Future aspects of SHM

- OMA based SHM of course

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A philosophical talk

The Danish Physicist Niels Bohr say:
A researcher is a person who has made all kinds of mistakes in a narrow field

This talk is not about Science
This talk is ideas about using science – and other technologies

It consist of ideas, thoughts.. Whishes, hopes and postulates

We can only use ideas about science
If we work together

Much easier to co-operate in multi-disciplinary projects
We do not compete – we complement

Content

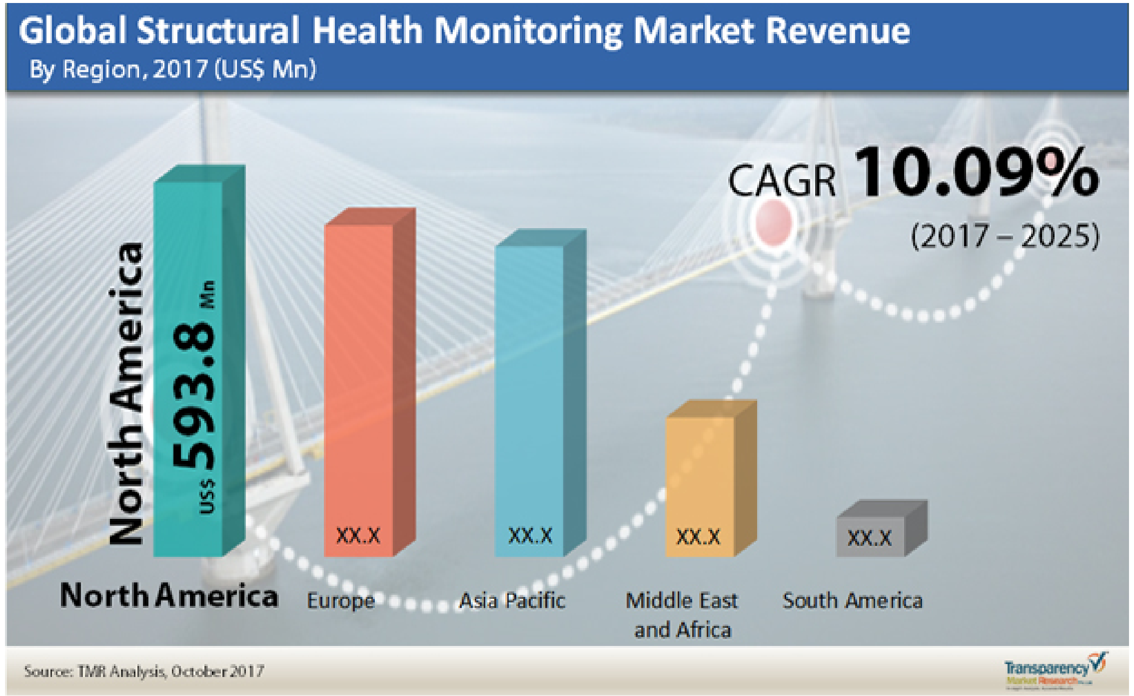
1. Market and status
2. Auto analysis
3. White and black swans
4. Information
5. Why we do this

- Conclusions?

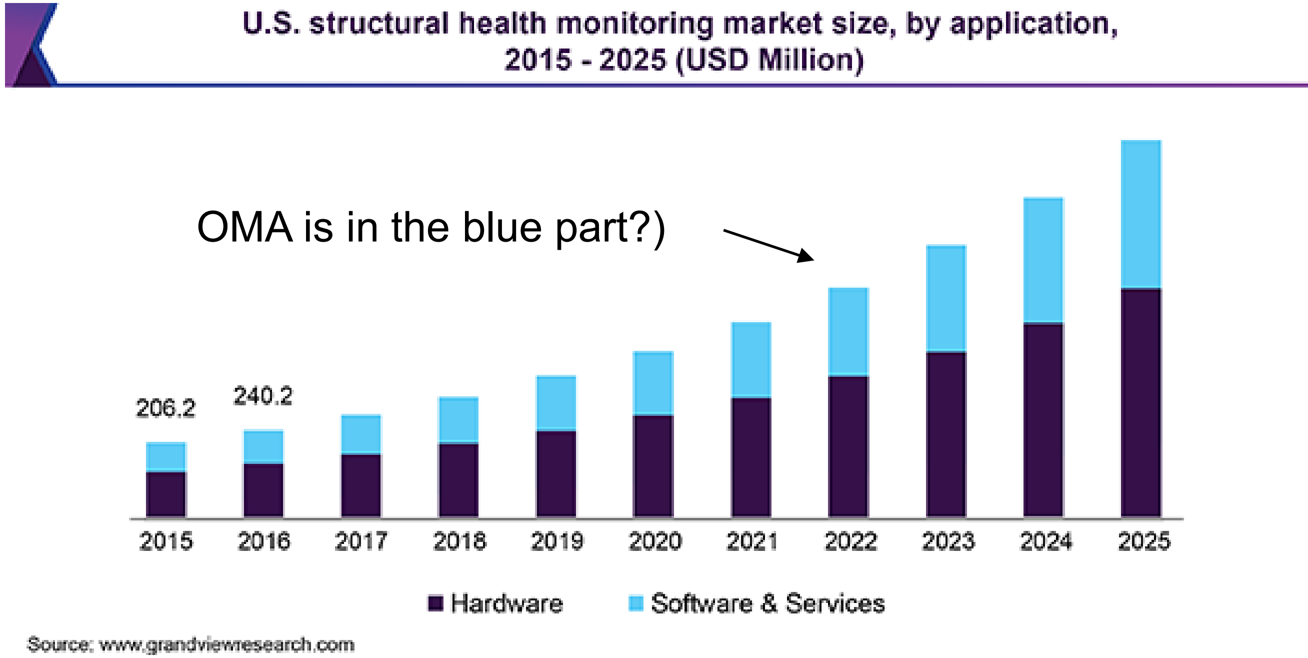
Market and status

- Market size and growth
- Scientific status
- Will OMA be included?
- Complexity of the problem
- Target of the final system
- Will I make it?

Market size and growth



Compound annual growth rate (CAGR)



OMA is in the blue part?)

Scientific status

Farrar and Worden (2007)

Rytter questions: 1-Existence, 2-Location, 3-Type, 4-Extent, 5-Prognosis

- We need a ***reference***, typically the virgin state of the structure.
- We need a ***model*** – to find out where the damage is located and how severe it is.

Brownjohn (2007)

SHM objectives: 1-Monitoring, 2-modification, 3-degradation (fatigue), 4-novel construction, 5-performance based design

- ***Mandatory*** demands play important role
- ***Special focus*** on dams, bridges, offshore structures, buildings, atomic plants, tunnels
- Novel ***sensor*** plays a role

Atkins (2009)

- Many different measurement ***techniques***
- Large frequency ***variation***
- 20 platforms WW using ***OMA***

NGI (2017)

- Many different measurement ***techniques***
- Good examples and ***illustrations***
- OMA based SHM ***mentioned***

[1] Charles Farrar and Keith Worden: An introduction to structural health monitoring. Phil. Trans. R. Soc. A (2007)

[2] John Brownjohn: Structural Health Monitoring of Civil Infrastructure. Phil. Trans. Math., Phys. and Eng. Sci. (2007

[3] Atkins: Structural integrity monitoring, RR685 report (2009)

[4] NGI (Norwegian Geological Institute): BSEE Offshore Wind Recommandations (2017)

Will OMA be included ?

The tendency

- More structures being monitored
- Many kinds of sensors being used
- Hundreds of signals acquired and stored
- Only a small fraction of data being used

=>

Big investment – small benefit

The chance for OMA

- Small and simple SHM system
- df = 0 => owner has peace
- Global damage measure
- Use all data – show it real time

=>

Small investment – big benefit

Postulate:

In the end nobody will be satisfied knowing a signal from a sensor in a single point

If they can know something about the structure in any point

Sensors are local – OMA is global

Complexity of the problem

OMA has to deal with

- Frequencies, damping mode shapes
- Non-linear and non-stationary systems
- Fatigue, yielding, cracks

And combine with

- Corrosion and other degradation data
- Manual inspections
- Environmental changes
- Modes that come and go

To provide information for

- Maintenance
- Hazardous situations
- Improved application
- Asset management

Target of the final system

We can only guess, but hopefully

- All data used
- Everything is automated
- Real time: On your screen - see the data that arrived 10 min ago
- Nothing on your computer – all in the Cloud
- Benefits taken into account up front (save steel)
- Use your structure to the limit
- It never fails (failure rate 10^(-4))

If SHM becomes a part of the design basis => Robustness becomes a key issue

Will I make it ?

In 1988 I started a project on Monitoring of offshore structures. Three PhD's:

- Identification: Jakob Laigaard
- Damage detection: Anders Rytter
- Optimal sensor placement: Poul H Kirkegaard

Bent Lyngberg question: Mr Brincker, if I do as you say, and install monitoring – how much can I save on the next structure?

In 1999 I started SVS together with Palle Andersen

- 2000 made the first manual ID for OMA
- I left SVS in 2008

In 2015 I published the OMA book with Carlos Ventura

In 2018 I started again in SHM

- At DTU we try to have a team of 3-5 young researchers
- Brincker Monitoring is working on a solution

Auto analysis

- Auto OMA important?
- Auto OMA - how (stability diagrams, narrow band)
- Auto updating
- Auto fatigue
- Auto force
- Auto environment
- Auto SHM ☺

Important ?

Why important?

Auto is very important because it makes information available

- real time
- At low cost

Example:

- Consider an OWT park with 100 WT's
- Data coming in 24/7 from all WT's, one data set/h
- I takes 1 h to analyze and document manually
- This then 300 full time engineers to do the OMA

So manual and nearly "real time" means enormous cost – this is why only a fraction of the data is being used.

What important?

It is important that the auto OMA is extremely robust to

- Allowed system changes (mass – friction)
- Changes in the loading (can be removed)
- Sensor malfunction

However, it also important, that if we have changes in the system that indicates a damage, then

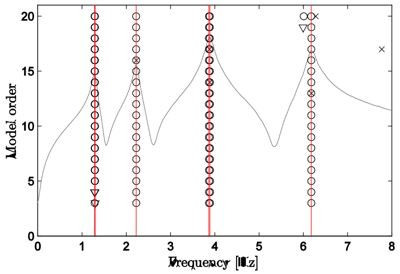
- We can perform a damage detection
- Information to make improved decisions

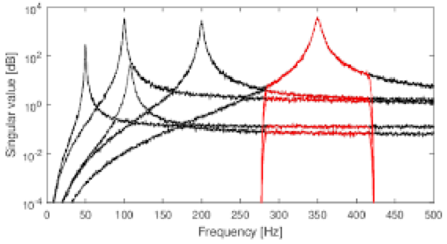
Auto OMA – and updating (Sandro)

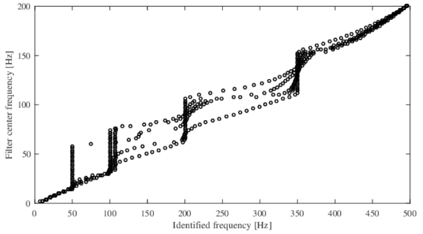
Properties of the structure

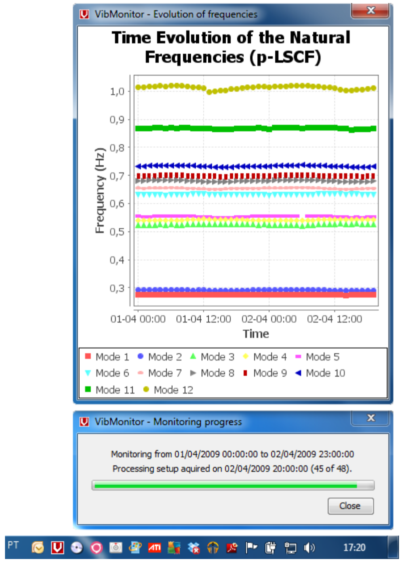
No time for manual..

- stability diagrams,
- narrow band
- Sliding filter





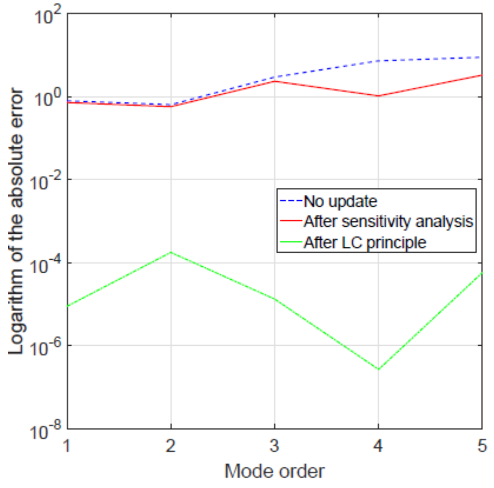




Properties of the model

No time for manual..

- Auto version of manual – remove the few big errors
- Perturbation based – remove the many small errors



With some luck – can we end with

90 %.. 95 %.. 98 % FE versus Test correlation?

Auto loading

Auto fatigue

Example:

- Decompose the response y(t) = A*q(t)
- Express exp. mode shapes A = B*T
- Expand response yx(t) = Bx*T*q(t)

So now we know displacement in all points, and we can then find the strains

We then have the real fatigue – that is normally 3-5 smaller than the design fatigue

=> **Life extension**

Auto force

Example:

- FD response y(f) =H(f)*x(f)
- Difficult to invert due to noise
- But it is easier mode-by-mode

Spatial distribution is not easy, but time function and total force might be good estimates

=> **Design optimization**

Auto traffic light

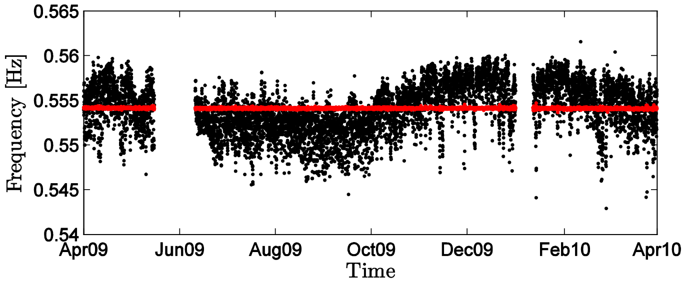
Auto environment

We need a model for how environment influence the modal parameters

- Temperature, humidity...
- Wind loads
- Wave loads
- Bridge loads
- Amplitude

And we need to report the SHM without the environmental effects

reference state



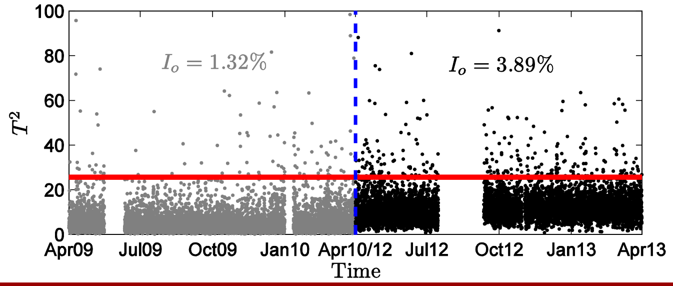
Auto SHM

In the reference state, we have to use classical statistics to see if the current state has deviated significantly from the past states.

We should refer to a **structural reference state,** but

We should allow an **acceptable degradation**

If this is OK – then green light



Sleep tight- you can be sure that everything is good

White and black swans

- Structure still OK?
- Hazards
- Damage detection

Structure still OK? (Evangelos)

This is the white swan situation – nothing seriously happened

- Maybe things are getting slightly worse, but it is expected
- Maybe we have a large change in the system properties, but we know why (empty a tank)
- Maybe we have different sources of nonlinear performance (bridge friction) but not related to actual damages

White swan definition:

Everything that we can expect/foresee or not to happen and may learn about from earlier monitoring data.

Everything that do not push the structure to abandon the realm of linearity and experience permanent and undesired changes (damages) in the system properties

Conditions for green light:

- Everything is as expected / No changes that degrade the performance of the structure
- We have no black swans – We have white swans

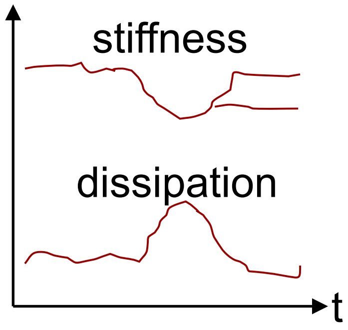
Hazards

Black swan definition:

- rare events of large importance (damage implication)
- beyond the realm of normal expectations and linear performance

The only thing we can say, is that if we have a non-linear material behavior where

- We have a softening (stiffness degradation, strength deterioration)
- We have an increased dissipation



Then, in principles, we can detect the nonlinearity and hence, damage, by, for example, a generalized time-frequency analysis or other damage detection techniques

For a real structure this can be investigated by combining advanced nonlinear simulation schemes and recorded data (if available) during the hazardous event

If we have a black swan, then we should flash the red light

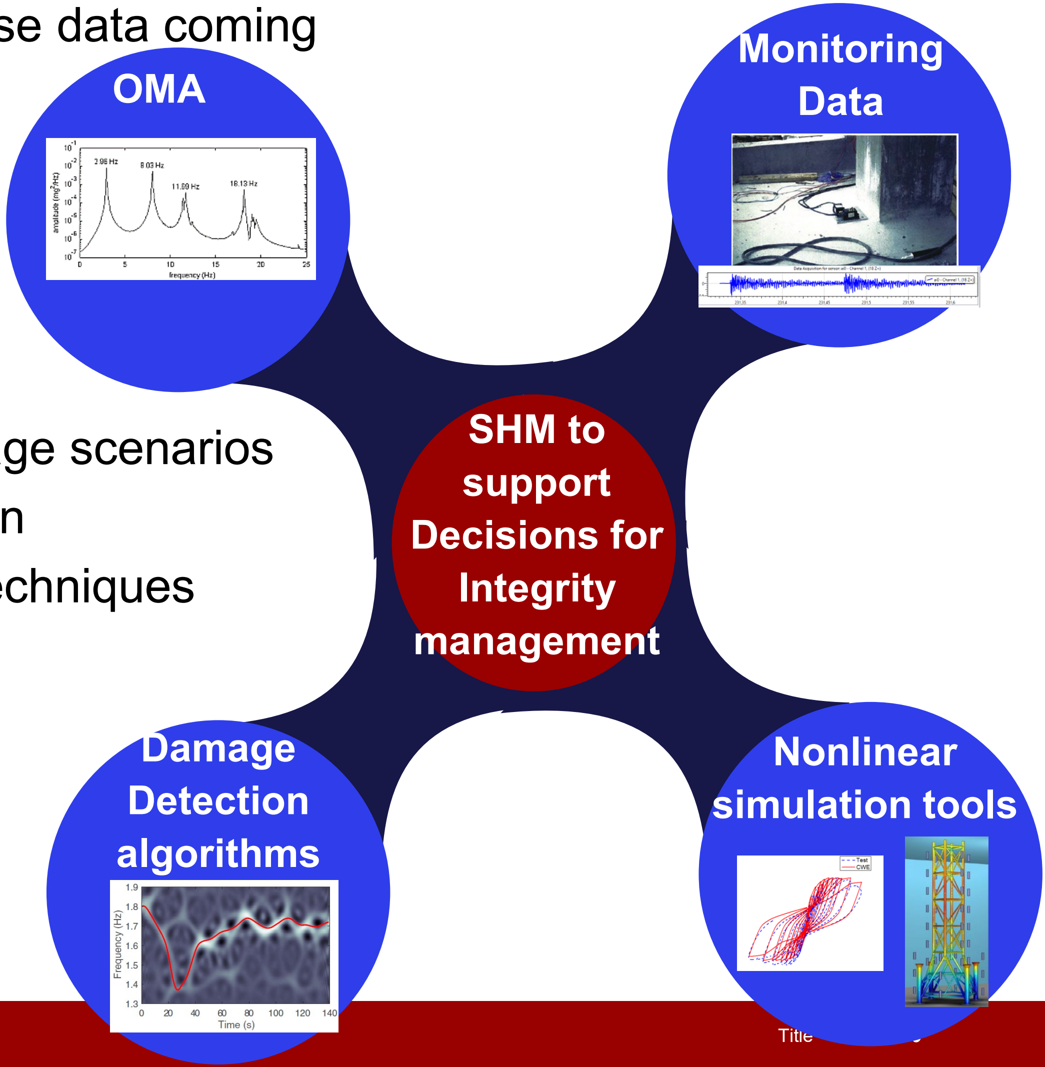
Damage detection

In case of slowly-accelerated changes:

- We have plenty of time to find the right explanation
- We can correlate data from inspections with load-response data coming both from monitoring campaigns and simulations

In case of sudden change:

- We have very little time to respond appropriately
- We have to rely on pre-investigations with simulated damage scenarios
- We have to make decisions based on the coupling between OMA-based system identification and damage detection techniques



Information

- Trust sensors
- Local/global information
- Inspections
- Better decisions
- Value of information

Trust sensors ?

Our experience

- Sensor noise and sensor failures
- Many different kinds
- Uncertainty in location and direction
- Wrong calibration information

How do we take all this into account?

How do we make sure that SHM still works if we loose sensors?

Can we make a SHM system that can work for 20 years?

Can we improve?

- Self calibrating sensors?
- Redundant sensor systems?
- Merging different sensors?

Possibility:

- Take advantage of correlation through the mode shape.
- Expand to un-measured point (virtual sensing)
- Get rid of faulty sensors
- Re-place when practical

Sensors are local – OMA is global

Inspections

OMA is

- Frequencies, damping, mode shape
- Using this to update the model
- Using the model to find loads and strains
- Use this in SHM

Reality is also

- Degradation like chemical reactions
- Corrosion and local damage
- Foundation settlements
- Change of ground properties

Good Information is when a balanced picture has been established

When Information from several sources has been merged and validated

Improved decisions (Guangli)

Situation B (Before)

1. We gather information I_B
2. We take decision
3. With value V_B

Situation A (After)

1. We gather information I_A
2. We take decision
3. With value V_A

Let us assume that we extend the amount of information with ΔI

So that $I_A = I_B \cup \Delta I$

Then the value of the added information ΔI

$$\Delta V = V_A - V_B$$

We need to well understand ways to do this

Why we do this

Benefits

By adding new information we can take better decisions – and gain more value:

If the added value is higher than the cost of getting the new information – then we will do it.

The only requirement is:

Quantify

Sustainability

We have to improve our procedures to become more sustainable – so that there is a world for our future generations

To know if we should replace a structure – or repair it…

Is being sustainable

Be informed

It is an ethical demand for us to be informed

Example: if you drive in the middle of the night without your front lights on – is this OK?

For us to do the right thing we have to use the information that is available

Conclusions ??

- Total have decided to use OMA-based SHM in the North Sea
- Large OWT operators are moving towards using OMA data
- Large consultant companies like Rambøll and COWI are now more open to use OMA based SHM

The Danish Physicist Niels Bohr say:

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→

We could say:

Let us be more multi-disciplinary and work more together to make this happen

- We have to search – before we can find
- We have to doubt – before we can believe
- We have to discuss – before we can agree