CMVA
Canadian Machinery Vibration Association

ACVM
L'Association Canadienne en Vibrations de Machines

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Development of a Physics-based Model for Machine Condition Monitoring

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AP DYNAMICS

Concept

Complex dynamical systems (such as rotating equipment) are difficult to model from first principles as they usually involve complex interactions between mechanical, electrical, thermal, chemical and fluid mechanical phenomena.

Thus, at the time of characterizing a functioning machine with the objective of diagnosing its “health” (defined as its adequacy with respect to some ideal performance envelope), it has been the standard practice to study the machine response using statistical relationships between measured parameters and follow the evolution of these parameters over time.

Having a physics based model of the machine implemented in a computer will help with the task of exploring the potential range of outputs “in real time” the comparisson between this output and the measurement of the monitored prameters will give a clear idea of the health and also help with the diagnostic of potential failure ahead of time without having to “experience all these potential scenarios during the operating life of the machine

The advantages of the proposed methodology would be that the time needed for determining the parameters of “normal” (or perfect condition) functioning will be small. Also, to assess the range of possible variations or deviations from normal, it will not be necessary to run over the whole range of possible conditions because the basic governing laws can be used to predict the normal outcome at those operating conditions that have not been yet explored. Also, the normal governing laws can be found for the system assuming some imperfections. Study of the outcome of the system with imperfections will give insight on how to diagnose the causes of failure based only on measurement of functioning parameters and its changes over time, something that is already a standard practice.

Models and Theories

Phenomenological models

Based on data analysis only

Statistical Analysis

Multi-variable regression analysis

Neural networks

.....

"Glorified Interpolation"

Physics based models

Based on theory and experimental validations

Differential equations

Conservation laws

Close form solutions

Numerical solutions

"You can always get the right solution to problems for which the solution is known"

In the end, all models are wrong, although some of them are more useful than others, said the Philosopher

I use models to make actual predictions about real systems, with quite a good track record, says, humbly the Engineer.

MOTIVATION:

Most Condition Monitoring and fault diagnosis of operating machinery systems employ data driven models That is, the machine is being studied as one would study a complex system whose governing laws are to be discovered. The rationale of this approach is that with complex enough dynamical systems, the governing equations are too difficult to solve in practical situations for the purposes of diagnostic and performance prediction.

The availability of modern computational tools however can offset the advantages of this method and make the calculation based method of prediction more attractive. In general the equations describing the evolution in time of the state parameters of machinery are known. However in practical cases the difficulty to predict exact outputs resides in the fact that the small differences in the determination of the exact physical parameters that are subjected to tolerances and differences between different machines will prevent the computation of the evolution of the machine with adequate precision. These parameters would need to be determined experimentally for each particular case

with poor prediction capability and extremely long training and tuning time, hard to adapt to new operating conditions or changes

Challenges:

1) *Creation of the system of differential equations that describe the system in terms of the variables of interest*.

This involves the determination of what ‘physics’ and to what level of detail should it be included, how much a 'physics' influence others (coupling), linear vs. non-linear effects, the existence of possible chaotic states, etc.

Challenges:

2. *Solution in real time (meaning fast enough to be effective) of the resulting system of equations.*

What is included in the model determines the size and complexity of the computational tasks, therefore one needs to make sure that this task can be implemented in software or hardware. There may be cases in which the pre-computation of solutions for certain operating conditions will be necessary.

Challenges:

3. *Discrimination between what constitute an erroneous reading due to noise or higher order effects not modelled, and what is an erroneous reading due to degradation/failure of machine components.*

Some statistical analysis of the date stream may be necessary before comparing the measured signal against the theoretical response for the ‘perfect state’ and all the possible responses that are included in the set of altered responses.

Perfect or Reference State

- This model would be represented by a set of ODEs, based on the system's geometry, operating conditions, and other parameters. The form of these ODEs would be based on physical relations and laws, hence the term "physics-based model".

health

- is defined as the some measure of the divergence between the actual state of the machine and the "perfect state" predicted by the solution of the system of equations representing the system.

Challenges:

1) *Creation of the system of differential equations that describe the system in terms of the variables of interest*.

Answer:

Bond Graph Methodology.

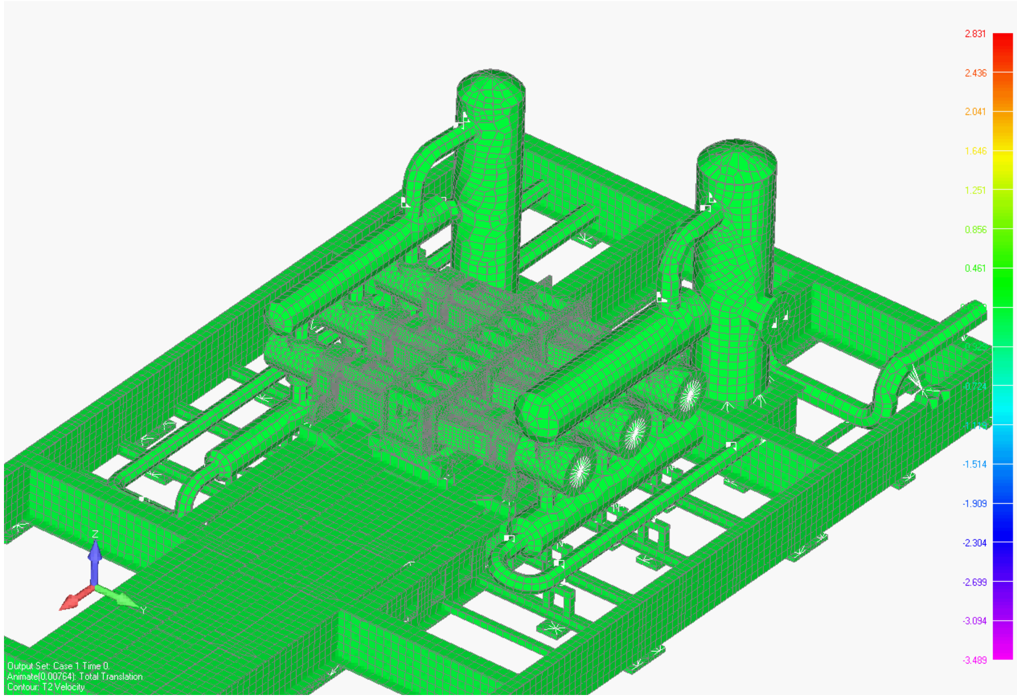
Challenges:
Challenges:

2. *Solution in real time (meaning fast enough to be effective) of the resulting system of equations.*

Response:

Include only the variables that can be measured.

If model is large, precompute


2.831
2.436
2.041
1.646
1.251
0.856
0.461
-0.724
-1.514
-1.909
-2.304
-2.699
-3.094
-3.489
Z
Y
Output Set: Case 1 Time 0.
Animate(0.00764): Total Translation
Contour: T2 Velocity

Challenges:

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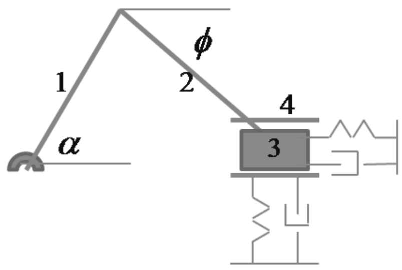
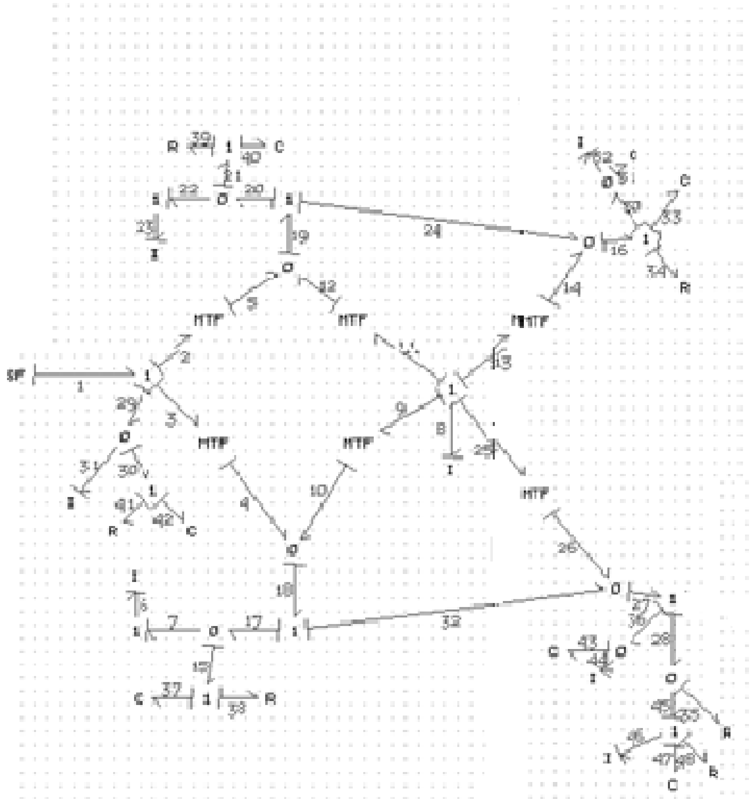
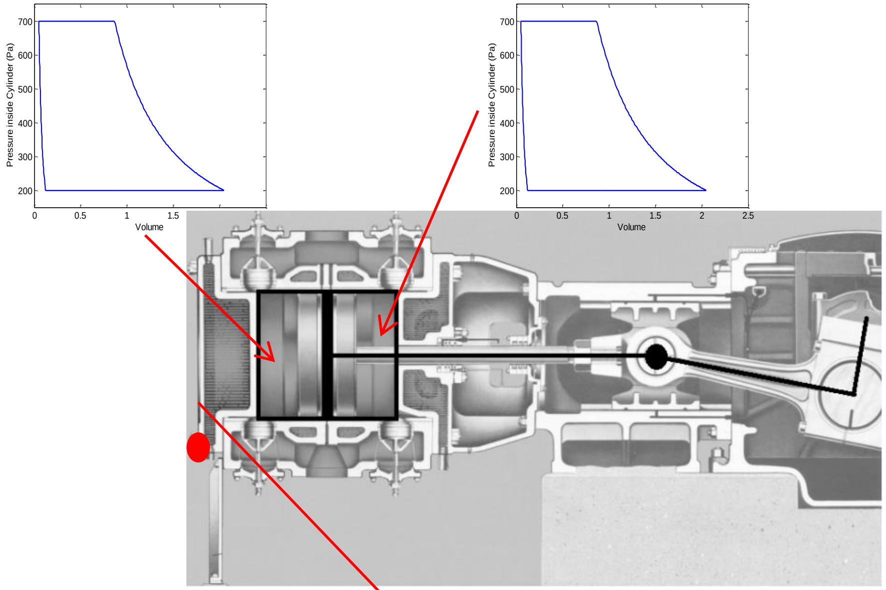


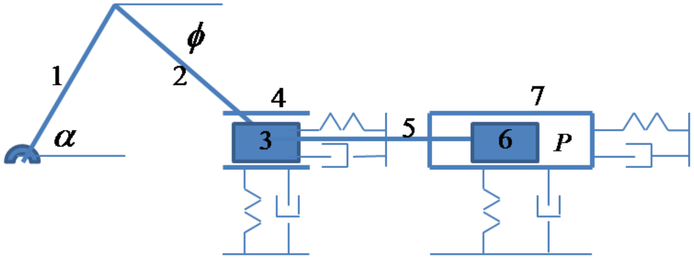
Slider-Crank system

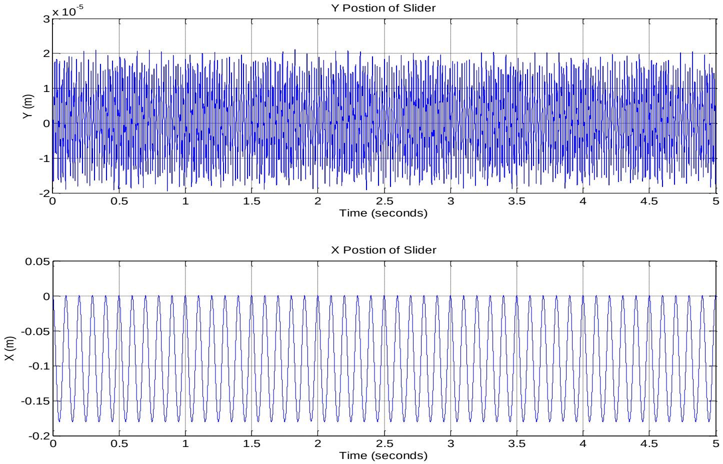


Bond graph model of slider-crank

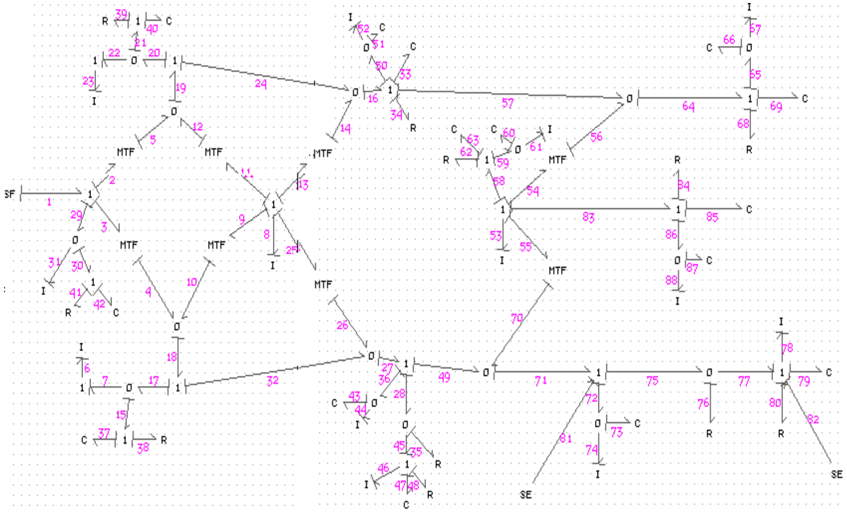
Bond graph model of a reciprocating compressor

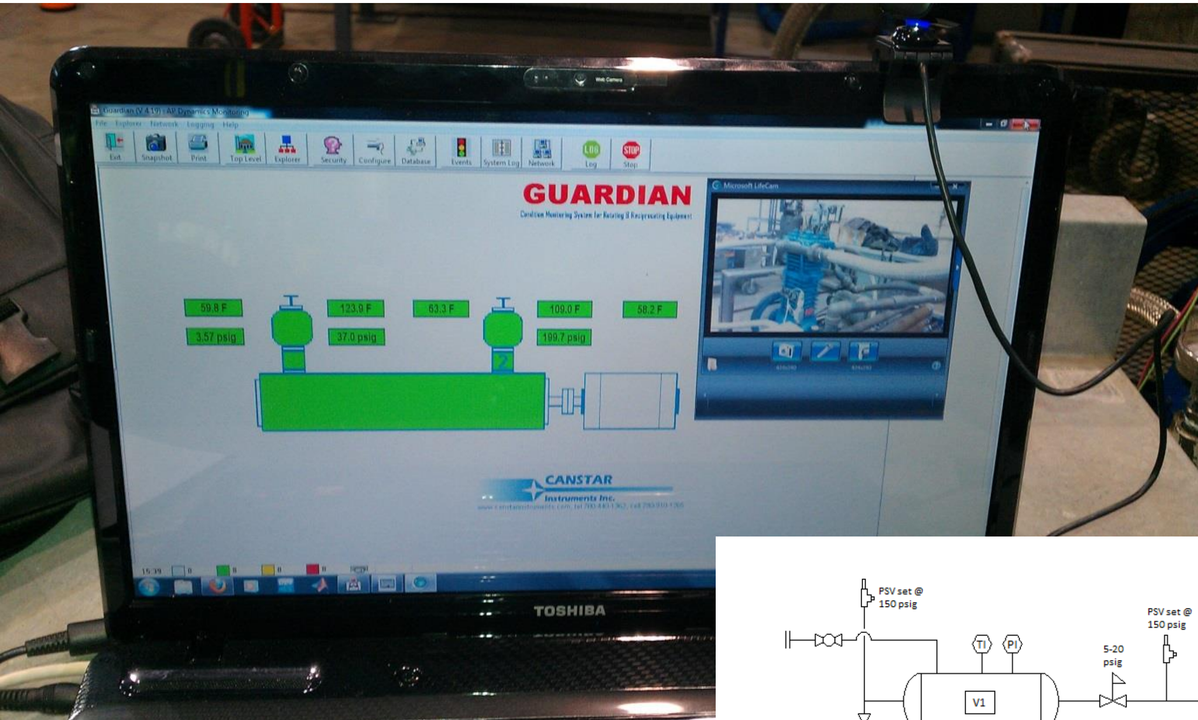


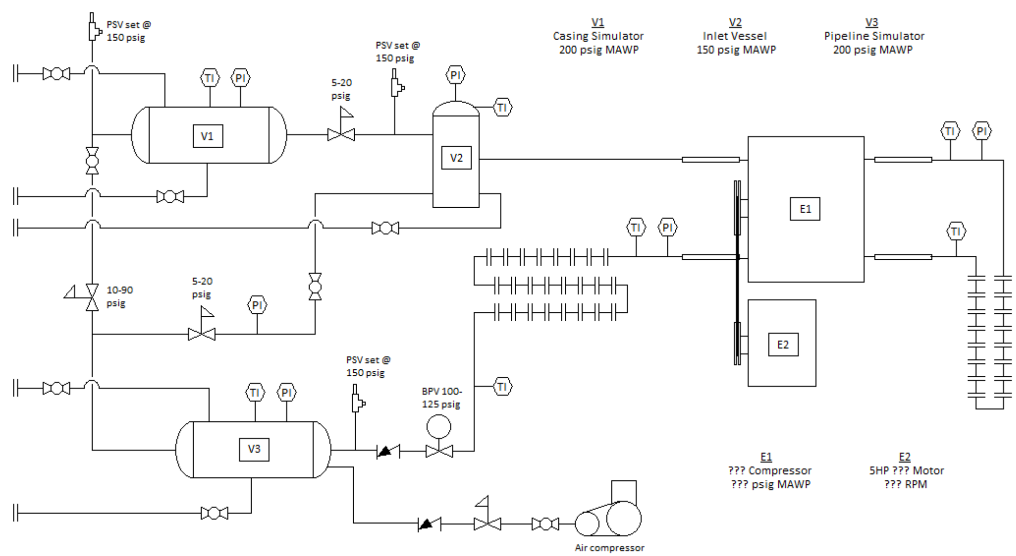




after: E. Mollasalehi, S. A. Zareian Jahromi, M. Forcinito, W. Hu, Q. Sun




GUARDIAN
59.8 F
3.57 psig
123.9 F
37.0 psig
63.3 F
109.0 F
199.7 psig
58.2 F
CANSTAR
Instruments Inc.
TOSHIBA


PSV set @ 150 psig
PSV set @ 150 psig
5-20 psig
V1 Casing Simulator 200 psig MAWP
V2 Inlet Vessel 150 psig MAWP
V3 Pipeline Simulator 200 psig MAWP
TI
PI
V1
V2
E1
E2
10-90 psig
5-20 psig
PSV set @ 150 psig
BPV 100-125 psig
V3
E1 ??? Compressor ??? psig MAWP
E2 5HP ??? Motor ??? RPM
Air compressor

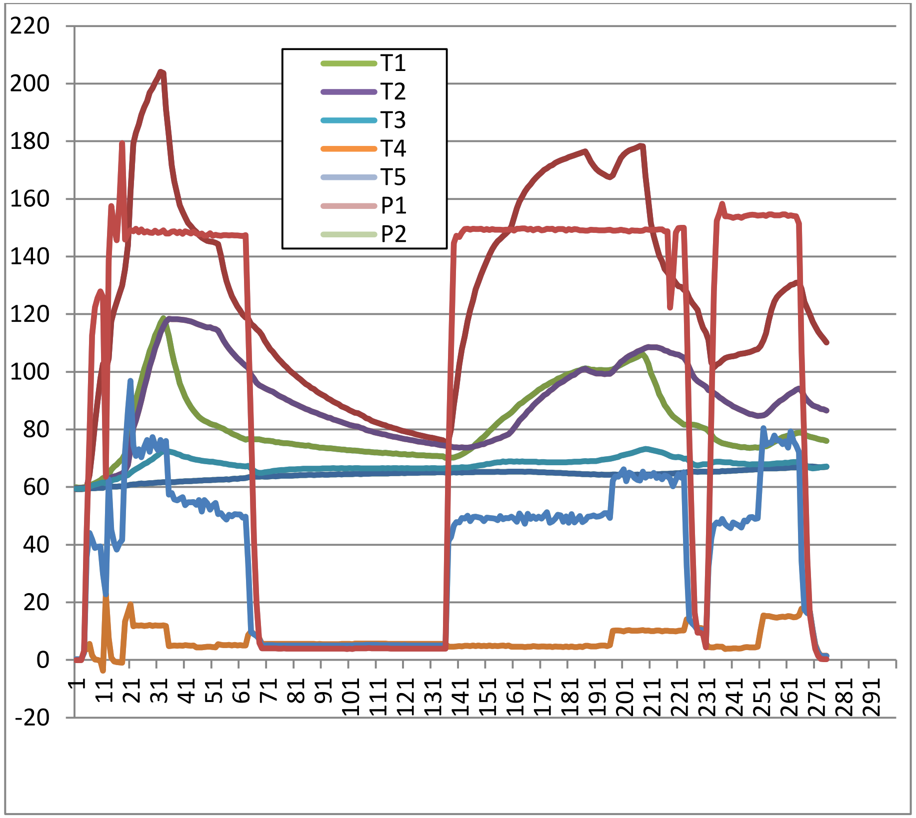


Figure 6: Typical collection of data over several days

The silicon revolution, Moore's law and the cheapening of electronics

Co-founder of Intel Gordon Moore observed that the number of transistor in a chip doubles, roughly, every two years and predicted that this trend will continue in the future. Since then, advances in chip-making have been closely following his prediction

1965

Prices of everything based on silicon wafers have been dropping at an average of 30% per year

It is feasible to generate huge amounts of Data from 'Computer' Simulations

Early Computer Unit

The cost of each computation remains constant or grows slightly over time

Modern Processor

The cost of each computation decays exponentially over time

The same can be said for Analysis of monitored machinery

Data Volume
1 channel sampled at 1000 samples /sec
6 bytes per sample
= 6 Kb/sec
x 32 channels
=192Kb/s
x 60 sec
=11.25 Mb/min

Typical file size for troubleshooting of a high speed reciprocating compressor = 0.62 MB/sec
(sampling at 2 Khz, 24 bit)

Sampling at higher rates and with more channels changes the volume proportionally

1 Mb: A small novel

2 Mb: A high-resolution photograph.

5 Mb: The complete works of Shakespeare

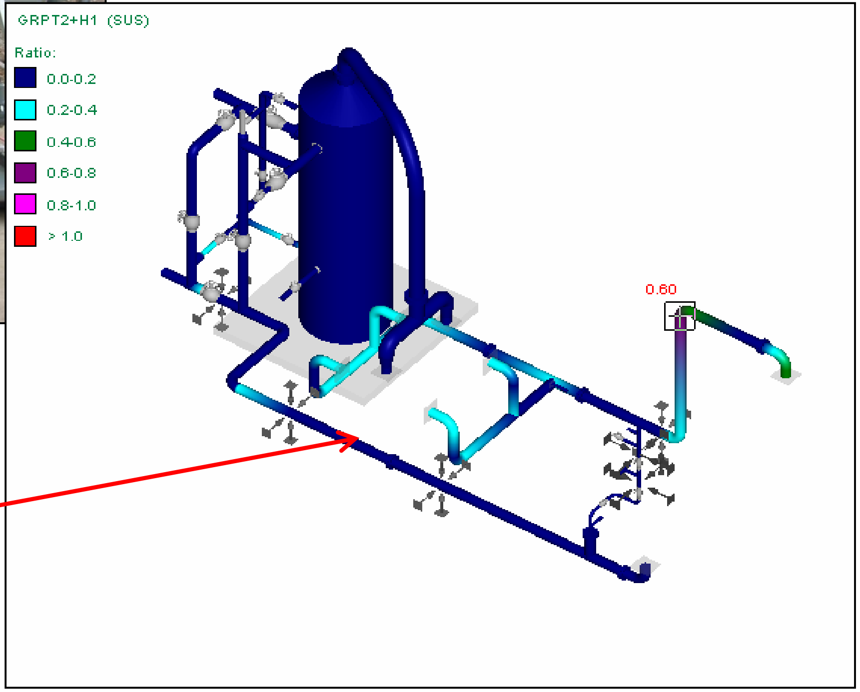
Where are we in the data volume ladder?

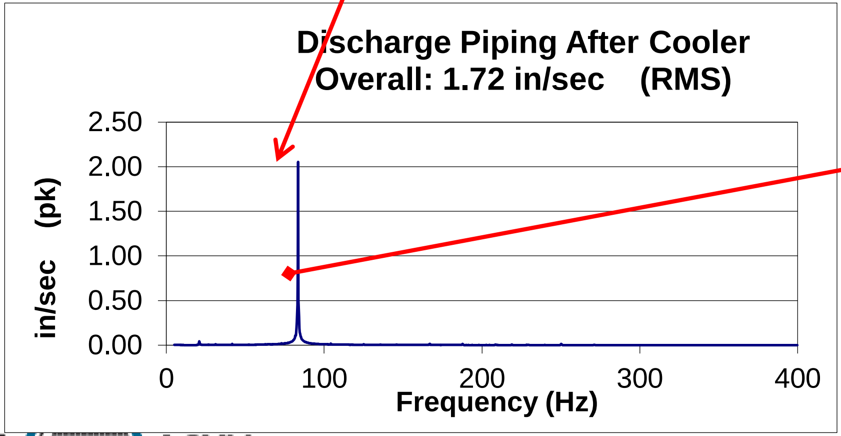
Kilobyte (KB)	***1,000 bytes OR 10^3bytes*** **-2 Kilobytes: A Typewritten page.** **100 Kilobytes: A low-resolution photograph.**
Megabyte (MB)	***1,000,000 bytes OR 10^6 bytes*** **1 Megabyte: A small novel** **5 Megabytes: The complete works of Shakespeare.** **10 Megabytes: A minute of high-fidelity sound.** **100 Megabytes: 1 meter of shelved books.**
Gigabyte (GB)	***1,000,000,000 bytes OR 10^9 bytes*** **1 Gigabyte: a pickup truck filled with books.** **20 Gigabytes: A good collection of the works of Beethoven.** **100 Gigabytes: A library floor of academic journals.**
Terabyte (TB)	***1,000,000,000,000 bytes OR 10^{12} bytes*** **2 Terabytes: An academic research library.** **10 Terabytes: The print collections of the U.S. Library of Congress.** **400 Terabytes: National Climactic Data Center (NOAA) database.**
Petabyte (PB)	***1,000,000,000,000,000 bytes OR 10^{15} bytes*** **1 Petabyte: 3 years of EOS data (2001).** **2 Petabytes: All U.S. academic research libraries.** **20 Petabytes: Production of hard-disk drives in 1995.** **200 Petabytes: All printed material.**
Exabyte (EB)	***1,000,000,000,000,000,000 bytes OR 10^{18} bytes*** **2 Exabytes: Total volume of information generated in 1999.** **5 Exabytes: All words ever spoken by human beings.**

Source:
HOW MUCH INFORMATION 2003? -Peter Lyman and Hal R. Varian
Project coordinator: Kirsten Swearingen - Berkeley University
http://www2.sims.berkeley.edu/research/projects/how-much-info-2003/execsum.htm

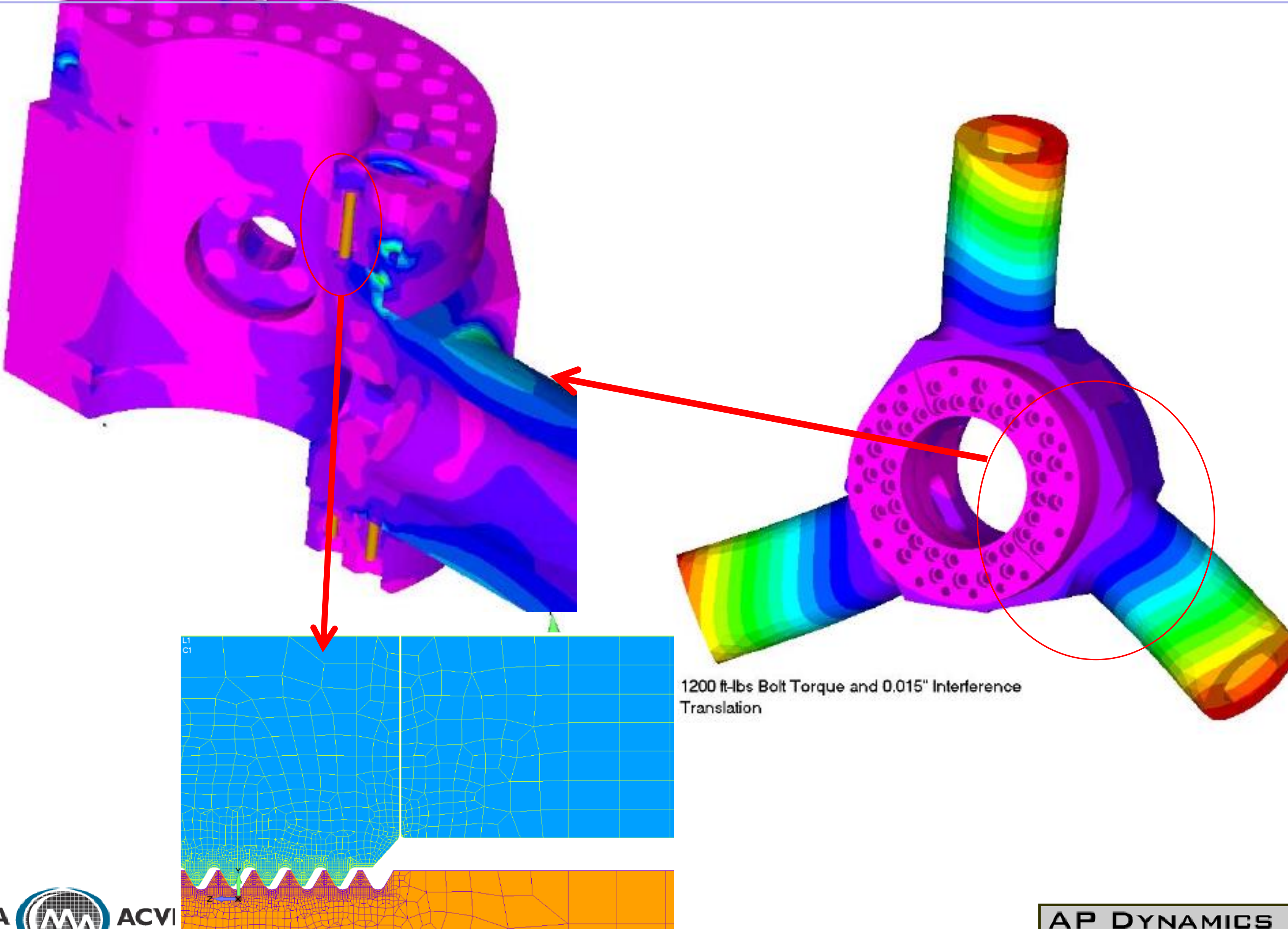
Model validation

Field measurements should be used whenever possible to validate modeling assumptions





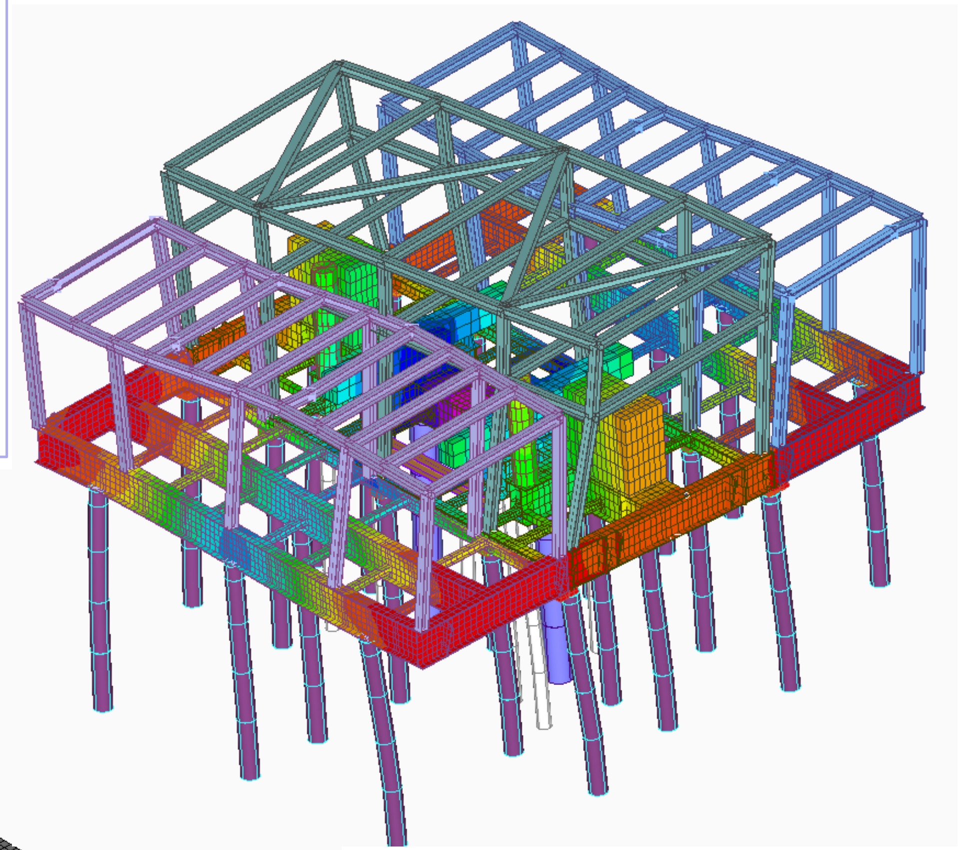
Where to stop? - Details

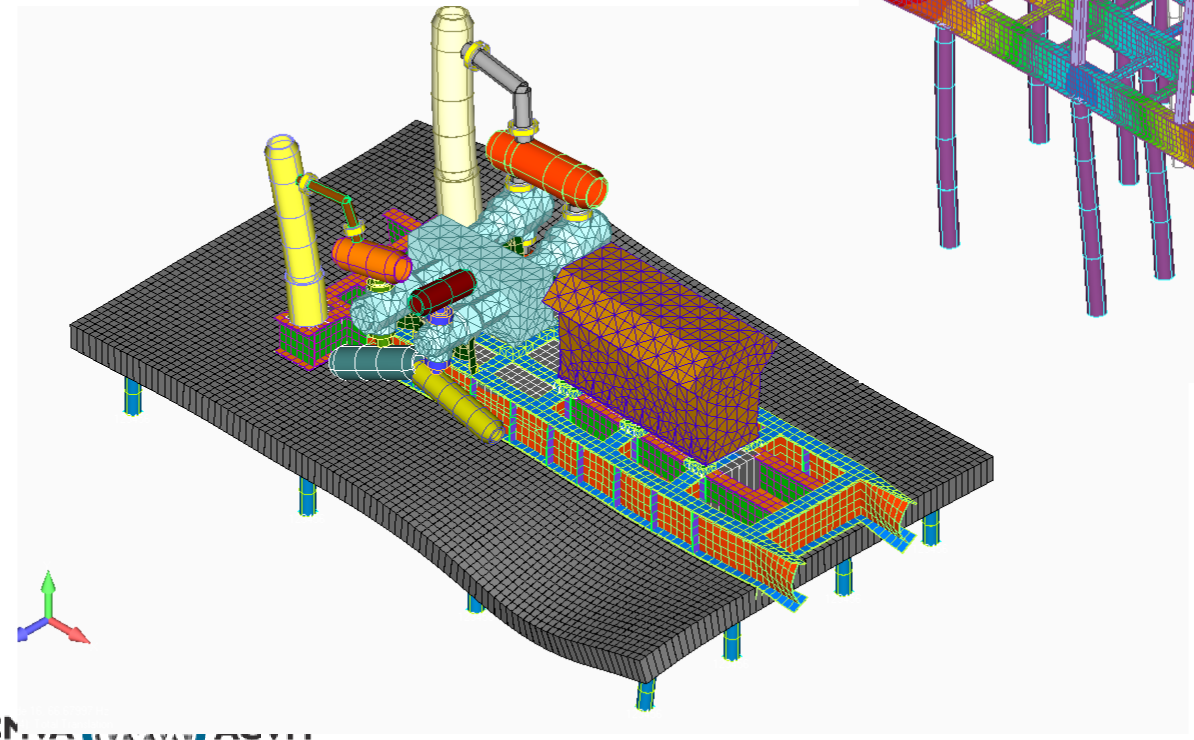


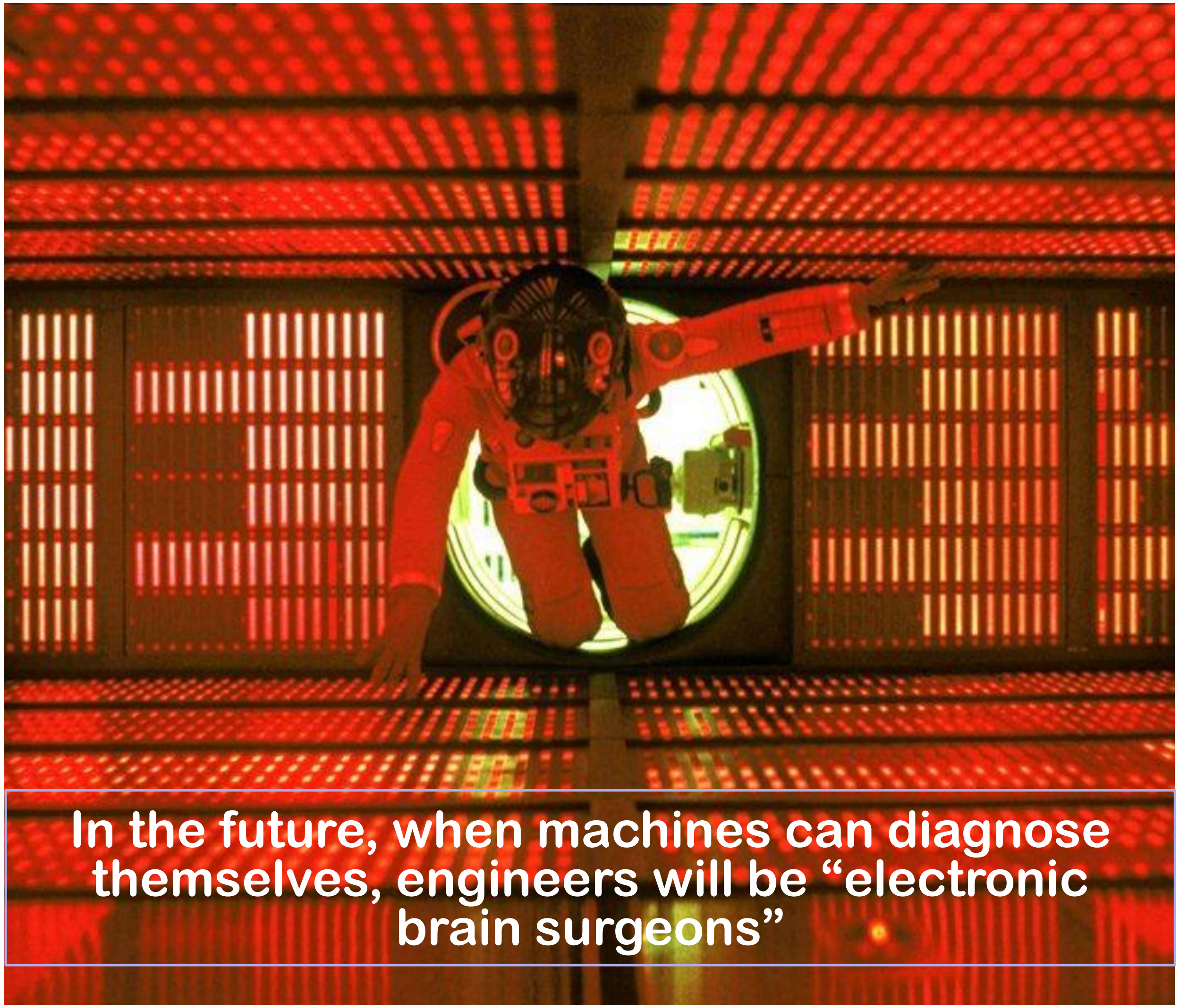
Where to stop? - Boundaries

One problem with the modeling of dynamical systems is to decide apply the boundary conditions.

Sometimes it is better to include the foundations rather than assume the boundary conditions.






In the future, when machines can diagnose themselves, engineers will be "electronic brain surgeons"

To wrap up:

We are swimming in an ocean of Data brought about by disruptive changes in technology dating from the 1940's

This is a new situation as Engineers used to have rather less and sparser data than the wished,

The same technologies that brought about the data deluge can be used to our advantage by enabling fast processing for display of relevant information, decision making and process control

Knowledge of appropriated modeling techniques and their strengths/limitations could make the difference between staying afloat or sink.

Thanks for your attention!