SF2 SEMANTIC FOLDING SENSOR FUSION

SF2 Systems – Leakage-Pattern Detection in Reciprocating Compressors

From Predictive to Precision Maintenance – based on complete sensor context

714.960
Data points processed

720
Measurements per revolution
= 0.5° crank angle resolution

993
Revolutions analysed

4
Fault-related contexts

THE CHALLENGE – Detecting Gradual Leakage in Complex Sensor Data

In double-acting reciprocating compressors, leakage at suction valves, discharge valves or piston rings can lead to substantial efficiency losses, thermal stress and unplanned compressor downtime. These conditions typically develop gradually. Purely threshold-based monitoring approaches can reach their limits under varying operating conditions or detect changes only once predefined thresholds for individual signals have been exceeded.

The core question is: Can characteristic changes in critical components be captured as stable multi-sensor patterns that can be used for future real-time early warning?

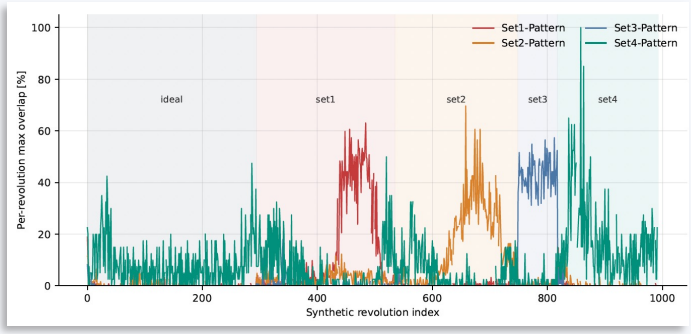
A leading manufacturer of reciprocating compressor components, control technology and drive components wanted to investigate whether characteristic operating states could be reliably distinguished and used as the basis for future real-time early warning.

THE SF2 SOLUTION – Sensor Context Instead of Individual Signals

Rather than evaluating pressure or temperature signals in isolation, SF2 transforms the complete physical sensor context into a semantic representation space.

The learned multi-sensor patterns are stored as **binary State Fingerprints** in a reference library. During subsequent operation, SF2 continuously measures the fingerprint overlap against these contextual anchors.

Gradual changes in machine state can become visible as a rising and persistent overlap in the corresponding context channel – rather than waiting for an individual sensor value to cross a predefined threshold.



Maximum overlap per revolution for the four State Fingerprints.

THE RESULT – Clearly Distinguishable State Contexts

Fingerprint / Pattern *	Mean	P90 **	Max	Revs. with Overlap ≥20%
Set1- Capacity loss/pressure drop	13.3%	46.7%	63.1%	26.1%
Set2 - Restriction/pressure amplitude changes	14.8%	35.0%	69.7%	34.1%
Set3 - Recirculation/temp. increase	41.9%	51.6%	57.4%	97.1%
Set4 – Dyn./thermal anomaly/pressure	16.5%	37.5%	100.0%	33.7%

Aggregated Overlap metrics per revolution within the respective source segment of the training stream. Overlap represents the semantic similarity between the current multi-sensor context and the learned state context.

* The four sets represent different operating/fault contexts investigated in the study.
** P90 = 90th percentile of the maximum Overlap per revolution.

Key Results

- ✓ **Four distinguishable state contexts:** Instead of simply differentiating between "normal" and "anomalous," SF2 represents four characteristic operating conditions as distinct multi-sensor patterns.
- ✓ **Continuous similarity instead of a binary alarm:** Overlap with a reference Fingerprint changes continuously, showing how closely the current machine state resembles a characteristic state context.
- ✓ **Explainable state analysis:** The resulting state assessment is substantially more transparent than conventional black-box classification.

SF2 makes component expertise actionable in day-to-day operation.

HOW SF2 WORKS

1 Data Normalisation (Binning)

Cylinder pressure data at 0.5° crank angle resolution and line data are synchronized, structured and transformed into discrete semantic contexts.

2 Semantic Mapping (Semantic Dictionary)

SF2 creates a semantic representation space in which operationally similar machine contexts are grouped together.

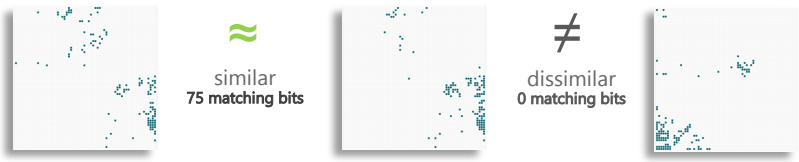
3 Fingerprint Aggregation (Stacking)

Individual process states are aggregated into stable fingerprints representing the current overall state of the system.

4 Real-Time Identification (Comparison)

Current fingerprints are matched against stored fault patterns. Greater overlap indicates a closer match to the corresponding fault condition.

SF2 represents operating conditions as **binary semantic fingerprints.** Real-time comparisons use fast binary operations instead of computationally intensive matrix multiplications, enabling execution directly on standard industrial PCs.



WHAT SETS SF2 APART

SF2 - Explainable State Intelligence

- ✓ State-based analysis of multivariate raw sensor data
- ✓ No large labeled fault datasets required
- ✓ Direct Overlap as a measure of similarity
- ✓ Interpretable results – no black box
- ✓ Efficient overlap comparisons (low computational overhead)
- ✓ Fully local and air-gap ready

Training-Intensive Machine Learning

- ✗ Statistical decision models derived from training data
- ✗ Often require larger historical datasets
- ✗ Results depend on the model and training data
- ✗ Explainability depends on the model architecture
- ✗ Model complexity defines computational requirements
- ✗ Often relies on cloud services (data & security risk)

IMPACT FOR COMPONENT MANUFACTURERS

Component expertise digitally usable
Characteristic states become reusable digital references

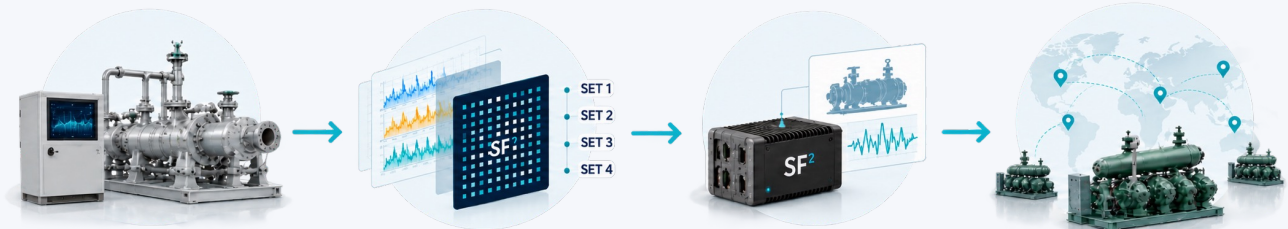
Make gradual degradation visible
State drift becomes measurable through fingerprint overlap

Reduce risk of secondary damage
Early detection supports targeted maintenance decisions

Edge-ready & data-sovereign
Local real-time analysis without cloud dependency

PRECISION MAINTENANCE – Towards More Targeted Maintenance

SF2 makes component expertise actionable in day-to-day operation.



TEST BENCH
Capture characteristic component states

DIGITAL REFERENCES
Store validated states as fingeprints

EDGE DEPLOYMENT
Roll out state intelligence to machines and assets

FLEET
Monitor states across machines and locations and optimize performance

CONCLUSION

This case study demonstrates that distinct compressor states can be represented as characteristic semantic State Fingerprints using high-resolution pressure, temperature and crank-angle data.

SF2 thereby provides the foundation for transforming component expertise into digital state references and continuously comparing the current machine state with these references locally at the machine.

Learn more at www.SF2systems.com

SF² SYSTEMS

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