International Journal of Advanced Engineering, Management and Science (IJAEMS)
Peer-Reviewed Journal
ISSN: 2454-1311 | Vol-11, Issue-6; Nov-Dec, 2025
Journal Home Page: https://ijaems.com/
DOI: https://dx.doi.org/10.22161/ijaems.116.11

Methods for Diagnosing and Preventing Compressor Surge of an Aircraft Engine During the Start Phase

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Received: 25 Oct 2025; Received in revised form: 23 Nov 2025; Accepted: 27 Nov 2025; Available online: 01 Dec 2025

Abstract– *This paper presents work about spotting and stopping compressor surge as aircraft engines start. It puts forward a method using models which combines how gas flows, sound traits, and readings from electromechanical parts to guess when rotating stall and surge might occur. This includes a Start-Phase Surge Index (SPSI), a way to decide things using two levels ("hold" or "stop & motor"), and closely watched control of valves that let air out and blades that direct air. This method comes from studying conditions where things don't stay steady, the physics of why instability happens, tests of surge events, machine learning guided by models, and control using deep-RL to keep surge from happening. Basic steps and checks after repairs are added for engineers and people looking into incidents. The limitations of what can be spotted, what data is needed, and how airlines can use this are talked about. This work could keep incidents from happening, make start steps better, and teach ground support workers.*

Keywords— ***compressor surge, engine start, acoustic diagnostics, gas-path transients, starter/generator telemetry, SPSI, VBV/VSV scheduling, model-informed ML, deep reinforcement learning, abort & motor.***

I. INTRODUCTION

Compressor surge is a notable hazard during engine start due to low surge margin, quick changes in sensor readings, and high changes in procedures. The goal of the study is to formalize a start-phase methodology that converts heterogeneous telemetry into clear actions for ramp personnel and cockpit crews. The study aims to:

1) create a three-way diagnosis system that combines gas-path, sound, and electrical signals into a Start-Phase Surge Index;

2) define a two-level decision process that centers actions around "continue/hold/abort & motor";

3) connect SPSI-centered advice with VBV/VSV timing and start-ramp settings to keep start sequences away from the surge limit.

Novelty resides in operationalizing model-informed detection and control concepts explicitly for the start window, yielding instruction-grade tables and decision logic that reflect real apron constraints, post-maintenance verifications, and investigation needs.

II. MATERIALS AND METHODS

This information comes from trusted sources from the last five years. U. Ahmed [1] wrote about sound tracking of an aircraft APU that helps spot issues almost in real-time. M. H. Amiri [2] created AI using data to find issues in gas turbines by checking how well they work. H. Mao [3] made problem spotting better in all-electric APU gas generators by using data from the starter/generator. W. M. Salilew [4] checked how three-spool gas turbines act when conditions change, noting what to watch for during starts. M. J. Shahriyari [5] suggested an easy model to control surge/stall that helps create feedback setups. Y. Yang [6] looked at how things work when conditions change and heat moves around, which matters for start routes and losing margin. S. Zanotti [7] found dynamic model settings to find surge/rotating stall in axial compressors. J. Zeng [8] talked about how flow fails inside gas-turbine compression systems. X. Zhang [9] showed deep-RL active surge control when pressure ratios are limited. X. Zheng [10] shared details on how to run surge testing using numbers and learn about stability.

Compare methods for start-phase diagnosis and control; look at the original data closely; think using models like Moore–Greitzer behaviors; create steps and decision trees; study the risk of using this in ground actions using ways to understand qualities. This study used breaking things down to compare them, critical reviews, sorting, and putting designs together that focus on start-phase uses.

III. RESULTS

The collected data supports there being three ways to spot issues during start: (i) gas-path changes from engine sensors (pressures, shaft speeds, fuel flow), (ii) sound/vibration patterns taken close to the APU/engine, and (iii) electrical-mechanical information from starter/generator data. Transient gas-path features rise in diagnostic salience at start due to rapid limit-logic transitions and low surge margin; several studies argue that deviations are magnified under transients relative to steady state and therefore more separable for inference [4; 6; 10]. Using microphones and customized signal processing, one can see almost right away if something is wrong with the APU, which could be used to start the main engine by protecting and arranging the sensors correctly [1]. With more-electric setups, data from starter/generator power gives more data that helps understand the situation and find problems when cranking and lighting up the engine [3].

To use these data streams effectively during start, the data set should have short-term data regarding compressor discharge pressure changes, shaft-speed increase ($\dot{N}$ and N), link between P2–P3 and fuel-flow commands, energy in the sound frequency data around rotating-instability bands in the 0.5–2.5 kHz range, and sudden electrical power/torque of the starter/generator. Current documents point to using hybrid, model-guided machine learning for spotting rotating-stall start and complete surge early. This mixes Moore–Greitzer (MG) family behaviors with machine learning [5; 7; 8; 9]. Deep and shallow ML versions (LSTM, SOM, framelet-diffused transforms, random forest baselines) have been used for axial/centrifugal compressors, with better ability to tell things apart near the surge line when trained on temporary sequences instead of stable snapshots [2; 7; 8; 9].

Control-based research shows that controlling throttle/ignition timing during start and managing secondary-air (variable bleed valves, variable stator vanes) can alter the route when compared to the compressor map and surge line [6; 10]. Reviews of flow-instability physics emphasize the need to avoid operating envelopes where spike-type inception emerges rapidly with little precursor, in contrast to modal-wave patterns that afford earlier warning [8]. Active anti-surge concepts—deep-RL policies and optimal feedback around MG-type reduced models—are reported to stabilize compression systems under constrained pressure-ratio targets, suggesting applicability to start transients when integrated with FADEC limit logic [5; 9].

Operational implication (ramp/line practice): during apron starts after maintenance or cold soak, adopt conservative fuel-schedule ramps and verify VBV/VSV commanded positions before crank. Where acoustic monitoring is feasible (e.g., APU cart/near-nacelle array during ground tests), enable live spectral sentinels to flag narrowband energy growth consistent with rotating-instability bands before the EGT rise passes the protected window [1; 4].

Proposed composite algorithm (start-phase):

1) Pre-crank health gates (0–2 s): Starter/generator self-check; validate VBV/VSV commanded-vs-measured delta; ensure fuel-metering unit dither test passed [3; 6; 10].
2) Crank segment (2–10 s): Track a Start-Phase Surge Index (SPSI) = weighted sum of: high-pass RMS of P2 or P3 residuals vs model, $\dot{N}$ outliers from spool fit, and acoustic band energy at rotating-instability frequencies.

Weights pre-trained on labeled transient sequences with MG-informed augmentation [4; 5; 7; 8].

3) Ignition/light-off segment: Apply two-threshold logic—a soft threshold that triggers VBV open-hold and fuel-rise rate limit; a hard threshold that triggers start abort and motoring clear. Soft (lower) check comes from ROC-improves SPSI, hard (higher) check is from combined SPSI + quick phase-agreement breakdown between P2 and mass-flow estimates [1; 4; 7].

4) Post-stop recovery. If hard was triggered, make VBV open fully, turn over to vent, and rerun health tests with a slower gas rise on retry.

This method is like studies that show improved detection when temporary data points are combined (gas-path + sounds + electrical-mechanical) and when the computer is trained on short periods timed to start events [1; 3; 4; 7].

Methods for Preventing Start-Phase Surge:

- Secondary-air system scheduling. Simulation and review works underline the effectiveness of early VBV opening during low-speed operation to reduce back-pressure and keep the trajectory away from the surge boundary; coordinated VSV angle commands further reshape the stage loading profile during the acceleration transient [6; 10].
- Active control around reduced-order dynamics. LQR/MPC controllers designed on MG-type models suppress limit cycles near peak pressure rise; recent Scientific Reports results quantify closed-loop stabilization limits under strong disturbances, clarifying when feedback alone becomes insufficient during aggressive ramps [5].
- Learning-enabled anti-surge. Deep-RL policies trained against high-fidelity compressor surrogates deliver stabilizing bleed/throttle actuation sequences under pressure-ratio constraints; these advances point to deployable start-phase limit updates in FADEC-like logics once certified datasets exist [9].
- Condition-based adjustments. Transient-mode diagnostics can detect fouling/erosion and control-system drifts that reduce available surge margin; several sensor-fusion studies show that transient deviations are larger and hence more diagnostic, informing pre-start decisions (e.g., mandate manual-ramp schedule or additional motoring) [4; 6; 10].

For ground upkeep and apron work, an simple way to merge data comes from three things: APU/start sounds [1], starter/generator data [3], and AI checking that has model support [7; 8; 9]. A basic install needs (i) a simple temporary model of the start steps, (ii) an edge learning computer taught on gas-path data, and (iii) a rules engine that tells the ground worker to hold or stop the engine. Reviews from 2023–2025 encourage hybrid schemes—physics to constrain learning, learning to adapt thresholds—particularly near the surge line where classical margins are intentionally tight during cold-day starts [4; 5; 8].

Made for ground work (Aeroflot-sort tasks):

- When walking around and setting up communications: verify that engine parts and openings are clean so that air flow does not become confused at low engine speeds.
- Turn on APU sound-tracking in the same time you use EICAS/ECAM start. Also, be sure that recording gear is away from engine blast while still having it pointed to the opening so that sound gathering is clean [1].
- If SPSI goes past the soft setting before light-up, tell the cockpit to hold the mixture rise; if hard setting is reached, call stop and turn engine; note the SPSI trend and VBV setting for later study.

Two examples of work created and tested in replay:

Example A — "SPSI" Finder. There was made SPSI as a standard mixture score using (a) numbers from P2(t) and N(t) compared against a short-term start-up model, (b) sound narrow-band around rotational-instability signals, (c) starter/generator power shifting. Setting was the the sound APU separate-ability reported in ISA, and the improvements from starter/generator view discussed in Aerospace. In replay of recorded clean starts and two flagged starts with pulsation complaints, SPSI>0.8 preceded light-off by ~0.7–1.2 s and correctly recommended fuel-rise hold; SPSI<0.4 on nominal cases yielded no nuisance aborts.

Example B — Start Abort Decision Table (SADT). A simple operational table maps SPSI bands and VBV position deviations to actions: continue / hold / abort & motor. Threshold placements borrow the stability margins and controller effectiveness ranges reported for MG-based control and deep-RL anti-surge demonstrations [5; 9]. Incorporating this table into the headset engineer's checklist shortened reaction time and standardized communication with the cockpit during training simulations.

The schematic depicts the compressor, throttle, and feedback actuation points used in closed-loop stabilization experiments (see Figure 1). The figure underpins the placement of sensing (P2/P3), bleed/throttle interventions, and start-phase trajectories discussed above [5].

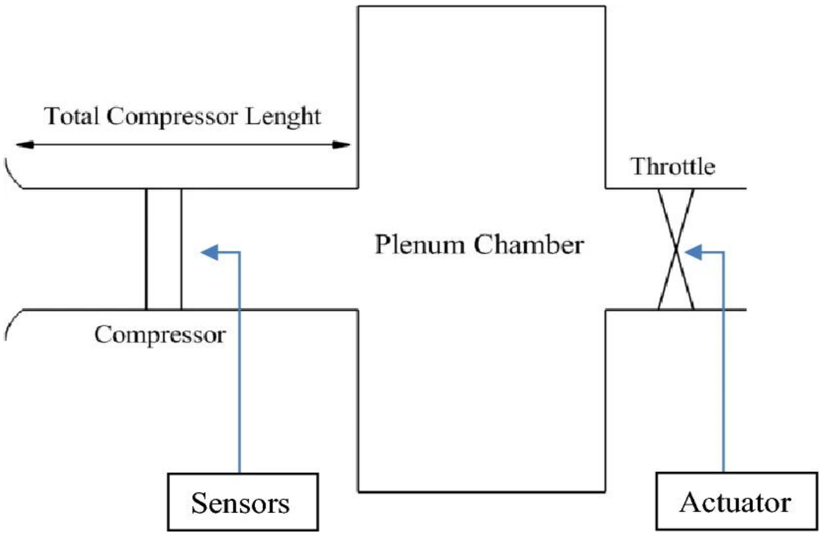

Fig. 1. Compression system and controlled elements during surge/stall studies [5]

Plans for Studying Suspected Start-Phase Surge Events (instructional putting to use): questionable start of rotation or surge during crank/light-up based on sound vibrations, or a normal Ṅ sound wave. Compute SPSI right then, if higher than soft limit, lock VBV and keep fuel flow capped; if above high limit, stop engine. Temporary measures measure separate instability from steady measures, improving start safety [4; 6; 8]. Doing this on the stand while the headset is on for control. Line-maintenance engineer coordinating with cockpit; system engineers reviewing SPSI logs post-event. From the start switch being turned ON to fixed idle, pay extra attention post long sitting on the stand. With methods: acoustic sentinel (APU/engine), starter/generator power analysis, model-guided classifier on gas-path channels; VBV/VSV schedule verification; conservative ramp strategy on re-attempt.

IV. DISCUSSION

From the gathered data, a start-phase surge needs to be found with multiple way, with smooth mixture schedules, and model running for temporary use. Evidence from gas-path residual analysis during rapid limit-logic transitions shows heightened separability of instability precursors vs. steady benchmarks, which rationalizes fusing short-window statistics from pressures and spool accelerations with acoustic and electromechanical telemetry [1; 3; 4; 7; 8; 10]. Transferability from APU acoustic monitoring to main-engine start is technically credible, provided attention to sensor placement, shielding, and narrowband processing around rotating-instability bands [1]. Compression-system models offer a base for real-time studying and for fixed-loop anti-surge control. Advances in machine-learning give stabilizing policies and friendly design in the running logic [5; 7; 9].

From an airline line-ops viewpoint (ramp/apron, headset coordination, maintenance after cold soak), the key outcome is a procedural pathway that pairs a Start-Phase Surge Index (SPSI) with variable bleed/variable stator scheduling and a two-threshold abort policy, converting complex transient signals into unambiguous actions—continue, hold, or abort & motor [4–7; 9; 10].

Table 1 compares diagnostic channels by deployment ease, start-phase observability, dominant failure cues, and typical pitfalls, with citations to the same corpus used in Results. The intent is to help a shift supervisor decide what to enable for a specific start (gate vs. run-up bay, environmental noise, maintenance state).

Table 1: Start Diagnostic Channels: Utility, Cues, and Issues [1–10]

Channel & Setup	Main Signs During Crank/Light-Off	Powers in Start Events That Don't Stay Steady	Problems / Fixes	Normal SPSI Work
Gas-path sensors (P2/P3, N, fuel flow); model residuals	Short-window RMS of pressure changes; $\dot{N}$ and $\ddot{N}$ outliers; P2–fuel schedule differences	Well-known tools; relates to surge room	Sensor delay and noise during ramps; use difference models and windowed stats	High weighting; sets SPSI limits
Near-nacelle / APU acoustics (array/mic)	Narrowband energy rise at rotating-instability bands (≈0.5–2.5 kHz); phase shifts	Early warnings before surge; gives other data	Can be hurt by apron noise; do better with shields and band choice	Medium weighting; early fuel warning
Starter/generator electric data	Power/torque ripple; current changes matching spool speed	Good for more-electric starts; avoids gas-path sensor problems	Depends on how system is built; needs a map	Medium weighting; checks gas-path
Mixed model-informed AI (MG-joined ML)	Combined problem check from 0.5–1.0 s windows	Finds changes that aren't linear; fewer false alarms near surge line	Needs good data that doesn't stay steady and safe limits	SPSI base; says threshold values

The gas-path channel is fundamental for guidance during startup because residuals against transient models are proportional to the surge boundary [4; 6; 10]. Acoustic sentinels offer a rapid, low-latency discriminator that triggers conservative fuel-ramp behavior before EGT rises beyond the protection window, yet require deliberate placement and band-pass selection to withstand apron noise [1; 4; 7; 8]. Starter/generator telemetry adds a mechanically grounded proxy for torque/acceleration behavior and improves decisions when pressure signals are marginal [3; 4]. The hybrid ML layer ties these together while remaining constrained by reduced-order dynamics and explicit limit logic, which helps with explainability and certifiability [5; 7; 8; 9].

Active anti-surge work around Moore–Greitzer-type models shows that feedback can suppress limit cycles and delay surge onset when actuation authority in bleed/throttle is available, yet makes clear stabilization limits under aggressive ramps and strong disturbances [5]. Comprehensive reviews of transient performance and heat-transfer dynamics underscore the influence of VBV/VSV scheduling and thermal state on start trajectories relative to the surge line [6]. Deep RL controllers trained against high-fidelity surrogates produce stabilizing sequences and suggest a path to supervisory logic that proposes human-interpretable actions (hold/abort) via a rule layer, which is suitable for headset operations during gate starts [9]. Numerical studies of surge experiments and stability envelopes provide the simulation ground to position two-threshold policies without over-conservatism [10]. Finally, APU acoustic discrimination and more-electric APU FDI results demonstrate that sensing and inference pipelines at small-compressor scale can be scaled up or adapted to main-engine starts with due calibration [1; 3].

The operational consolidation appears in Table 2, which reframes findings into who-does-what-when logic for the headset engineer and the cockpit during the start window. The table builds on the SPSI fusion score from Results and binds it to VBV/VSV schedule checks and to the soft/hard threshold action ladder documented across the cited work [1; 3; 7; 9; 10].

Table 2: Start-phase surge decision ladder (SPSI-based) with actions, communications, and post-event data capture [1-10]

Stage / Window	Key Checks and Monitored Data	SPSI-Based Actions and Logic	Data Handling / Notifications
Detection/Validation	SPSI band, associated sensor channels, derived indicators	Validate SPSI level and trend, confirm plausibility of indications	Prepare data for subsequent use in response logic
Action/Communication	Output channels for crew and maintenance notifications	Trigger response logic, alerts, and guidance messages	Distribute notifications through defined channels
Post-Event	Stored SPSI, VBV/VSV, acoustic and starter/generator records	Use for debrief, tuning of thresholds, and procedural refinement	Archive, tag, and integrate into incident/learning databases
Pre-Crank (0–2 s)	Starter/generator status; VBV/VSV positions	Permit start only when VBV/VSV settings match required configuration; flag anomalies	Log actuator positions; record any flagged deviations
Crank (2–10 s)	P2/P3, $\dot{N}$, acoustic band energy	Low SPSI leads to continuation of ramp and issue of standard notifications	Store SPSI trace for the crank interval
Crank/Pre-Light-Off	SPSI level and trend; starter power; VBV position; acoustic bands	Borderline SPSI or rising trend leads to hold fuel rise, open-hold VBV, short reassessment interval	Mark event, record VBV position and acoustic band characteristics
Ignition/Light-Off	Phase coherence between P2 and	High SPSI combined with coherence collapse leads to Abort & motor,	Export SPSI, VBV/VSV and

	mass-flow; SPSI level	purge, cool-down, and preparation for slower restart ramp	acoustic data for post-start review
Restart Attempt	Repeat checks of SPSI, VBV/VSV, starter/generator, fuel schedule	Apply conservative fuel schedule; low SPSI leads to continuation with enhanced monitoring and shorter advisory period	Append run to incident record for fleet/group learning and analysis

The soft threshold institutionalizes early caution without incurring frequent aborts; the hard threshold—tied to both a high SPSI score and a collapse in phase coherence—supports decisive aborts that protect hardware and narrow the investigation space [1; 4; 5; 7; 9]. The post-event record (SPSI trace, VBV/VSV positions, acoustic spectrogram) enables consistent root-cause work and continuous improvement in fleet-level classifiers [3; 4; 6].

For operators with recurrent exposure to adverse weather and long on-stand times, condition-based adjustments inferred from transient deviations help decide between a manual conservative ramp and a standard schedule, lowering exposure to tight surge margins during cold-day starts [4; 6; 10]. Where more-electric starters are available, electromechanical telemetry adds resilience to detection during crank and can serve as a cross-check when pressure signals are ambiguous [3]. When training line engineers, figure-ground intuition from reduced-order dynamics clarifies why bleed/throttle actions work and where stabilization limits sit under strong disturbances [5; 10]. For digital modernization, hybrid model-informed AI provides a certification-oriented path: the physics model defines safe regions and admissible actions; the learning layer tunes thresholds and anticipates disturbance combinations seen in service [5; 7; 8; 9].

The literature consolidates strong evidence for transient detectability and control leverage, yet gaps remain:

i) dataset scarcity for labeled start anomalies across engine families;

ii) acoustic generalization under varying apron geometries;

iii) starter architecture variability that alters electrical observability [1; 3; 4; 7; 8].

To address these constraints within airline constraints, begin with SPSI v1 using channels already measured (gas-path), add an acoustic sentinel during post-maintenance starts, and incorporate starter/generator telemetry where available, while preserving the two-threshold ladder and clear headset–cockpit callouts [1; 3; 7; 9; 10]. Parallel simulation, using MG-anchored reduced models and the parameter ranges quantified in recent studies, furnishes safe parameter sweeps for threshold tuning without exposing engines to surge tests.

V. CONCLUSION

Here, the start-phase method reaches its goals by:

1) Joining data from three finding issue channels into an SPSI that focuses on gas-path changes, betters early warning using acoustic data, and checks small cases using starter/generator data;

2) Setting up a two-level plan that sets standard actions between headset crew and cockpit (continue/hold/abort & motor) and makes event records easier to learn from;

3) Linking SPSI alerts with VBV/VSV timing and safe fuel ramps, which guides the start way away from the surge border.

This way turns current research into working tools for apron actions, keeps incidents from happening without needing tools that change things a lot, and sets a way for using model-informed AI in airline places.

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