Nonlinear Time-Series Diagnostics of Fluidization Quality

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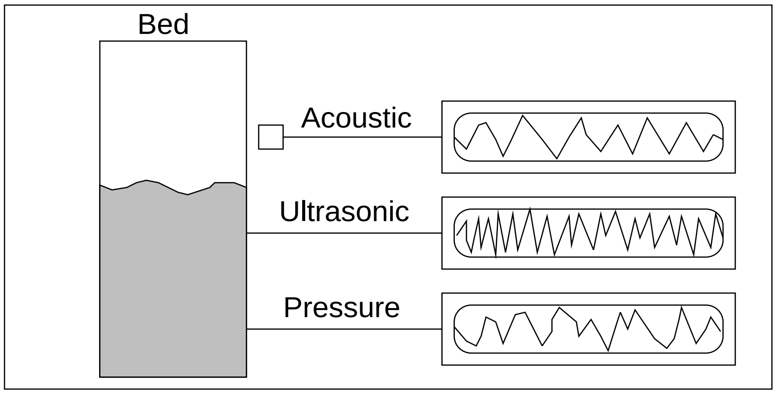
Motivation

Many processes in particle systems, such as mixing, reaction kinetics or bed motion, are dynamic. Common statistics assume that measurements are random and independent and often, by using time-averaged calculations, do not account for temporal correlation.

We wish to develop statistical procedures for monitoring fluidization processes on-line at near time. These procedures are specifically targeted at non-linear dynamic features that correlate with bed hydrodynamics.

Objectives



Given that we have an accessible measurement signal that is relevant to the fluidization state, we wish to determine:

- Stationarity — does the process change with time ?
- State classification — how close is the process condition to previously observed states ?
- Diagnostics

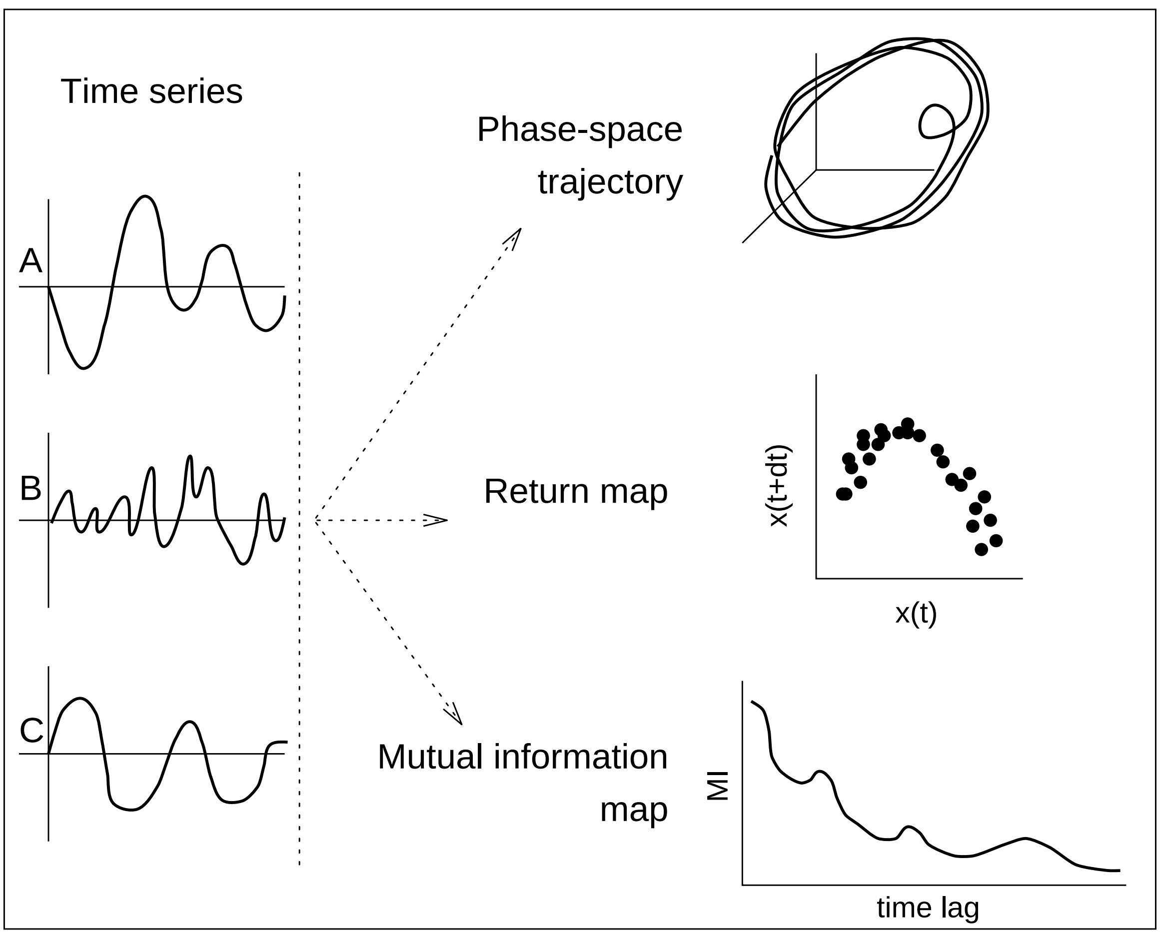
Methodology

We discuss two tests that may be used with many types of measurements:

- Correlation-integral test
- Kennel stationarity test

Data transformations

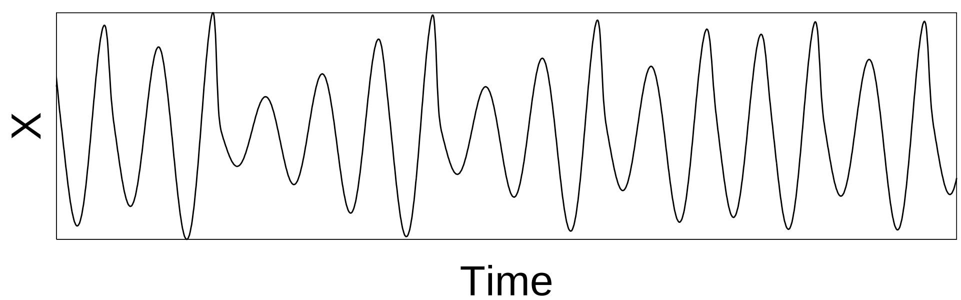
Patterns in time series are "mapped" through special tranforms to reveal underlying structure. This structure is characterized with a new class of nonlinear statistics which account for temporal relationships and do not rely on time-averaged values.

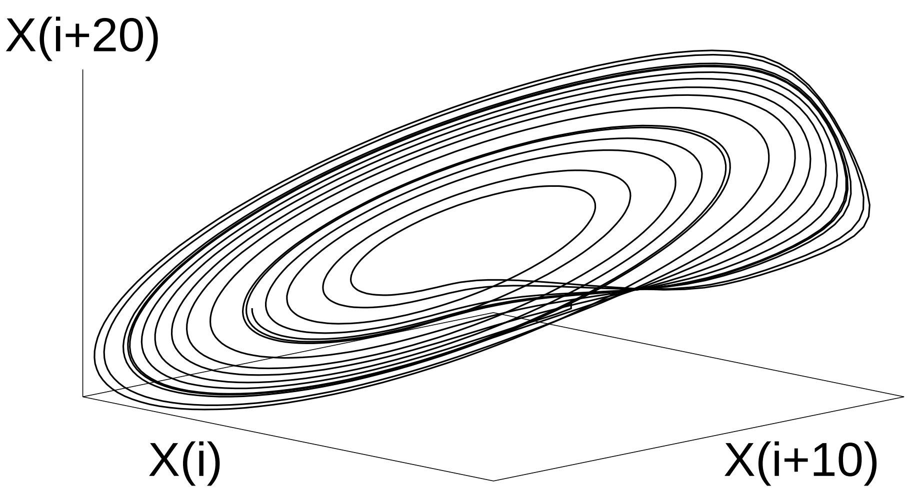


Time-delay embedding

Time-delay embedding transforms a scalar time series into a vector space.

Given time series $X = \{x_1, x_2, \ldots, x_N\}$, a series of vectors $\xi_i = \left\{x_i, x_{i+k}, x_{i+2k}, \ldots, x_{i+(m-1)k}\right\}^T$ forms a delay-vector or reconstructed phase space.



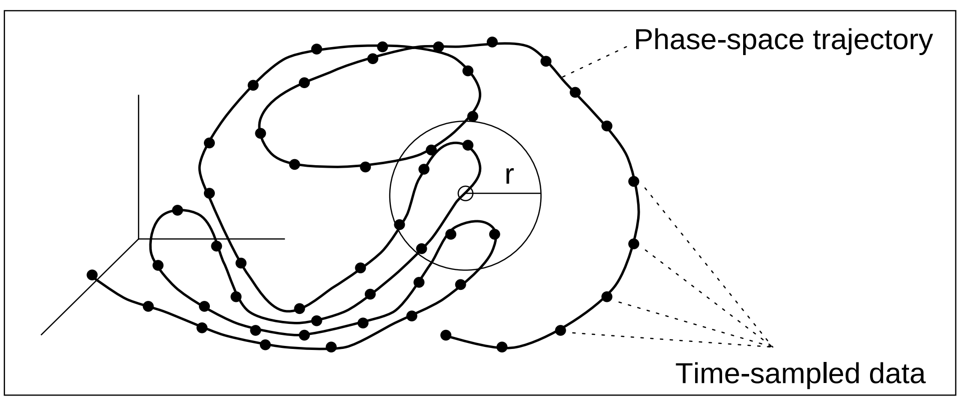


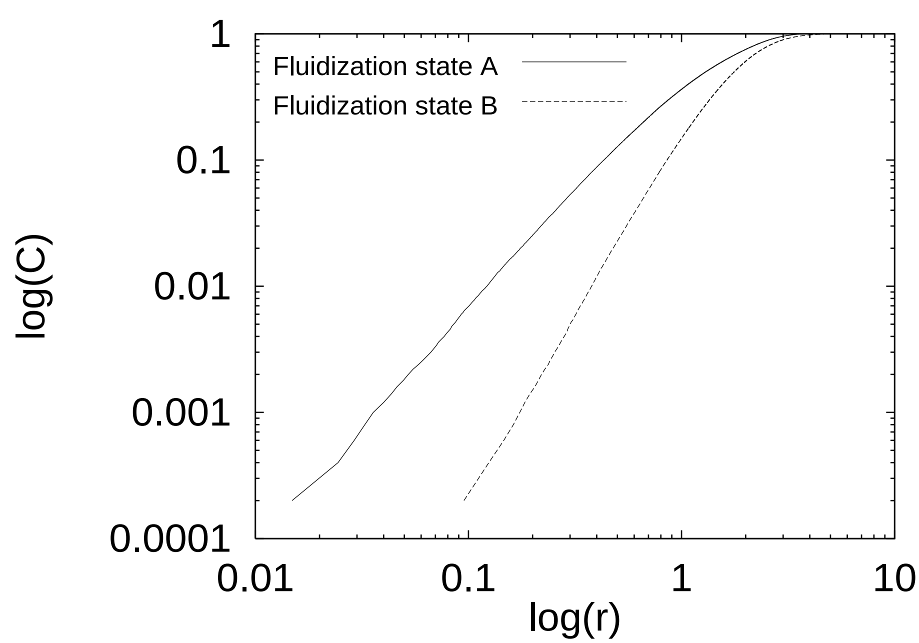
Correlation integrals

Correlation integrals describe the relationship of vectors in the time-delay reconstructed phase space. They describe the geometry of the trajectory.

The correlation integral is defined as

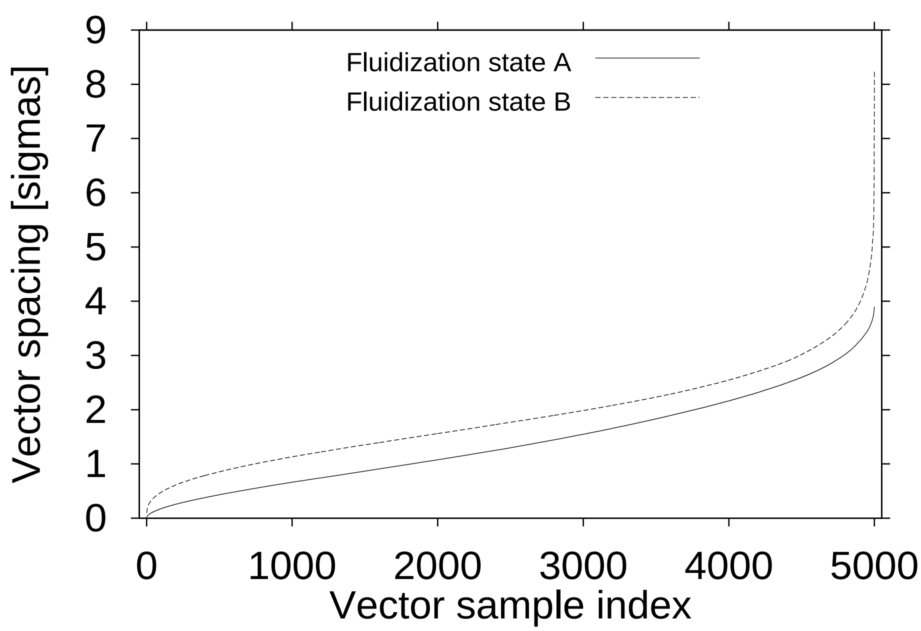
$$C(r,m) \approx \frac{1}{N^2} \sum_{i \neq j} \Theta \left(r - \|\vec{x}_i - \vec{x}_j\| \right)$$





Correlation-integral test

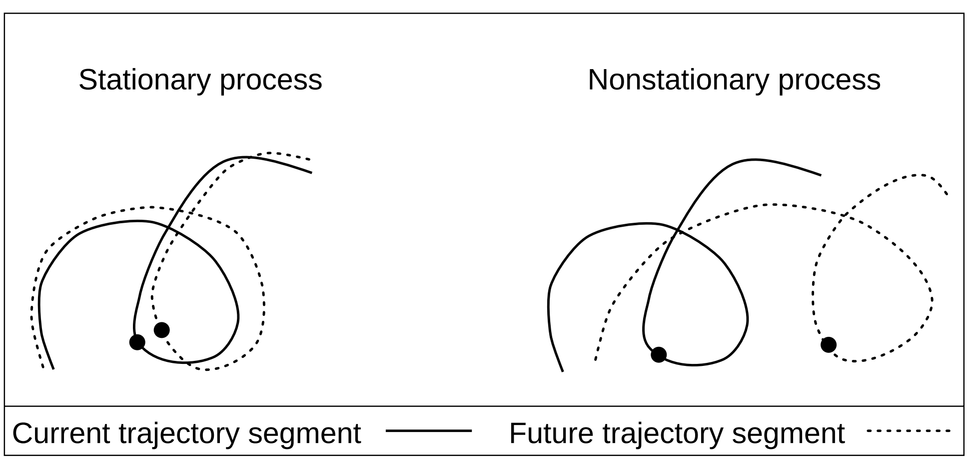
We use a nonparametric test such as the Kolmogorov-Smirnov test to compare the vector spacings used to form the correlation integral.



Kennel stationarity test

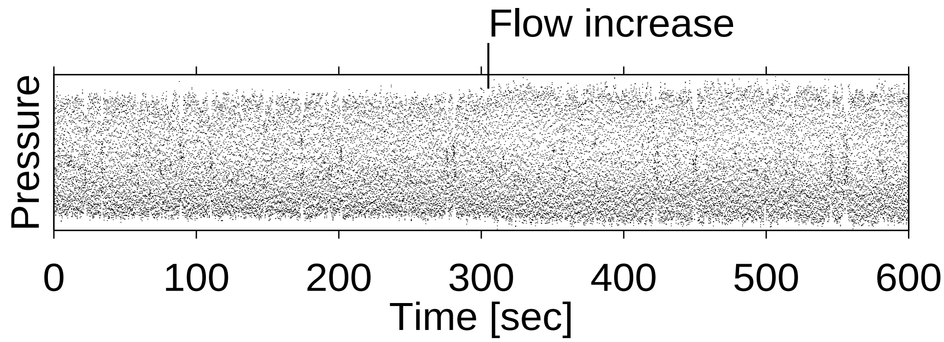
Time series patterns which are very close in phase space are termed "near neighbors". For a stationary process, neighbors in phase space can occur at any time. For a nonstationary process, neighbors in phase space are biased to occur closely in time.

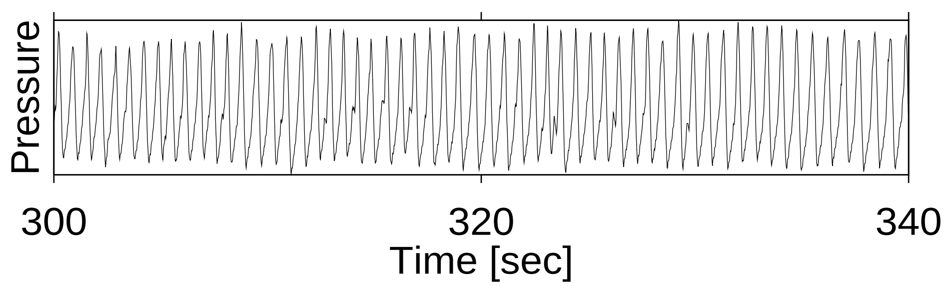
The stationarity test examines the distribution of nearest-neighbor time differences preceding and succeeding a chosen breakpoint.

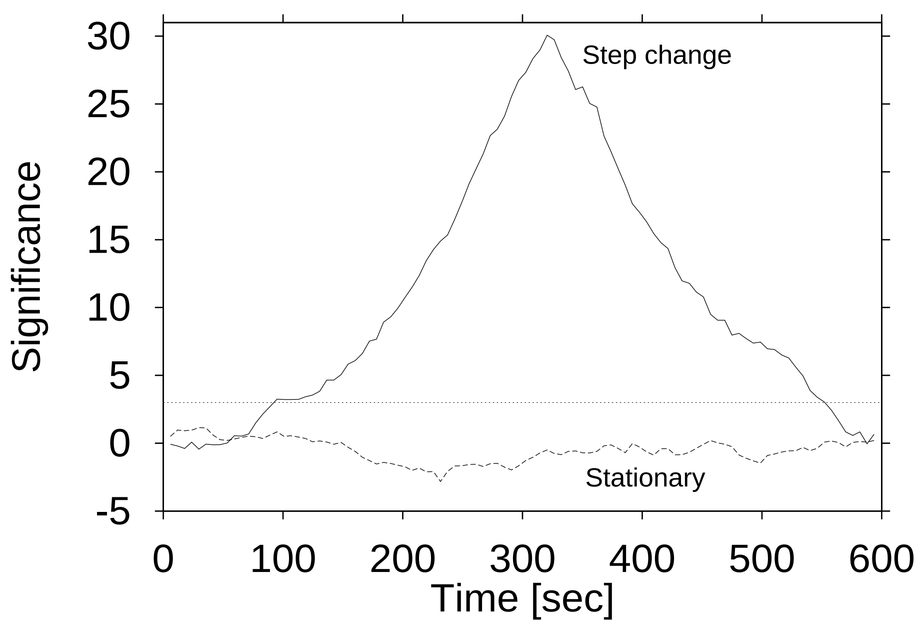


Stationarity-test example: step change

Flow is increased by 5% at $t \approx 300$ sec.

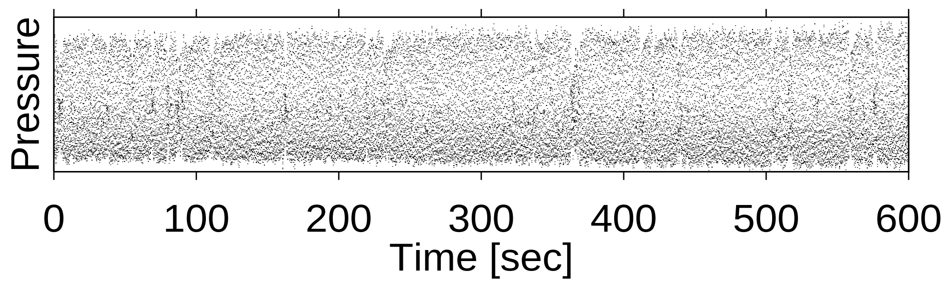


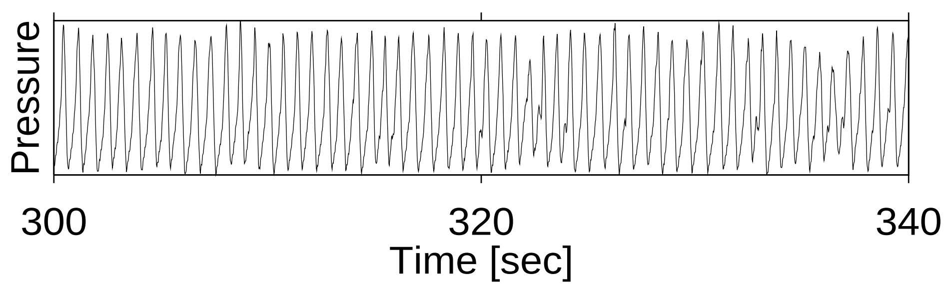


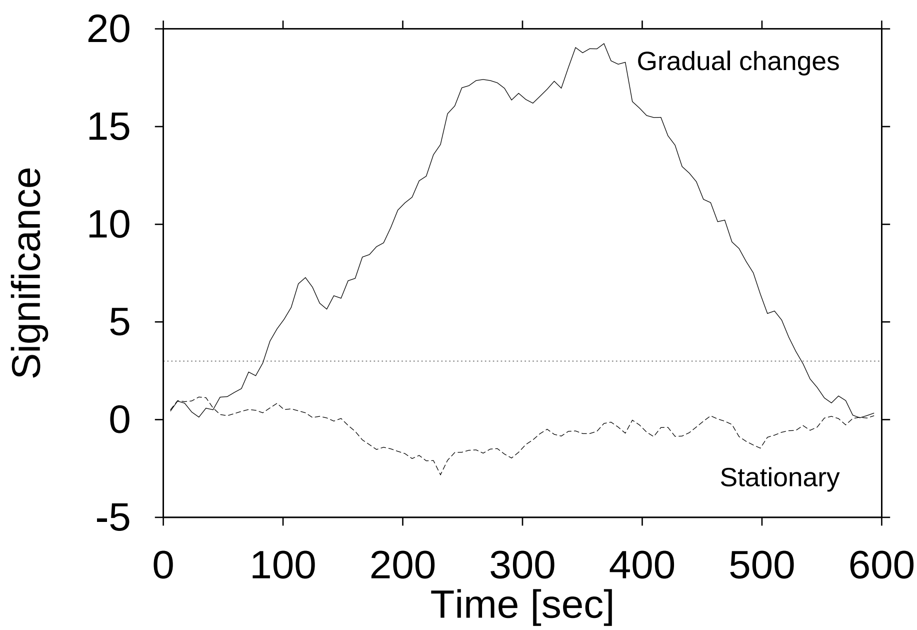


Stationarity-test example: gradual change

Flow is increased by 1% every 100 sec.





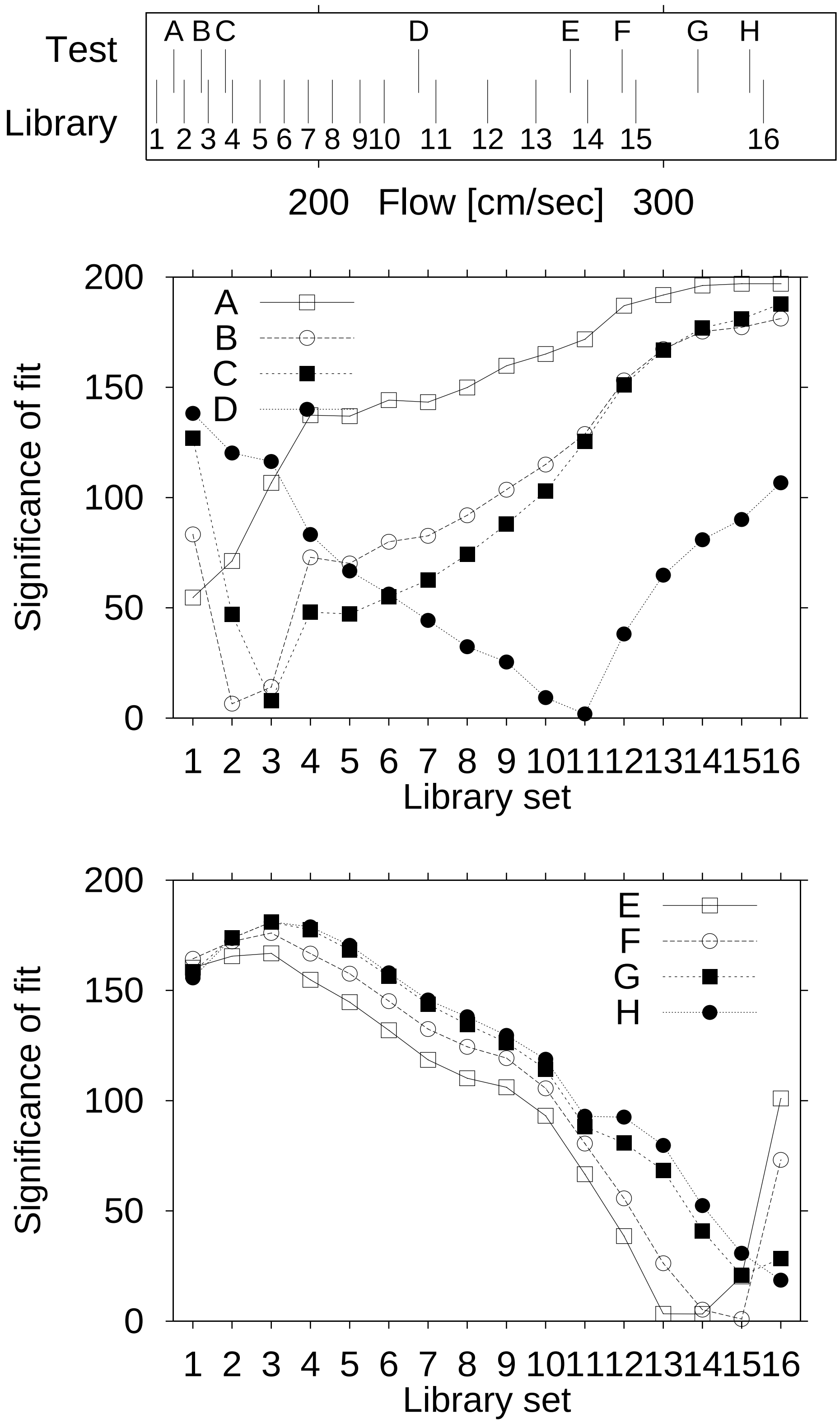


Data libraries and state classification

We wish to know how well a test fluidization condition matches previously observed reference conditions. This knowledge could be important for process control or for diagnostics.

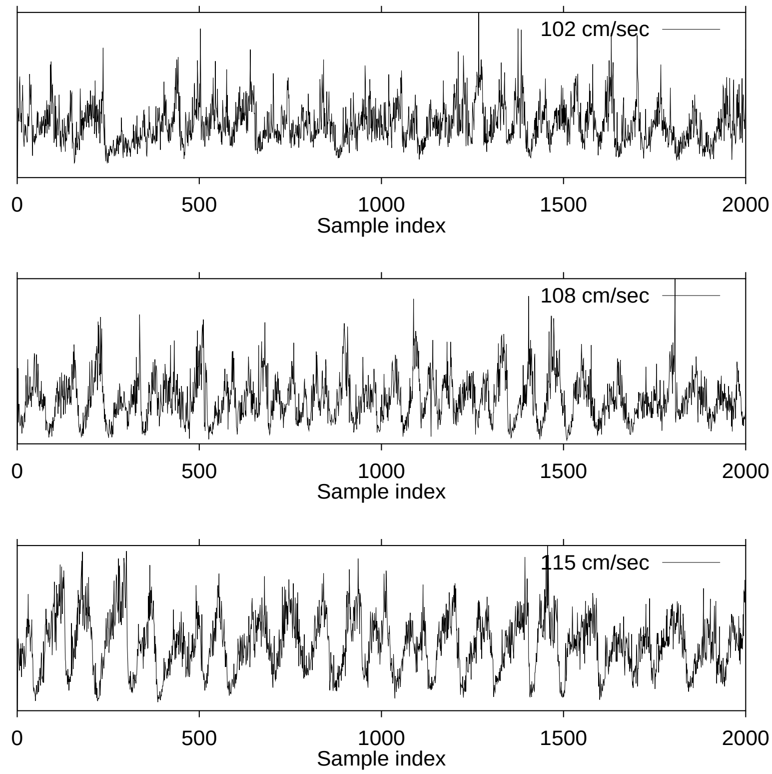
We maintain libraries of statistical descriptors (e.g., correlation integrals) or libraries of time series (for stationarity tests). Fluidization states may then be characterized by goodness of fit with the reference library states.

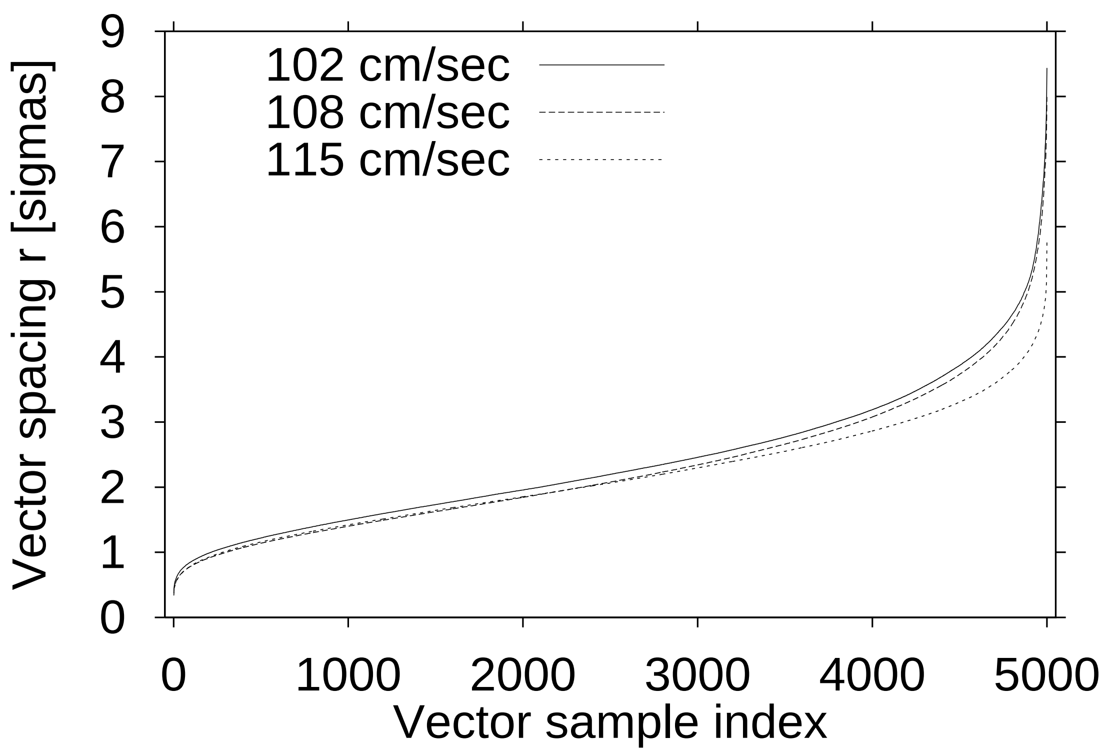
Classification example: slugging pressure data
(Stationarity test)



Classification example: acoustic data

(Correlation-integral test)





Summary

We have presented tests for stationarity based on dynamic descriptors of measurement signals. These tests involve transformations of time-correlated data in order to employ established statistical tests.

We have applied these methods to establish a reference libraries of fluidization states.