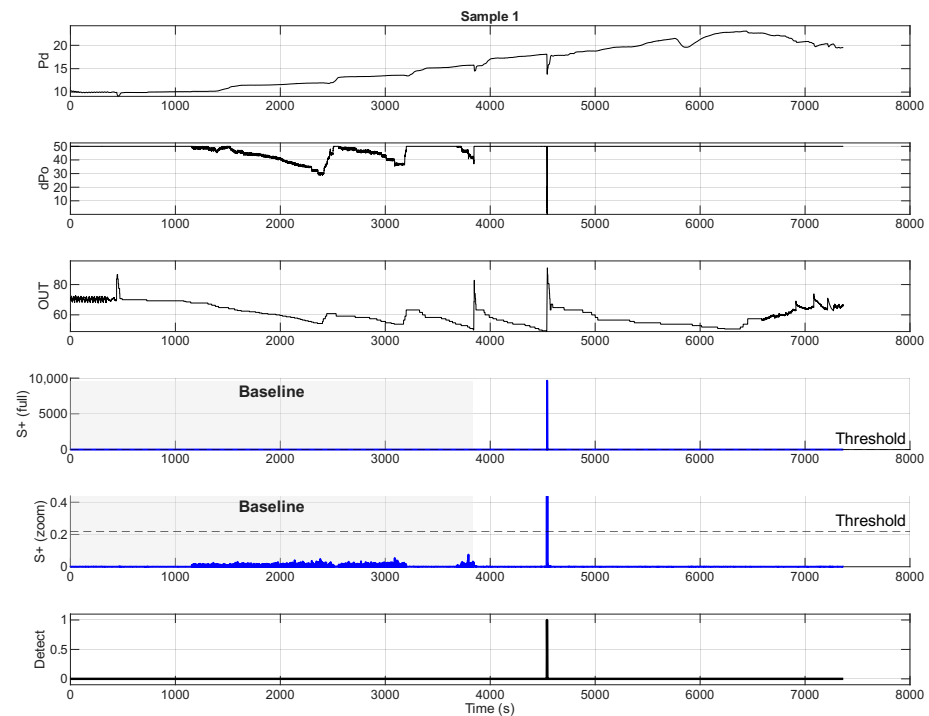


Figure 11. Representative field-recorded surge event (Sample 1) showing discharge pressure P_d , flow-related differential pressure ΔP_o , recycle-valve output, the derived S^+ indicator, the baseline-derived threshold, and the resulting detection signal. The black traces show the measured field signals and detection state, the blue traces show the derived S^+ responses, the dashed lines indicate the corresponding thresholds, and the shaded regions indicate the baseline interval used for threshold estimation.

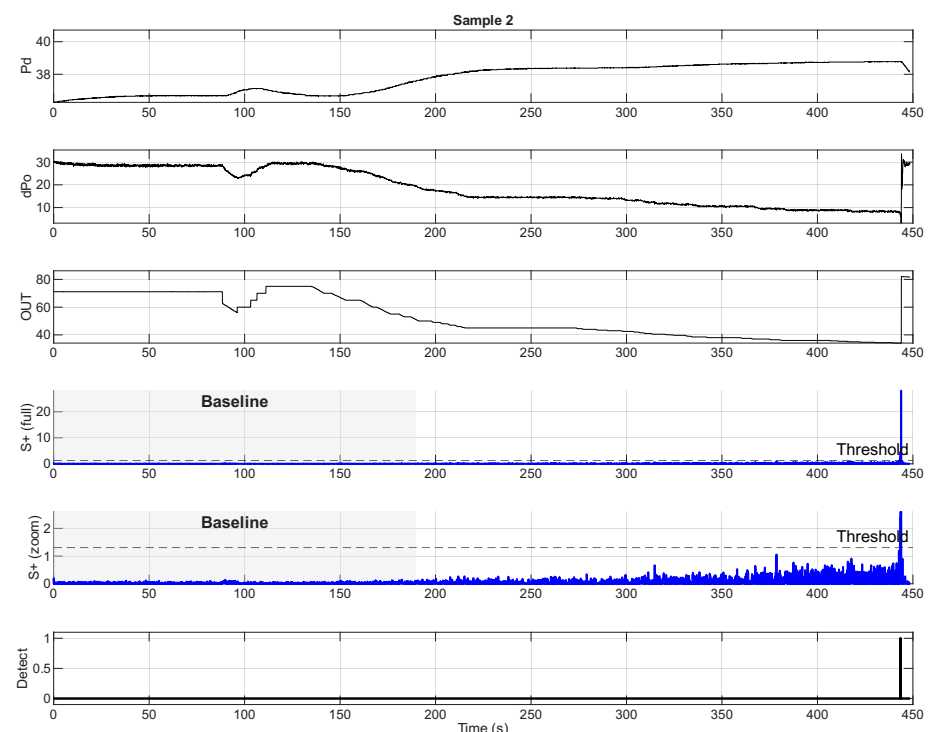


Figure 12. Representative field-recorded surge event (Sample 2) demonstrating the detector response under different signal magnitudes and operating conditions. The black traces show the measured field signals and detection state, the blue traces show the derived S^+ responses, the dashed lines indicate the corresponding thresholds, and the shaded regions indicate the baseline interval used for threshold estimation.

4.2. Recycle-Valve Transient Discrimination

Recycle-valve movement represents a particularly relevant non-surge transient for the proposed framework because valve-readiness verification is performed before the compressor is intentionally moved toward the surge boundary. Opening of the recycle valve can generate rapid changes in both discharge pressure and the flow-related differential-pressure signal. Consequently, a surge-event indicator based only on an individual signal derivative may respond strongly even though the compressor has not entered surge.

To examine this behavior, manually selected recycle-valve transient windows were evaluated separately from the confirmed surge episodes. Samples 1–3 contain both an independently confirmed surge episode and a representative recycle-valve transient and are therefore used for the direct within-record valve-to-surge comparison. Samples 4 and 5 do not contain retained recycle-valve transient windows for this analysis. Sample 6 is treated separately as a shutdown/non-surge case because no independently confirmed surge episode is available in that record, while Sample 7 provides an additional confirmed no-surge reference.

Table 3 summarizes the selected recycle-valve transients for Samples 1–3 and compares their peak responses directly with the corresponding confirmed surge response from the same record. The comparison includes the valve-to-surge ratios for S^+ , $|\dot{P}_d|$, and $|\Delta P_o|$. In addition, $S_{\text{peak, valve}}^+ / S_{\text{thr}}$ is reported to show how closely each selected valve transient approached the active surge-event threshold.

To provide a direct within-record comparison, the peak responses of the selected recycle-valve transient windows in Samples 1–3 were normalized by the corresponding peak responses of the confirmed surge events from the same records. Figure 13 compares the resulting valve-to-surge ratios for the coupled S^+ indicator and for the individual discharge-pressure and flow-related differential-pressure rates of change. A value of unity indicates that the valve-transient peak equals the corresponding surge peak in the same record.

Table 3. Within-record comparison of representative recycle-valve transients with the corresponding confirmed surge response for Samples 1–3.

Quantity	Sample 1	Sample 2	Sample 3
Valve-window start (s)	7550	150	800
Valve-window end (s)	7800	250	1250
Maximum valve output (%)	83.604	75.0	100.0
Peak valve-window S^+	0.1103	0.54419	7.2328
Peak surge S^+	12,233	139.53	1875.1
Valve-to-surge S^+ ratio, $R_{S^+, v/s}$	9.02×10^{-6}	3.90×10^{-3}	3.86×10^{-3}
$S_{\text{peak, valve}}^+ / S_{\text{thr}}$	0.1648	0.0385	0.3204
Threshold crossed in selected valve window?	No	No	No
Peak valve-window $ \dot{P}_d $	0.741	0.500	8.18
Peak surge $ \dot{P}_d $	3.104	0.500	129.69
Valve-to-surge $ \dot{P}_d $ ratio, $R_{\dot{P}_d, v/s}$	0.2387	1.000	0.0631
Peak valve-window $ \Delta P_o $	220.4	8.75	36.654
Peak surge $ \Delta P_o $	2171.1	224.25	190.3
Valve-to-surge $ \Delta P_o $ ratio, $R_{\Delta P_o, v/s}$	0.1015	0.0390	0.1926

Absolute S^+ and derivative values retain the native engineering units of the corresponding field record. The valve-to-surge ratios and $S_{\text{peak, valve}}^+ / S_{\text{thr}}$ are dimensionless and are therefore used for interpretation.

The comparison shows that the selected valve-transient S^+ response is substantially smaller than the corresponding surge response in all three records. The valve-to-surge S^+ ratios are approximately 9.02×10^{-6} , 3.90×10^{-3} , and 3.86×10^{-3} for Samples 1, 2, and 3, respectively. The individual derivative ratios, however, show considerably less separation

between the two event types. Most notably, in Sample 2, the peak $|\dot{P}_d|$ during the selected valve transient is equal to that observed during surge, whereas the corresponding valve-to-surge S^+ ratio is only 3.90×10^{-3} . This contrast indicates that a large individual pressure rate of change is not, by itself, sufficient to distinguish surge from recycle-valve-induced process transients. The coupled S^+ formulation therefore provides stronger within-record discrimination by capturing the combined pressure and flow-related response.

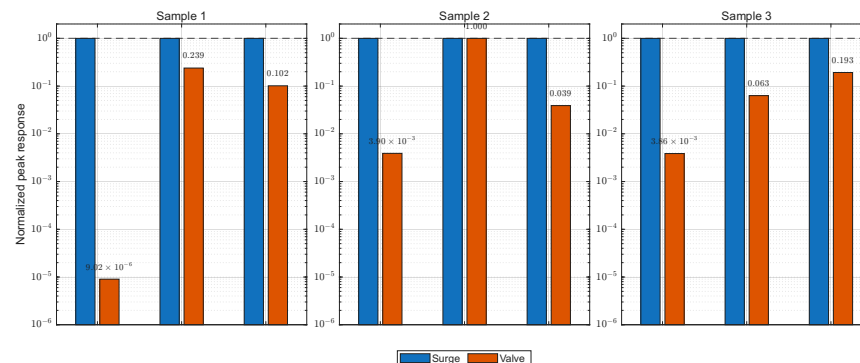


Figure 13. Within-record comparison of confirmed surge and selected recycle-valve transient responses for Samples 1–3. For each sample, the peak surge response is used as the reference value of unity, while the corresponding valve-transient peak is expressed relative to that reference. The comparison includes the coupled S^+ indicator, the discharge-pressure rate of change $|\dot{P}_d|$, and the flow-related differential-pressure rate of change $|\Delta\dot{P}_o|$. A logarithmic vertical scale is used because the valve-to-surge S^+ ratio in Sample 1 is several orders of magnitude below unity.

Sample 6 was evaluated separately because the record represents a shutdown/non-surge transient rather than an independently confirmed surge episode. Within the selected recycle-valve window from 2800 to 2860 s, the maximum S^+ response was 130.29, corresponding to

$$\frac{S_{\text{peak, valve}}^+}{S_{\text{thr}}} = 0.7128, \quad (61)$$

and no threshold crossing occurred within the selected window. The same interval nevertheless contained substantial process activity, with peak values of 199.69 for $|\dot{P}_d|$ and 153.24 for $|\Delta\dot{P}_o|$.

During the subsequent shutdown evolution, S^+ crossed the active threshold at 2864.5 s and later reached a substantially larger response. This behavior demonstrates that the proposed S^+ indicator should not be interpreted as a universal stand-alone classifier for arbitrary shutdown transients. Instead, its use is intended to be gated by the supervisory test state, permissive conditions, and operating context defined by the proposed surge-verification framework.

Sample 7 provides an additional confirmed no-surge reference. No post-baseline S^+ threshold crossing was observed over the complete record. The maximum S^+ response was 23.171, corresponding to

$$\frac{S_{\text{peak}}^+}{S_{\text{thr}}} = 0.1455. \quad (62)$$

Thus, the maximum detector response remained well below the active threshold throughout the record. This case complements the shutdown behavior observed in Sample 6 by showing a confirmed no-surge operating record in which ordinary process variations did not produce a surge declaration.

The comparison remains limited to the available manually annotated valve transients and should not be interpreted as a complete false-alarm validation against all possible

non-surge disturbances. Broader evaluation across other process transients, operating conditions, and installations remains necessary.

4.3. Simulation-Based Surge Limit Verification Result

The simulation results presented in this subsection are interpreted qualitatively only. The supporting model was not calibrated to, derived from, or intended to reproduce any of the field-recorded compressor cases. Consequently, direct quantitative comparison of transient amplitudes, frequencies, or time constants between the simulation and field records is not used as a validation metric.

A representative simulation-based surge limit verification case was used to examine the complete supervisory sequence under controlled conditions. This case illustrates the interaction between the staged surge-margin reduction, the baseline-referenced event-recognition logic, the detected surge event, and the resulting update of the surge limit and surge-control-line representation in compressor-map coordinates.

Figure 14 shows the synchronized surge-detection result for the representative simulation case. The discharge pressure P_d and flow-related differential pressure ΔP_o exhibit the disturbance associated with the surge event. The corresponding S^+ indicator rises above the baseline-referenced threshold, after which the detection signal is latched for logging and post-test interpretation.

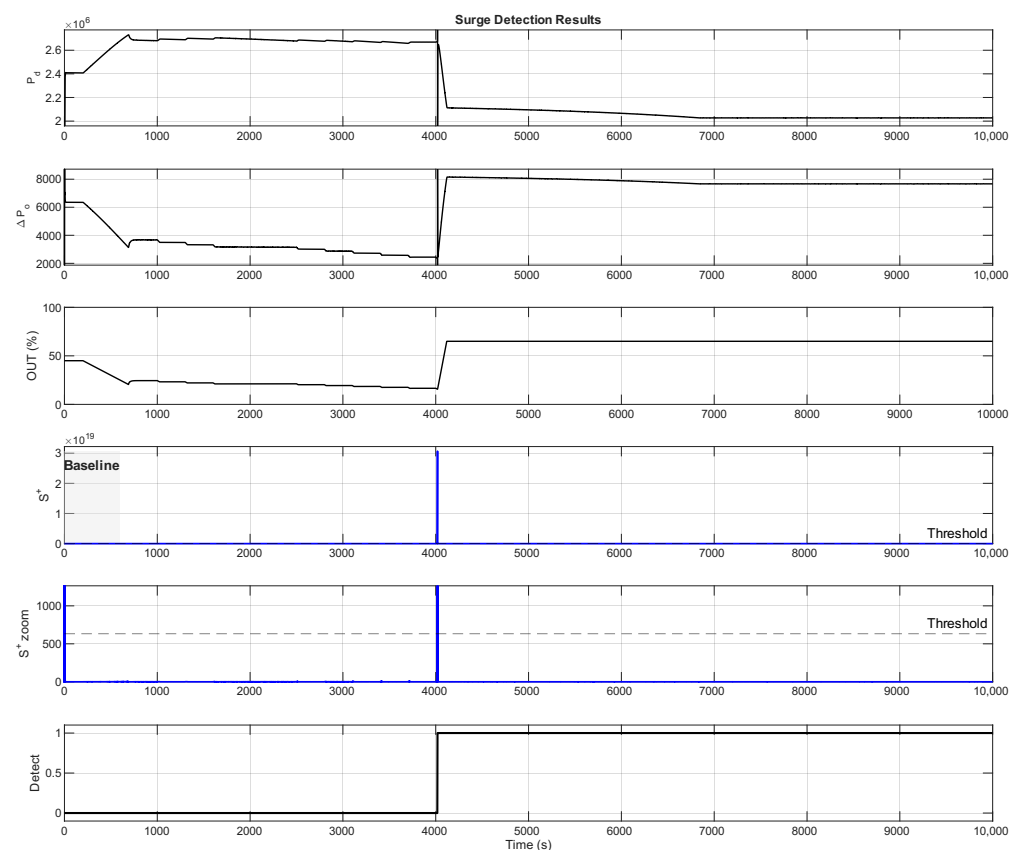


Figure 14. Representative simulation-based surge detection result showing process signals, the S^+ indicator, detection threshold, and resulting detection signal. The black traces show the simulated process signals and detection state, the blue traces show the S^+ detector response, the dashed line indicates the active detection threshold, and the shaded region indicates the baseline interval used for threshold estimation.

The supervisory sequencing variables associated with the same test are shown in Figure 15. The parameters b_1 and K represent the commanded modification of the surge

limit representation during the controlled approach. In this representation, K defines the slope of the surge limit line (SLL), while b_1 represents the prescribed safety margin between the surge limit line and the surge control line (SCL). The constructed detection signal is plotted in the lower panel to show the instant at which the test logic identifies the surge event and latches the event state.

Figure 16 presents the corresponding compressor-map interpretation. The initial and final surge limit lines are shown together with the associated surge-control lines. The shaded region indicates the recovered control margin obtained from shifting the line representation during the verification sequence. The detected surge point is plotted in terms of the flow coefficient ϕ and pressure coefficient ψ , allowing the event location to be interpreted directly on the compressor characteristic.

A closer view of the local surge signature is provided in Figure 17. The figure focuses on the short interval surrounding the detected event and shows only the discharge pressure and flow-related differential pressure. This representation is useful for reviewing the physical surge signature independently from the full detection and sequencing plots.

Taken together, Figures 14–17 demonstrate that the proposed supervisory sequence can be exercised in the dynamic simulation environment from the staged approach through detection, event latching, map interpretation, and local signature review. The results show that the different elements of the framework operate in a coherent manner, linking surge-margin reduction, event recognition, recovery logic, and surge limit verification within a single workflow. Although the simulation environment is not intended to reproduce the behaviour of a specific compressor installation with full quantitative accuracy, it provides a useful platform for evaluating supervisory logic and examining the interaction between compressor dynamics, surge detection, and recovery actions. The simulation results therefore support the practical feasibility of the proposed workflow and illustrate how structured records can be generated for engineering review following surge limit verification.

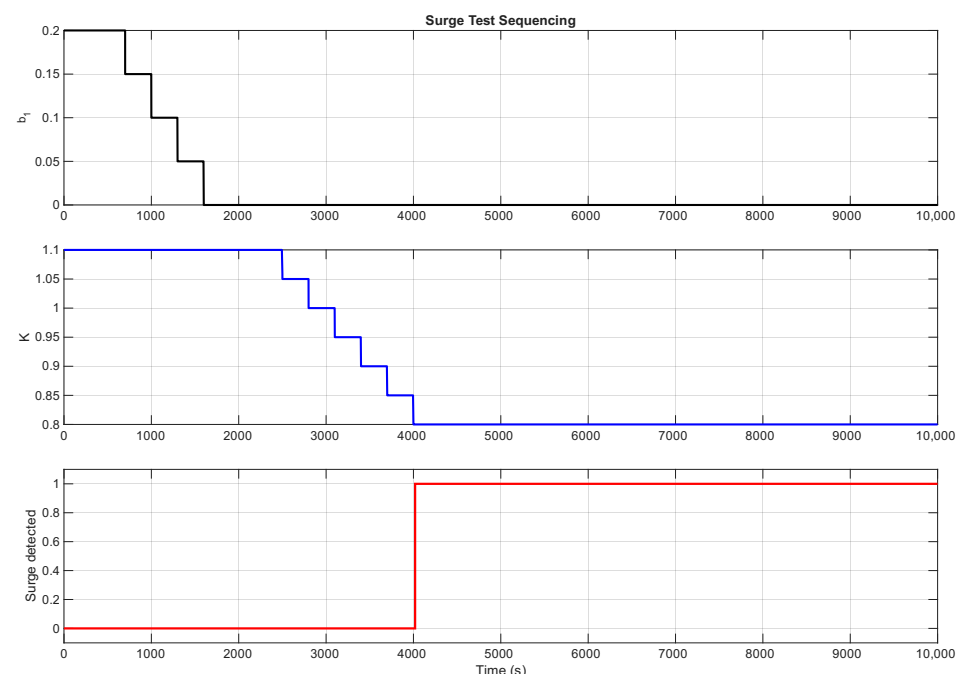


Figure 15. Supervisory sequencing for the representative simulation case. The upper panels show the staged variation of the surge limit parameters b_1 and K , while the lower panel shows the latched surge-detection signal. The black trace represents b_1 , the blue trace represents K , and the red trace represents the latched surge-detection state.

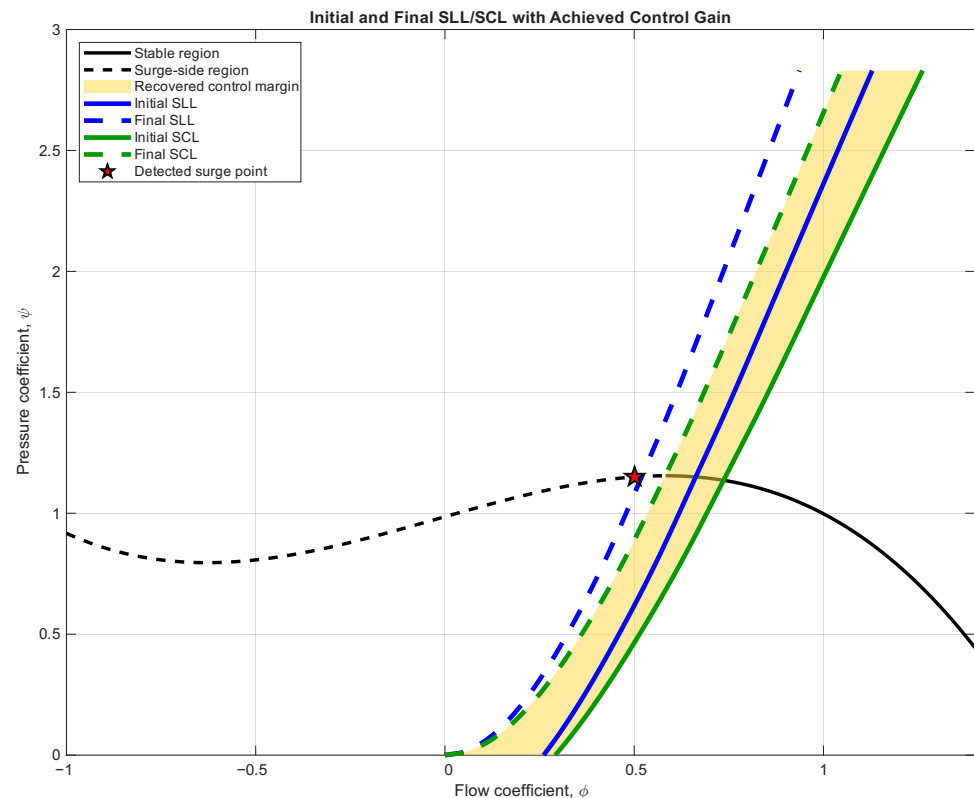


Figure 16. Initial and final surge limit and surge-control-line representation for the representative simulation case. The map is shown in terms of flow coefficient ϕ and pressure coefficient ψ . The shaded region indicates the recovered control margin, and the red marker identifies the detected surge point used for event interpretation.

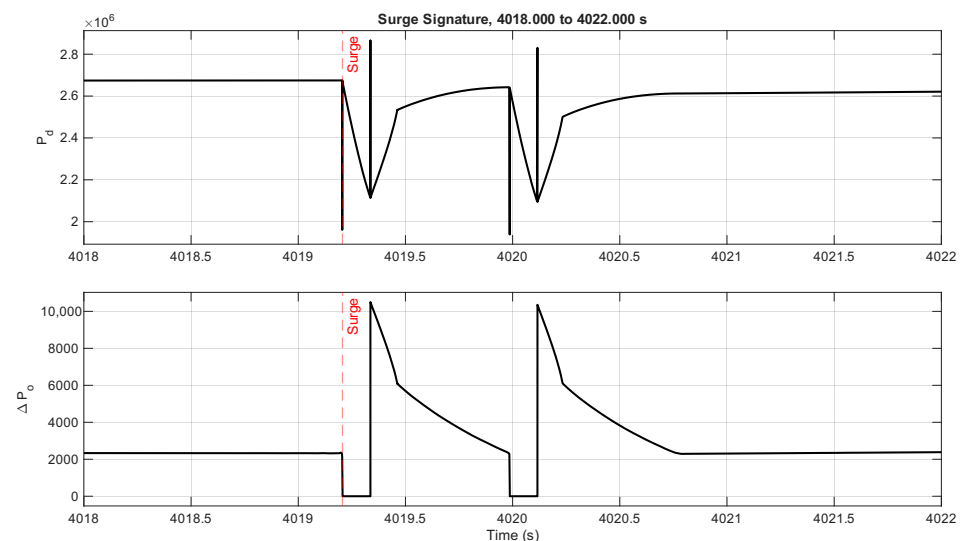


Figure 17. Zoomed surge signature for the representative simulation case. The interval is restricted to the local event region, showing the transient response of discharge pressure P_d and flow-related differential pressure ΔP_o around the detected surge event.

4.4. Representative Recovery-Tuning Behavior

The recovery-tuning results presented in this subsection are likewise simulation-based and qualitative and are not calibrated to the field records.

A representative recovery-tuning sequence is used to demonstrate how the proposed search procedure distinguishes between insufficient and successful recovery settings after surge limit verification. Starting from the verified operating condition, a staged recycle-valve

recovery profile is imposed in the form of an initial opening step, a fixed hold interval, and a gradual release. The tuning objective is to identify a successful recovery opening resolved by the staged search that produces a baseline-referenced recovery response satisfying

$$\Delta D_{\text{peak}} \geq \Delta D_{\text{target}}. \quad (63)$$

The resulting selection behavior is summarized in Figure 18, where each point corresponds to one tested recovery opening and the resulting peak baseline-referenced recovery response ΔD_{peak} . Openings for which

$$\Delta D_{\text{peak}} < \Delta D_{\text{target}} \quad (64)$$

are classified as insufficient, whereas openings satisfying $\Delta D_{\text{peak}} \geq \Delta D_{\text{target}}$ are considered successful. The preferred candidate is the successful opening resolved by the staged search and bracket-refinement procedure.

The complete set of tested trials is presented in Figure 19. The upper panel shows the baseline-referenced recovery responses $\Delta D(t)$ for all tested recovery openings, while the lower panel shows the corresponding staged recycle-valve recovery commands.

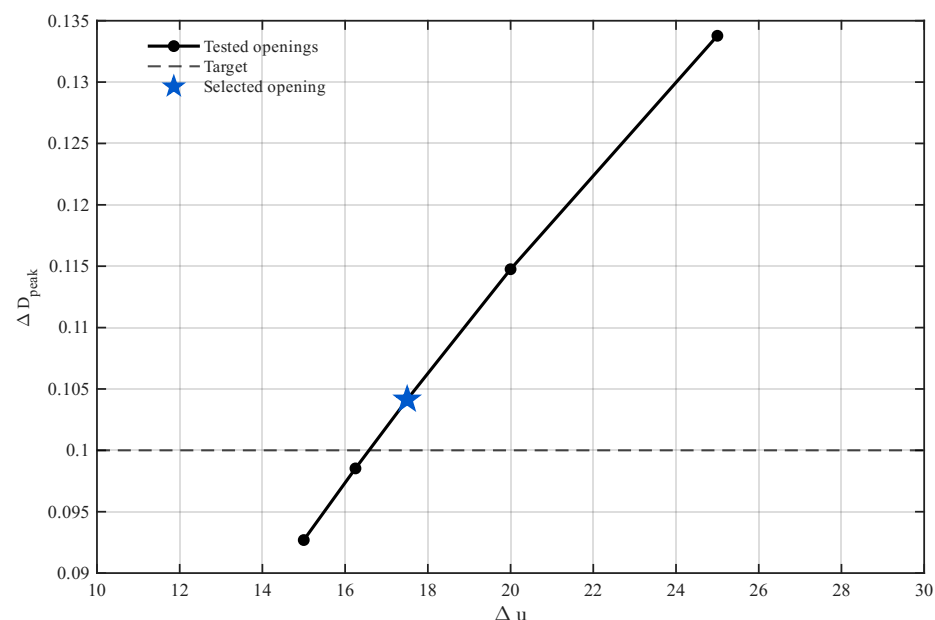


Figure 18. Selection curve for the representative recovery-tuning sequence. Each point corresponds to a tested recovery opening Δu and the resulting peak baseline-referenced recovery response ΔD_{peak} . The dashed horizontal line indicates the target ΔD_{target} . The highlighted marker denotes the selected recovery opening satisfying the prescribed recovery criterion.

The selected case satisfies the prescribed recovery criterion while avoiding an unnecessarily large recycle opening within the explored candidate range.

The transient corresponding to the selected recovery setting is shown in Figure 20. The baseline-referenced recovery response $\Delta D(t)$ and the imposed recovery command $\Delta u(t)$ are plotted together to show the applied opening, hold interval, and release profile for the selected case.

The timing interpretation used by the tuning logic is shown separately in Figure 21. For the selected candidate, T_{process} is measured from application of the recovery action at t_0 to the peak of the baseline-referenced response $\Delta D(t)$. The repeat timing used by the tuning rule is then defined as

$$T_{\text{repeat}} = \beta T_{\text{process}},$$

where β is a prescribed scaling factor. In the representative case shown here, $\beta = 0.80$. The displayed time interval is restricted to 10 s after the response peak in order to emphasize the timing construction.

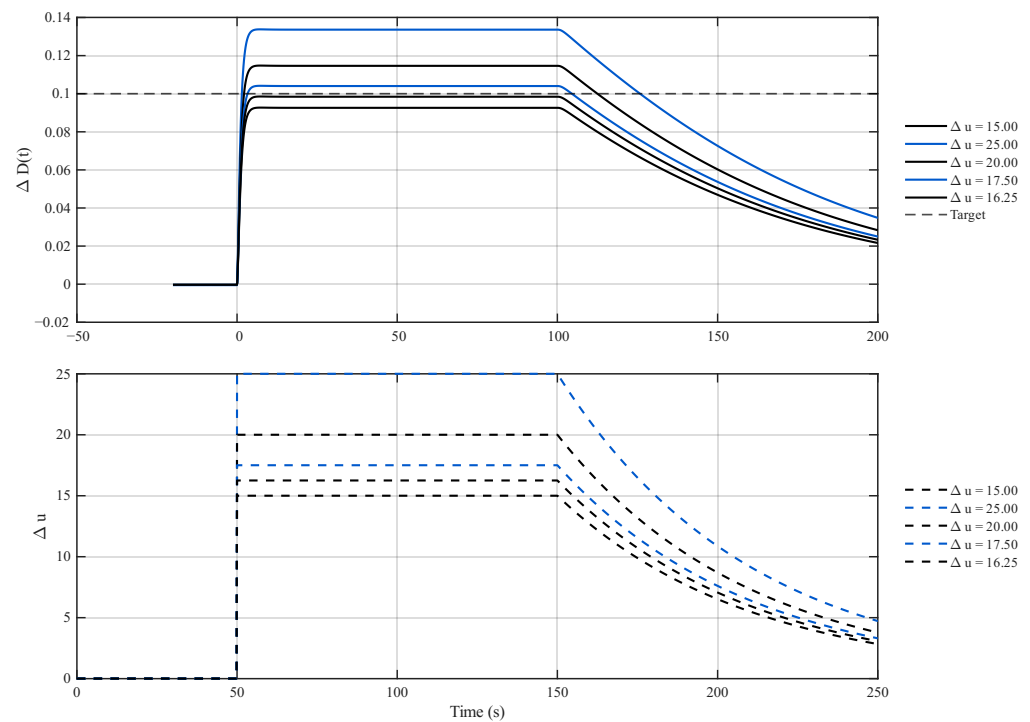


Figure 19. All tested recovery-tuning trials. The upper panel shows the baseline-referenced recovery response $\Delta D(t)$ for the tested recovery openings, and the lower panel shows the corresponding staged recycle-valve recovery commands $\Delta u(t)$.

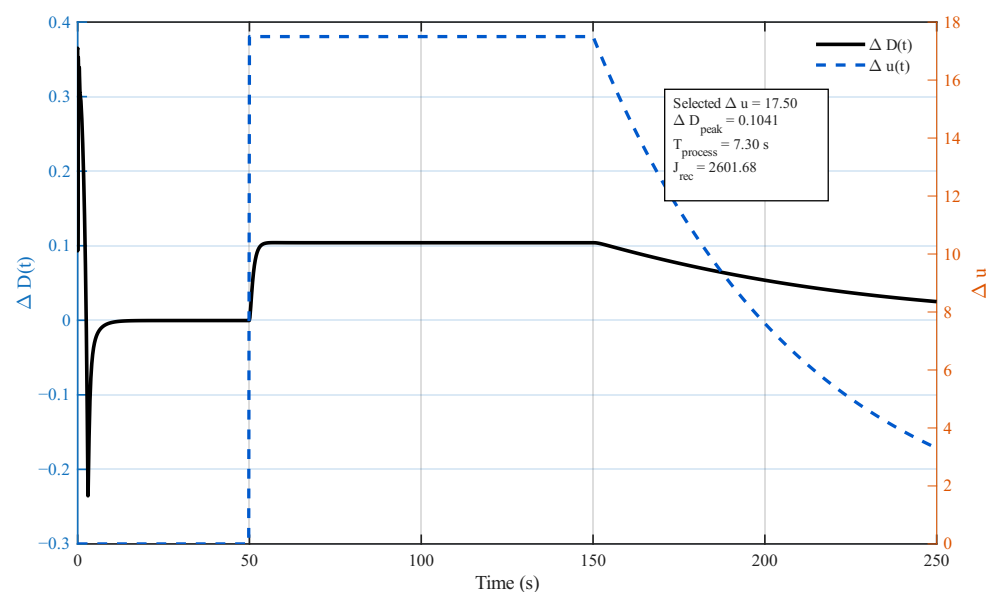


Figure 20. Representative transient for the selected recovery setting. The baseline-referenced recovery response $\Delta D(t)$ and recovery command $\Delta u(t)$ are shown together to illustrate the applied opening, hold interval, and release profile.

Taken together, Figures 18–21 demonstrate how the proposed recovery-tuning procedure can identify a recovery setting that satisfies the prescribed response criterion while avoiding unnecessary recycle action. The results support the use of a limited number of staged field tests to select both the recovery opening and its associated repeat timing. An im-

portant observation is that the procedure does not attempt to find a mathematically optimal recovery policy. Instead, it identifies a successful recovery action within the explored candidate range that restores the required operating margin while avoiding unnecessarily large recycle opening. This approach is well aligned with practical field requirements, where robustness, transparency, and ease of validation are often more important than highly optimized tuning. The results also show that relating the repeat timing to the measured process response provides a physically meaningful basis for parameter selection, linking the tuning directly to the observed behavior of the installed compressor–process system rather than treating it as an independent setting.

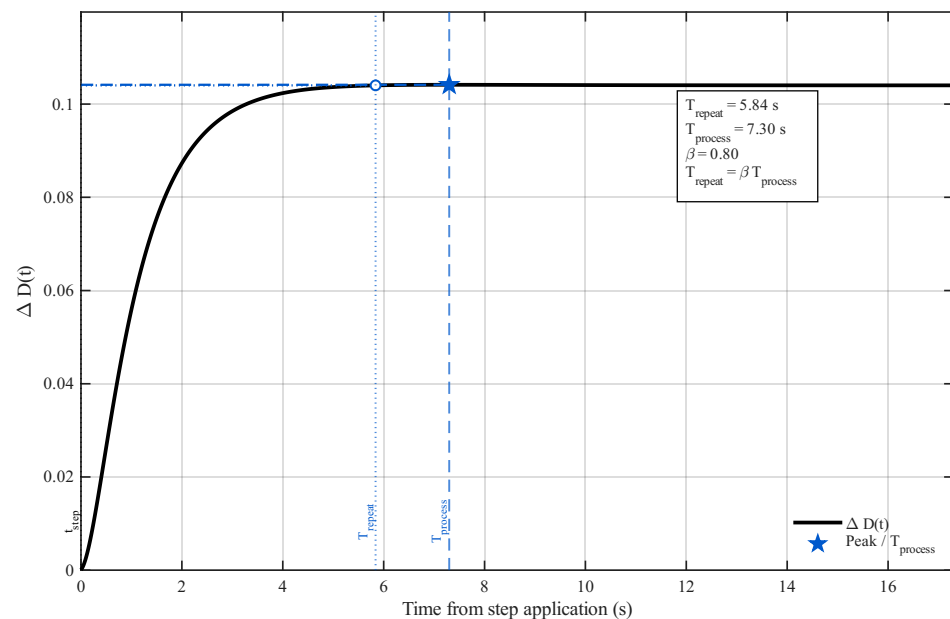


Figure 21. Timing construction for the selected recovery response. The process recovery time T_{process} is measured from recovery-action initiation at t_0 to the peak of $\Delta D(t)$. The repeat timing is defined by $T_{\text{repeat}} = \beta T_{\text{process}}$. Only the interval up to 10 s after the response peak is shown to emphasize the timing interpretation.

5. Limitations

Several limitations should be considered when interpreting the results of this study. First, the field evaluation is based on seven field records comprising five independently confirmed surge cases, one shutdown/non-surge transient, and one confirmed no-surge record. Although the records span different compressor services, drivers, gas compositions, operating speeds, and flow-measurement arrangements, the dataset remains small relative to the diversity of industrial centrifugal-compressor installations. The reported detection-delay, normalized-response, and non-surge comparison results should therefore be interpreted as field evidence supporting the proposed methodology rather than as universal performance statistics.

Second, the independent surge-onset reference used for detector evaluation was established by manual review of the characteristic coupled pressure and flow-related oscillations in each field record. This provides a detector-independent physical reference, but the annotation remains subject to the temporal resolution of the recorded signals and to engineering interpretation. All analyzed records were sampled at 10 Hz, corresponding to a time resolution of 0.1 s.

Third, the direct recycle-valve-to-surge comparison was limited to Samples 1–3, for which both a confirmed surge episode and a retained recycle-valve transient were available in the same record. These cases provide targeted evidence that substantial individual

pressure or flow-related derivative excursions can occur during valve movement while the coupled S^+ response remains much smaller than the corresponding surge response. Sample 6 was evaluated separately as a shutdown/non-surge transient, and Sample 7 provided an additional confirmed no-surge reference. These cases do not constitute a comprehensive false-alarm validation against all possible non-surge disturbances. Other transients, including process trips, load changes, transmitter disturbances, controller mode changes, and other valve movements, should be examined in a broader validation campaign.

Fourth, the baseline-referenced threshold used in the present field implementation employs $p = 95$ and $\alpha = 50$. These values were adopted for the present field-data characterization and should not be interpreted as universally optimal for all compressor systems. The lower threshold bound $S_{\min}$, baseline-selection rules, derivative window, and threshold scaling may require adaptation where instrumentation characteristics, sampling rate, process noise, or compressor dynamics differ substantially from those represented in the present dataset.

Fifth, the S^+ formulation contains the square of the flow-related differential-pressure signal in the denominator. Although a protected lower bound is applied to avoid numerical instability, the detector magnitude can become highly sensitive when ΔP_o approaches the protected near-zero region. This behavior is evident in Sample 4. Consequently, the absolute magnitude of S^+ should not be interpreted as a direct measure of physical surge severity.

Sixth, the method depends on the quality and dynamic response of standard industrial instrumentation. Transmitter bandwidth, signal damping, filtering, control-system scan time, sensor location, and measurement configuration may affect both the observed surge signature and the resulting detection delay. These characteristics were not available in sufficient detail for all field records to support a systematic bandwidth-sensitivity analysis.

Seventh, the supporting Simulink environment is a reduced-order engineering model intended for supervisory-logic development and qualitative assessment. It is not a validated high-fidelity digital twin of any of the field compressors. The compressor characteristic outside the measured map region is a numerical extension used to preserve continuity during surge and flow reversal, and the simulation results should therefore not be interpreted as installation-specific quantitative predictions.

Finally, the proposed post-verification Recycle Trip[®] tuning procedure is presently a structured engineering concept demonstrated through representative simulation-based behavior. Its initial opening guess, coarse-search increment, opening tolerance, recovery target, hold/release profile, and repeat-time factor require broader field validation before general industrial recommendations can be established.

6. Future Work

Future work may extend the framework in several directions, including:

- Richer integration with vibration and protection data;
- Quantitative repeatability studies across multiple machines and operating conditions;
- Validation of the staged coarse-search and bisection RT tuning procedure on a wider set of field cases;
- Online or adaptive refinement of RT candidate selection from prior tuning results;
- Development and validation of machine-learning methods for surge-cycle recognition from labeled field data;
- Further comparison between measured field signatures and dynamic-simulation transient behavior;
- Formal study of operator workload and trust during guided test execution.

Such extensions should complement, rather than replace, the practical supervisory structure established in this work.

7. Conclusions

This paper presented a semi-automated supervisory framework for field surge limit verification of centrifugal compressors using standard industrial anti-surge instrumentation. The framework organizes the field test into a structured sequence comprising readiness verification, instrumentation and process-stability checks, controlled approach to the stability boundary, surge-event recognition, recovery actions, and structured event logging while retaining engineer authority over safety-critical decisions.

A baseline-referenced surge-event recognition method based on the positive derivative of the discharge-pressure/flow-differential quotient, $S^+ = \max[d(P_d/\Delta P_o)/dt, 0]$, was evaluated using five field-recorded and independently confirmed surge cases. Using a record-specific threshold of $50Q_{95}$ of the pre-event baseline, all five confirmed surge episodes produced an associated threshold crossing. After application of the predefined 0.5 s event-association tolerance, the reported detection delay ranged from 0 to 0.1 s, with a median value of 0 s. The threshold crossings were therefore coincident with the manually identified surge onset within the temporal resolution of the field records and manual annotation. These results support the intended interpretation of the method as a surge-event recognizer rather than an incipient-surge predictor.

The developed surge response exceeded the corresponding record-specific threshold in all five confirmed surge cases. The peak normalized response, $S^+_{\text{peak}}/S_{\text{thr}}$, ranged from 9.8665 to 1.1188×10^8 . The wide variation reflects differences in the field-recorded signal dynamics, native engineering units, and flow-measurement behavior. In particular, when the flow-related differential pressure approaches the protected lower-denominator region, the quotient derivative can become very large. Accordingly, neither the absolute nor normalized magnitude of S^+ should be interpreted as a direct measure of physical surge severity.

A targeted within-record comparison with manually selected recycle-valve transients was performed for Samples 1–3, for which both a confirmed surge episode and a representative valve transient were available. The selected valve-transient responses remained below the active surge-event threshold, with $S^+_{\text{peak, valve}}/S_{\text{thr}}$ values of 0.1648, 0.0385, and 0.3204, respectively. Relative to the confirmed surge response from the same record, the corresponding valve-to-surge S^+ peak ratios were approximately 9.0×10^{-6} , 3.90×10^{-3} , and 3.86×10^{-3} . The comparison also showed that large individual pressure or flow-related derivatives can occur during recycle-valve movement without producing a comparable coupled S^+ response. In Sample 2, for example, the maximum $|\dot{P}_d|$ was the same during the selected surge and valve-transient windows, while the valve-associated S^+ peak was less than 0.4% of the corresponding surge peak. These results provide targeted field evidence that the coupled pressure–flow formulation offers useful discrimination between confirmed surge and representative recycle-valve transients within the intended supervised test sequence.

Sample 6 provided a complementary shutdown/non-surge case. Within the selected recycle-valve transient window, the peak S^+ response remained below the active threshold, with $S^+_{\text{peak}}/S_{\text{thr}} = 0.7128$, despite substantial pressure and flow-related derivative activity. During the later shutdown evolution, however, S^+ subsequently crossed the threshold. This result shows that the proposed detector should not be interpreted as a universal stand-alone classifier for arbitrary shutdown transients and reinforces the need for the supervisory state, permissive, and test-sequence gating described in the proposed framework.

Sample 7 provided a confirmed no-surge operating record. No post-baseline S^+ threshold crossing was observed over the full record, and the maximum normalized response remained well below the active threshold, with $S^+_{\text{peak}}/S_{\text{thr}} = 0.1455$. This case

provides an additional non-surge reference showing that ordinary operating variations did not produce a surge declaration under the adopted record-specific threshold.

A reduced-order dynamic simulation environment was additionally used to exercise the complete supervisory sequence and to support development and qualitative assessment of the surge limit verification and recovery logic. The simulation model is intended as an engineering development platform rather than as a high-fidelity digital twin or installation-specific predictive model.

Finally, the work introduced a structured post-verification approach for selecting a staged Recycle Trip[®] recovery opening using a limited number of candidate tests. The procedure searches for a successful recovery opening that satisfies a prescribed recovery-margin target and subsequently refines the established opening interval. The repeat timing is then derived from the measured process response.

Overall, the results support the feasibility of combining structured supervisory automation, field-based surge-event recognition, and post-verification recovery tuning to improve the repeatability and practical execution of centrifugal-compressor surge limit testing. Broader field validation across additional compressors, operating conditions, instrumentation configurations, and non-surge disturbances remains necessary before universal detector thresholds or performance claims can be established.

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Abbreviations

The following abbreviations are used in this manuscript:

ASV	Anti-surge valve
GMRC	Gas Machinery Research Council
HART	Highway Addressable Remote Transducer
IGV	Inlet guide vane
MPC	Model predictive control
OEM	Original equipment manufacturer
RT	Recycle Trip [®]
SCL	Surge control line
SLL	Surge limit line
SwRI	Southwest Research Institute

ISA	International Society of Automation
IEC	International Electrotechnical Commission
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers

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