The Development of an In-Process Monitoring Solution for Inertia Friction Welding: An Investigation into Feature Descriptors

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Problem Statement

Both small- and large-lot manufacturing environments need in-process quality assurance:

- ***Small-lot*** *(high precision, performance-critical or man-rated):*
  - *Number of parts made is low*
  - *Destructive evaluation is very costly*
  - *Non-destructive evaluation techniques are not able to detect all of the possible fault conditions*
- ***Large-lot*** *(low(er) precision, high volume):*
  - *Number of parts made is high*
  - *Destructive evaluation (bookend'ing) is inconsistent*
  - *Non-destructive evaluation techniques are not able to detect all of the possible fault conditions*

Problem Statement, cont.

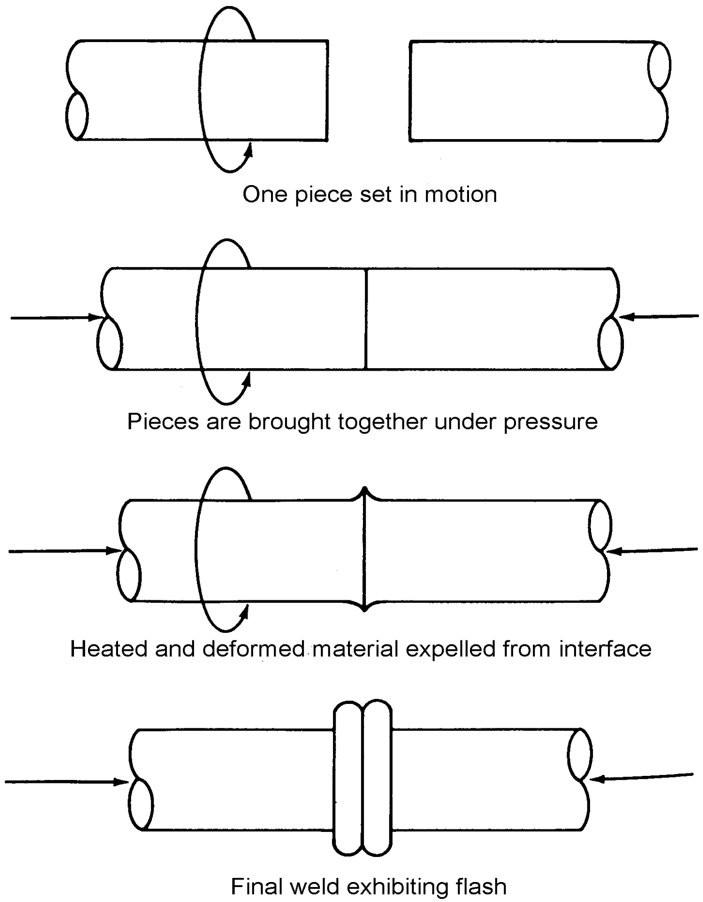
- Collecting data is not in-process monitoring
- Data instills a false sense of security

Problem Statement, cont: Fusion Welding

- Examples: GTA, EB, LB
- Typical approach to in-process monitoring:
  - Quantifies the heat source:
    - GTA: Voltage and Current
    - EB: Beam Profile (Faraday Cup)
    - LB: Beam Profile
  - Neglects the fundamental key in-process parameter!
    - Energy transfer: Heat source-to-material interaction

Inertia Friction Welding: The Process

The current industry approach maintains absolute upset within a predetermined ±3σ envelope.



Inertia Friction Welding: The Process

INDIRECT WELD PARAMETERS

- Inertial mass
- Rotational speed
- Axial force
- Dwell time

MATERIAL PARAMETERS

Thermal conductivity
Thermal expansion
Hardness and strength
Oxidation resistance
Plastic temperature range
Forging temperature range
Forging temperature
Metallurgical properties

INFLUENTIAL PROCESS VARIATIONS

Joint variation
Surface condition

DIRECT WELD PARAMETERS

- Surface appearance, i.e., flash formation
- Upset
- Heat and deformation affected zone
- Cooling rate
- Strength and ductility
- Internal discontinuities
- Metallurgical structure

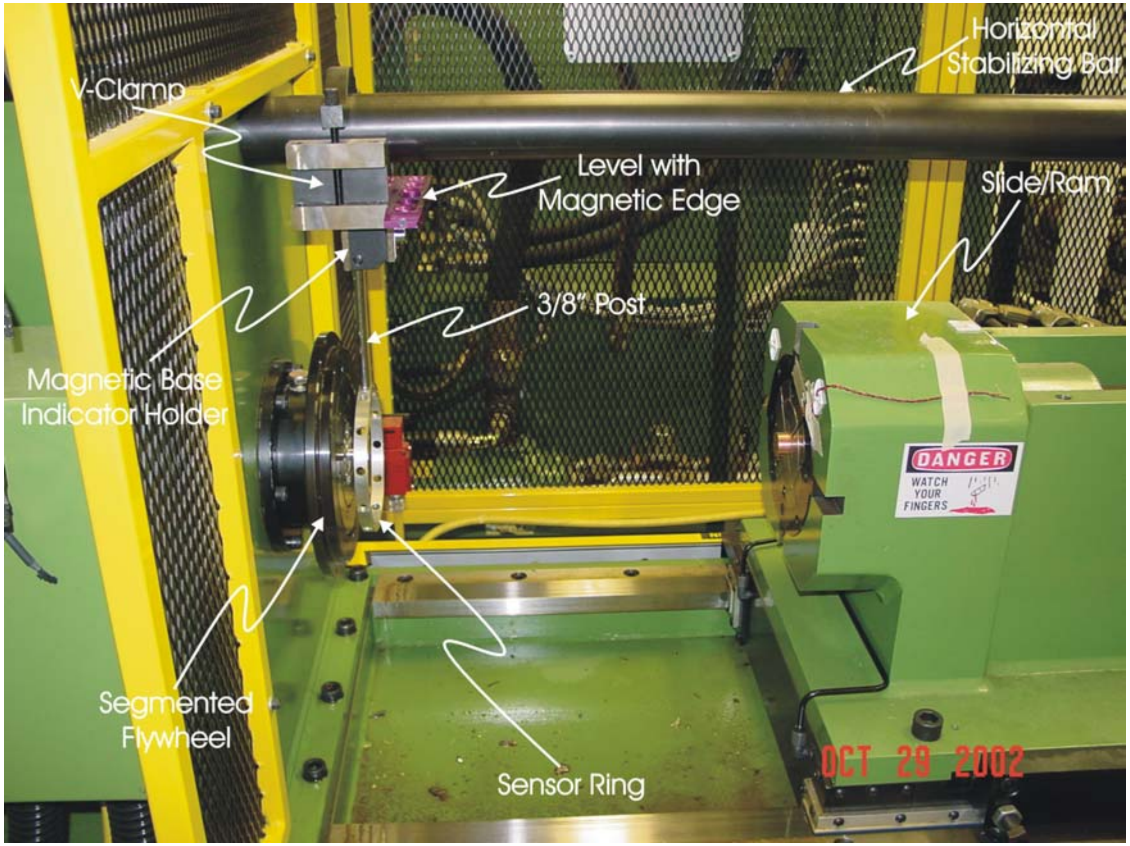
Research Objective

Investigate the development of a in-process monitoring system for bond integrity during inertia friction welding.

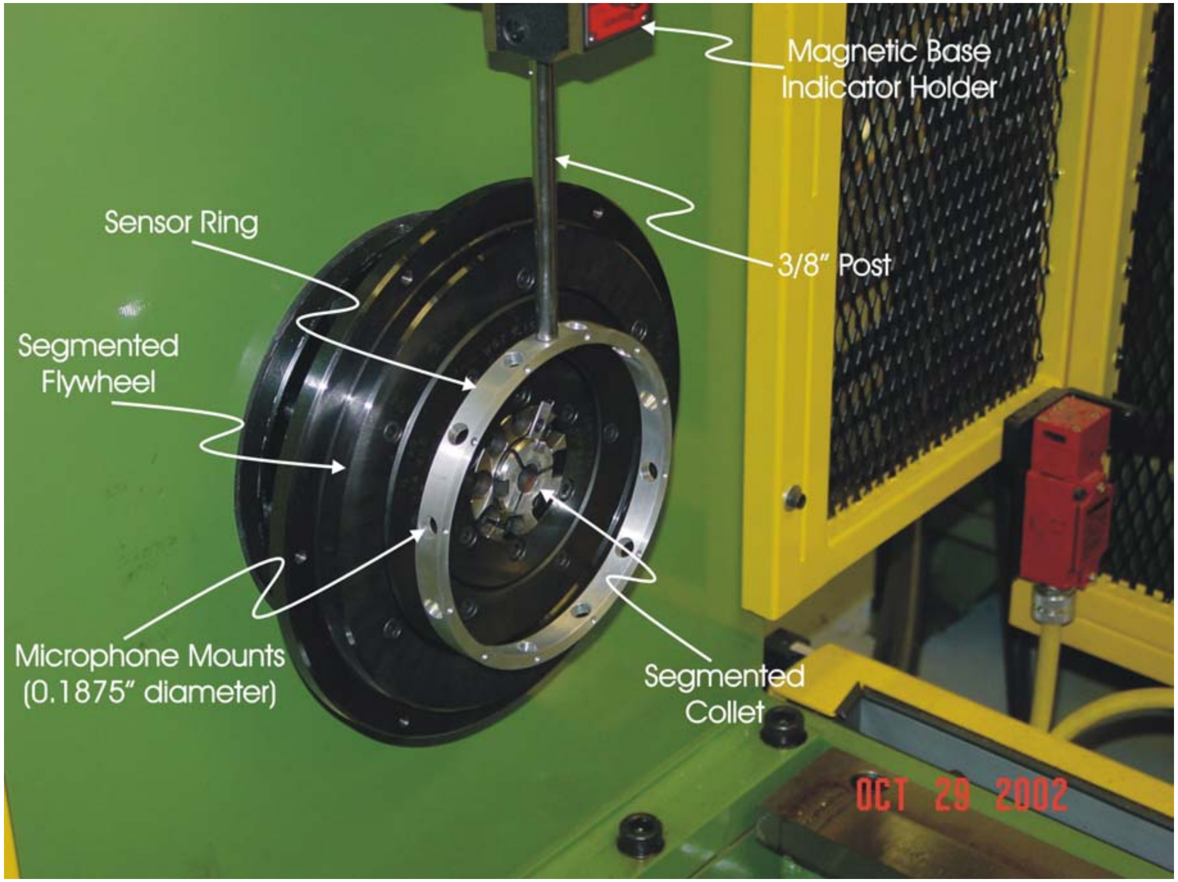
Inertia Friction Welding: Sensor

- Acoustic emission sensing ring:
  - Free standing Aluminum ring.
  - Capable of holding up to 12 acoustic transducers (microphones).
  - Non-contact.
- Collects the rapid release of energy (in the form of sound pressure) due to the mechanical, thermal, and metallurgical phenomena occurring during friction welding.
- The acoustic transducers used in this research are off-the-shelf electret condenser microphones (approx. $0.99 each).

Inertia Friction Welding: Machine and Sensor



Inertia Friction Welding: Sensor



Experimental Objective

- **Problem:**
  - **Cu-SS exhibits only marginal weldability.**
  - **Surface contamination (e.g., oxidation or other forms of contamination) prevents a metallurgical bond from being formed.**
- **In-Process Monitoring Objective:**
  - **Detect material contamination by identifying features within the in-process data: machine and acoustic energy.**

Experimental Approach

- Materials
  - OFHC Cu: 1.0 inch dia. bar
  - Type 304L: 0.5 in. dia. Bar with 3° taper
- Conditions
  - Freshly machined
  - Machined and exposed to atmosphere for 4-5 weeks
  - Surfaces contaminated with fingerprints
- Bond Quality Tests
  - Unguided bend tests
- Characterization
  - Optical microscopy
  - Image analysis

- Equipment & Parameters
  - MTI Model 90B IFR System
    - 4500 rpm (589 sfpm)
    - 1092 psi (7100 lb_f)
    - 1.52 lb_m-ft^2
    - 0.100 in. prebond gap
    - One diameter of stickout
  - Microphones
    - Frequency response: 0 - 16 kHz
    - Relatively flat response over its entire range
  - Data acquisition
    - Sampling rate: 40 kHz
    - Amplified and low-pass filtered @ 20 kHz

Experimental Approach, cont.

Generate an experimental matrix with only one variable:

Surface preparation $\Rightarrow$ <u>bond quality</u>

Post-Process Analysis: Mechanical Properties

- Bend tests were performed as a semi-quantitative determination of bond quality.
- Image analysis of the fracture surfaces provided a reasonable approximation of the percent of interface area bonded.
- Specimens having acceptable bond quality exhibited ductile tearing without any lack of bonding over the majority of the interface.
- All of the specimens that were welded as-is exhibited a lack of bonding over the majority of the interface.

Bend Test Results

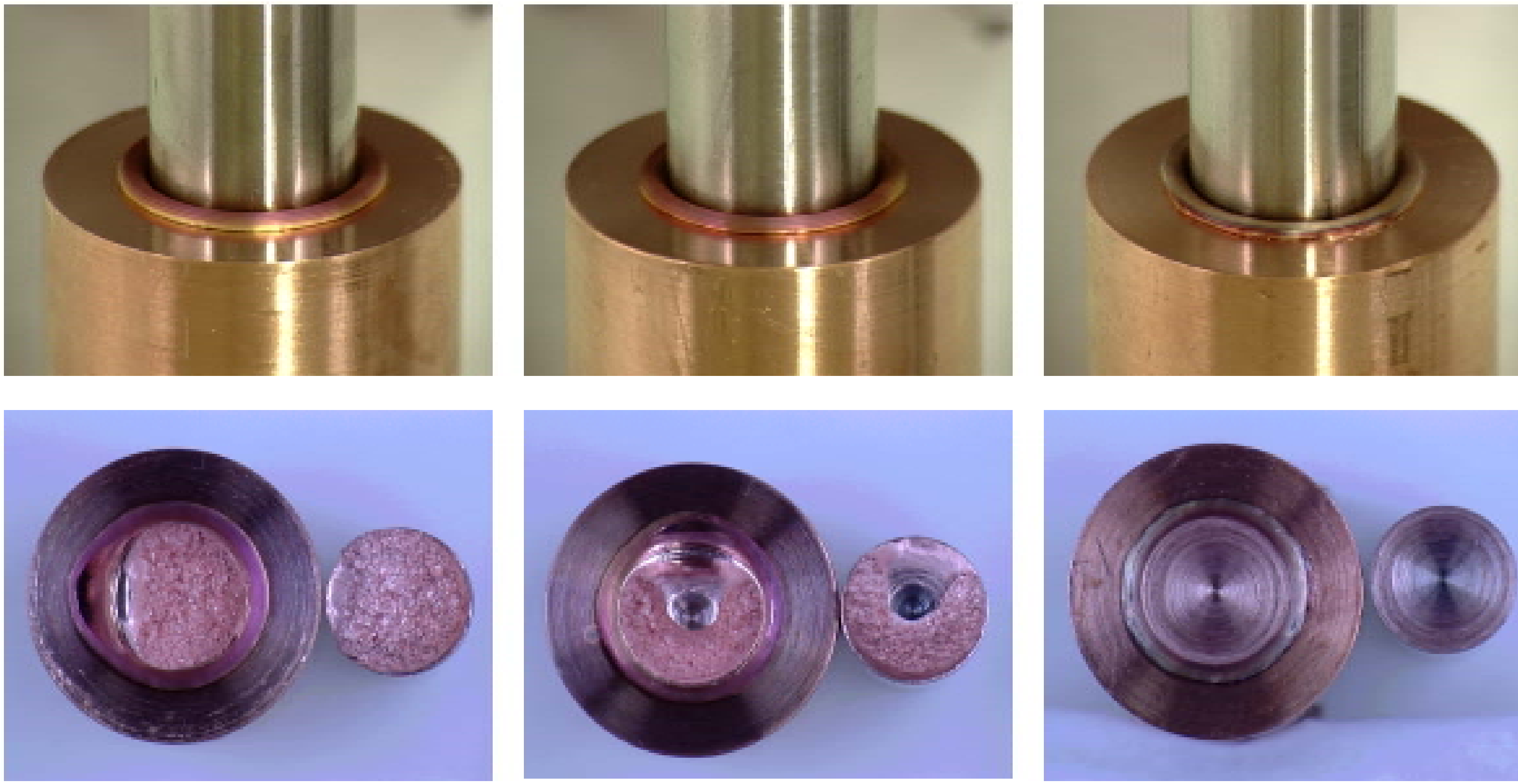
Weld #	Surface Condition	Bond Quality	Bonded Area, (%)
1 – 12	Freshly machined	Acceptable	100
13	Freshly machined	Conditional	80
14	Freshly machined	Conditional	70
15	Freshly machined	Conditional	69
16	Freshly machined	Conditional	67
17	Freshly machined	Conditional	54
18	Freshly machined	Conditional	48
19	Freshly machined	Conditional	26
20 – 24	Not machined	Unacceptable	0

Bond Quality

- Three bond quality classes were created in the experimental matrix:
  - ***Acceptable***: approximately 100% bonded area
  - ***Unacceptable***: approximately no bonded area
  - ***Conditional***: everything in between
- Acceptable and Conditional welds: freshly machined copper surface prior to welding.
- Unacceptable welds: welded as-is, i.e., machined copper surface that was exposed to the atmosphere for 4-5 weeks.

Bond Quality, cont.

Acceptable | Conditional | Unacceptable

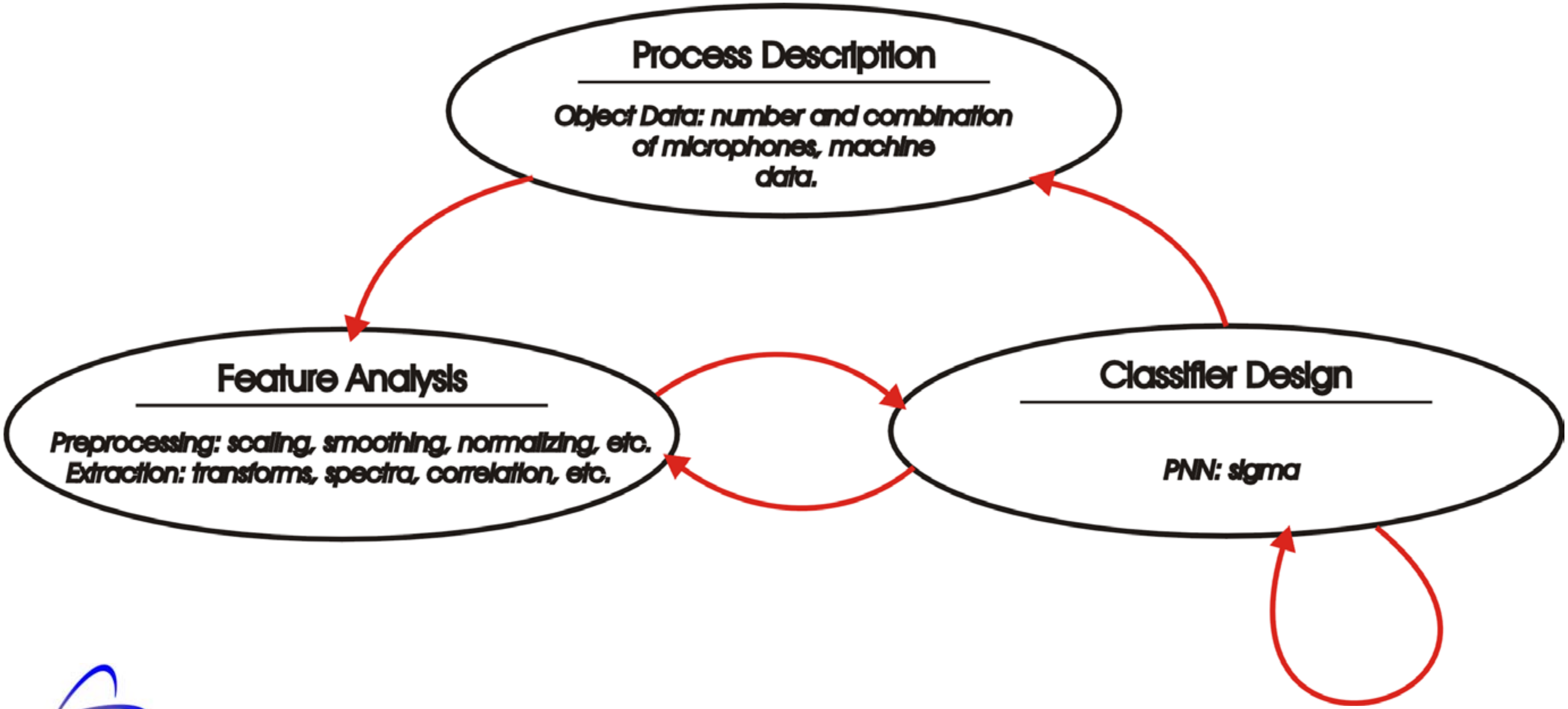


Pattern Classification: Goal

Goal:

- **Identify features within the in-process data that can be correlated to bond integrity.**

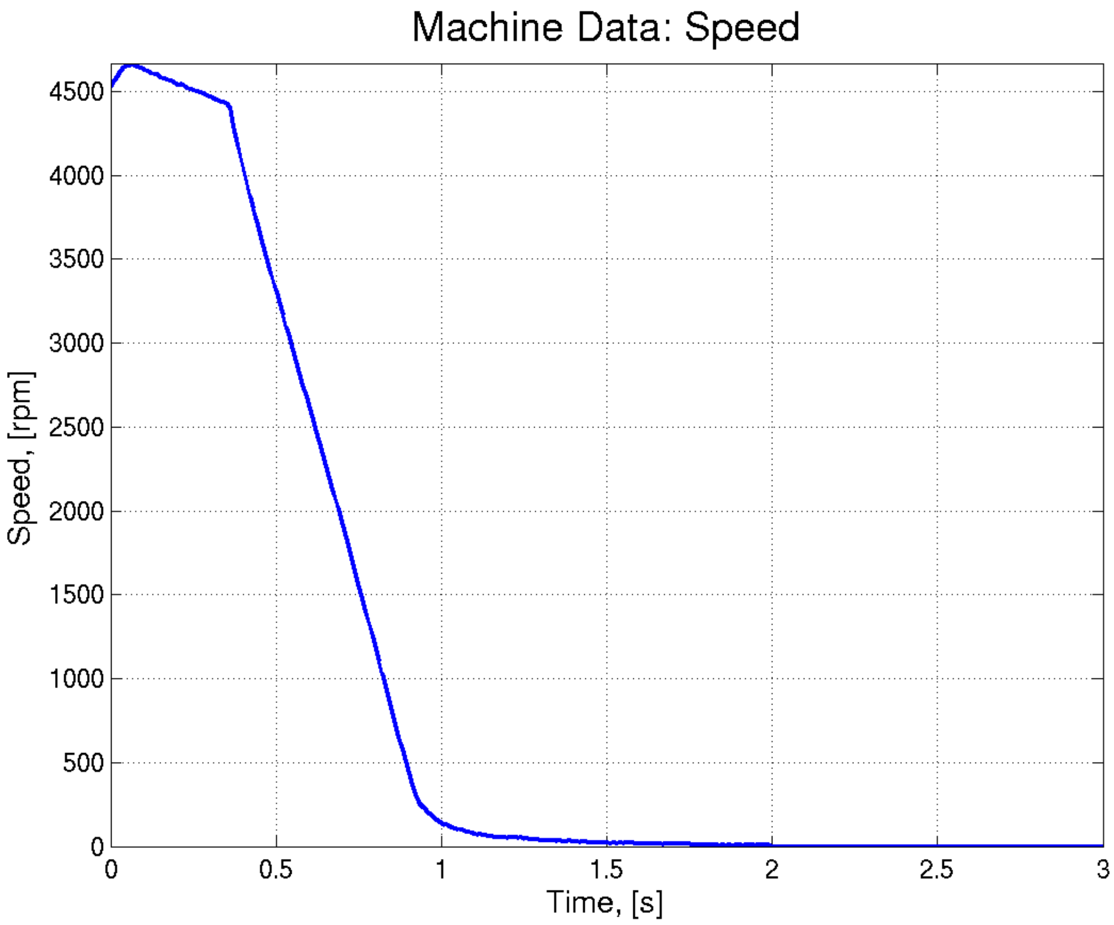
Pattern Classification: Modules



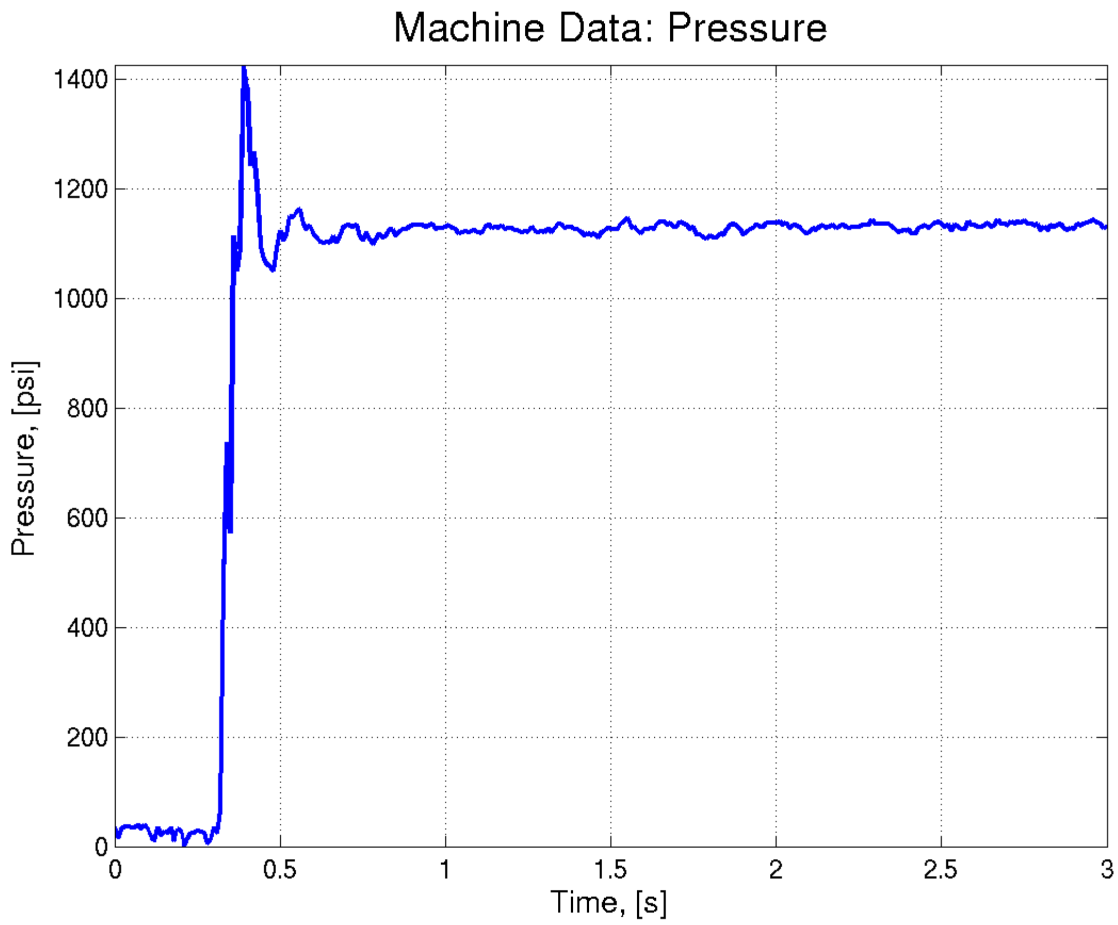
Pattern Classification: Modules, cont.

- Process description:
  - Machine data: speed, pressure, and upset (100 Hz)
  - Sensor data: acoustic energy, (40 kHz)
- Feature Analysis:
  - Normalize, RMS, Energy, Attack and Decay, and Power Spectrum
- Classifier:
  - Probabilistic Neural Network

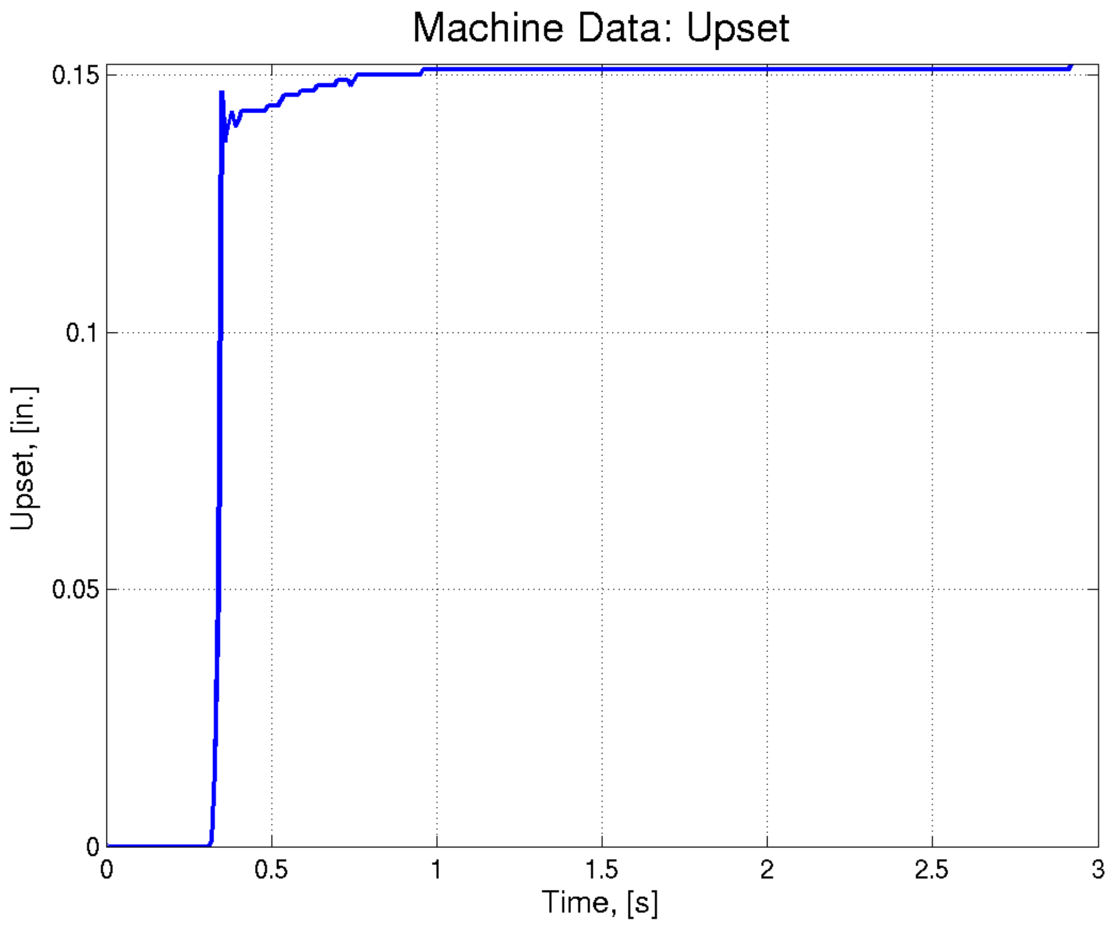
Process Description: Speed



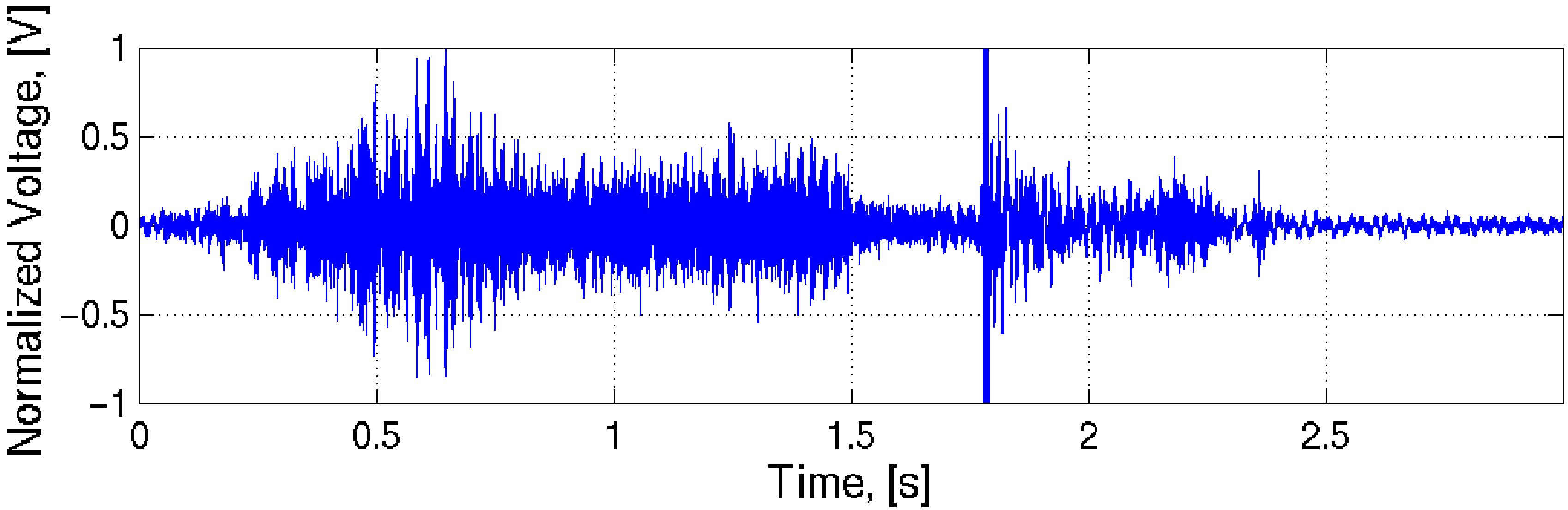
Process Description: Pressure



Process Description: Upset



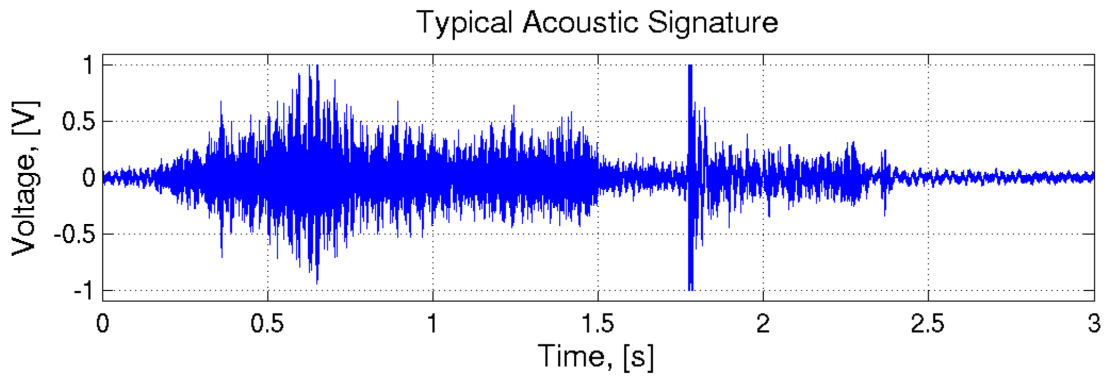
Process Description: Acoustic Energy

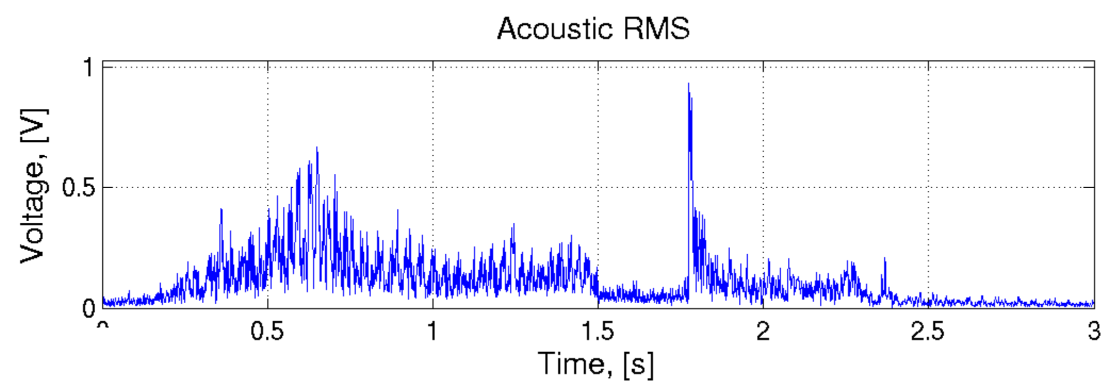


Feature Analysis: Goal

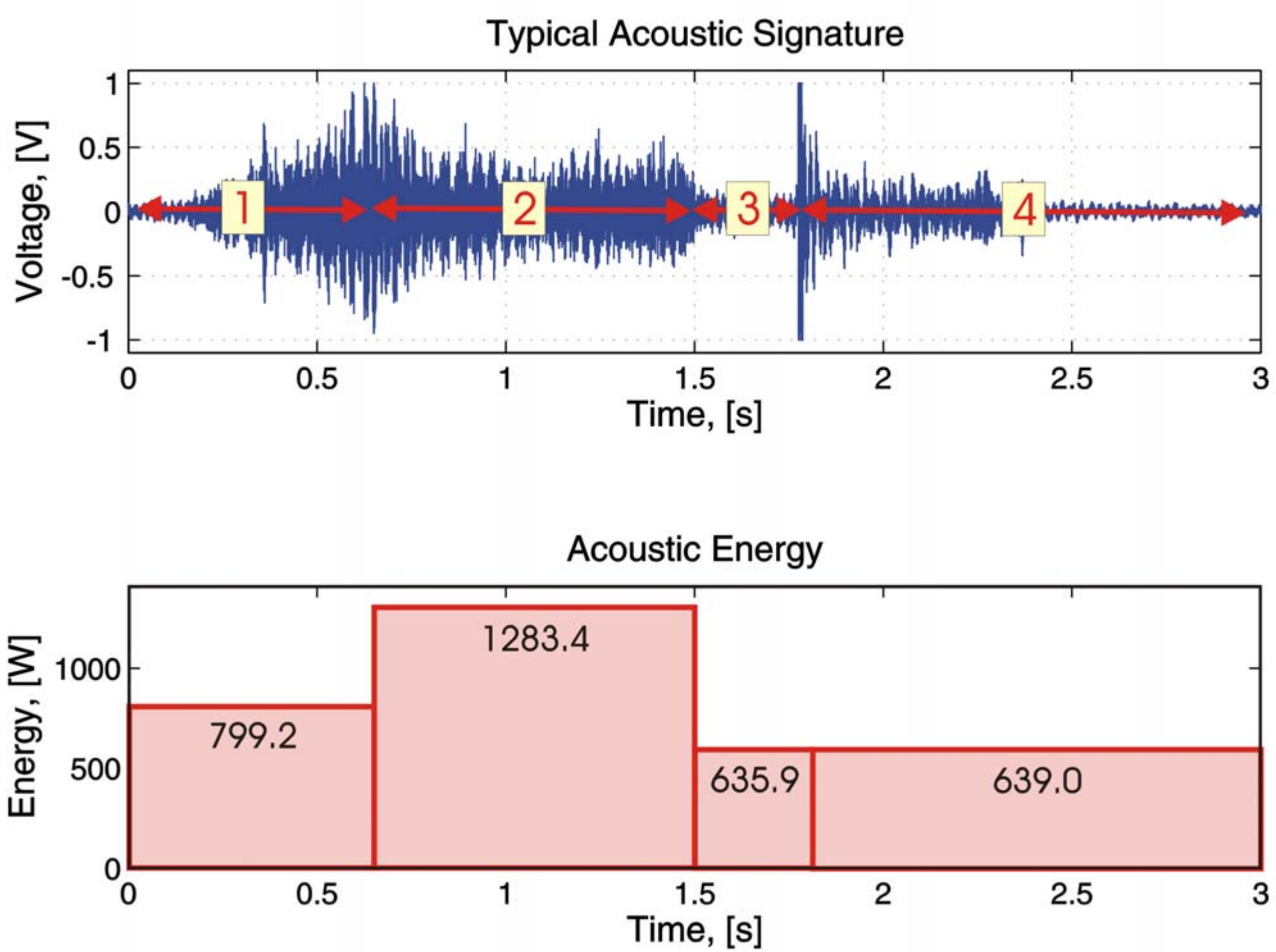
- Goal:
  - Explore and, potentially, improve upon the raw data.
- Ultimate goal:
  - Make the job of the classifier trivial.

Feature Analysis: RMS

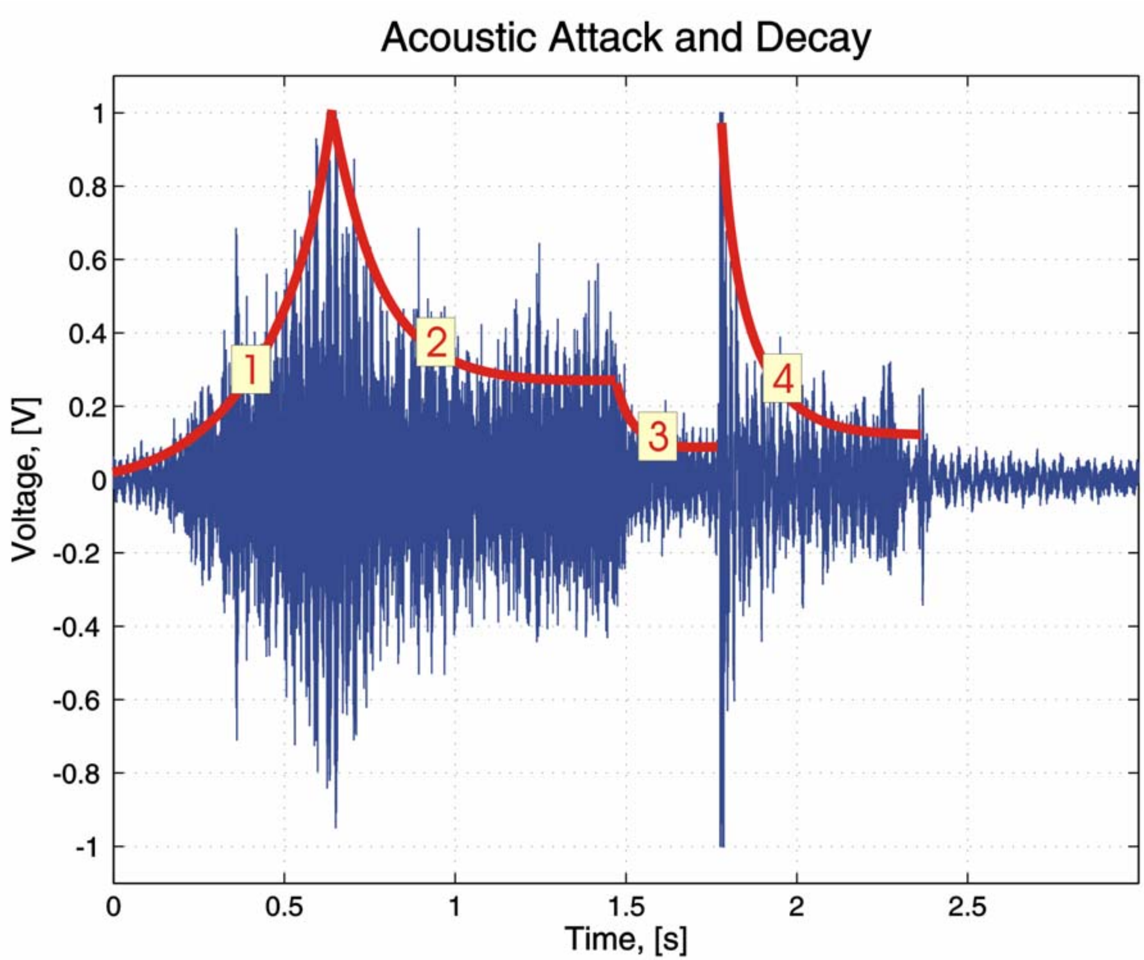




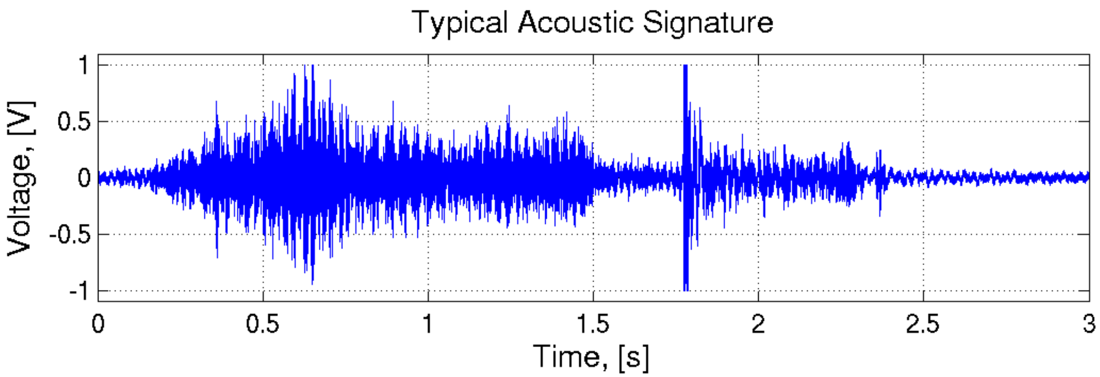
Feature Analysis: Energy

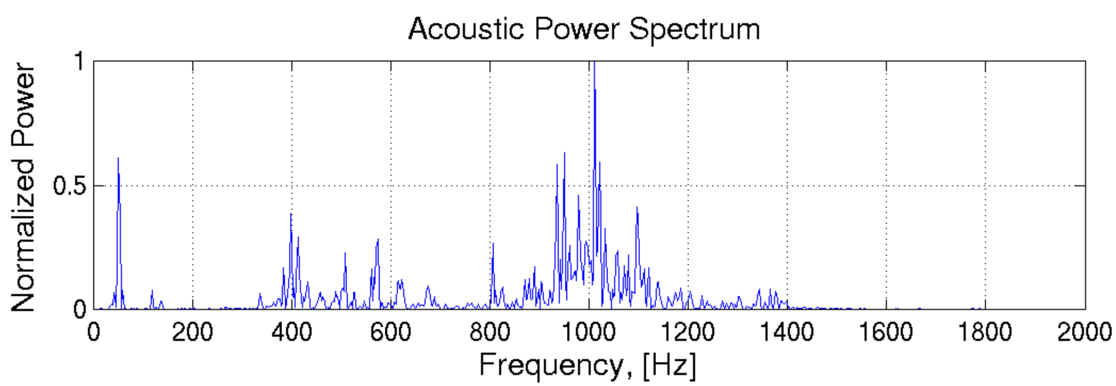


Feature Analysis: Attack and Decay



Feature Analysis: Power Spectrum

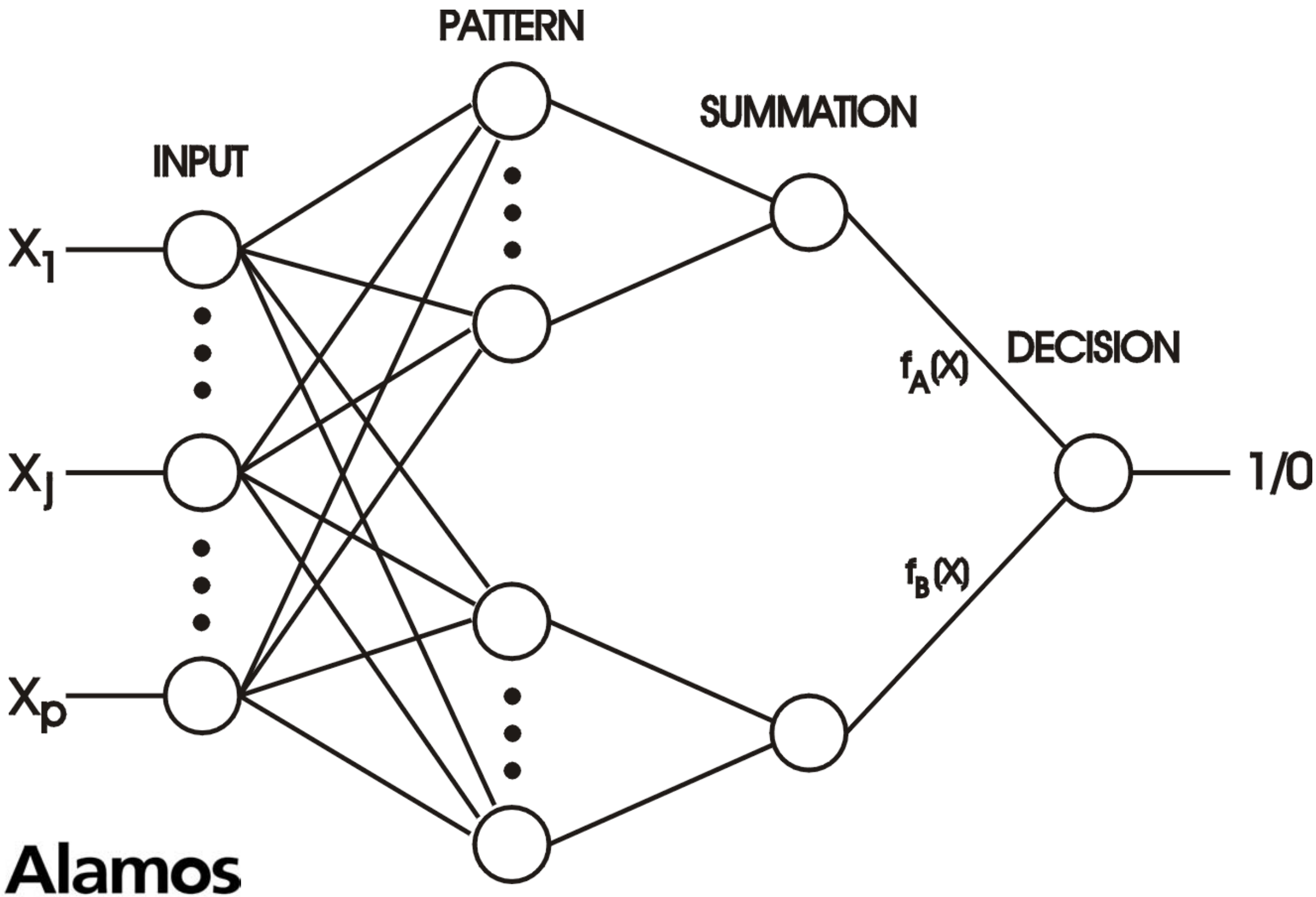




Classifier: PNN

A probabilistic neural network is a feedforward implementation of a Bayesian classifiers that provides a framework for solving pattern classification problems.

Classifier: PNN, cont



Classifier: PNN, cont

- **Advantages over other neural network implementations:**
  - **Can begin classifying after having just one training pattern from each category.**
  - **Orders of magnitude faster to train than a traditional back propagation neural network.**
  - **Can be shown to asymptotically approach Bayes' optimal decision surface without the possibility of getting stuck in a local minima.**
  - **Conducive to enabling a human to interpret and understand how the network works.**

Classifier: PNN, cont

A PNN is therefore ideal for exploring data sets in which the structure is ill-defined and that contains both deterministic and random signals.

Classification Results: Machine Data

Test	Process Data	Feature Descriptor	Acceptable Unacceptable	Acceptable Conditional	Acceptable Conditional Unacceptable
1	Speed	Normalize	82	74	63
2	Pressure	Normalize	59	58	42
3	Upset	Normalize	59	74	63
4	Speed, Pressure	Normalize	76	63	54
5	Speed, Upset	Normalize	59	68	58
6	Pressure, Upset	Normalize	59	63	54
7	Speed, Pressure, Upset	Normalize	59	63	54

Classification Results: Machine Data, cont.

Test	Process Data	Feature Descriptor	Acceptable Unacceptable	Acceptable Conditional	Acceptable Conditional Unacceptable
8	Speed	Attack & Decay	71	63	50
9	Pressure	Attack & Decay	65	68	50
10	Upset	Attack & Decay	47	68	50
11	Speed, Pressure	Attack & Decay	65	68	54
12	Speed, Upset	Attack & Decay	47	68	50
13	Pressure, Upset	Attack & Decay	59	63	46
14	Speed, Pressure, Upset	Attack & Decay	59	63	46

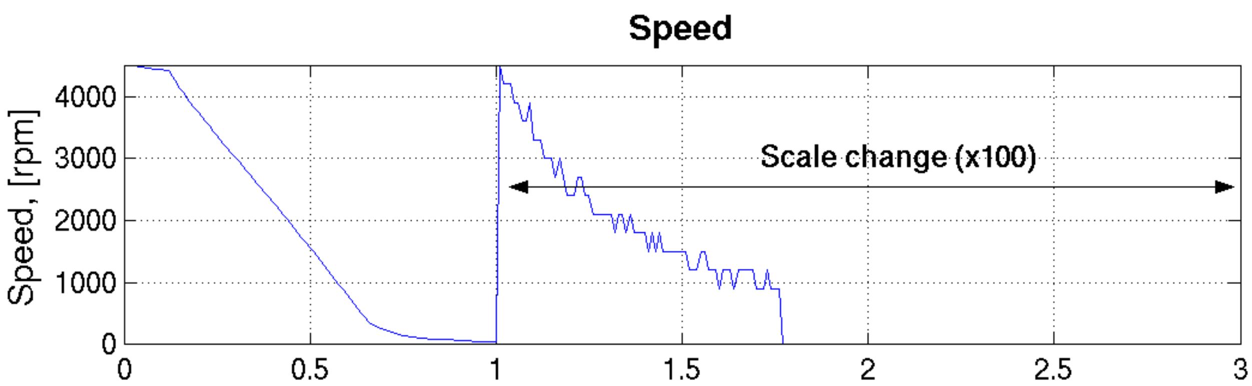
Classification Results: Acoustic Energy

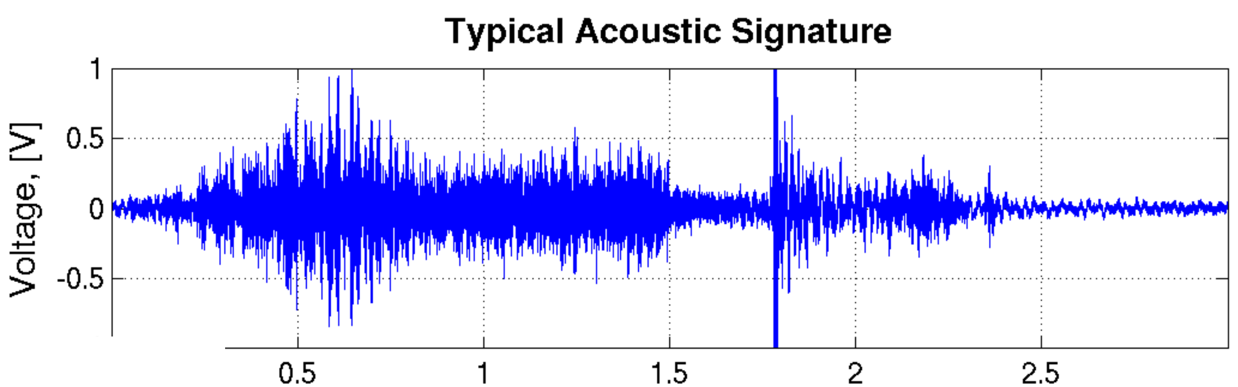
Test	Process Data	Feature Descriptor	Acceptable Unacceptable	Acceptable Conditional	Acceptable Conditional Unacceptable
15	AE	RMS	71	47	46
16	AE	Energy (1 seg)	76	58	54
17	AE	Energy (4 segs)	94	31	41
18	AE	Attack & Decay	88	63	54
19	AE	Attack & Decay, Energy	94	52	50
20	AE	Power Spectrum	100	100	54

Classification Results: Acoustic Energy, cont.

Test	Process Data	Feature Descriptor	Acceptable Unacceptable	Acceptable Conditional	Acceptable Conditional Unacceptable
21	AE, Speed	Attack & Decay	82	68	71
22	AE, Pressure	Attack & Decay	71	68	63
23	AE, Upset	Attack & Decay	72	68	63

In-Process Data: Acoustic Energy & Speed





Conclusions

- ***A classification system was developed with a new acoustic emission sensing technique.***
- ***The classification system is capable of detecting subtle bond-plane contamination conditions.***
- ***It exploits the capabilities of a neural network to interpret multidimensional and ill-defined data.***

Successful Implementation

The successful implementation of an in-process monitoring system requires:

- *Thorough (sufficient?) understanding of the process*
- *Identification of the key variables*
- *Appropriate sensing mechanism*
- *Data analysis techniques that can identify features within the data that can be correlated to quality*

Benefits

• ***Fast***: Provides a real-time response immediately after welding is complete.

• ***Inexpensive***: No additional hardware requirements are necessary.

• ***Robust***: Is capable of mapping complex or ill-defined multidimensional input/output systems and is tolerant of noisy data commonly found on production floors.

• ***Consistent***: Sensing and interpretation is performed without operator intervention and, therefore, ensures an accurate, repeatable, and reproducible system.

• ***Thorough***: Examination is performed for each weld, rather than randomly, to ensure joint integrity.

• ***Efficient***: Only suspect welds are examined further using an “inspect for cause” methodology, which, thereby ensures nuclear safety and promotes weapon system reliability