MULTI NON-LINEAR STRUCTURAL CONDITION MODELLING AND ASSESSMENT

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ABSTRACT

System identification methodologies have reached a mature state. Starting from mechanical engineering it quickly conquered civil engineering as well as aerospace applications. Damage detection has been the key topic of recent research work in this field. Learning from evolution of dynamic characteristic throughout the damage process, one can validate damage detection methods or set benchmark studies for typical aging processes of a structure. When dynamics gain a guiding role in the behaviour of a structure our conventional approaches fail. The influence of the various non-linearities can not be neglected anymore. This paper is determined to describe a number of these non-linearities and their embedment into the system identification procedure. The results show that changes of natural frequencies are clearly visible, but not a reliable identification approach. Identifying the non-linearities helps to identify damage at an early stage and enables even damage quantification, location and most important remaining lifetime prediction.

Keywords: Non-linear dynamic behaviour, system identification, damage detection, health monitoring

1. INTRODUCTION

Structural Health Monitoring (SHM) is a subject that has received considerable attention in recent years. Incidents such as the collapse of the I-35 Bridge in the U.S. give a clear indication of the importance of SHM. In practice, bridge assessment includes several measures, such as inspection, data interpretation, risk assessment and development of engineering recommendation.

For global structural assessment in particular, vibration monitoring (Wenzel 2005) has been widely used. The authors have been involved at the frontline of development of SHM in civil engineering and particular SHM of bridges (Wenzel 2009). Vibration characteristics captured from vibration monitoring provide global information on structural behaviours such as stiffness, connectivity, boundary conditions, mass distribution and energy dissipation. The basic principle of vibration based structural assessment is that structural performance changes from defects will create changes in the dynamic response that can be detected from the changes in the vibration characteristics. In other words changes in energy distribution, frequencies, mode shapes, vibration intensities and system damping can be used as indicators of the changes of physical properties of structures such as mass distribution, vibration energy contribution, stiffness, connectivity, boundary conditions and energy dissipation. Extensive works have been done on developing methods and algorithms for damage detection using vibration characteristics. Döbling et al (1996) present a comprehensive list of literature in damage detection, divided the detection algorithms into 4 levels of increasing complexity. They are:

- level 1 determination that damage is present in a structure,
- level 2 determination of the geometric location of the damage,
- level 3 quantification of the verity of damage, and
- level 4 prediction of the remaining service life of a structure.

2. MULTI-NON-LINEAR-SYSTEM-IDENTIFICATION

Many algorithms have been developed during the long period this methodology has been identified as being a promising tool. Most of it has been of theoretical or computational nature with finite element simulations as the key element. In parallel laboratory scale experiments were performed for verification. Large field tests became possible after the monitoring equipment reached a mature stage, PCs were introduced and the handling and storage of large quantities of data became feasible.

It quickly showed that the laboratory experiments can not be simply transferred into nature. The simple reason is that the influence from environmental and other sources is big enough to cover the desired information in unintended noise. It further has been found that these influences show a distinct non-linear character. In addition the combination of these non-linearities can almost show random patterns producing random looking results. This has led to a first frustration phase in the 1980th. With increasing knowledge on these phenomena a new wave of enthusiasm has reached the research community. The underlying MIMOSA project is determined to considerably contribute to this evolution.

The principle of the methodology shall be explained using the equation of motion. In a complex form it describes the dynamic behaviour of a structure.

$$[m]\{\ddot{z}\}+[c]\{\dot{z}\}+[k]\{z\}=F \tag{1}$$

where m represents the mass matrix, c the damping matrix and k the stiffness matrix of the system.

The non-linearities observed in nature can be linked to some of its particular elements.

2.1. Change of Temperature

The first and most basic effect on a structure is the change of temperature. Temperature influences the stiffness of a structure by altering its material properties particular the Young's modulus but also on smaller scale its geometry. Linked to that, a change in boundary conditions might happen. The simplest form would be the linear change of the stiffness matrix over time. The stiffness matrix k in equation (1) has the form

$$k=\begin{bmatrix} k_{11} & k_{12} & \cdots & k_{1n} \\ k_{21} & k_{22} & \cdots & k_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ k_{n1} & k_{n2} & \cdots & k_{nn} \end{bmatrix}. \tag{2}$$

In large structures we observe the fact that non-linearity not only develops over time but also over location. This means that the elements of the stiffness matrix might develop non-linear relationships depending on temperature changes due to radiation from sun on particular local scale. This might add a torsional effect, changing the structures geometry and stress level. Despite the complexity of this phenomenon modern finite element simulations are able to deal with it reasonably.

2.2. Added Mass

The main purpose of bridges is to enable transportation. This brings considerable added masses to the structure. These masses are furthermore moving at various speeds producing a non-linear interface relation due to the vehicle suspensions. At small structures, where the own weight of bridge compared to the added mass is low this effect might dominate the entire behaviour.

At large structures the volume of air captured in the box of a bridge can not be neglected as lesson learned from bridge aerodynamics. These non-linearities are residing in the 1st term of our equation. The vehicle interaction can be alternatively expressed in the right side of the equation.

$$m\ddot{z}+c\dot{z}+kz=F(z,\dot{z}) \tag{3}$$

It is needless to say that a good solution to this problem can only be found if online information on traffic, which has to be classified, becomes available. This is a considerable challenge for the monitoring community.

A typical example of a lively bridge is given below. One graph shows the unprepared result representing all influences from traffic and the other is the cleaned result after simulation.

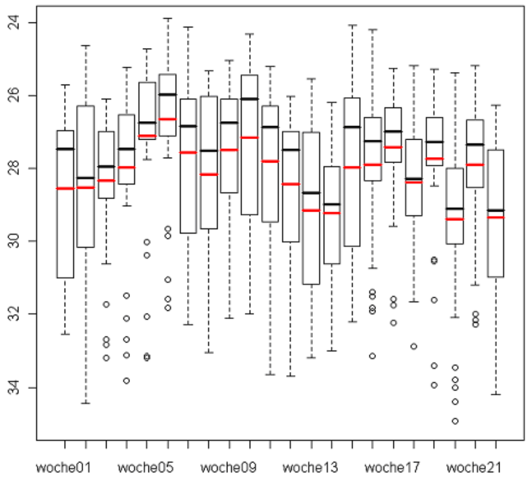

Figure 1: Bridge Performance unprepared

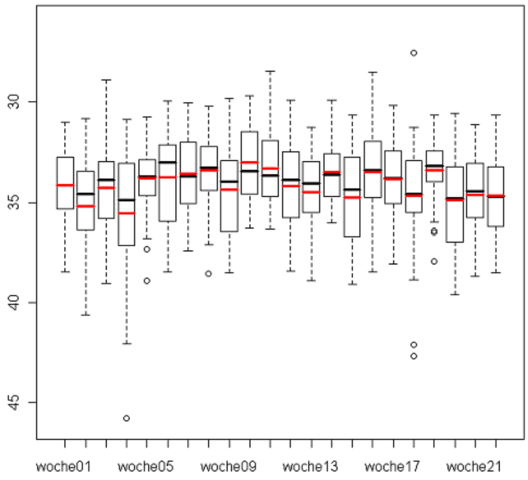

Figure 2: Bridge Performance cleaned

2.3. Material and Structural Aging

Knowledge has been collected by VCE over the thousands of monitoring campaigns performed in the past 12 years. The character of a spectrum changes not only when damage is present, but also due to aging effects. It is no surprise that this is more expressed in concrete structures than in those using any other material. High focus has been put on post-tensioned concrete structures in the past due to their complexity and importance within our transportation networks. This produced huge amounts of data and resulting knowledge.

The performance of concrete over time (aging) is well defined. Nevertheless the exposure creates considerable uncertainties. The bridges in the alpine regions are particularly exposed to an attack of salt used for de-icing. Carbonation is also highly non-linear and exposure dependent. The dependency on exposure can be handled in the stiffness matrix in case that a respective constitutive law can be formulated properly. How drastic exposure contributes to non-linear behaviour of structures has been demonstrated through the various permanent monitoring campaigns performed. At the Gossensass Bridge on Brennero Autostrade in Italy 2 equal structures are placed side by side. The performance of the one exposed to sunshine from the west is entirely different from the one residing in the shade. A considerable difference on quality has been found in these 40 years old structures. Exposed to the same air temperature the difference between the carriage ways south and north is considerable as shown in the next figure.

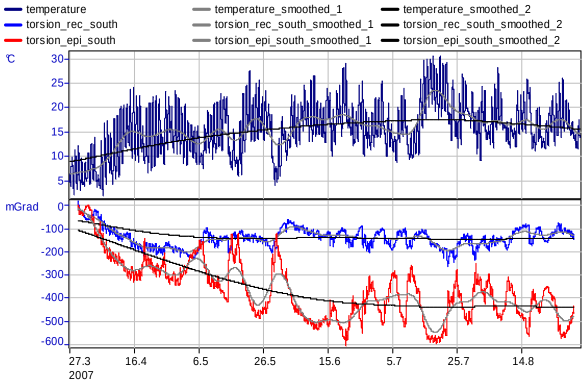

Figure 3: Different response of equal structures due to exposure

2.4. Non-Linear Damping

This most complex phenomenon has turned out to be a promising approach towards structural health monitoring. This phenomenon seems to be much more sensitive to damages than any expected reduction of stiffness. From large scaled damaging tests it has been found that there is a relationship between the amplitude of the fundamental frequencies of a structure and the damage state. Reduced amplitudes normally show a broader peak which implies increased damping (referring to a simple half power band widths approach).

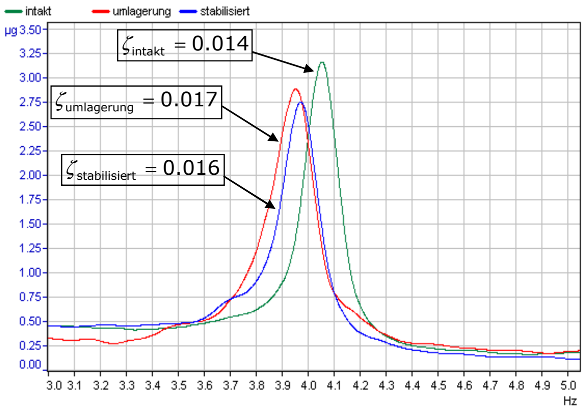

Figure 4: Change in amplitude with damage and related damping value

Targeted laboratory tests (SAFE PIPES Project FP6 STRP-013898) showed a phenomenon which we called energy cascading with the increasing non-linearity of the dynamic system.

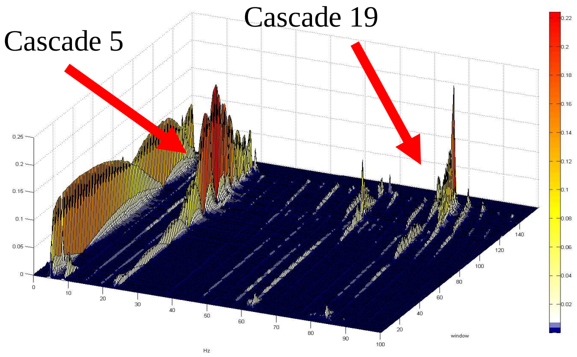

Figure 5: Energy cascading with damage (SAFEPIPES test at MPA Stuttgart)

Cascading energy transfer in a dynamical system could be caused by the development of nonlinear characteristics of the structural response caused by various reasons.

Suppose there is a development of nonlinear mechanism in both damping and stiffness of the structure, whose dynamic behaviour is simply expressed by a SDOF model, associated with the progress of a structural damage. It can be typically represented in the equation of motion by modifying both damping and stiffness terms as follows:

$$m\ddot{z} + c[1+\varepsilon_2(z)]\dot{z} + k[1-\varepsilon_1(z)]z = 0 \qquad (4)$$

where ε_1 and ε_2 are the nonlinear terms introduced corresponding to the development of structural damage and $z(t)$ represents the dynamic response of the structure in general. Eq.(1) can be rewritten as

$$m\ddot{z} + c\dot{z} + kz = k\varepsilon_1(z)z - c\varepsilon_2(z)\dot{z} = F(z,\dot{z}) \qquad (5)$$

where $F(z,\dot{z})$ is generally a nonlinear function of z and/or $\dot{z}$, such as

$$F(z,\dot{z}) = C_1 z^2 + C_2 \dot{z}^3 \tag{6}$$

for example. It implies that if z is given as a vibration with frequency ω, $F(z,\dot{z})$ is generally a function of fluctuations with the frequencies expressed by the multiples of ω. For example, substitution of $z = A\sin\omega t$ to (3) results in

$$F(z,\dot{z}) = \frac{C_1 A^2}{2}\left(1-\cos 2\omega t\right) + \\ + \frac{C_2 A^3 \omega^3}{4}\left(3\cos\omega t + \cos 3\omega t\right) \tag{7}$$

which in turn will result in the dynamic response including functions of twice, thrice higher frequencies of the original for this case. The same process will be repeated as time allows and, as a result, a part of the system's dynamic energy will be gradually distributed to higher and higher frequency range.

Where would this process end? For the case of damage-caused nonlinearity, the high frequency energy components dissipate as heat or noise and, if not, the destruction or rupture of the structure plays a roll. Even if it does not reach the destruction point, the mechanism of structural response will change largely when damage progressed.

An example from the damage test at the S101 Bridge in Austria is provided below. It shows the results of above described algorithms for the 2 damages introduced during this demonstration within the IRIS Project (FP7 CP-IP 213968-2).

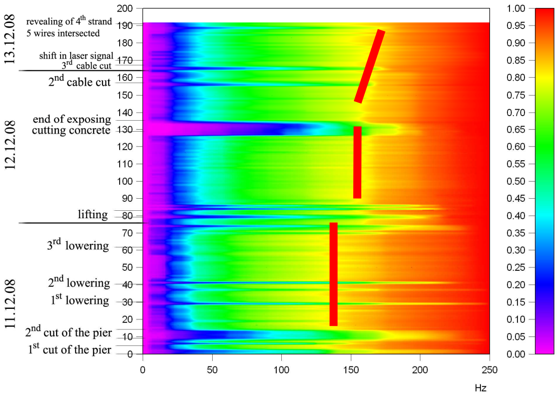

Figure 6: Simulation S101 with damage (IRIS test at A1, Austria)

3. THE MIMOSA PROJECT

MIMOSA is determined to develop necessary models to allow online updating of the multi non linear behaviour of our infrastructure. The product should be a Modeling and Simulation Tool Box able to provide the user with all the necessary information.

The current practise shall be considerably enhanced through expertise in multi non linear modelling solutions with the necessary mathematical formulations in the background.

The Finite Element Model Updating (FEMU) is a model based numerical technique used to minimize the differences between a real structure and a FE-model. The basic idea is to use the recorded structural response to update some selected structural parameters of the numerical model (such as stiffness, mass and internal forces) as well as some boundary conditions (such as translational or rotational springs), until an adequate agreement between numerical and experimental results are achieved. The resulting structure presents a better dynamic agreement with the physical reality. Moreover, the parameter distributions obtained as outcomes can provide useful information about the possible structural damage.

The physical explanations are partly offered in the literature, energy cascading is one of these solutions and shall be explained further.

3.1. Structural Nonlinearity and Energy Transfer

Cascading energy transfer in a dynamical system could be caused by the development of nonlinear characteristics of the structural response caused by various reasons.

A development of nonlinear mechanism in both damping and stiffness of the structure is often associated with the progress of a structural damage. In the description of structural vibration, it can be typically represented by additional nonlinear correction terms introduced to damping and stiffness terms. It implies that if a simple harmonic oscillation of the structure takes place with certain frequency, whatever the reason is, the vibration will soon become mixed with higher frequency components generally expressed by the multiples of the original frequency. This process will be repeated as time allows and, as a result, a part of the system's dynamic energy will be gradually distributed to higher and higher frequency range.

3.2. Nonlinear Damping

Energy cascading can be associated with various types of nonlinear physical phenomena. Another example of it is typically observed in dynamics of turbulent fluid flow. In fact, the case of fully developed turbulence, the energy cascading process is one of the most central issues. Relationship of energy cascading with nonlinearity of dynamical systems is therefore evident in these two different phenomena.

A very interesting aspect of this point is that the detection of energy cascading could be potentially utilized as a tool for the structural health monitoring.

The traditional idea of knowledge-based structural health monitoring is by identifying the reduction of stiffness, which has been proved to be far less sensitive than desired for practical purposes. In contrast to that, by finding the transfer of dynamic energy to higher frequencies through spectral analysis of the ambient vibration survey, it may be possible to detect the damage development in a structure at its earlier stage. Any extent of structural damage can of course change the local structural damping or energy dissipation and stiffness. As a consequence, the global dynamic properties of the structure, i.e., the eigen-frequencies, mode shapes and modal damping would be all somewhat influenced.

It needs to be kept in mind that structural nonlinearity is attributed, however, not only to developing damages. Field experience indicates that the magnitude of modal damping is often amplitude dependent. Increase of damping, when the vibration amplitude is significant, is due to energy consumption at increased friction at bearings, bending action of piers, behaviour of the bridge outfitting and also the structure-vehicle interaction.

Admittedly the present method would also detect the developing structural nonlinearity due to large motion. However, if there is a development of structural damage as its consequence, the nonlinear characteristics will remain with the structure after the large amplitude motion disappeared and should be thus detected.

3.3. Progress in the Proposed Project

The method described above has been experimentally applied to some bridges to investigate how effectively it can be employed for identifying the existence of structural damages. Sample structures chosen for this experimental project include ordinary healthy bridges, bridges with progressive deterioration, and also some bridges that were to be demolished. For the case of the last category, the structure was given artificial damages before their demolition and its influence on their dynamic behaviour was examined. The identification of the energy cascading phenomena was performed by time-limited spectral analysis of acceleration data obtained by a standard BRIMOS ambient vibration survey, which has been established by VCE. An ideal condition for this measurement would be when the structure is excited by micro tremors, which can be regarded as white noise excitation. It would be even better if the measurement was continued for a while under the same conditions. However, the reality is often not under such conditions.

Spectral analysis of the vibration record has clearly indicated that dynamic energy tends to be gradually transferred to higher frequency range when structural damages exist. The most fundamental principle of this measurement has been thus confirmed. This was evidenced particularly clearly when the structure was artificially damaged and measurement was carried out under rather ideal conditions, namely without being disturbed by the on-going traffic loads directly on the structure.

When the vibration was measured with the structures under service conditions, on the other hand, the measured data were much contaminated, as expected, by direct excitation due to traffic loads. The energy transfer due to possible structural nonlinearity, hence, needs to be carefully concluded by somehow subtracting the effects of traffic load excitation. A few different approaches have been tried out but the work is still continuing at this point in time.

4. OUTLOOK

The described non-linearities do not comprise the entire subject in its full complexity. Further non-linearities are to be considered until a closed solution can be offered. These are among others:

- Non-linear changes of the boundary conditions
- Dynamic effects from wind loads
- Earth tide effects on large structures particularly in steep valleys
- Strain from external phenomena, i.e. creeping slopes
- Other influences not yet identified

Out of the simple finite element model a most complex, multi-dimensional simulation is to be developed in order to describe these phenomena properly. A major problem is the combination of the single non-linearities which might lead to extinction resulting in difficulties for identification. Monitoring results provide us the complex system without good ways for isolation of the single phenomena. It will therefore be continuously necessary to search for well expressed non-linearities, trying to establish them in a well controlled laboratory test and subsequently formulate the laws for modelling and simulation. We still see a long way to go until numerical simulation alone can deal with these circumstances.

In the recent years a database containing 1200 structures with more than 4 million measurement files has been erected. It will be tried to apply case based reasoning routines to identify single phenomena out of this extension knowledge base. A breakthrough in identification could be expected.

A further subject of interest will be the online application, where well defined structures equipped with a suitable monitoring system run a numerical simulation online permanently. The final target will be an online risk assessment tool enabling the operators of the structures to see an actual status anytime.

ACKNOWLEDGMENTS

The MIMOSA project is an Austrian National Research Initiative called MOD-SIM initiated by the Austrian Ministry of Infrastructures (BMVIT) and handled by the Austrian Research Promotion Group FFG. It provides the basis for the theoretical works carried out.

The extensive monitoring and testing campaigns in the field and the large laboratories are performed under the European Research Project SAFE PIPES (FP6 STRP-013898) in the 6th framework program and IRIS (CP-IP 213968-2) in the 7th framework program of the European Commission. Without this valuable support from the European Commission and the National Science Foundation this complex work would not have been possible.

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