An Overview of Nonlinearity in SHM

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The Second Engineering Institute Workshop:
Nonlinear Methods in SHM

Outline

- Feature extraction in structural health monitoring (SHM) process

- Sources of nonlinearity
  - material (small scale)
  - geometric or constraint (medium and large scale)
  - connectivity (all scales)
  - damage inception and evolution (all scales)

- How nonlinearity is 'exploited' for SHM purposes
  - detection/characterization of nonlinearity
  - interrogation with nonlinearity
  - control/mitigation of nonlinearity

- Barriers to further progress?

SHM Hierarchy

The feature extraction process primarily seeks to convert one or more measured time series into ‘compressed,’ lower-dimensional information forms that presumably are used to make an SHM assessment at some level of the Rytter[1] hierarchy:

1. Detection (Is damage present?)
2. Location (Where is the damage?)
3. Quantification (What is the severity of the damage?)
4. Classification (What kind of damage is this?)

Quick survey (based on the IWSHM and EWSHM conference proceedings since 1999):

100% of all features can do Level 1 (otherwise, why report it?)
~70% of all features can do Level 2 (mostly ‘local’ dynamic features, GUWs, etc.)
~30% of all features can do Level 3 (studies are typically very incomplete or unclear, though)
~0% of all features can do Level 4 (people pre-focused on one damage type or just too hard?)

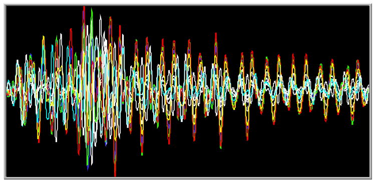
The ‘holy grail’ of SHM may be thought of as the fifth level in the hierarchy, that of **‘Damage Prognosis’**, where feature extraction must be combined with (1) a probabilistic future loading model and (2) A probabilistic model of failure mode(s) evolution

[1]A. Rytter, “Vibration Based Inspection of Civil Engineering Structures,” PhD dissertation,University of Aalborg, Denmark, 1993.

General SHM Feature Extraction Approaches

Passive
(use ambient excitation)

Active
(impart special excitation)

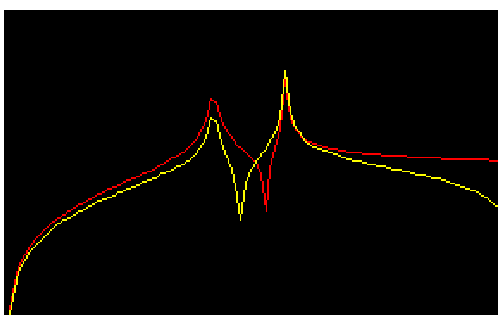


Distributed response measurements

almost always kinematic/kinetic quantities (acceleration, strain, force, etc.) in SHM applications

Direct waveform/image comparison

- *'viewgraph' norm comparisons*
- *simple statistics*
- *FRFs or spectra*

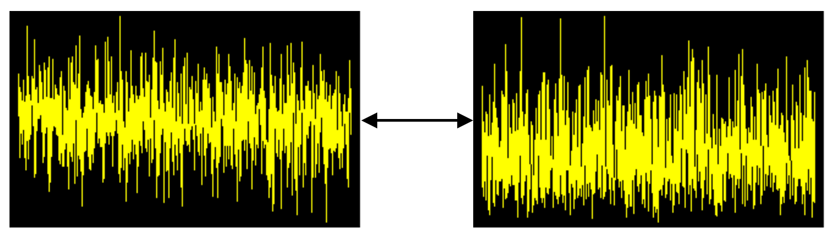


Build and use a model

- *state space estimator*
- *modal model*
- *AR/ARX or other time series, etc.*
- *FE model*

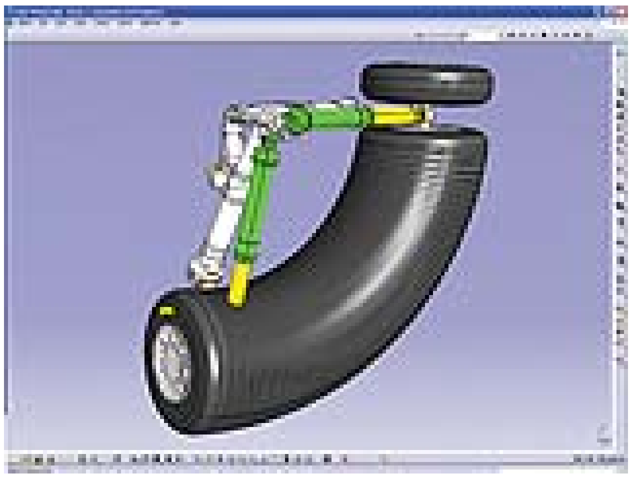
Use model parameters

Use initial model's predictive capability



Where Does Nonlinearity Fit In?

Traditionally, linear approaches to model-building or signal comparison are used to extract damage-sensitive features, even though many systems have inherent nonlinearities (even in 'pristine' or 'baseline' conditions) in design or function or develop nonlinear behavior as a result of damage inception and evolution.



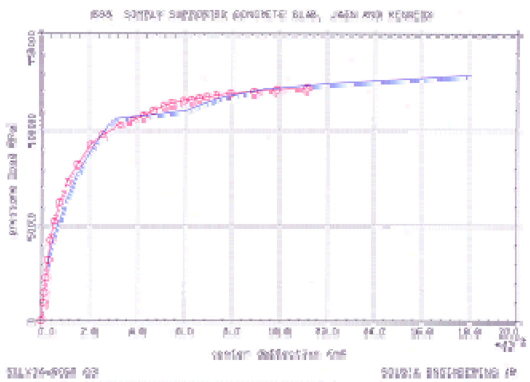
Inherent position-dependent damping in Renault shocks

Wear initiates backlash impacts (stiffness discontinuity)

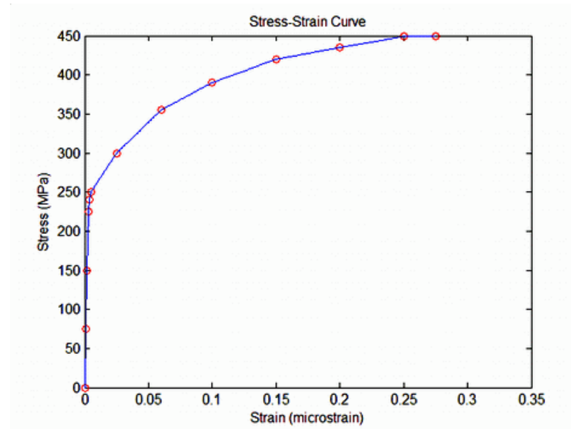
Approaches have taken two broad tracks: (1) identifying sources of nonlinearity, whether they be inherent (designed) or damage-induced or (2) exploiting nonlinear behavior or interactions for enhanced sensitivity to dynamic events that may indicate damage

Sources of Nonlinearity: Material

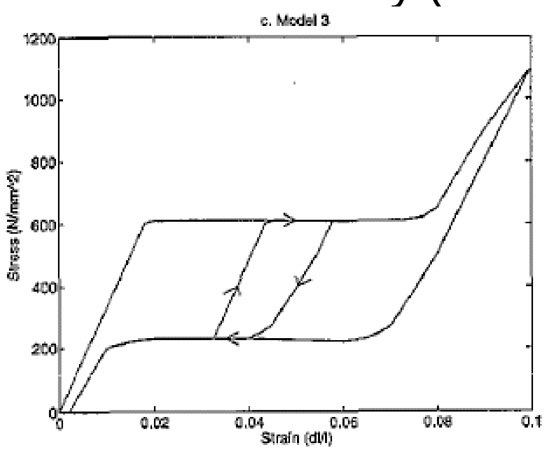
Materials themselves have non-proportional stress/strain elastic and plastic properties, hysteretic behavior, etc.



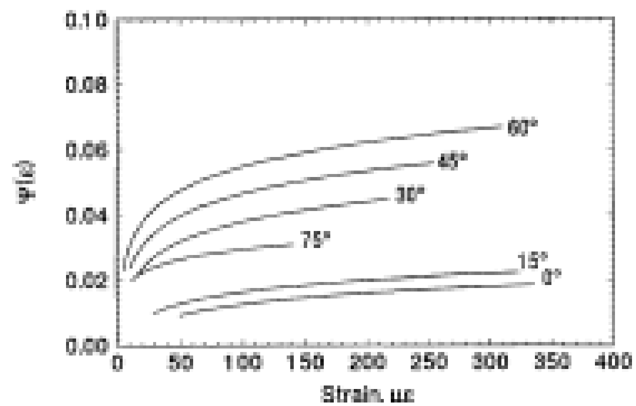
nonlinear elasticity (concrete)



elastic/plastic transition (metal)



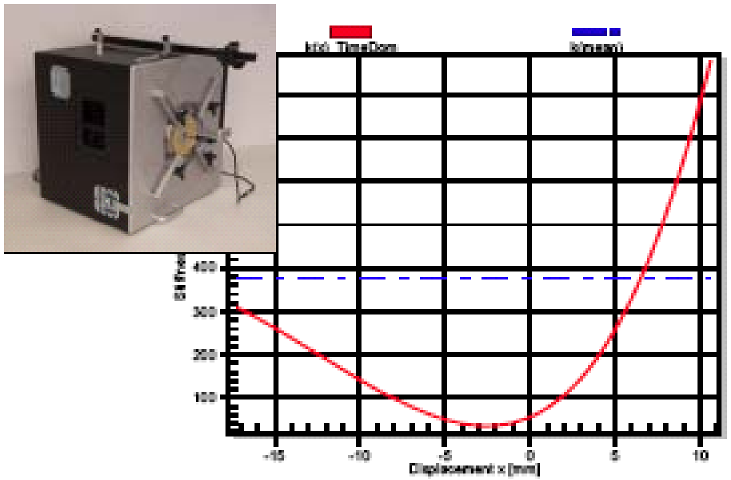
hysteretic stress/strain (shape memory alloy)



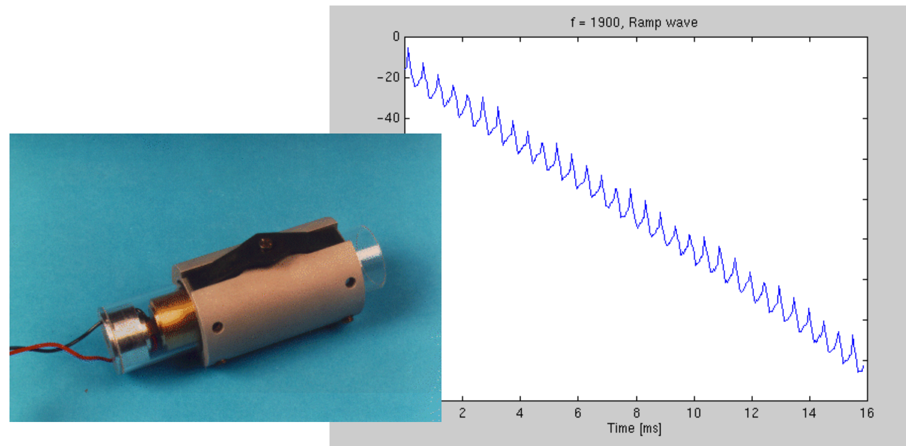
strain-dependent damping in a metal matrix composite

Sources of Nonlinearity: Geometric/Constraint/Connectivity

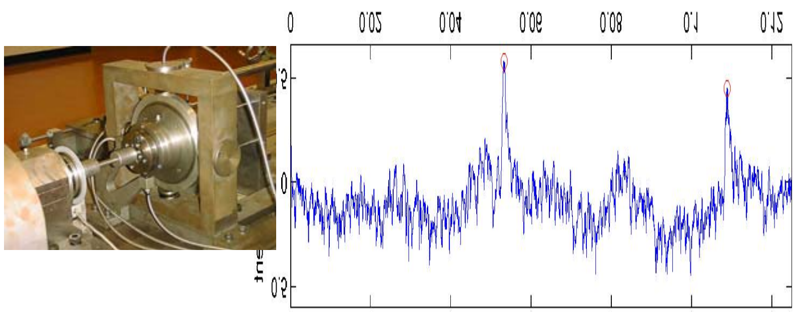
System inherent design, boundary conditions, contacts, or constraints induce nonlinearity



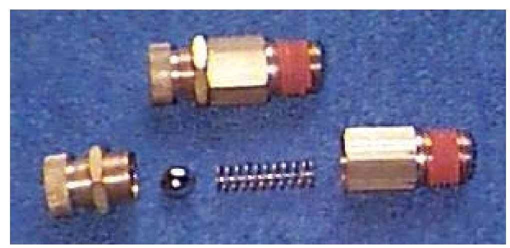
spider stiffness depends on deflection

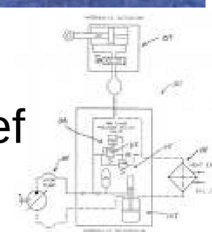


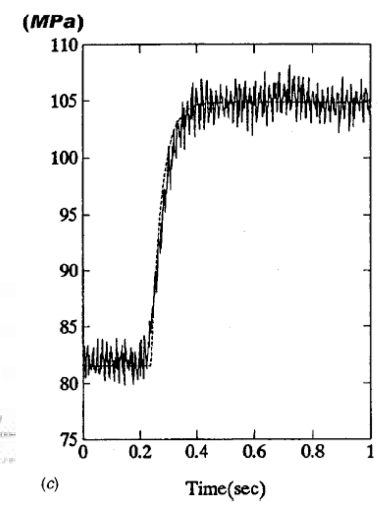
linear PZT actuator stick/slip motion



normal small bearing clearances induce impacts



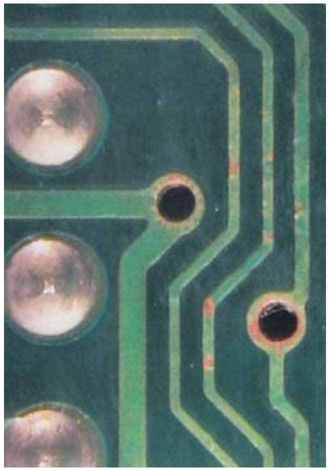




two-stage pressure relief valve

Sources of Nonlinearity: Damage

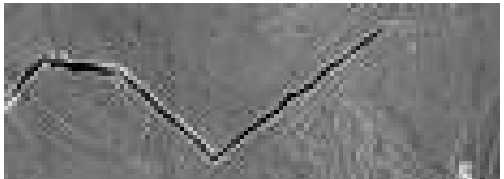
Damage mechanisms can turn a nominally linear system into a nonlinear one



trace delamination in a microelectronic assembly

corrosion of a KC-135 lap joint region

impact damage due to hail

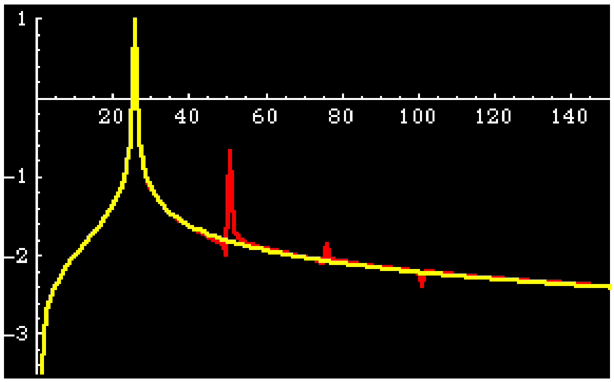


fatigue crack inception and growth

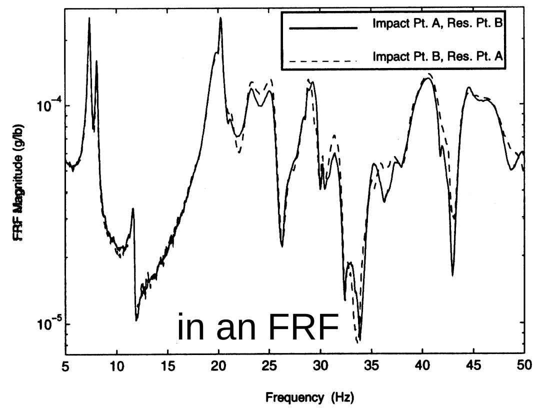
Fatigue crack 'run' caused May 2002 B747 disintegration in flight TPE to HKG

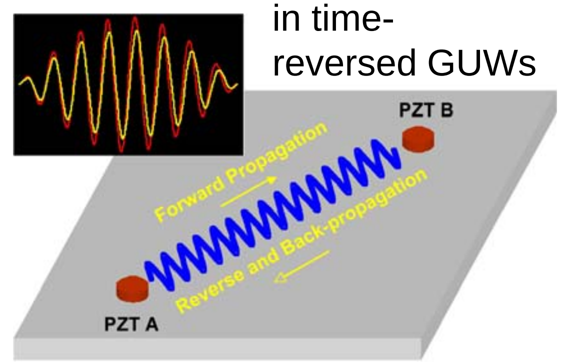
bolt connectivity loss in a wheel hub

Nonlinearity Use: Detection/Characterization

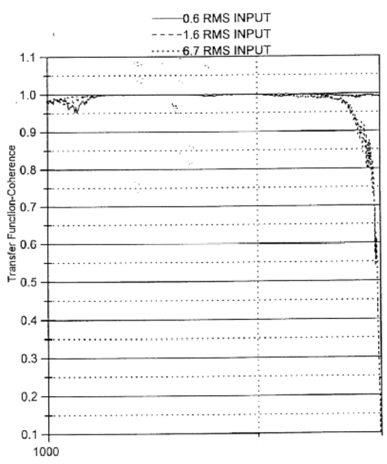


spectrum harmonic detection

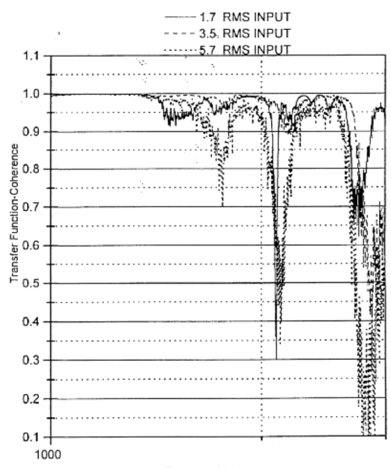




reciprocity check

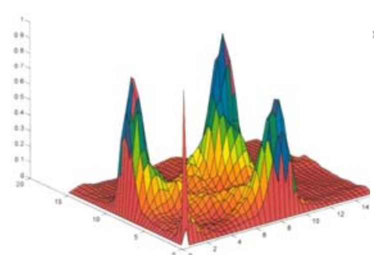


no loose parts

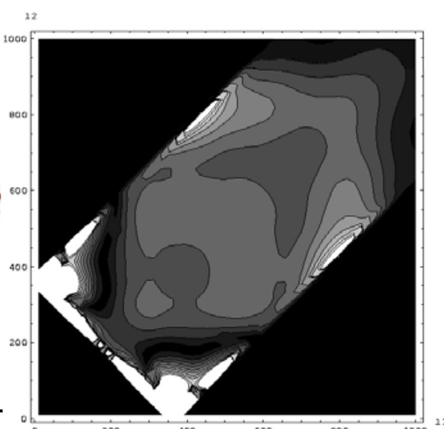


several loose parts

coherence distortions



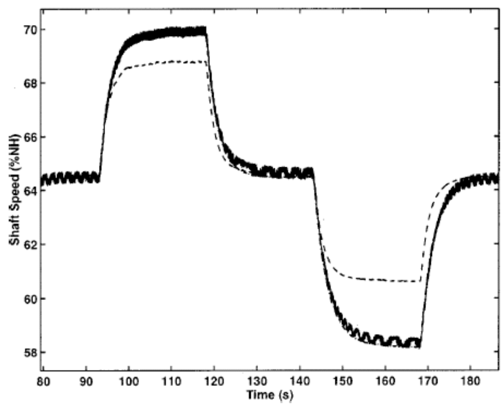
bispectrum



trispectrum contour

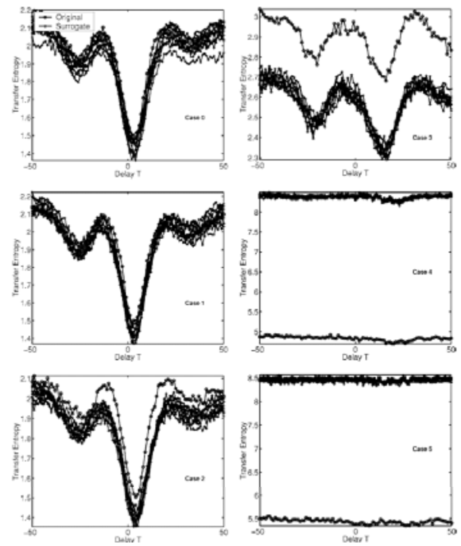
higher-order spectra

Nonlinearity Use: Detection/Interrogation



$$y(n) = \mathbf{F}(y(n-i), u(n-j), e(n-k)) + e(n)$$

generalized time/freq. domain modeling (e.g., NARMAX)

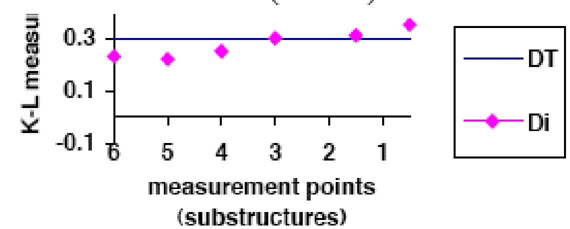


transfer entropy

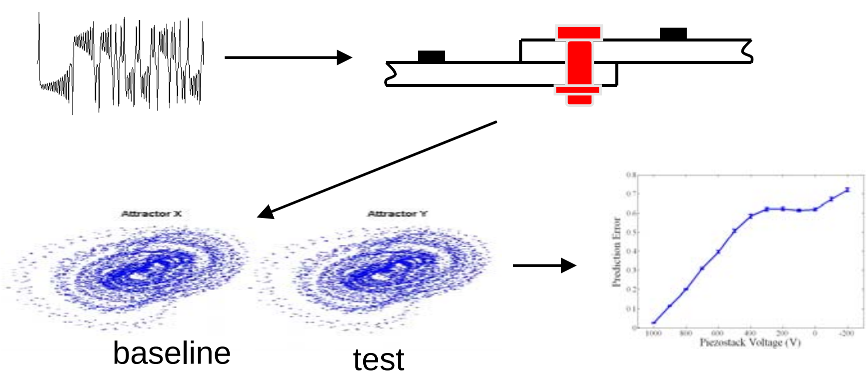
$$I(a, a^L) = \int_{t_0}^{t_1} a(t)\log\left(\frac{a(t)}{a^L(t)}\right)dt.$$

$$\cdot\int_{t_0}^{t_1} a^L(t)\log\left(\frac{a^L(t)}{a(t)}\right)dt$$

Kullback-Leibler dissimilarity



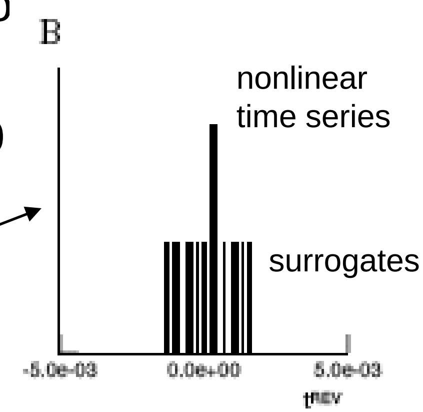
information theoretics, symbolic enco... etc.



chaotic interrogation, nonlinear interaction, state comparison

$$p(x_n, \ldots, x_{n+k\tau}) = p(x_{n+k\tau}, \ldots, x_n)$$

$$t^{\mathrm{REV}}(\tau) = \langle (x_k - x_{k-\tau})^3 \rangle$$



time reversibility

Where We Are and Where We Are Going

- Most nonlinear techniques are still primarily laboratory-scale tools
  - they don't generalize in the same ways linear techniques do
  - they can be relatively computationally cumbersome, expensive, and/or 'tweak-sensitive,' all of which can outweigh perceived benefits (especially in the eyes of economically-sensitive managers)
  - design, operations, and maintenance engineers aren't very comfortable with nonlinear concepts and their associated 'baggage'

- This workshop seeks to do three things in nonlinear methods as they relate to SHM
  - assess the state-of-the-art in nonlinear methods and how they're being applied to SHM problems (classify, organize, categorize…a taxonomy issue!)
  - assess the viability of nonlinear methods in general to SHM problems…where do these techniques hold the most promise and where are we barking up the wrong tree?
  - assess what the progress barriers for transitioning to practice

The Workshop

• We have assigned each of you to a small focus group that will spend time discussing these and other issues centered on four major themes:

- classifying sources of nonlinearity
- classifying, grouping, and analyzing nonlinear techniques for SHM
- nonlinearity vs. nonstationarity
- barriers to progress and what do we need to do to get to where we need to be (doesn't that sound like a vague management question?)

• Each group has fixed moderators and recorders so that all discussion, ideas, feedback are capture and retained for inclusion into a formal report

Engineering vs. Management

A man in a hot air balloon realized he was lost. He reduced altitude and spotted a man below. He descended a bit more and shouted, "Excuse me, can you help me? I promised a friend I would meet him half an hour ago, but I don't know where I am."

The man below replied, "You are in a hot air balloon hovering approximately 30 feet about the ground. You are between 40 and 42 degrees north latitude and between 58 and 60 degrees west longitude."

"You must be an engineer," said the balloonist.
"I am," replied the man, "but how did you know?"

"Well," answered the balloonist, "everything you told me may be technically correct, but that information is essentially useless, because the fact is, I still have no idea where I am!"

The man below stared at him and responded, ”Then you must be a manager."
"I am," replied the balloonist, ”but how did you know?"

"Well," said the man, "you don't know where you are or where you are going, you made a promise which you have no idea how to keep, you expect me to solve your problem, and the fact is you are exactly in the same position you were in before we met, but now, somehow, it's my fault!"